Throughput Analysis of an Extended Service Set in IEEE 802.11

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***Abstract*— In this paper, we introduced a novel method to determine the throughput of an extended service set in IEEE 802.11 network. The method leverages indoor radio propagation models and RF prediction. We introduce a new analytical Markov Model of DCF access mechanism. Markov Model introduced here has capability to support non-saturated traffic and different data rates. IEEE 802.11a is selected as the physical layer and more than one access point has been considered in the analysis.**

I. INTRODUCTION

Wireless Local Area Networking has been proliferated after the standardization; with the rapid decrease in the price of the 802.11 radios, 802.11 chips have been integrated to most of the gadgets of modern life. Wireless network performance is becoming more and more important for enterprisers deploying business-critical wireless networks. As the networks grow in size and become an integral part of our daily life, throughput intensive applications like voice over WLAN are also gaining popularity. In such applications, where network throughput performance is critical, detailed network planning, monitoring and management become essential. Network planning includes detailed site surveys, determining the number of access points, locations, access point configurations. Currently, choosing how many access points to deploy, where to place them are ad hoc processes and can be very time consuming. In this paper, we present a software simulation platform which automates all of these issues. Our simulator consists of a 3-D RF prediction engine which models the RF environment as well as the interactions between the devices and a throughput estimation engine which estimates the individual throughput of the mobiles and APs using the RF prediction data and analytical Markov model of IEEE 802.11 [1], [2]. The simulator can be used in the detailed planning of a wireless LAN or it can be used as part of a real-time network management system which monitors the network in real-time and takes therapeutic actions depending on the state of the wireless network.

II. IEEE 802.11 NETWORK ARCHITECTURE

IEEE 802.11 network introduces two different channel access mechanisms: Distributed Coordination Function (DCF) and Point Coordination Function (PCF) [4]. DCF is a random based protocol which implements Collision Avoidance Carrier Sense Multiple Access Mechanism CA/CSMA. PCF is on the other hand has a point coordination function which schedules transmission. DCF is widely used access mechanism and it is based on contention. Stations content for the channel and when they find channel busy they backoff for a random interval. Figure 2 shows a time realization for 6 stations and medium. In order to overcome hidden stations, RTS/CTS exchange has been introduced. Station who has packet to transmit first transmits RTS packet and waits for the CTS from the addressee. After getting CTS, data packet is sent and receiving ACK completes the transmission. Detecting the channel before transmission at least DIFS amount of time after successful packet transmission and EIFS amount of time after collision are mandatory [4], [5], [6].

III. INDOOR RF PROPAGATION

Phenomena related to RF propagation, like multi-path propagation, reflection, diffraction and shadowing have a significant influence on the received power. So, the propagation models should consider these phenomena to obtain accurate results.

The prediction model used in the simulator is a variant of the COST 231 Multi Wall Model with some additions for optimizing the ray-tracing implementation. This 3-D model calculates the path loss according to both the distance between the transmitter and receiver and the penetration losses through walls and ceilings. The equation is as follows;

$$L = L_{FS} + L_e + \sum_{i=1}^{I} k_{wi} L_{wi} + k_f^{\left[\frac{k_f+2}{k_f+1} - b\right]} L_c \qquad (1)$$

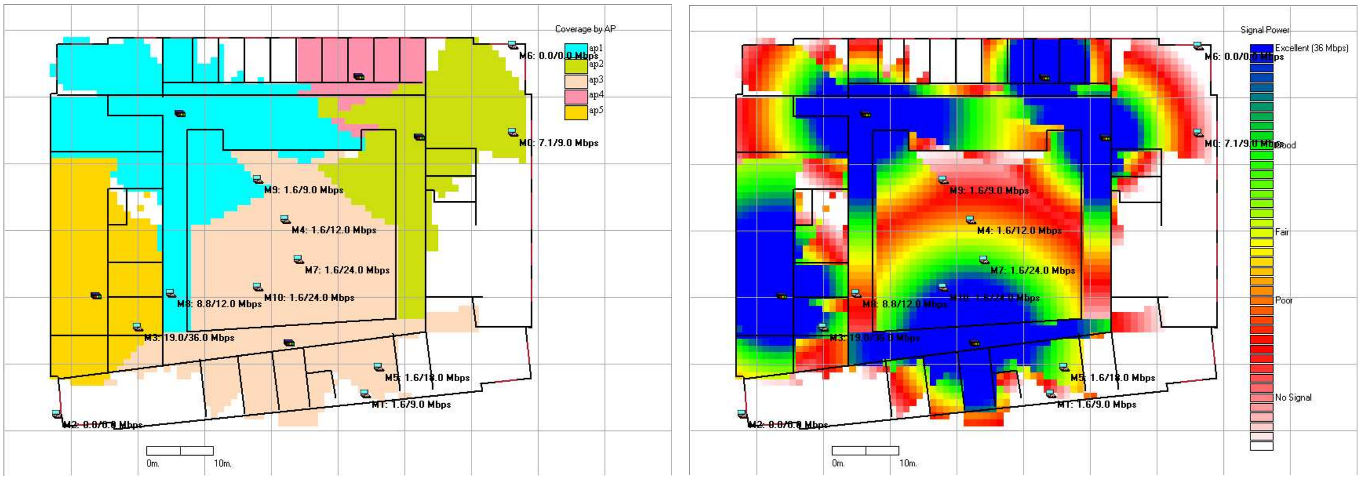
where L_{FS} is free space loss of the path in dB, L_e is constant excess attenuation of the path in dB, L_{wi} is loss of wall type i in dB, L_c is loss between adjacent floors in dB, k_{wi} is number of walls of wall type i penetrated by the path, k_f is the number of ceilings penetrated by the path, I is number of wall types, b is multi-floor parameter.

IV. RF PREDICTION

RF prediction models, being capable of predicting the path loss between the transmitter and receiver antennas, are basic tools in coverage prediction and throughput estimation in wireless LANs.

Our simulator uses the 3-d RF propagation model to compute the RF coverage inside a building, the model also takes into account the RF interference caused by unwanted or interfering devices present in the environment.

In addition to advanced modelling techniques it is essential that the performance of the propagation models is verified by



(a) AP Coverage (Individual Throughput/ Data Rate)

(b) Signal Power Map

Fig. 1. Propagation Model Simulation

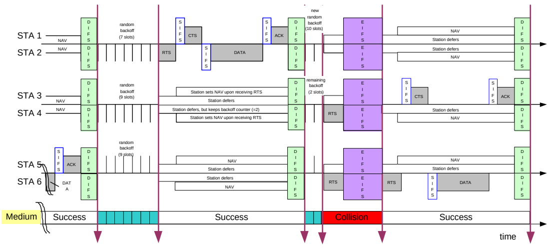


Fig. 2. DCF Procedure

comparison with measurements. Several extensive measurement campaigns have therefore been carried out using the Site Survey tool which was developed to validate the accuracy of the RF propagation model used in the simulator and to calibrate the model if needed.

Knowing the data rate and access point of each station we can determine the system throughput by using a analytical model of IEEE 802.11 introduced first in [2] and extended at [1].

V. THROUGHPUT ANALYSIS

The analytical model derived here is based on semi-discrete Markov chain model. Similar to the models in [2], [7], [8] DCF is represented by a two dimensional Markov chain. In throughput analysis we consider the saturated and non-saturated case where the station always has packet to transmit and the station transmits with probability λ. The derivation has two phases first obtaining the τ which is *the probability that the station transmits a packet in a given slot time* and then placing the τ in throughput calculation.

Observation of the time leads to identify the operation in terms of slots (See Figure 2). There is either an empty slot during which the backoff counter is decremented, or a transmission during which the backoff counter stays the same. Therefore, the events that drive the Markov model are empty slot or transmission. In regard to this, Markov chain shown in Fig. 3 has two dimensions which are $s(t)$ and $b(t)$ representing backoff depth and state number respectively. Adopting the key approximation in [2], p represents the *conditional collision probability* and is independent and constant in each packet collision regardless of the number of retransmissions suffered. p also stands for *probability of detecting the channel busy*.

Having $b_{i,k}, i \in (-1, m), k \in (0, W_i - 1)$ as the stationary distribution we can solve this Markov chain by balance equations. Sum of the probabilities of each state is equal to 1,

$$1 = \sum_{i=-1}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} \tag{2}$$

In order to find the τ, we need the stationary probability of $b_{0,0}$. Packet is transmitted in states $b_{i,0}$ where $i \in (0, m)$. We can express the transmission probability τ as

$$\tau = \sum_{i=0}^{m} b_{i,0} \tag{3}$$

When the station is not in the saturation state, station waits in the idle state for a packet that is sent from upper layers to transmit. That corresponds to delay in the idle state. One can infer that the dashed box represent the idle state with λ traffic probability. τ is

$$\tau = \frac{1}{\frac{(1-2p)(W+1)+pW(1-(2p)^m)}{2(1-2p)(1-p)} + (1-p)(\frac{1}{\lambda^2} - 1)} \tag{4}$$

where contention window doubles with $W_i = 2^i W$ and where -1 in the equation is put to make the equation consistent with the saturation operating case ($\lambda = 1$). Since adding additional states introduces at least one slot time delay to the system. When there is no -1 that will result in a situation where the station waits one slot time for transmission. Although this will not have significant value when λ is high, it is important to note the characteristic of modelling a finite state machine by a Markov model.

τ is a function of $\tau(p, m, W, \lambda)$ where only p is unknown. τ should depend on the number of active users since it is highly

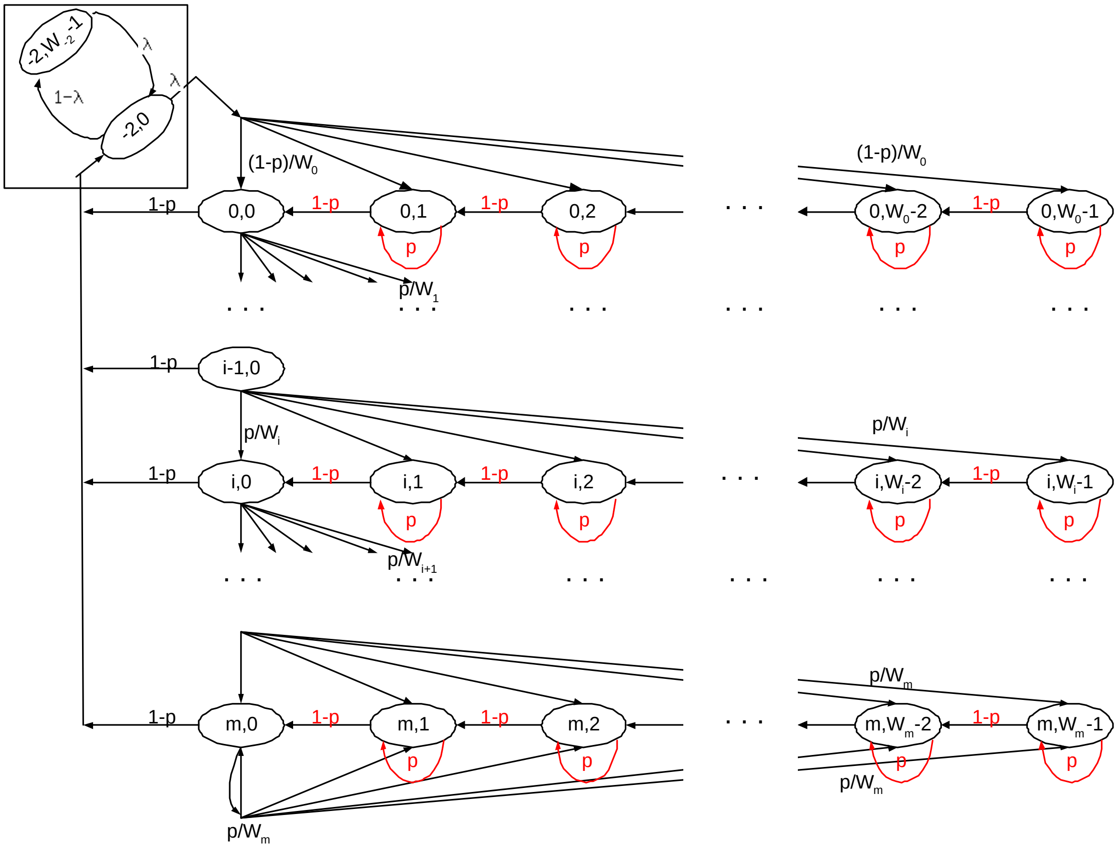


Fig. 3. Markov Model for the IEEE 802.11 DCF Model in Normal Operating Condition

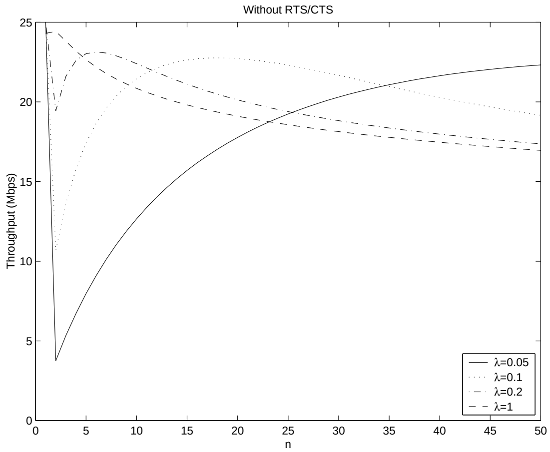


Fig. 4. Data Rate=54Mbps w/o RTS/CTS

correlated with p. Collision probability depends on the active number of stations n. Therefore p and τ in steady state are tied by equation 4 and

$$p = 1 - (1-\tau)^{n-1} \; or \; \tau(p) = 1 - (1-p)^{\frac{1}{(n-1)}} \qquad (5)$$

Now, τ is a function of known variables $\tau(n, m, W, \lambda)$. Since $p \in (0,1)$, $\tau \in (0,1)$ and both equations (4) and (5) are continuous, the solution of τ is unique.

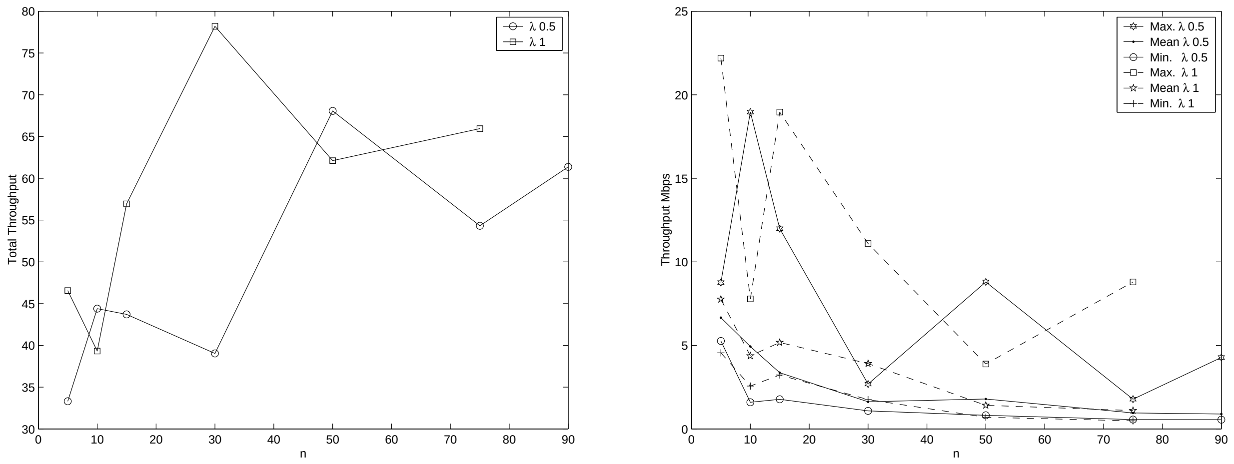
Following [2], "the throughput is the fraction of time the channel is used to successfully transmit payload bits." Define the probability P_{tr} that there is at least one transmission in the considered slot time and the probability P_s that a transmission occurring on the channel is successful as

$$\begin{aligned} P_{tr} &= 1 - (1-\tau)^n \\ P_s &= n\tau(1-\tau)^{n-1}. \end{aligned} \qquad (6)$$

Let's express the total throughput S as the ratio

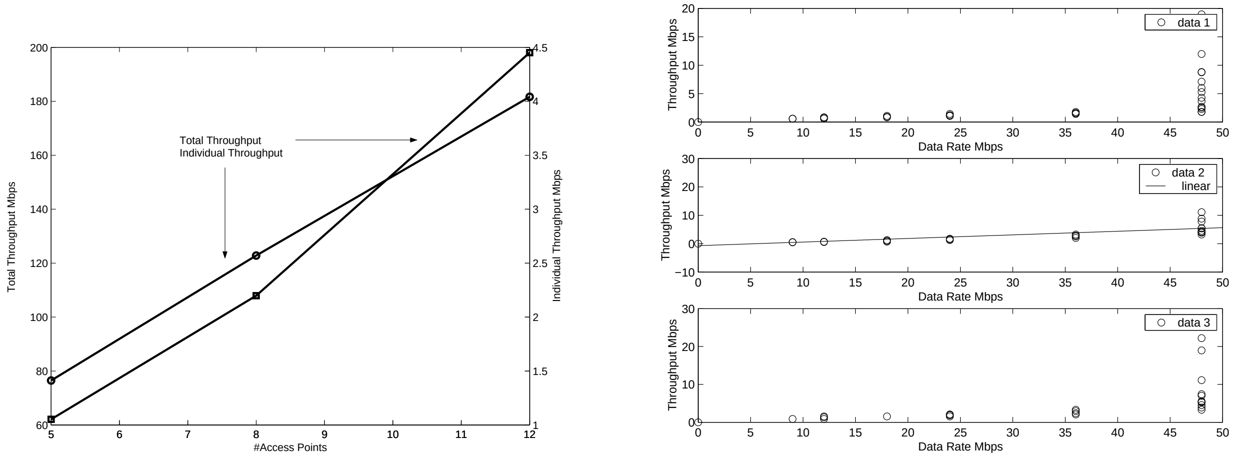
$$S = \frac{P_s E[P]}{(1-P_{tr})\sigma + P_s T_s + (P_{tr} - P_s) T_c}. \qquad (7)$$

where $E[P]$ is the average packet payload size, P_s is the probability for successful transmission. The average length of empty slot time is with probability $1 - P_{tr}$ and with probability $(P_{tr} - P_s)$ there is a collision. T_s is the average time the channel is sensed busy due to a successful transmission, and T_c is the average time the channel is sensed busy by each station during a collision. σ is the duration of an empty slot time [2]. For two different access mechanism the time values are represented in equation 8. T_{DATA} is the time that takes to send a packet with size $E[P]$ and T_{RTS},T_{CTS},T_{ACK} are the times that take to send the corresponding frames. T^*_{DATA} stands for average time that takes to send $E[P^*]$ which is the average length of the longest packet payload involved in a collision. When all packets have the same size, $E[P] = P = E[P^*]$ [2]. δ is the propagation delay. Unlike the "basic" access mechanism T_c^{rts} only contains T_{RTS} since only possibility to experience a collision occurs in the RTS frame transmission.



(a) Total Throughput (b) Individual Throughput

Fig. 5. Performance when there are 5 AP



(a) Total Throughput when there are 50 STAs (b) Utilization

Fig. 6. Performance and Utilization

$$
\begin{aligned}
T_s^{basic} &= T_{DATA} + SIFS + \delta + T_{ACK} + \delta + DIFS \\
T_c^{basic} &= T^*_{DATA} + \delta + EIFS \\
T_s^{rts} &= T_{RTS} + SIFS + \delta + T_{CTS} + SIFS + \delta + T_{DATA} + SIFS + \delta + T_{ACK} + \delta + DIFS \\
T_c^{rts} &= T_{RTS} + \delta + EIFS.
\end{aligned} \tag{8}
$$

IEEE 802.11a physical layer (PHY) uses OFDM for the modulation scheme. IEEE 802.11a PHY provides eight PHY modes with different modulation schemes and coding rates as seen in Figure 7. SNR values are proprietary by vendor.

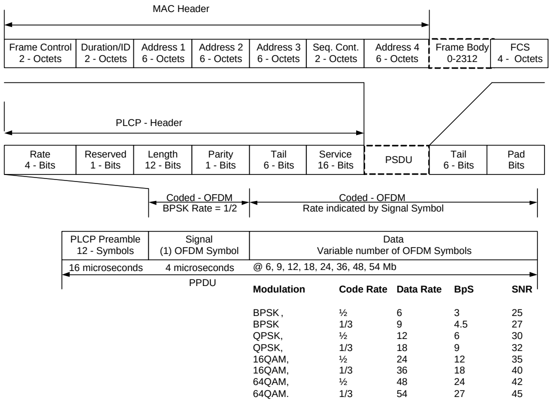
The above analysis lead us to obtain the duration of each packet. Transmission duration of a frame with $E[P]$ octets data payload with the IEEE 802.11a PHY 7 is as follows [6];

$$
\begin{aligned}
T_{DATA}(m) &= 20\mu s + [\tfrac{28+(16+6)/8+E[P]}{BpS(m)}] \cdot 4\mu s \\
T_{RTS}(m) &= 20\mu s + [\tfrac{20+(16+6)/8}{BpS(m)}] \cdot 4\mu s \\
T_{CTS}(m) = T_{ACK}(m) &= 20\mu s + [\tfrac{14+(16+6)/8}{BpS(m)}] \cdot 4\mu s.
\end{aligned} \tag{10}
$$

Figure 4 shows the system performance of single access point in different traffic intensities.

The key contribution of the formula is to introduce individual throughput if the data rate is different for each user. The 802.11 gives the same chance to each user even if the data rate is different. Data rate only changes the duration values thereby average

$$\bar{T}_s = \frac{P_s}{n} \sum_{i=1}^{D} n^i T_s^i$$
$$\bar{T}_c = \sum_{i=1}^{n-1} \sum_{j=1}^{D} \sum_{k=1}^{n^j} \binom{n-k-\sum_{l=1}^{j-1} n^t}{i} T_c^j \tau^{i+1}(1-\tau)^{n-1-i} \quad (9)$$



Modulation	**Code Rate**	**Data Rate**	**BpS**	**SNR**
BPSK ,	½	6	3	25
BPSK	1/3	9	4.5	27
QPSK,	½	12	6	30
QPSK,	1/3	18	9	32
16QAM,	½	24	12	35
16QAM,	1/3	36	18	40
64QAM,	½	48	24	42
64QAM.	1/3	54	27	45

Fig. 7. IEEE 802.11a OFDM Packet

duration value changes. Successful duration is the average of the duration of each user and collision duration is determined by the longest duration of the station involving in the collision. If T_s^i and T_c^i are the duration for data rate i and if n^i is the number of nodes with data rate i, the expected duration values are calculated in equation 9; where D is the total number of data rates supported and $n = \sum_{i=1}^{D} n^i$. Throughput of STA x_i is as follows;

$$S_i = \frac{1}{n} \frac{P_s E[P]}{(1-P_{tr})\sigma + \bar{T}_s + \bar{T}_c} \quad (11)$$

VI. PERFORMANCE ANALYSIS

We used fixed floor plan to determine the throughput. Access point power levels are pre-selected between 20mW and 100mw. E[P] is constant and 1024 bytes. Stations are distributed randomly and stations that falls out of any AP coverage are considered *inactive*. All access points are set to the same channel to see the negative effect of interference. Variables are number of access points, number of stations and traffic intensity.

Figure 5(a) depicts the system when there are 5 fixed AP as seen in Figure 1(a). The number of stations scattered are varied and analysis is repeated for two different traffic intensity which are 0.5 and 1. The figure depicts that the total network throughput is also almost concave as in Figure 4 where a single access point performance is illustrated.

Figure 5(b) illustrates the individual throughput of the stations when the *inactive* stations are deducted. This graph is useful to observe the minimum individual throughput of the network.

Figure 6 shows the throughput performance of the system when the number of access points are 5, 8 and 12. As the access points increase in number, the total throughput of the system and individual throughput also increase. This is because of the increase in the signal strength in each point and decrease in the number of stations associated to an access points.

We expect decrease in the performance when there is an increase in the number of stations. Although the data rate of each stations are determined by the random distribution and fixed location of the access points, the throughput performance can be abstracted out by looking at the individual utilization of each station which is defined as “individual throughput/data rate”. The average utilization versus the number of nodes for two different traffic intensity has been showed in Figure 6(b) and figure confirms the decrease in utilization.

VII. CONCLUSION

A novel indoor radio propagation model has been considered with a novel analytical throughput model to determine the system throughput of a IEEE 802.11 network.

Markov Model introduced in [2] has been modified for non-saturated traffic and different data rates. Considering different data rates for each station is another modification in the throughput analysis since duration values of successful transmission and collision now becomes dependent to the data rates of each station.

Indoor Radio propagation simulation determines the coverage area of each access point and signal to noise ratio of each station. Signal to noise ratio sets the data rate of the station and number of associated stations to an access point is determined by the number of stations whose location falls into the coverage of the access point.

Performance analysis has been conducted for varied number of access points and stations.

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