Effect of Hidden Terminals on the Performance of IEEE 802.11 MAC Protocol

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Abstract

The hidden terminal problem is unique to wireless networks and as of now, there is very limited understanding about it's effects on network performance. Results are presented from a simulation study of the IEEE 802.11 MAC protocol when operating in the presence of hidden terminals. We also propose a framework for modeling hidden terminals which can handle complex scenarios of both mobility and static obstructions. Our simulations indicate that hidden terminals can have a very detrimental effect on the performance of the IEEE 802.11 MAC protocol. Although throughput is acceptable when about 10 percent of station pairs are hidden, packet delay can increase by an order of magnitude. Performance of the protocol drops sharply when the number of hidden pairs exceeds 10 percent.

1. Introduction

Wireless Networking is one of the fastest growing areas in the network industry today. Wireless Local Area Networks(WLANs) are gaining special interest as they provide flexibility of location along with low infrastructural and maintenance costs. Of late only proprietary solutions for WLANs were available, but with the adoption of the IEEE 802.11 MAC and physical layer standards, WLANs are expected to become more ubiquitous.

Wireless communications are inherently error prone and introduce greater concerns for security and human safety. Wireless links are less reliable, more susceptible to fading and interference and have a limited bandwidth due to scarcity of the radio spectrum. Communicating hosts can be mobile, and maintaining connectivity without loss of performance is a challenge. Several new issues must be considered in WLAN MACs [2] which are not important in their wired counterparts:

1. A station cannot transmit and sense the channel at the same time. This is because the receiver is overwhelmed by the transmitting power of it's own transmitter. Hence MAC protocols like CSMA/CD, which were applicable for wired networks, cannot be used.

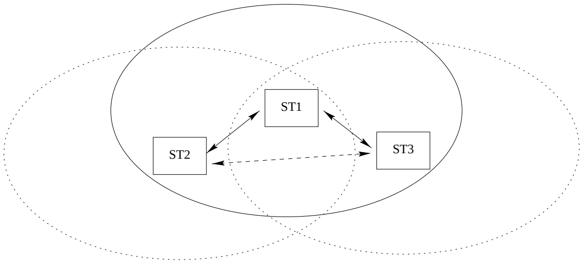

Figure 1. Hidden terminal problem

2. Due to signal fading and attenuation, transmission of a station may not be heard by another, ie. it is *hidden* from the first station. As shown in figure 1, ST1 can communicate with both ST2 and ST3 but ST2 and ST3 are hidden from each other. Thus two stations hidden from each other have a different view of the channel state (busy or idle). Collisions can result if two stations hidden from each other, both believing the channel to be idle, try to simultaneously transmit to a common destination.

3. Maximum channel utilization can be achieved by allowing multiple users to contend for the same channel, but this results in degradation of Quality of Service (QOS). With the advent of multimedia applications, there can be strict QOS requirements for data. In wired networks QOS can be supported by providing more bandwidth, but this is not possible in WLANs as the radio spectrum is limited. Thus support for QOS at the MAC layer becomes necessary.

In this paper we present simulation based results for the performance of the IEEE 802.11 MAC protocol operating in the ad-hoc (DCF) mode, in the presence of hidden terminals. We propose a structured scheme for modeling hidden terminals in a WLAN. While the DCF operation of IEEE 802.11 has been studied by several researchers [1] [3] [4] [7], they have either ignored the effect of hidden terminals or proposed trivial ways of modeling them. We model the geographical area of a WLAN as a mesh of hexagons and evaluate hidden terminals caused by both mobility and static obstructions. Our simulations show, that throughput is acceptable when the number of hidden pairs is less than 10%, but can fall sharply with an increase in the number of hidden terminals. The blocking probability increases with an increase in the number of hidden terminals but the average packet delay is the worst affected and increases by an order of magnitude, even under moderate hidden terminal conditions. The use of the RTS/CTS mechanism results in an improvement in both throughput and delay with best results obtained when RTS/CTS is used for each frame, regardless of it's length.

The rest of the paper is organized as follows. In Section 2 we give an overview of the IEEE 802.11 WLAN specification for MAC. In Section 3 we present our hidden terminal model which is followed by the simulation model in Section 4. In Section 5 we present results of our simulation and close the paper with a conclusion in Section 6.

2. IEEE 802.11 MAC Protocol

The IEEE 802.11 WLAN has a hierarchical architecture with the fundamental building block known as the Basic Service Set (BSS). A set of stations residing in a certain geographical area (known as the Basic Service Area(BSA)), communicating with each other using the same coordination function (DCF or PCF) form a BSS. All transmissions by stations in a BSS are broadcasts, and should conceptually be heard by all other stations in the BSS.

Three different types of frames are supported: management, control and data. The management frames are used for timing and synchronization, and authentication and deauthentication. Control frames include positive acknowledgments. Data frames handed down from the LLC to the MAC may be fragmented if they exceed a threshold value *Fragmentation_threshold*. Each fragment MPDU formed from the fragmented MSDU, other than the last, is of length *Fragmentation_threshold*. In Point Coordination (PCF) mode polling occurs with a point coordinator determining which station has the right to transmit. In the Distributed Coordination Function (DCF) mode, a BSS operates as an ad-hoc network in which any station can communicate with any other station in the BSA without the intervention of a centralized access point (AP) by contending for a shared channel. All stations have equal priorities and hence an equal chance of getting the channel.

The DCF is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). As stated earlier, Collision Detection (CSMA/CD) cannot be used because a station cannot transmit and listen to the channel at the same time. This increases the cost of a collision in the system because a station cannot detect collisions until it has transmitted the entire frame. There is also a greater vulnerability to collisions due to the presence of hidden terminals in the system as two stations hidden from each other may concurrently try to send data to another station which is not hidden from either of them. Hence various mechanisms incorporated into the protocol to either avoid collisions, or to minimize the penalty on system performance when a collision does occur are :

1. The time at which a station can start transmission is slotted. This ensures that a collision takes place only when two stations start transmission in the same time slot. In order to avoid simultaneous transmissions, each station executes an exponential back-off procedure whenever it has a frame to send and senses the channel to be idle.

2. Positive acknowledgments are implemented along with a timeout mechanism. Acknowledgment frames enable a station to determine whether it's transmission was successful or not, since it cannot detect a collision otherwise.

3. The protocol implements a concept of Virtual Carrier Sensing in which a frame carries the transmission duration of succeeding frames, in it's header. Each unfragmented data frame carries the duration of it's acknowledgment in it's header. Fragment MPDUs carry the time that succeeding fragments will take to transmit. All stations listening to a frame set their Network Allocation Vector(NAV), equal to the duration value. Stations start contending for the channel only after their NAV elapses and they physically sense the channel to be idle. This ensures that stations do not contend for the channel while a transmission is in progress.

4. There is a high penalty for collisions between long data frames. As a station cannot hear collisions, it continues the transmission of a frame even when there are simultaneous transmissions. This results in wastage of bandwidth. To overcome this problem, control frames namely Request to Send (RTS) and Clear to Send (CTS) have been introduced. If the length of a data frame is greater than a preset RTS Threshold, the station sends an RTS, reserving the channel for the following data frame by setting it's duration field to the time it would take to transmit the long data frame. All stations hearing the sender set their NAVs to this value and the destination responds with a CTS, which again

carries the duration information. All stations hearing the destination again set their NAVs and once this pair has been exchanged, the stations are assured of having no collisions. Since all stations set their NAVs both for the RTS and CTS frames, it helps combat the hidden terminal problem as it is likely that a station will hear the CTS even if it is hidden from the station sending the RTS or vice versa and will not try to transmit during the period

5. Frames have a prioritized access to the channel. Highest priority is given to acknowledgment, CTS and Fragment frames, which wait only for a Short Inter Frame Space(SIFS) duration before accessing the channel. Other frames like Data and RTS have to wait for a DFS-IFS(DIFS) interval to access the channel. This also provides a randomization effect to avoid collisions.

3. Hidden Terminal Model

We consider an ad-hoc network of independent stations capable of communicating with every other station in the BSS. The model for hidden terminals is based on the following observations

1. Stations in a wireless LAN can change their location. Due to it's mobility a station may move out of the transmission range of another station, causing the pair to be hidden from each other. The number of stations a given station is hidden from varies over time and at any given time it can hear only the stations in it's vicinity.
2. Hidden terminals can also be caused by static obstructions, which prevent signals of one station from reaching the other.

We base our modeling of hidden terminals on groups as proposed in [6].

- Consider a symmetric matrix $\mathbf{H}$.

$$H_{ij} = \left\{ \begin{array}{ll} 1 & \text{station i is hidden from station j} \\ 0 & \text{otherwise} \end{array} \right\}$$

$$H_{ij} = H_{ji}$$

- All stations that can hear exactly the same subset of stations constitute a *group*. Stations with identical rows or columns in $\mathbf{H}$ form a group. Also, if station i cannot hear station j, station j also cannot hear station i. This would be the case when all stations have the same transmission power and the cause of their being hidden is also isodirectional.
- Two groups able to hear transmissions from each other are said to be *dependent*.
- A *hearing graph* can be constructed based on dependencies between groups. Each node in the graph represents a group and there exists an edge between two nodes if they are *dependent*.

We extend this model to include the following.

- The geographical area of a WLAN and its vicinity are modeled as a mesh of hexagonal cells.
- Stations occupy cells and the number of stations in a hexagonal cell varies over time. In our simulations we populate cells with stations according to a probability distribution.
- All stations in a given hexagonal cell form a *group* as they can hear exactly the same subset of stations. Here the assumption is that each cell is small enough to approximate the location of each station to the center of the hexagon.
- Different scenarios under which hidden terminals can occur are modeled by assigning dependencies between groups. When hidden terminals caused only by the transmission range of stations and their mobility are considered, dependencies can be assigned on the basis of distance between cells. When static obstructions in the geographical layout of the WLAN are considered as the cause of hidden terminals, dependencies can be assigned by analyzing which locations are hidden from each other due to obstructions. More complex interactions taking both the mobility of stations and the geographical layout into account, can also be similarly modeled.

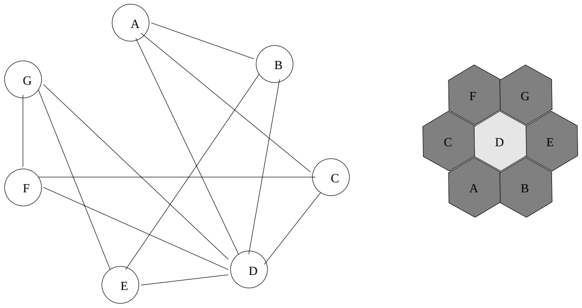

Figure 2. Groups: Hearing graph and hexagonal cells for $d = 1$

- When assigning dependencies based on distance, a station in a given cell is assumed to be able to communicate with stations in neighboring cells within a radius of d cells from it's cell (Figure 2 shows dependencies between groups with $d = 1$). The value of d would depend on the granularity at which the region is divided into hexagons and the transmission range of each station. By increasing the number of cells representing a given region, better approximations for the location of a station can be obtained. The value of d will have to be correspondingly increased when more cells represent a given area.

- When a geographical layout is considered, dependencies between cells are defined according to the location of the static obstructions.

Next, we show how the concept of geographical hexagonal areas can be used to model hidden terminals caused by both mobility of stations (section 3.1), as well as obstructions (section 3.2).

3.1. Dynamic Location Model

In this section we consider hidden terminals caused by mobility of stations. Our model is based on associates a *location probability* with each station. We make the following assumptions:

- Stations are most likely to be located in their BSA but occasionally move out. They are more likely to be near the BSA, rather than far from it. The probability of their being at a distance n from the center of their BSA (in hexagonal units), decreases as n increases, tending to zero, as n approaches infinity.
- This probability does not vary with time. Every *Reassignment_Time* seconds we reassign the geographical location of each station based on this probability. Thus a station belongs to different cells (groups) at different times.
- Besides other stations in the same group as it, a station can also hear stations in the neighboring six hexagonal cells but none outside that region i.e d is assumed to be one.
- Each station has the same location probability.

We can view our model as composed of ring of hexagons (numbered from 1 to ∞) around the central hexagon constituting the BSA (numbered 0)(figure 3). The n^{th} ring of hexagons around the BSA has $6n$ cells. We assume that within a given ring a station is equiprobable to be in any of the cells. Thus the probabilities of a station being in a hexagon in ring n, around the BSA (location probability) is assigned as follows.

$$p_n = \frac{\alpha(1-\alpha)^n}{6n}; n \geq 1$$

A station is in the BSA with probability

$$p_0 = \alpha$$

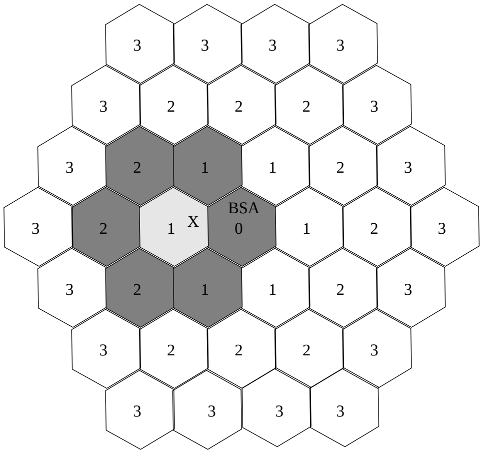

Figure 3. Dynamic Location Model: Shaded portion shows locations which are within hearing range of a station in cell X

α is a measure of the likelihood of a station remaining in it's BSA. By varying the value of α the average number of stations hidden from each other at any given time changes. An estimate of the average number of pairs hidden from each other based on the value of α can be obtained as follows.
Let N be the number of stations.
Let X_n be the average number of stations at a cell in level n

$$X_n = \sum_{i=0}^{N} i p_n^i (1 - p_n)^{N-i}$$

Let Y_n be the number of stations that can be heard by a cell at level n.

$$Y_n = 3X_n + 3X_{n+1} + X_{n-1} \; ; \; n \geq 1$$

$$Y_0 = X_0 + 6X_1$$

Thus at a cell at level n, each of X_n stations is hidden from $(N - Y_n)$ other stations. Moreover there are $6n$ cells at each level. Thus, average number of hidden pairs is

$$\frac{\sum_{n=1}^{\infty} X_n(N - Y_n).6n + (N - Y_0)X_0}{2}$$

Figure 4 gives a plot of alpha versus the percentage of hidden terminals. By varying the value of α we model different mobility scenarios. By measuring the throughput, average delay and blocking probability for each case we obtain a measure of the performance of the IEEE 802.11 protocol.

3.2. Wall Model

In this model we consider hidden terminals caused by static obstructions neglecting the effect of mobility. We assign stations to geographical areas, only once at the start of

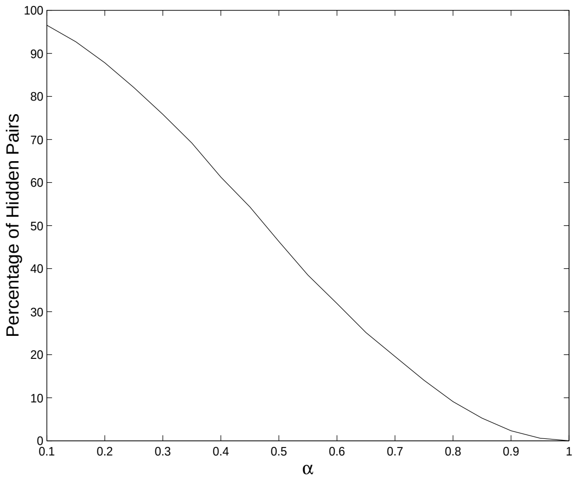

Figure 4. Relationship between α and the percentage of hidden terminals

the simulation. Their position does not change with time. Stations in a given hexagonal region can hear stations in the same cell and those in other cells that have an unobstructed path between them. Figure 5 gives an example of such a scenario and also gives the associated hearing graph. Note that here we have used a geometric granularity much smaller than that for the model in the previous section. The model in fact can be extended to cover both conditions simultaneously.

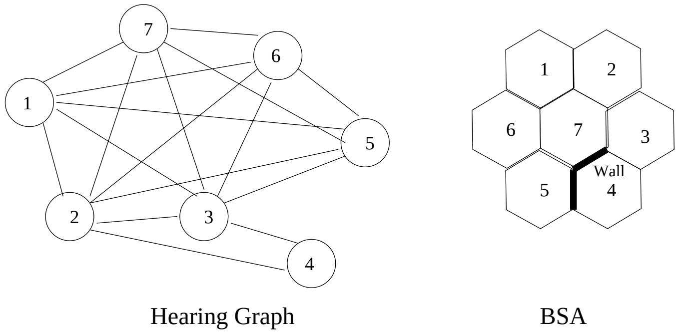

Figure 5. Modeling hidden terminals due to static obstructions

4. Simulation Model

Two separate models have been considered for fixed and mobile stations as explained above. The following assumptions have been made in both cases in order to simplify the models :

- The effect of bit errors in the channel has been neglected. This is necessitated because our objective is to study how the performance of the network deteriorates in presence of hidden terminals. The addition of bit errors complicates the interpretation.

- We assume that no station operates in the "power saving" mode. This implies that a station will respond immediately after the receipt of a frame with some kind of acknowledgment.

The arrival of packets to the MAC from higher layers has been modeled as a Poisson process. The rate of arrival of packets at each station is assumed to be the same. The packet lengths have been modeled as a truncated geometric distribution with a maximum length of 2312 octets. A finite buffer is maintained by each station and all packets that exceed the capacity are dropped. A sender selects the destination for a message with equal probability for all stations. In case of a collision, retransmission takes place and stations execute the random back-off procedure. The number of retransmissions of a packet is limited by a Retry_Limit.

An ongoing transmission can be corrupted only when another station within the hearing range of either the sender or the receiver, and not hidden from either, starts a simultaneous transmission. Thus it is possible for two simultaneous transmissions to go on if the senders and receivers in the two transmissions belong to *groups* not *dependent* on each other. This condition is also termed as the capture effect and has been implemented in our simulations.

We assume that the physical layer uses Direct Sequence Spread Spectrum (DSSS). This entails addition of a DSSS header and DSSS preamble to each packet and adds to the protocol overhead.

4.1. SES Implementation

The simulation was carried out using SES/Workbench, [5] a simulation and modeling tool. SES uses an object oriented approach, defining a set of nodes and transactions to model system behavior. Different nodes have different functionality, e.g. a blocking node to block transactions till a condition is satisfied, a delay node to delay the transaction for a specific simulation time interval etc. Transactions follow a predefined path between nodes, executing specific code at each node. A graphical interface provides an easy way to put simulation objects together. Our implementation has different modules to model the sending of frames, receiving of frames and the wireless channel. Each of these is dimensioned on the number of stations in the system. Thus by actually tracing a path that a frame takes from the sender to the receiver, the implementation of the protocol was greatly simplified. However, the use of SES had the disadvantage of large binaries and slow execution times.

4.2. Simulation parameters

Values for system parameters were taken as defined in table 1, unless otherwise specified.

Parameter	**Default Value**
Data Stations	40
Average MSDU Length	1000 octets
Channel Rate	1Mbps
RTS_Threshold	250 octets
Fragmentation_Threshold	800 octets
Retry_Limit	7
DSSS preamble	144 bits
DSSS header	48 bits
Station Buffer Size	300 frames
Slot_Time	$20\mu s$
SIFS_Time	$10\mu s$
DIFS_Time	$50\mu s$
Propagation_Delay	$5\mu s$
Reassignment_Time	5s
Offered Load	0.65Mbps

Table 1. Simulation Parameters

5. Simulation Results

In this section we present simulation results for the dynamic location model under various hidden terminal conditions. We also give results for the wall model explained in section 3.2.

Effect of hidden terminals on the protocol can be explained as follows :

- When there are no hidden terminals, the time window for a collision is equal to the *slot time* plus the propagation delay of the first packet. This is because a station that has data to transmit, executes an exponential backoff in which it checks the state of the channel after each *slot time* duration. If another station starts transmission, then the information about channel status can be at most *slot time* plus the propagation delay duration old. Any transmission started within this duration would result in a collision.

- In the presence of hidden terminals, the collision window can be much larger. When a packet is being transmitted without the exchange of the RTS/CTS control frames, a station hidden from the sender but in vicinity of the receiver can cause a collision by transmitting anytime during the entire transmission duration of the frame. By exchanging the RTS/CTS pair, this window can be reduced to the transmission delay of RTS (refer to section 2(4)), but it is still much larger than the ideal case.

A larger contention window results in more collisions which in turn has a detrimental effect on system performance.

5.1. Dynamic Location Model

Here we present results for the model explained in section 3.1. All graphs have been plotted for different values of α and the relationship between α and the number of hidden terminals is given in Figure 4.

5.1.1. Effect of Hidden Terminals on Throughput

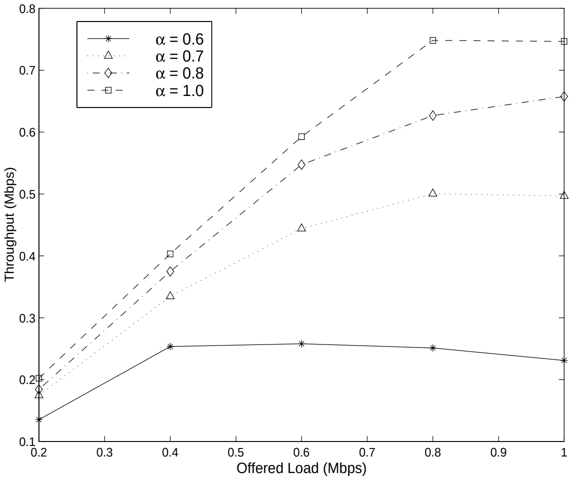

Figure 6. Effect of hidden terminals on throughput

Offered load is defined as the average number of bits per second passed down to the MAC sublayer at the source. Throughput is the average number of bits per second passed up from the MAC sublayer at the destination.

Figure 6 shows the aggregate throughput in Mbps versus offered load in Mbps for various numbers of hidden terminal pairs in the system. When all stations can hear each other ($\alpha = 1$), system throughput saturates at approximately 75 percent. However, when approximately 30 percent of stations pairs are hidden ($\alpha = 0.6$), throughput can drop to as low as 22 percent. The throughput actually becomes slightly lesser with increasing load because at higher arrival rates, chances of simultaneous transmissions become higher. A system with $\alpha = 0.8$, on an average can see about 10 percent hidden stations and the protocol performs acceptably under these conditions with a maximum throughput of 65 percent.

5.1.2. Effect of Hidden Terminals on Delay

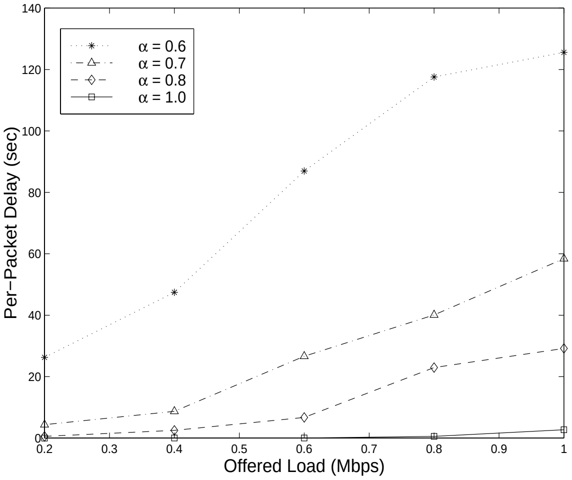

Figure 7. Effect of hidden terminals on delay

Presence of hidden terminals has a pronounced effect on the average packet delay in the system. Delay is defined as the difference between the time at which a frame is accepted by the sender's MAC sublayer and the time at which it receives an acknowledgment from the receiver's MAC. Figure 7 shows the average delay in seconds versus offered load in Mbps, for different number of hidden terminal pairs. The average delay increases by about an order of magnitude even under conditions of moderate load and 10 percent hidden stations. The performance becomes much worse as the load increases.

5.1.3. The Effect of Hidden Terminals on Blocking Probability

Blocking probability is defined as the fraction of packets dropped from the system after experiencing *Retry_Limit* number of collisions. Figure 8 shows blocking probability versus the number of hidden pairs at an offered system load of 0.65 Mbps. The blocking probability increases steadily with a increase in the number of hidden terminals and can reach about 13% when approximately 30% of station pairs are hidden.

5.1.4. The Effect of RTS on Delay

As explained in section 2(4), the RTS/CTS mechanism is used to reduce the chances of collisions in the presence of hidden terminals. In figure 9, average delay in seconds is plotted against RTS_Threshold for a number of hidden terminal pairs. Minimum delays are achieved when the RTS_Threshold is zero, ie. the RTS/CTS pair is exchanged for all packets. Delays can increase by more than two orders of magnitude when RTS/CTS is never used (RTS_Threshold = 2400). The curves even out after RTS_Threshold is about 1100 because the average MSDU length for the experiment was taken as 1000 bytes. Experiments with lower average MSDU lengths, yield similar results.

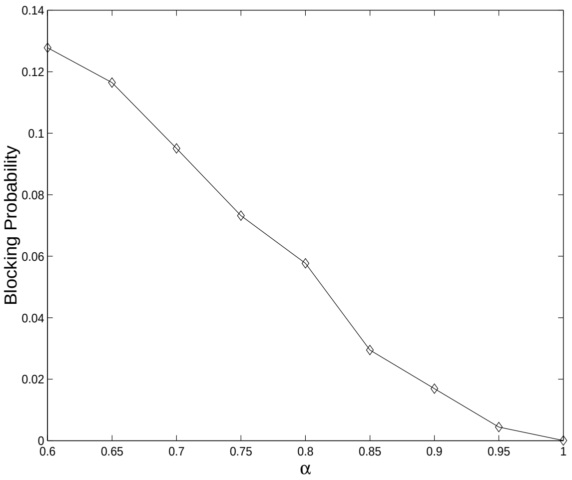

Figure 8. Effect of hidden terminals on blocking probability

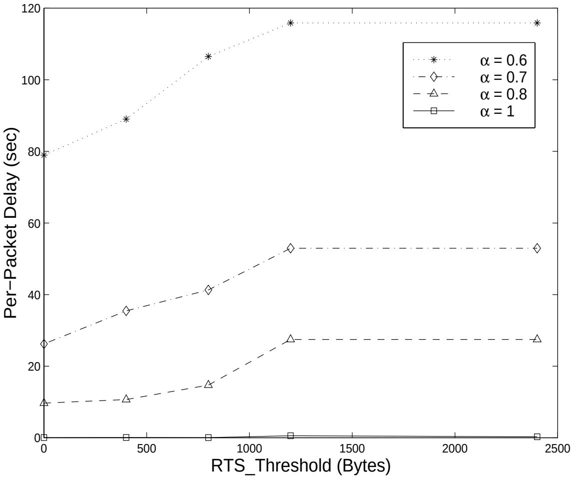

Figure 9. Effect of RTS on delay

5.1.5. The Effect of RTS on Throughput

Figure 10 shows the throughput against RTS_Threshold, for various numbers of hidden terminal pairs (α). As expected, the throughput for a given value of α decreases with an increase in RTS_Threshold. The maximum achievable throughput also decreases with an increase in the number of hidden terminals. Also, of importance is the shape of the curves for different values of α. When there are a large

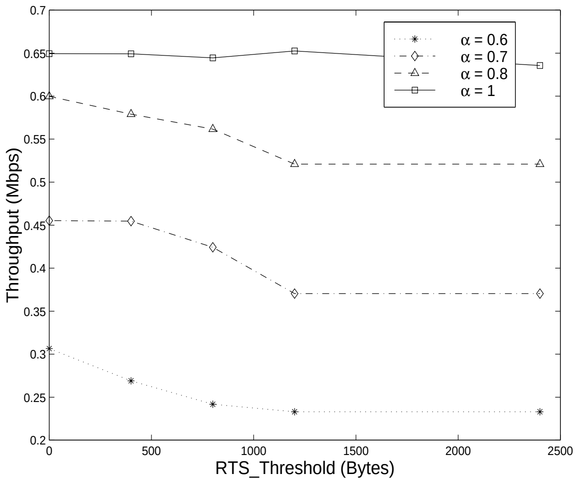

Figure 10. Effect of RTS on throughput

number of hidden terminals (α = 0.6), throughput drops much more sharply for a small increase in RTS_Threshold.

5.2. Wall Model

Simulation results are presented for the the example layout shown in figure 5. We used the following simulation parameters :

- Each cell has 6 stations
- Each station generates the same load, with an aggregated offered load of 0.6 Mbps
- Stations remain static for the entire simulation run. The H matrix also remains constant for the entire duration of the simulation.

As shown in figure 5, stations in cells 2 and 3 can hear all other stations. Stations in cell 4 are hidden from all other stations, except stations in cells 2,3 and 4.

5.2.1. Effect on Throughput

In Figure 11, throughput is represented as a percentage of the offered load aggregated over all stations in a cell. A 100% throughput means that stations in a cell were able to transmit all generated frames. Stations in cells 2 and 3 can hear all stations, and hence get a 100% throughput, but stations in cell 4 which are hidden from all others except those in 2 and 3 get almost 0% throughput. Although the rest of the cells are hidden only from 4, they have a substantial decrease in throughput and can manage to get only about 20% of their frames through.

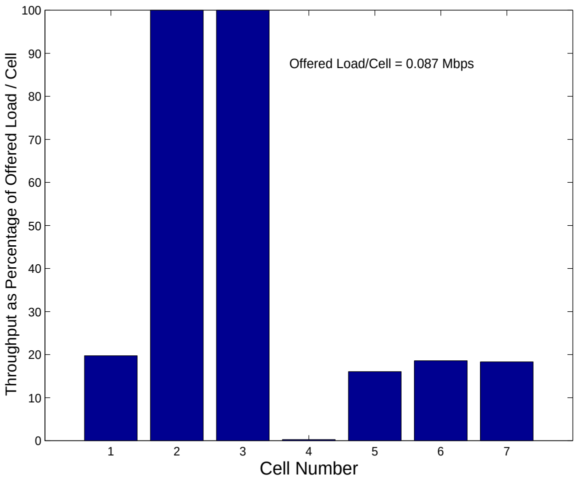

Figure 11. Wall model : Effect on throughput

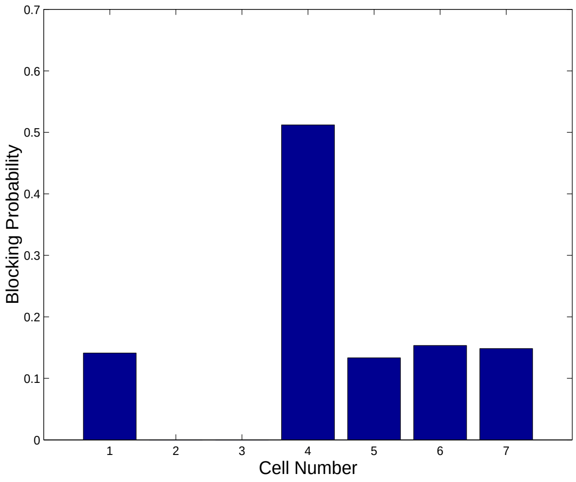

Figure 12. Wall model : Effect on blocking probability

5.2.2. Effect on Blocking Probability

As shown in figure 12, stations in cell 4 have a very high blocking probability, as they are hidden from most other stations. Stations in cells 2 and 3 experience no blocks while rest of the stations have about 15% of their packets blocked.

5.2.3. Effect on Delay

Figure 13 shows the average packet delay experienced by stations in each cell. Stations in cell 4 have a low delay because most of their frames are directed towards hidden stations. These are blocked, and hence do not contribute towards average delay. Stations in cells 5,6,7 and 8 experience delays of more than an order of magnitude as compared to

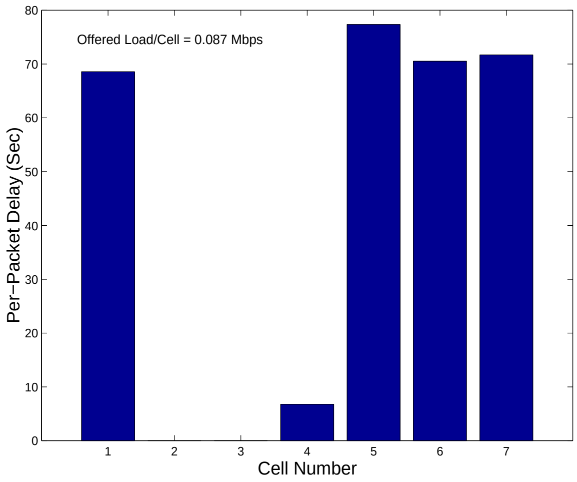

Figure 13. Wall model : Effect on delay

stations in cells 2 and 3 which are within the hearing range of all other stations.

6. Conclusion

In this paper we have studied the performance of the IEEE 802.11 MAC protocol in the presence of hidden terminals. For this we have proposed a general model for modeling hidden terminals in a WLAN.

Our simulations show that the performance of the IEEE 802.11 protocol deteriorates in the presence of hidden terminals. While the throughput is acceptable when less than 10 percent of station pairs are hidden, the average per frame delay increases by as much as an order of magnitude.

Given other system parameters, the system throughput, average packet delay and blocking probability is dependent only on the percentage of station pairs hidden from each other. The average delay, throughput and blocking probability seen by a particular station is not uniform and varies greatly depending on the number of stations hidden from it.

The RTS/ CTS mechanism used in the protocol helps improve it's performance. In the presence of hidden terminals best throughput and average delay are obtained when RTS/ CTS is used before the transmission of each frame regardless of the frame length.

Our modeling of hidden terminals is general enough to be able to model complex scenarios of mobility and static layouts. In this paper we have considered two simple scenarios. Although other intricate models may depict more realistic scenarios, we expect their effect on protocol performance to be similar as it is a function of the number of hidden terminals, rather than their cause.

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