INSTITUTO TECNOLÓGICO Y DE ESTUDIOS SUPERIORES DE MONTERREY

Campus Monterrey

PROGRAMA DE GRADUADOS DE LA DIVISIÓN DE
TECNOLOGÍAS DE INFORMACION Y ELECTRÓNICA

Performance Analysis of the IEEE 802.11 CSMA/CA for the transmission of VoWLAN under high interference scenarios

THESIS

PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN ELECTRONICS ENGINEERING WITH MAJOR IN TELECOMMUNICATIONS

BY

Alberto Jorge Hernández Estala

Monterrey, N.L. November, 2005

INSTITUTO TECNOLÓGICO Y DE ESTUDIOS SUPERIORES DE MONTERREY

Campus Monterrey

PROGRAMA DE GRADUADOS DE LA DIVISIÓN DE TECNOLOGÍAS DE INFORMACION Y ELECTRÓNICA

Performance Analysis of the IEEE 802.11 CSMA/CA for the transmission of VoWLAN under high interference scenarios

THESIS

PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN ELECTRONICS ENGINEERING WITH MAJOR IN TELECOMMUNICATIONS

BY

Alberto Jorge Hernández Estala

Monterrey, N.L. November, 2005

INSTITUTO TECNOLÓGICO Y DE ESTUDIOS SUPERIORES DE MONTERREY

Campus Monterrey

PROGRAMA DE GRADUADOS DE LA DIVISIÓN DE TECNOLOGÍAS DE INFORMACION Y ELECTRÓNICA

The members of the evaluation committee hereby recommend accepting the thesis presented by Alberto Jorge Hernández Estala in partial fulfillment of the requirements for the degree of

Master of Science in Electronics Engineering
with major in Telecommunications

Thesis Committee

____
Dr. David Muñoz Rodríguez
Thesis Advisor

____
Dr. José Ramón Rodríguez Cruz
Synodal

____
Dr. César Vargas Rosales
Synodal

____
Dr. David Garza Salazar
Director of the Graduate Program

November 2005

To my parents, Alberto and Isela
For giving me their never-ending
love and support.

To my brothers, Ivan and Marcela
For always being with me.

Acknowledgements

First of all I want to thank my father and mother for all their unconditional support, motivation, orientation, guidance, patience and love. I also want to thank my brother and sister for being with me all the time, for the patience and love. To all my family for motivating me to never give up and accomplish all my goals and dreams.

I want to thank the Instituto Tecnológico y de Estudios Superiores de Monterrey for giving me the opportunity to realize my graduate studies in this city.

I want to express my gratitude to my thesis advisor, Ph.D. David Muñoz Rodríguez, for all the support given to make this work possible and for all the enriched sessions in which I learn invaluable lessons, including lessons for life. His knowledge and experience played an important role in the development of this thesis.

I also want to thank Ph.D. José Ramón Rodríguez Cruz and Ph.D. César Vargas Rosales, for all their valuable comments, ideas and support to improve and conclude this work.

I want to thank my friend Tamara Caballero for her motivation, support and patience during my graduate studies, and for showing me no to take life so seriously. Also, to my friends of the CET, Hugo, Marco, Mario, Michel, Hilda, Javier, Juan Carlos, Rolando and all the persons who gave me their support during this period of my life.

Alberto Jorge Hernández Estala

Instituto Tecnológico y de Estudios Superiores de Monterrey
November 2005

Abstract

Wireless LAN technologies are becoming increasingly important and the IEEE 802.11 standard is the most mature wireless technology for data transmission throughout the Internet. It is based on the CSMA/CA protocol and provides Internet access to each station throughout a common shared medium, the air.

Recently, with the rising popularity of delay sensitive applications such as Voice over Internet Protocol (VoIP) via a wireless local area network, the IEEE 802.11 is poised to become an important low cost voice transfer solution.

In this thesis, we investigate the performance of the IEEE 802.11 Distributed Coordination Function in terms of the voice packets average delay experienced by the stations and the system throughput. We determine the situations and the required scenarios for the transmission of voice over WLAN under the presence of Rayleigh fading, near/far effect and co-channel interference.

We also identify the required scenarios for the transmission of voice over WLAN in terms of the number of stations, its spatial distribution and we determine the maximum number of non desired overlapping cells in the same frequency band that a WLAN system can tolerate for the transmission of VoWLAN. Finally, for theoretical optimal VoWLAN transmission scenarios, the cumulative distribution function of the voice packet delay is given in terms of the number of stations, with the objective of having a quality measure for the voice transmission throughout the WLAN.

Resumen

Las tecnologías inalámbricas de redes de área local (LAN) son cada vez más importantes y el estándar IEEE 802.11 es la tecnología inalámbrica mas madura para la transmisión de datos a través del Internet. El estándar se basa en el protocolo CSMA/CA y proporciona una conexión a Internet utilizando un medio compartido por todas las estaciones, el aire.

Actualmente, con la creciente popularidad de aplicaciones sensibles a los retrasos en la transmisión, tales como Voz sobre IP a través de una red inalámbrica, el estándar IEEE 802.22 se perfila para ser una solución de bajo costo para la transmisión de voz.

En esta tesis se investiga el desempeño de la Distributed Coordination Function (DCT) del estándar IEEE 802.11 en términos del retraso de paquetes de voz en las estaciones y del throughput del canal. De manera que se determinan las situaciones y los escenarios requeridos para la transmisión de voz sobre una red inalámbrica de área local (VoWLAN); bajo la influencia de desvanecimiento tipo Rayleihg, el efecto near/far e interferencia co-canal.

También se identifican los escenarios requeridos para la transmisión de voz a través de una WLAN en función del número de estaciones, su distribución espacial y se determina el número máximo tolerable de celdas traslapadas no deseadas funcionando en la misma banda de frecuencia, para poder transmitir VoWLAN. Finalmente, para los escenarios teóricamente óptimos para transmitir voz, se obtiene la función de distribución acumulativa del retraso en los paquetes de voz dada en términos del número de estaciones, con el objetivo de tener una medida de calidad para su transmisión a través de la WLAN.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Wireless LANs have recently gained attraction by the public. So-called hot spots have been installed in many cities around the world based on the IEEE 802.11 standard which is expected to evolve to an important access technology for future 4th generation (4G) mobile networks. The bandwidth of up to 54 Mbps in hot spot environments encourages ISPs to provide high-speed Internet access to wireless users. However, as more Wireless LAN cells are installed, the restrictions of the technology become more obvious. The IEEE 802.11b standard operating in the 2.4 GHz band provides only three non-overlapping channels using the DSSS physical layer technology, while the 5 GHz band provides eight non-overlapping channels using the OFDM physical layer. This will cause serious interference problems in highly populated areas especially if multiple providers are co-located and users are setting up a Wireless LAN as a replacement of a wired local area network in their private homes. On the other hand, the hardware is cheap compared to other wireless access technologies; the frequency band is free of any license fees, while the data rate is high. These factors make Wireless LAN an interesting alternative to other wireless access technologies.

Voice over Internet Protocol (VoIP) over a wireless local area network (WLAN) is poised to become an important Internet application and is one of the fastest growing Internet applications today. Although, voice over WLAN suffers from a technical problem, which is that the system capacity for voice can be quite low if the number of stations increases and is also degraded if other interfering Wi-Fi systems are present.

Various performance studies of the Wireless LAN Medium Access Control (MAC) protocol can be found in the literature, such as [1] and [2]. These publications, however, focus on MAC protocol performance issues within single cell scenarios, assuming ideal and interference free channel conditions and it is assumed that all frames involved in a collision are destroyed. This is not sufficient for the evaluation of Wireless LAN as a future access technology in 4G networks because the interference free and the ideal channel condition are unrealistic assumptions in mobile radio environment and the deterministic path loss attenuation, shadowing and multipath fading must be considered; also, due to the capture effect a frame with the strongest received signal strength can be correctly decoded at the receiver even in the presence of simultaneous transmission of multiple stations [3], [5].

This thesis presents a model to evaluate the performance of the IEEE 802.11 Distributed Coordination Function (DCF) under the presence of near/far effect, Rayleigh fading and co-channel interference (inherently to the model proposed, the hidden terminal problem is also included in the analysis). Under these conditions an analytical expression is obtained to estimate capture probabilities, and their impact over the channel throughput and delay in a traffic-saturated IEEE 802.11 Basic Service Set (BSS). An evaluation on the performance of the CSMA/CA MAC protocol for users in different cells is realized; and situations where the communication of a user is completely blocked due to high collision probabilities are identified.

1. 1 Objective

The objective of this work is to evaluate the performance of the IEEE 802.11 CSMA/CA for the transmission of voice over WLAN under high traffic conditions and high interference scenarios, in terms of the delay and the throughput; so that a theoretical maximum system's capacity for the transmission of VoWLAN can be achieved.

1.2 Justification

Wireless local area networks (WLANs) are becoming ubiquitous and increasingly relied upon. From airport lounges and hotel meeting rooms to cafes and restaurants across the globe, wireless LANs are being built for mobile professionals to stay connected to the Internet. Since the year 2000, the sale of IEEE 802.11b wireless LAN adapters have increased dramatically from about 5,000 to 70,000 units per month [6]. Currently, nearly a million 802.11b adaptors are being sold per month and newer versions of notebook computers have such adapters integrated already.

Although interference is an issue, unlicensed frequency bands provide a far more significant advantage in that they remove exorbitant overheads associated with acquiring radio spectrum, thereby lowering the barrier for new entrants. This in turn drives down product costs because of increased competition. This advantage, coupled with improved data rates and the proliferation of cheaper but more powerful personal devices, has accelerated the demand for wireless LANs tremendously in the last few years. The increasing attractiveness of public access networks that involve the integration of high speed wireless LANs and cellular networks under a unified billing/identification system is poised to launch another rich avenue of growth in the future. Wireless LANs need not to transfer purely data traffic. They can also support packetized voice and video transmission, [6].

Due to the continuous growth of multi-cell wireless LAN's and the limited number of license free channels, we must consider interference interaction among different cells. It is the purpose of this thesis to provide a model, which gives us the behavior of the promising IEEE 802.11 systems in a more realistic scenario.

1.3 Contribution

A model for the IEEE 802.11 system has been a research focus since the standard has been proposed.

In most studies of the CSMA/CA protocol an infinite number of stations are considered for the channel traffic generation and is modeled as a Poisson process, as in the case of [7], where a co-channel interference model for the CSMA/CA is proposed. This approach is unsuitable for WLANs systems with a relatively small number of stations because it does not include the radio propagation problems as fading and near/far effect, and it calculates the channel throughput as a function of the offered load.

Chhaya [10] calculates the throughput of CSMA/CA with a simple model that is space dependent and evaluates the fairness properties of the protocol, in the possibility of capture and presence of hidden stations for a single cell. And [11] gives the theoretical maximum throughput of IEEE802.11 based on a *p* – persistent variant.

However, all the above performance evaluation of the IEEE 802.11 had been carried by means of simulation or by means of analytical models with simplified backoff rule assumptions. In particular, constant or geometrically distributed backoff window has been used in [10], [9] and [11]. None of these captures the effect of the Contention Window (CW) and binary slotted exponential back-off procedure used by the DCF in IEEE 802.11. Unlike those, [1] uses a Markov process to analyze the saturated throughput of IEEE 802.11 and shows that the Markov analysis works well. [2] modifies the model used in [1] by taking into account the busy medium condition and how they affect the use of the backoff mechanism. Both [1] and [2] assume ideal channel conditions. In [3] a slotted Aloha protocol with capture in presence of Rayleigh fading and log-normal shadowing is presented.

The contribution of this thesis is to provide a new model which represents the behavior of an IEEE 802.11 system under the influence of co-channel interference, Rayleigh fading and near/far effect using the ideal channel model for the saturation throughput given by [2], and to extend it taking into account the channel capture based on the principles of radio propagation given by [3].We also study the co-channel interference due to systems operating in the same frequency band. With the objective to determine the average system throughput (channel utilization), the system's throughput variance, the average expected delay of a station in the system, as well as the delay variance of a station and the probability density function for the delay in the system. A delay below 250 ms in one direction assures a good quality transmission of VoWLAN in the system.

1.4 Hypothesis

The objective is to determine the throughput and the average delay of each station in a IEEE 802.11 system.

The following results are expected to be obtained:

- The throughput of the stations near de AP will be greater than the most distant ones. This is a consequence of the near/far effect: the instantaneous received power at the AP due to a distant station will be much smaller than the instantaneous power received due to a near station.
- As a consequence of the above hypothesis, the average delay for transmission of the far away stations will be greater than the near ones.
- When an overlap between IEEE 802.11 cells operating in the same frequency band exist, the throughput of all the station will be affected (adversely). The stations that will suffer the most, are the ones located exactly at the overlapped zone (their throughput will be the most deficient of all the stations). As a consequence their average delay will be the highest of the system.
- The throughput and the average delay are highly dependent on the number of stations in the system. If the number of stations increases, there will be more stations contending for the channel and trying to transmit, thus the probability of collision and the probability of sensing the channel busy will increase and the throughput will decrease and the average delay will increase.

As a result of the above hypothesis, it can be inferred that the throughput and the average delay are highly dependent on the position of the stations relative to the AP and highly dependent on the position relative to other stations on the same cell and from other co-channel interfering stations/systems and is also highly dependent on the number of stations in the system.

Chapter 2

Fundamentals of Wireless Local Area Networks

Proliferation of computers and wireless communications together has brought us into an era of wireless networking. Continual growth of wireless networks is driven by, to name a few aspects, ease of installation, flexibility and mobility. These benefits offer gains in efficiency, accuracy, and low business costs. The growth in the market brought forward several proprietary standards for wireless local area networks (WLANs). The resulting chaos was resolved by harmonizing efforts of IEEE, which brought forward an international standard on WLANs: IEEE 802.11.

In this chapter, fundamental aspects of wireless LAN networks are presented and the IEEE 802.11 standard is briefly explained

2.1 Classification of Channel Access

In the organizational development of communications, one of the central tasks is to find an answer to the question of who can access the transfer channel and when they can do so. An endless variety of answers have evolved to allow this to be implemented technically, just like the many ways that human being has found to communicate with each other. All these implementations have one thing in common: try to restrict the number of rules they use to the minimum, and as far as possible attempt to avoid dealing with exceptions.

Centralized vs. decentralized distribution

It is essential to ask who actually manages the accesses. Here, there is a choice of centralized or non central management. In centralized management one central station, the master, assigns the channel to other stations. In decentralized management, all the station share responsibility for assigning the channel

Deterministic vs. non-deterministic assignment

In addition it is also important to define how the channel is assigned. In a deterministic assignment process each stations has a pre-defined maximum length of time (as in TDMA systems), or an assigned frequency band (as in FDMA) or a code (as in CDMA). In non-deterministic assignment no such maximum length of time is defined and the channel access is defined as random access; an example of this type of channel access is the Aloha network or the CSMA/CD used in Ethernet. This is not dependent on whether centralized or decentralized assignment is used.

Introduction to time slots

Given the various stations synchronized, timed access is a way of reducing the probability of collisions. In this way almost all modern transmission protocols use what is known as time slots, which are a fundamental time unit in data transfer. This also requires the stations functionality to be synchronized.

2.2 Demands on transfer networks

The demands on a network are categorized according to different types of traffic present. In particular, it is important to highlight the difference between voice and data transfer. Here it is clear that wireless networks are expected to do something that wired networks have until now either not been capable of, or only to a limited extent: transmit voice data over an Ethernet IP network, [14].

2.2.1 Traffic types

The quality of service at the network level is defined by four fundamental parameters:

- Data rate
- Delay time (latency time)
- Jitter
- Loss rate

Many protocols have already taken the particular quality requirements of different traffic types into account. For pure data applications (classic data transfer) high data rates are required for short and medium-length transmission times. In the case of propagation delay time, if present, the only important thing is that the entire process must complete within a acceptable period of time. High bandwidths are usually not required for voice transfer. However, there are a few special requirements concerning the transfer latency time and jitter. These can usually only be met by reserving pre-defined channels. On the other hand the meaning of voice message is still clear, even if a few bits go missing during the transfer. By contrast multimedia data, as a combination of moving images and sound, presents a different combination of demands for applications such as transferring films. It requires high bandwidths along with low jitter levels. However, the amount of latency time is of secondary importance. To a certain extent the loss rate is not critical, because the human eye can fill in the missing incorrect pixels [14].

2.2.2 Transfer speed

The bandwidth of a transfer channel is usually described by the bit rate in bits per second. When describing the performance of transfer networks we should take particular notice of the transfer efficiency as shown by the difference between the gross and net data rate.

A data rate or 10 Mbps simply means that a new bit is output to the channel at an average rate of every 100 ns. However, in real life, this gross data rate is hardly ever achieved. The basic reasons for the reduced net data rates are:

- Time slots are not used. It sometime happens that no station wants to access the channel at various points in time. In many transmission protocols collision between tow stations may occur which then disrupt the data packets and make a new transfer attempt necessary.
- The station must also deal with protocols as well as the data itself. For example, in packet-switching networks, address and control information is added to the actual data, so that packets can find their way through the network. The stations exchange information about their own particular configuration. This communication usually takes place via normal transfer channel. Therefore these times are not available for the actual data traffic.

2.3 Special features of wireless networks

The wireless transfer of information has a number of special features, which do not affect wired systems (or only to a very limited extent). The crucial point is that the transfer takes place through the air, which is therefore a common medium.

2.3.1 Wireless networks use a common medium

In wireless networks different stations access the same medium, and can therefore mutually influence each other. If they use the same transfer channel it is vital that they comply with specific regulation for accessing the medium.

The regulation governing the use of air interfaces are issued by a range of authorities to ensure that general commercial interests are represented.

2.3.2 Spatial Characteristics

The installation of transmitters and receivers in a particular space leads to various effects that play an important role in the design of wireless networks. As the signals are distributed spatially it is no possible to monitor the channels from one location. In particular it is no possible for the transmitter to use collision identification, as supported in classic Ethernet architecture. This problem is known as the Near-Far o Hidden Station Problem. Also, the signal's spread is unrestricted. However, a signal's strength reduces the relationship to the effects of attenuation. This has four particular effects:

- The relationship between the strength of the signal and the interference (Signal to Noise Ratio - SNR) is only large enough for satisfactory reception quality within a specific distance.
- If several radio cells are in operation it may happen that one device receives signals form several radios cells at the same time. The device must then decide which radio cell is active at the time.
- It is possible that unauthorized stations may also receive signals sent within the ratio range. To prevent unauthorized "eavesdropping" appropriate security measures will be needed.
- The spatial characteristics of the transfer channel may change over time. This is why the channel cannot be modified as in wired media when suppressing the reflections at the end of a cable. In the same way, transferred messages may not only be destroyed by the overlapping of two different messages packets but also by the overlapping of the original and the reflected signals.

2.4 Frequency allocations

The regulatory bodies in each country govern the ISM band. The FCC (U.S), IC (Canada), and ETSI (Europe) specify operation form 2.4 GHz to 2.4835 GHz. For Japan, operation is specified as 2.4 GHz to 2.497 GHz. France allows operation from 2.4465 GHz to 2.4832 GHz, and Spain allows operation from 2.445 GHz to 2.475 GHz. However, in France the availability of the 2.4 GHz ISM band from 2.4 to 2.4835 GHz is in progress. Further, Europe, the United States, and Japan have also allocated a 5 GHz unlicensed national information infrastructure (UNII) band for use as unlicensed spectrum.

The maximum allowable output power measured in accordance with practices specified by the regulatory bodies is shown in Table 2.1. In the United States, the radiated emission should also conform to the ANSI uncontrolled radiation emission standards.

Table 2.1 Frequency Bands and Power Levels for WLANs

Country	Ragulatory Range (MHz)	Maximum Output Power (mW)	Standard
Europe	2,400-2,483.5 5,150-5350 5,470-5725	10mW/MHZ (max 100) 200 1,000	IEEE 802.11b, HomeRF, Bluetooth HIPERLAN/2 IEE 802.11a
US, Canada and Latin America	2,400-2,483.5 5,150-5,250 5,250-5,350 5,725-5,825	1,000 2.5 mW/MHz (max 50) 12.5 mW/MHz (max 250) 50 mW/MHz (max 1,000)	IEEE 802.11b HomeRF, Bluetooth HIPERLAN 2, IEEE 802.11a
Japan	2,400-2,497 5,150-5,250	10 mW/MHz (max 100) 200 (indoor)	IEEE 802.11b, HomeRF, Bluetooth MMAC: HIPERLAN 1, IEEE 802.11a, wireless home-link.

2.5 The IEEE 802.11 Standard

An 802.11 network, in general, consists of Basic Service Sets (BSS) that are interconnected with a Distribution System (DS); see Figure 2.1.

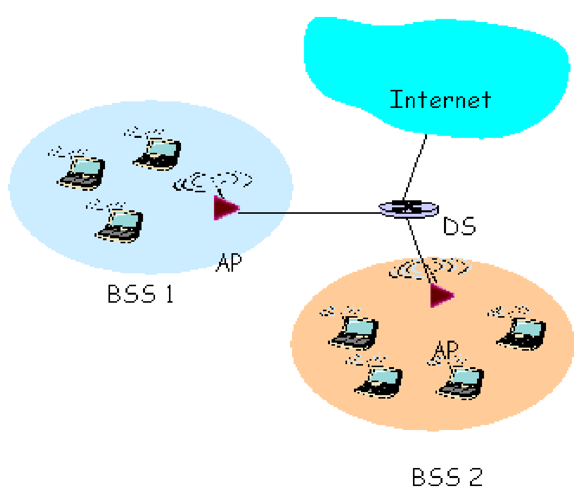

Figure 2.1 Components of an IEEE 802.11 WLAN System

Each BSS consists of mobile nodes, henceforth referred to as stations that are controlled by a single Coordination Function (CF) — logical function that determines when a station transmits and receives via the wireless medium.
Stations in a BSS gain access to the DS and to stations in ``remote'' BSSs through

an Access Point (AP). An AP is an entity that implements both the 802.11 and the DS MAC protocols and can therefore communicate with stations in the BSS to which it belongs and to other APs (that are connected to the DS). Before a station can access the wireless medium it has to be associated with an AP. A station can be associated with only one AP at any given time. The DS supports mobility by providing services necessary to handle the address to destination mapping and the integration of BSS's in a manner that is transparent to stations, i.e., hosts (either mobile or wired) do not need to know the physical location of other hosts for communication. A network of interconnected BSSs, as in Figure 1, in which mobiles can roam without loss in connectivity, is frequently referred to as an Extended Service Set (ESS).

Before describing the MAC layer protocols in detail it is relevant to first describe the IEEE 802.11 physical layers.

The three most used physical layers of the IEEE 802.11 systems are the Direct Sequence Spread Spectrum for the IEEE 802.11b operating at the 2.4 GHz band; the IEEE 802.11g and IEEE 802.11a both use Orthogonal Frequency Division Multiplexing for the physical layer, operating at the 2.4 GHz band and at the 5 GHz band, respectively.
It is important to notice when using DSSS a single spreading sequence is used in any given BSS; thus all stations use the same spreading sequence. The frequency bands used when employing DSSS in neighboring BSSs (which are potentially overlapping) are chosen to be different in order to minimize the interference between BSSs.
The physical layer and some important characteristics for actual commercial IEEE 802.11 systems used in this thesis are shown in Table 2.2.

Table 2.2 IEEE 802.11 Systems.

System	802.11b	802.11a	802.11g
Year	1999	2000	2003
Frequency Bands	2.4-2.4835 GHz	5.150-5.350 GHz 5.725-5.825 GHz	2.4-2.4835 GHz
Data Rate	1, 2, 5.5, 11 Mbps	Up to 54 Mbps	Up to 54 Mbps
Physical Layer	DSSS	OFDM	OFDM

It is important to mention that the physical layer is the technique of transferring the information throughout the channel, i.e., it is designed so it can transfer bits in the most effectively way possible. And it is very different to the Multiple Access Technique used which is the CSMA/CA and is common for all the IEEE 802.11 systems, i.e., the Multiple Access Technique can be seen as a moderator technique which controls which and when a station is going to transmit.

The IEEE 802.11 wireless LAN standard specifies the lowest layer of the OSI network model (physical) and a part of the next higher layer (data link). In addition, the standard specifies the use of the 802.2 protocol for the logical link control (LLC) portion of the data link layer. See Figure 2.2.

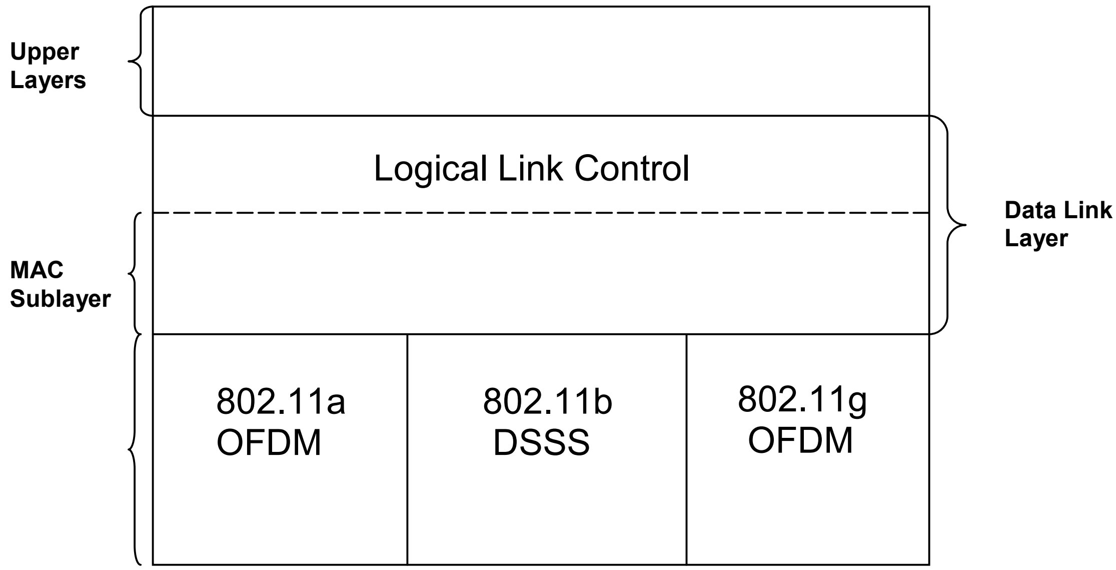

Figure 2.2 IEEE 802.11 and the OSI model

2.5.1 Channel Access

The channel access layer (MAC layer) described in the 802.11 standard is very closely related to the definition in the Ethernet standard. However, the wireless standard must also take into account the special features of its transmission routes. In particular, collision monitoring, as carried out on wired transmission media, is impossible for wireless transmission (due to the near/far problem)

The basic access method in the 802.11 MAC protocol is the Distributed Coordination Function (DCF) which is best described as the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In addition to the DCF the 802.11 also incorporates an alternative access method known as the Point Coordination Function (PCF), which is an access method that is similar to “polling" and uses a point coordinator (usually the AP) to determine which station has the right to transmit. Further, an optional Distributed Time Bounded Service (DTBS) may be provided by the DCF. DTBS is a ``best effort" service that provides bounded delay and bounded delay variance. We now describe the DCF in detail (since we do not analyze the PCF and the DTBS protocols, they are not described here).

Distributed Coordination Function

CSMA/CA

The Distributed Coordination Function (DCF) describes the principal method used by the IEEE 802.11 algorithm standard to access the transmission channel. It is based on the CSMA/CA algorithm:

- Multiple Access (MA) means that several communications participants can use the same transmission channel (shared medium).
- Carrier Sense (CS) means that each communications participant can monitor the same channel and adjust their own activity to match the channel's state. In particular, no station can start transmitting if it detects that the channel's state is busy. Here the IEEE 802.11 standard differentiates field strength to evaluate a channel's activity, and virtual listening (virtual sensing). A station can use a special protocol to reserve a specific channel for a particular time interval (RTS-CTS mechanism)

However, in this context, it must be emphasized that avoidance does not guarantee that collision will never happen again. Even In 802.11 networks, collisions can still occur that lead to data loss on the transmission channel. In the same way as for wired transfer mechanisms, the sending station is responsible for storing the data until a transfer can be carried out successfully.

So, the best way to think o the algorithms is that they are intended to reduce the probability of collisions as far as possible. Nevertheless, users should be aware that in normal operations, just like in wired Ethernet networks, collisions will still occur quite frequently and are not an exceptional event.

When using the DCF, a station, before initiating a transmission, senses the channel to determine if another station is transmitting. The station proceeds with its transmission if the medium is determined to be idle for an interval that exceeds the Distributed Inter Frame Space (DIFS). In case the medium is busy the transmission is deferred until the end of the ongoing transmission. A random interval, henceforth referred to as the backoff interval, is then selected and is used to initialize the backoff timer. The backoff timer is decremented only when the medium is idle; it is frozen when the medium is busy. After a busy period the decrementing of the backoff timer resumes only after the medium has been free longer than DIFS. A station initiates a transmission when the backoff timer reaches zero. To reduce the probability of collisions, after each unsuccessful transmission attempt the value of the random backoff interval is increased exponentially until a predetermined maximum is reached. Immediate positive acknowledgments are employed to determine the successful reception of each data frame (note that explicit acknowledgments are required since a transmitter cannot determine if the data frame was successfully received by listening to its own transmission as in wired LANs). This is accomplished by the receiver initiating the transmission of an acknowledgment frame after a time interval Short Inter Frame Space (SIFS), which is less than DIFS, immediately following the reception of the data frame. Note that the acknowledgment is transmitted without the receiver sensing the state of the channel. In case an acknowledgment is not received the data frame is presumed lost and a retransmission is scheduled (by the transmitter). This access method, henceforth referred to as Basic Access is summarized in Figure 2.3.

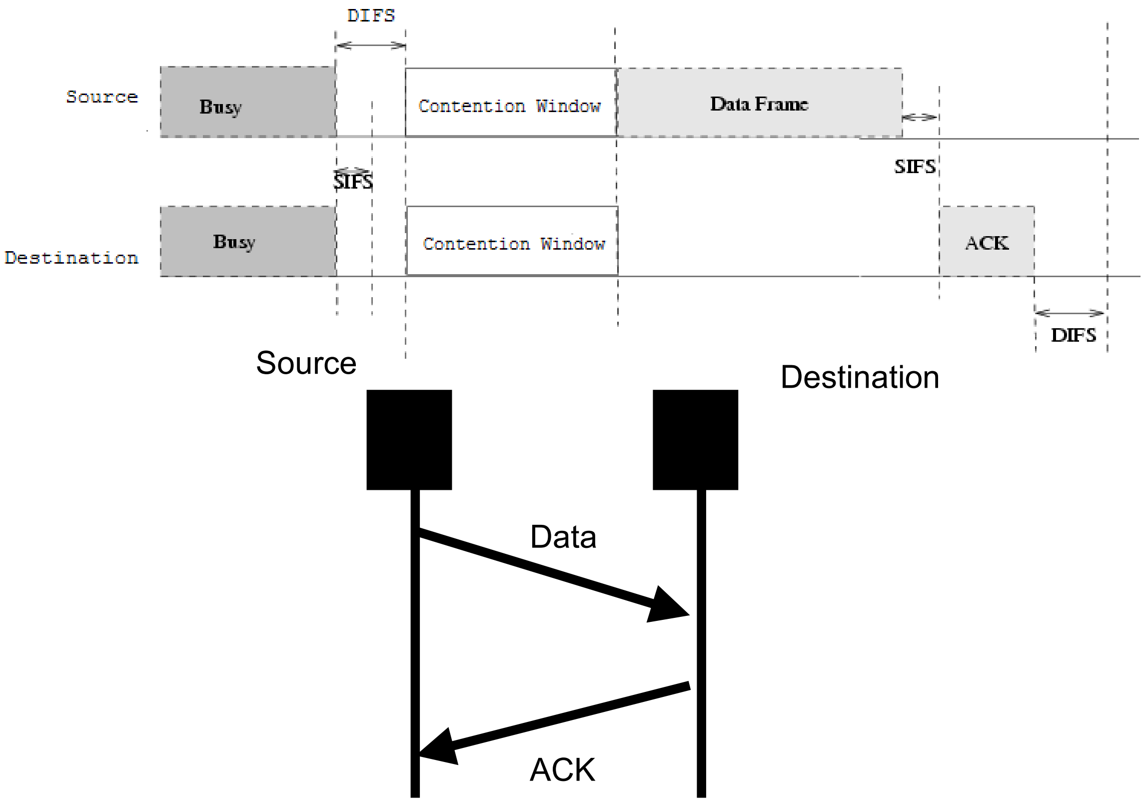

Figure 2.3 Basic Channel Access Method

A node on a wireless LAN cannot always tell by listening alone whether or not the medium is in fact clear. In a wireless network a device can be in range of two others, neither of which can hear the other but both of which can hear the first device. The access point in Figure 2.4 can hear both station A and station B, but neither A nor B can hear each other. This creates a situation in which the access point can be receiving a transmission from station B without station A sensing that node B is transmitting. Station A, sensing no activity on the channel, may then begin transmitting, jamming the access point's reception of node B's transmission already under the way. This is known as the "hidden node" problem.

To solve the hidden node problem and overcame the impossibility of collision detection, 802.11 wireless LAN DCF also provides an alternative way of transmitting data frames that involve transmission of special short Request To

Send (RTS) and Clear To Send (CTS) frames prior to the transmission of the actual data frame. A successful exchange of RTS and CTS frames attempts to reserve the channel for the time duration needed to transfer the data frame under consideration. The rules for the transmission of an RTS frame are the same as those for a data frame under basic access, i.e., the transmitter sends an RTS frame after the channel has been idle for a time interval exceeding DIFS. On receiving an RTS frame the receiver responds with a CTS frame (the CTS frame acknowledges the successful reception of an RTS frame), which can be transmitted after the channel has been idle for a time interval exceeding SIFS. After the successful exchange of RTS and CTS frames the data frame can be sent by the transmitter after waiting for a time interval SIFS. In case a CTS frame is not received within a predetermined time interval, the RTS is retransmitted following the backoff rules as specified in the basic access procedures outlined above. The channel access method using RTS and CTS frames is summarized in Figure 2.5.

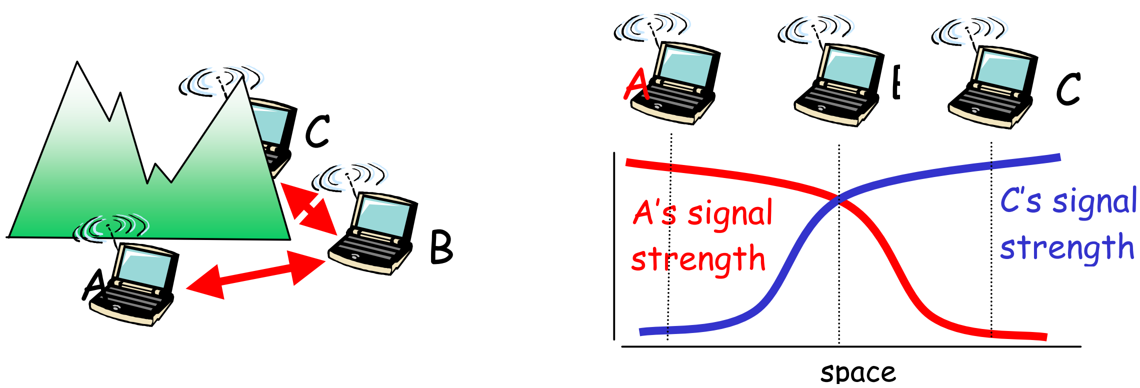

Figure 2.4 Basic Service Set, showing the Hidden Node Problem.

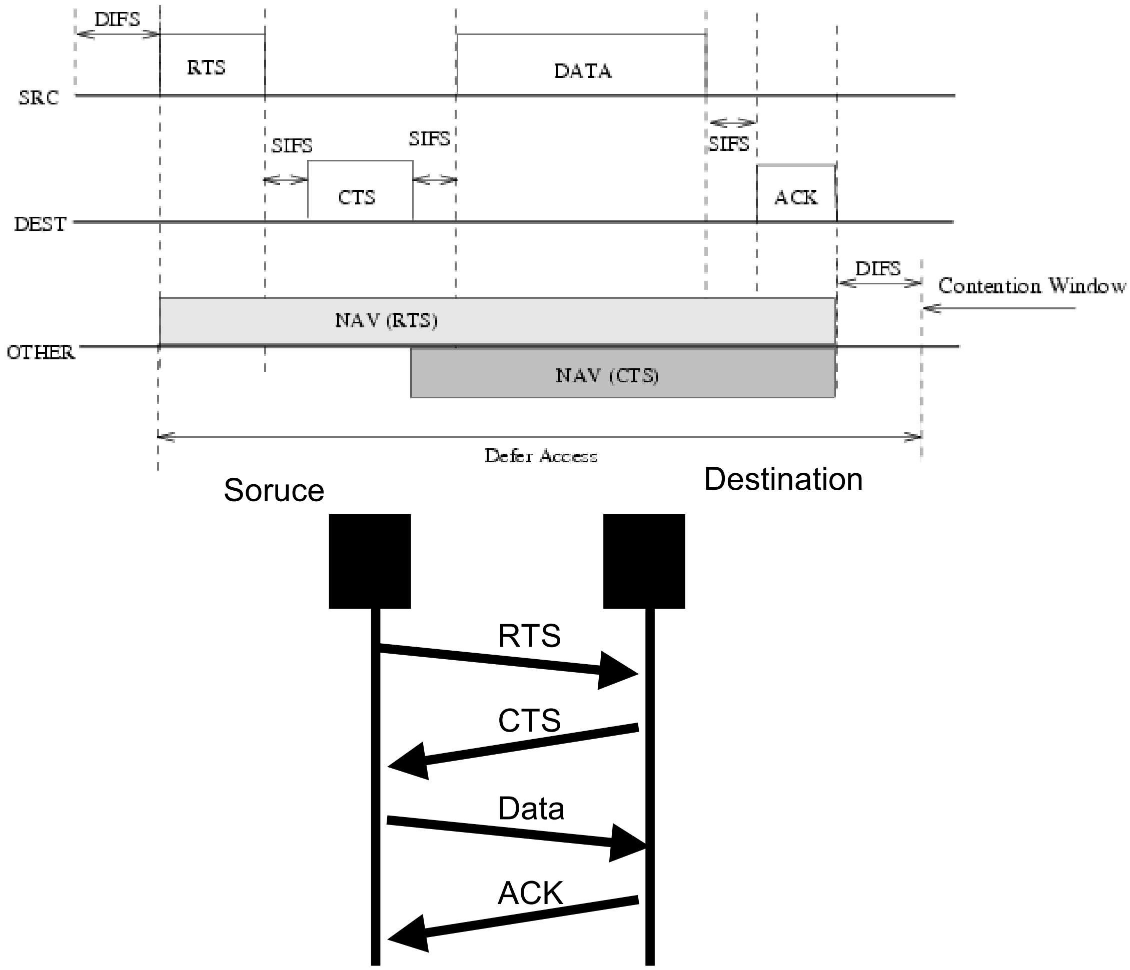

Figure 2.5 Channel Access using RTS/CTS

The RTS and CTS frames contain a duration field that indicates the period the channel is to be reserved for transmission of the actual data frame. This information is used by stations that can hear either the transmitter and/or the receiver to update their Net Allocation Vectors (NAV) -- a timer that is always decreasing if its value is non-zero. A station is not allowed to initiate a transmission if its NAV is non-zero. The use of NAV to determine the busy/idle status of the channel is referred to as the Virtual Carrier sense mechanism. Since stations that can hear either the transmitter or the receiver resist from transmitting during the transmission of the data frame under consideration the probability of its success is increased. However, this increase in the probability of successful delivery is achieved at the expense of the increased overhead involved with the exchange of RTS and CTS frames, which can be significant for short data frames as voice packets.

Binary Exponential Backoff

Before attempting to transmit, each station checks whether the medium is idle. If the medium is not idle, station defer to each other and employ an orderly exponential backoff algorithm to avoid collisions.

A period called the contention window or backoff window follows the DIFS. This window is divided into slots. Slot length is medium-dependent; higher-speed physical layers use shorter slot times.
After a station finds the channel busy, the station waits a NAV time and after the DIFS time, the stations pick a random slot and wait for that slot before attempting to access the medium; all slots are equally likely selections. When several stations are attempting to transmit, the station that picks the first slot (the station with the lowest random number) wins.

As in Ethernet, the backoff time is selected from a large range each time a transmission fails or collides. Figure 2.6 illustrates the growth of the contention window, as the number of consecutive collisions exists, using the number from the direct sequence spread spectrum (DSSS) physical layer. Other physical layers use different sizes, but the principle is identical. Contention window sizes are always 1 less than a power of 2 (e.g., 31, 63 127, 255). Each time the retry counter increases, the contention window moves to the next greatest power of two. It means that under high utilization, the value of CW (contention window) increases to relative high values after successive retransmissions,

When the contention window reaches its maximum size, it remains there until it can be reset. The contention window is reset to its minimum size when frames are transmitted successfully.

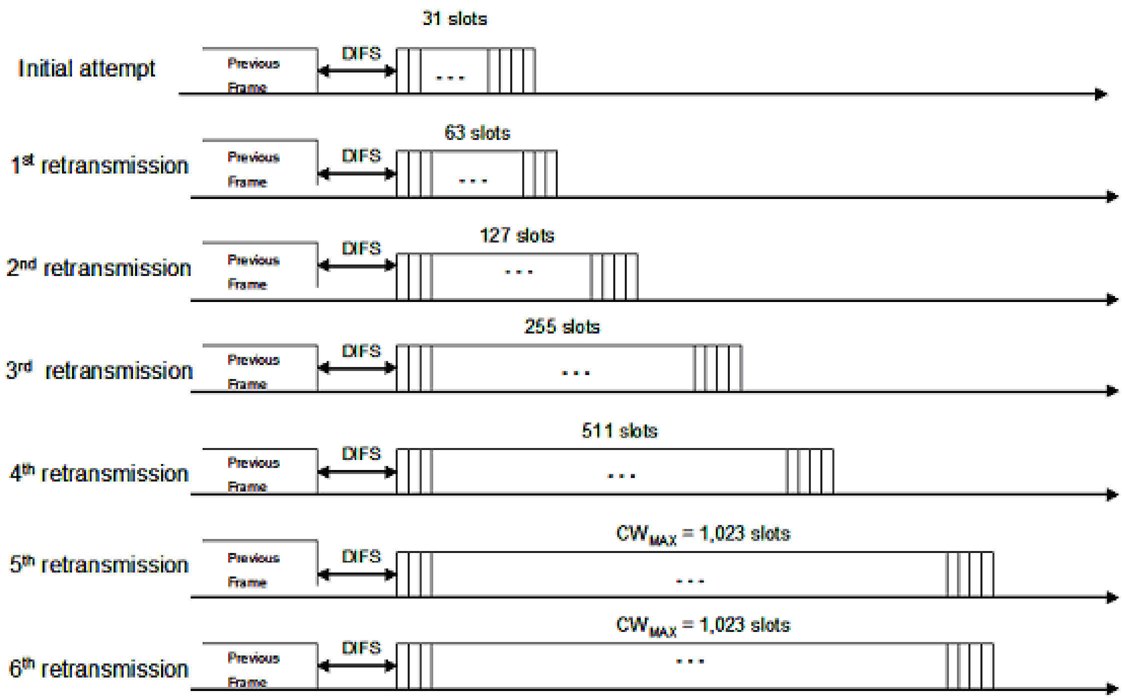

Figure 2.6 IEEE 802.11 Contention Window Exponential Backoff

Some important time parameters for the IEEE 802.11a and IEEE 802.11b and IEEE 802.11g are shown in Table 2.3.

Table 2.3. Slot Time, Minimum, and Maximum *W* for different PHY Layers

System	Slot Time	CW_{min}	CW_{max}
802.11a	9 µs	16	1024
802.11b	20µs	32	1024
802.11g	20 µs	32	1024

The binary exponential backoff can be resumed as follows:

At each packet transmission, the backoff time is uniformly chosen in the range (0, ω - 1). The value ω is called contention window, and depends on the number of transmissions failed for the packet. At the first transmission attempt, ω is set to a value CW_{min} or W_{min},, called minimum contention window. After each unsuccessful transmission, ω is doubled, up to a maximum value
$CW_{max} = 2^m\ CW_{min}$. The values of CW_{min} and CW_{max} for different PHY are shown in Table 2.3.

The backoff counter is decremented as long as the channel is sensed idle, and it's "frozen" when a transmission is detected on the channel and reactivated when the channel is sensed idle for more than a DIFS. The station transmits when the backoff time reaches zero. [1]

As general overview of the IEEE 802.11 CSMA/CA functionality, [13] gives a step by step description of the system operation as follows:

1. In Figure 2.7, [12] shows a general flowchart representing how is sending a data under CSMA/CA protocol. When a station is turned on, first of all it identifies an existing network by the process called scanning, where a station scans all possible frequencies that could exist in the access points, until the station chooses the frequency sensed, and therefore, the station may establish communication with the Access Point.
2. A station when is associated to an AP, it waits for data to transmit, and when the data is ready to be transmitted, the station may start to transmit after a period of time DIFS, as long as the medium is idle, see Figure 2.8, and the part A of Figure 2.7 that represents the mentioned in this point.
3. If the medium is not idle after the period of time DIFS, the station defers a time until medium is idle, and this deferred time is known as NAV (Network Allocation Vector). In Figure 2.9 [12] shows a transmission of a frame, where after this transmission, a DIFS period of time starts and if the station after this period of time finds the channel busy, the station has to wait a time (NAV) until the channel is idle again. In Part B of Figure 2.7 is shown this process.
4. When the medium is already idle after waiting the NAV time, the station sets the backoff counter to a random number (see part C of Figure 2.7) between 0 and *CW* (Contention Window), where *CW* increases by exponential amount if the station collides more than once. *CW* was described before as ω, were at the first transmission attempt, $\omega = W_{min}$ where $W_{min} = W$ is called minimum contention window (CW_{min}) and after each unsuccessful transmission, ω is doubled, up to a maximum value $W_{max} = 2^{m}W$.
5. After choosing the backoff counter, if the medium is not idle after the DIFS period of time, the station defers until the channel is idle again; when the medium is already idle the station listen for the DIFS period, and if the medium continues idle, the station decrements its backoff timer as long as the medium is idle, see Figure 2.10 and part C of Figure 2.7.
6. When the medium is not already idle, a station defer until the medium is idle again, when the medium is already idle, listen for a DIFS period and if it continues idle the station continues decrementing its backoff counter, and when the backoff counter arrives to 0, the station transmits, see Figure 2.11 and part C of Figure 2.7.
7. If there is a collision in the transmitting frame, the station increases *CW* by an exponential amount and continues with step 4 (but instead of NAV time is EIFS time), and if consecutively there is not collision the station resets *CW* to CW_{min}, and it waits for data to transmit, see Figure 2.12 and part D of Figure 2.7.

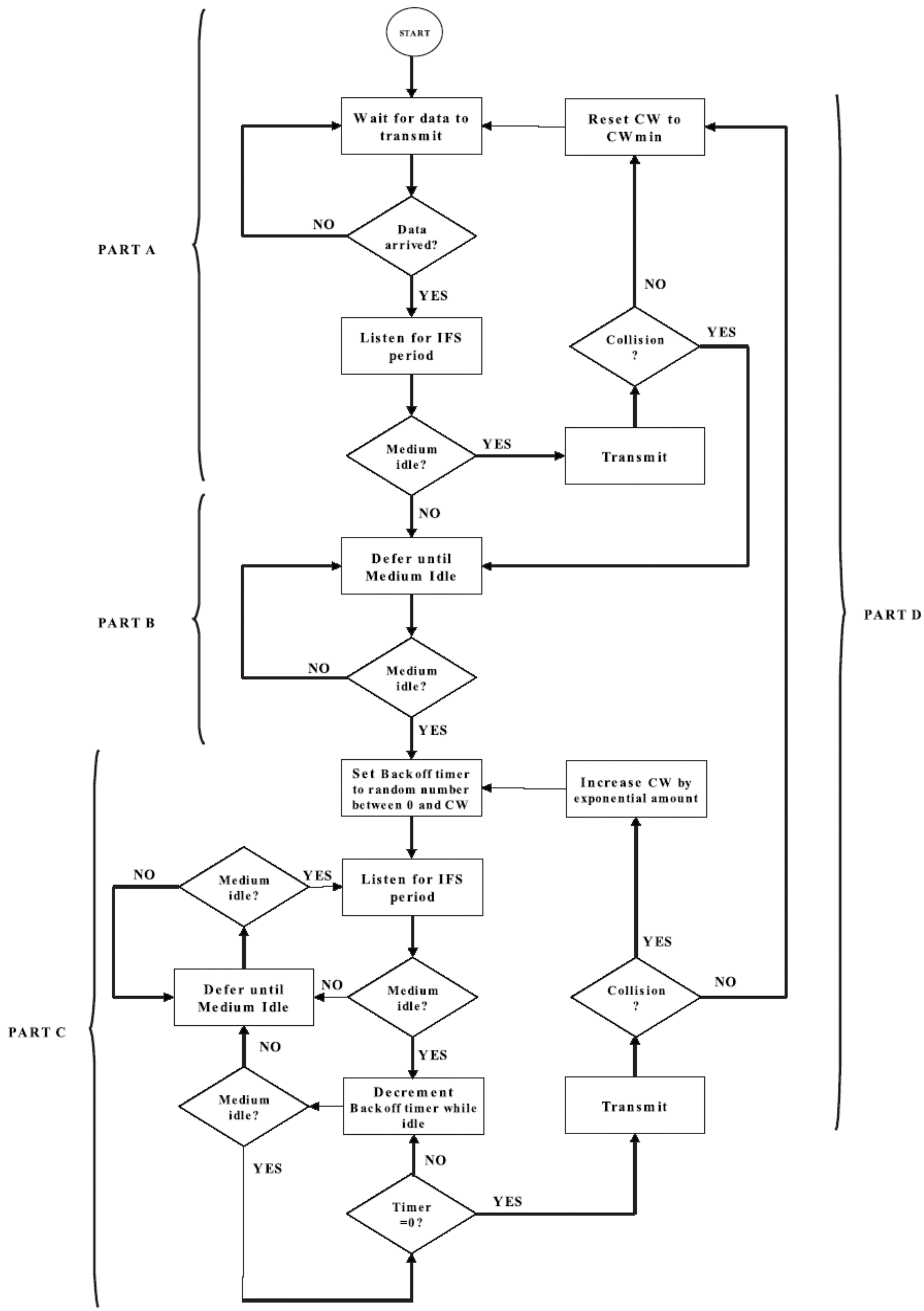

Figure 2.7 Flowchart of the process of sending data packets under CSMA/CA [13]

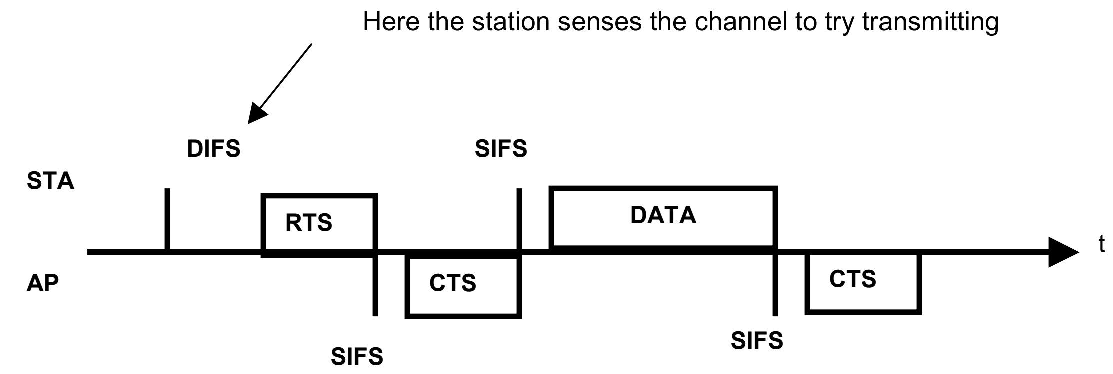

Figure 2.8 RTS-CTS Access Mechanism

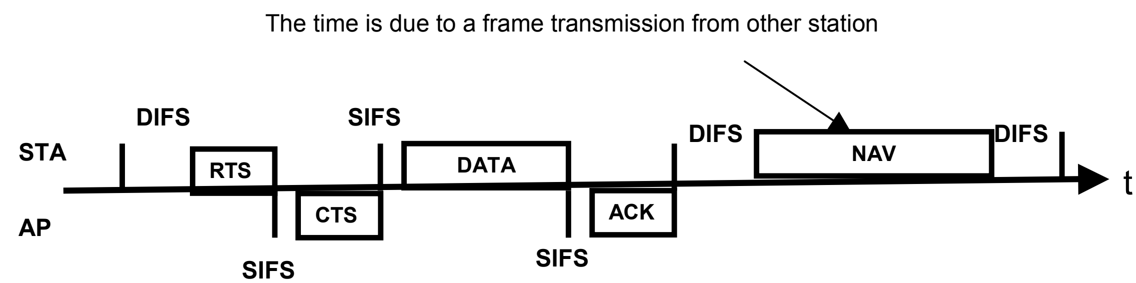

Figure 2.9 Using the NAV in RTS-CTS

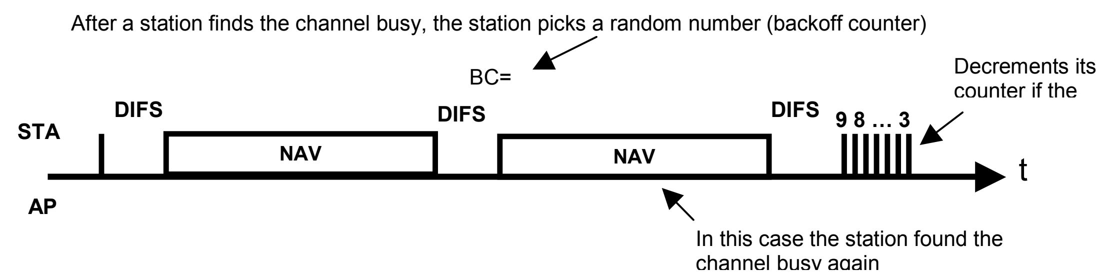

Figure 2.10. Using the Backoff Counter in RTS-CTS Access Mechanism

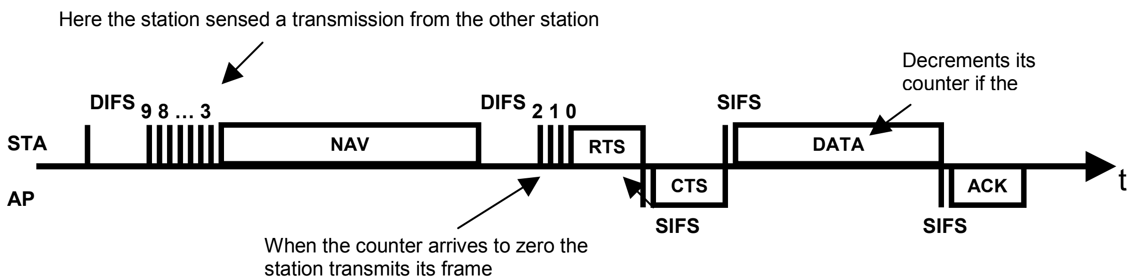

Figure 2.11 Decrementing the Backoff Counter in RTS-CTS Access Mechanism

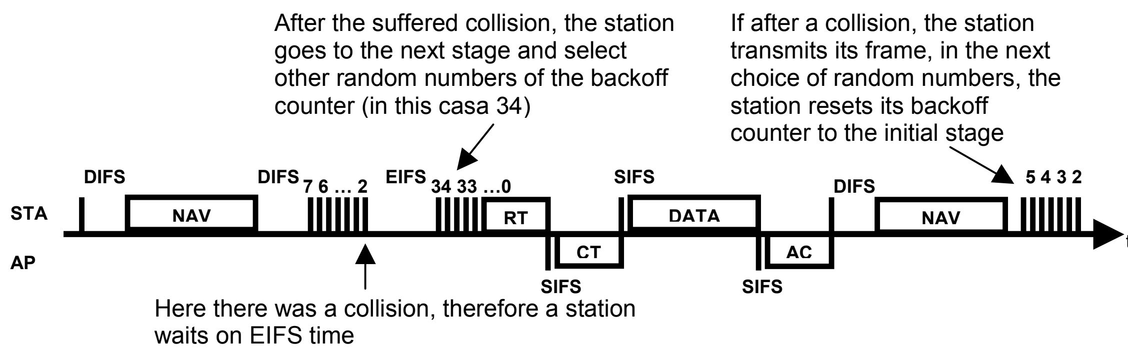

Figure 2.12 Suffering a collision in RTS-CTS Access Mechanism

2.5.2 IEEE 802.11 Frequency Allocations

Since the electromagnetic spectrum is a limited resource, the use of its radio frequency bands is regulated by governments in most countries, in a process known as frequency allocation or spectrum allocation. Since radio propagation and RF technology markets do not stop at national boundaries, there are strong technical and economic incentives for governments to adopt harmonized spectrum allocation standards.

IEEE 802.11b Channels

802.11b systems operate in the 2.4 GHz license free bands with a bit rate up to 11 Mbps. According to Table 2.4, there are 11 channels available for free use in North America; each channel has a separation of 5 MHz between center frequencies.

In 802.11 systems different carrier frequencies are used to differentiate between the various channels, as part of an FDMA procedure. In this case a channel can achieve 22 MHz bandwidth when separated with an 11-bit PN code.

In North America and Europe this method can be used to operate *three* non overlapping channels. Although only channels 1, 6 and 11, with an interval between bands of 3 MHz, shown in Figure 2.13, can be operated in a non-overlapping manner in North America, in Europe the 13 selection channels can provide different combinations or grater band intervals. For example, channels 1, 7 and 13 can be used to give a band interval of 8 MHz. If channels 1, 6 and 13 are used, the band interval between channel 6 and 13 is still 30 MHz.

Table 2.4. Regulatory Domain and Channels in the 2.4 GHz License Free Band.

Channel ID	Center Frequecy (MHZ)	USA (FCC)	Canada (IC)	Europe (ETSI)	Australia	France	Japan (MKK)
1	2,412	X	X	X	X	-	X
2	2,417	X	X	X	X	-	X
3	2,422	X	X	X	X	-	X
4	2,427	X	X	X	X	-	X
5	2,432	X	X	X	X	-	X
6	2,437	X	X	X	X	-	X
7	2,442	X	X	X	X	-	X
8	2,447	X	X	X	X	-	X
9	2,452	X	X	X	X	-	X
10	2,457	X	X	X	X	X	X
11	2,462	X	X	X	X	X	X
12	2,467			X	X	X	X
13	2,472			X	X	X	X
14	2,484						X

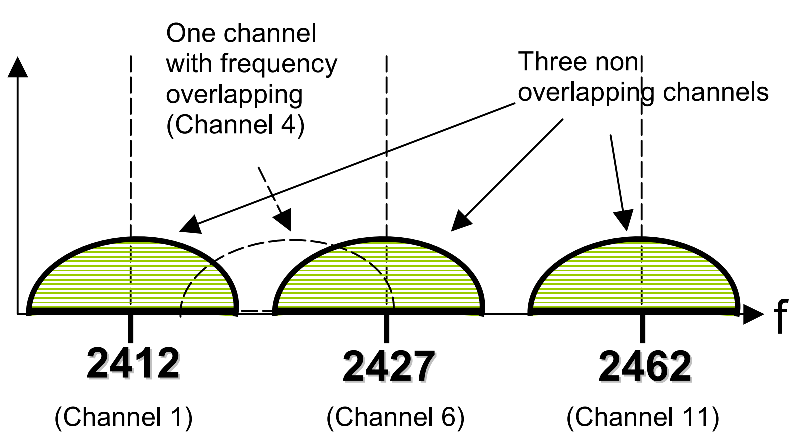

Figure 2.13 Channel assignment in IEEE 802.11b

IEEE 802.11g Channels

The IEEE 802.11g systems operate in the same frequency band than IEEE 802.11b. The main difference is that the IEEE 802.11g utilizes OFDM as the physical layer and it can achieve up to 54 Mbps. It can be seen that due to the use of OFDM we can get more non-overlapping channels than 802.11b, which is true. But there is a compatibility problem between IEEE 802.11g and IEEE 802.11b due to the different physical layers. As mentioned, the IEEE 802.11b standard has 3 non overlapping channels in the 2 GHz frequency band (reuse factor of 3). When using OFDM as the physical layer we can use the orthogonally of the signals to compress the channel bandwidth and as a result we would have more available channels. Although both system must coexist in the same frequency band, and to avoid interference between both systems the IEEE 802.11g also utilizes the same 3 non overlapping channels in the 2 GHz frequency band as the IEEE 802.11b [12].

IEEE 802.11a Channels.

802.11a utilizes 300 MHz of bandwidth in the 5 GHz Unlicensed National Information and Infrastructure (U-NII) band. Although the lower 200 MHz is physically contiguous, the FCC has divided the total 300 MHz into three distinct 100 MHz domains, each with different legal maximum power output, see Figure 2.14. The "low" band operates form 5.15 to 5.25 GHz, and has a maximum power output of 50 mW. The "middle" band is located from 5.25 to 5.35 GHz, with maximum power output of 250 mW. The "high" bandwidth utilizes 5.725-5.825 GHz, with a maximum of 1 W. Because of the high power output, devices transmitting in the high band will tend to be building to building products. The low and medium bands are more suited to in-building wireless products. [12]

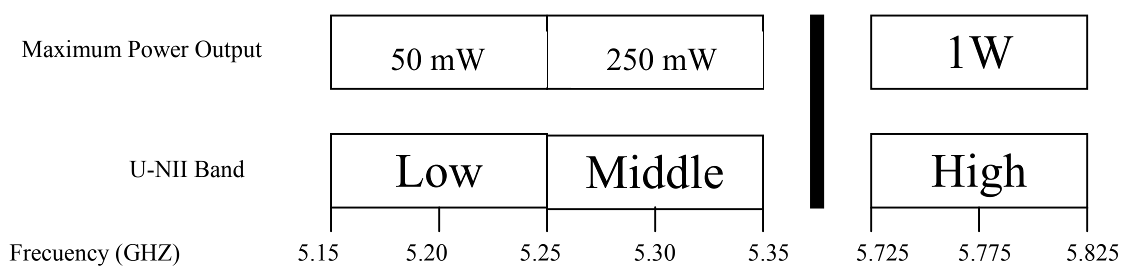

Figure 2.14 Specification of the U-NII 5 GHz

802.11a uses Orthogonal Frequency Division Multiplexing (OFDM), a new encoding scheme that offers benefits over spread spectrum in the channel availability and data rate. Channel availability is significant because the more independent channels that are available, the more scalable the wireless network becomes. The high data rate is accomplished by combining many lower speed subcarriers to create one high-speed channel. 802.11a uses OFDM to define a total of *eight* non-overlapping 20 MHz channels across the tow layer bands; each of these channels is divided into 52 subcarriers, each approximately 300 KHz wide, see Figure 2.15. By comparison, 802.11b uses three non-overlapping channels.

A large (wide) channel can transport more information per transmission than a small (narrow) one. As described above, 802.11a utilizes channels that are 20 MHz wide, with 52 subcarriers contained within. The subcarriers are transmited in “parallel”, meaning that they are sent and received simultaneously. The receiving device processes these individual signals, each one representing a fraction of the total data that, together, make up the actual signal. With this many subcarriers compressing each channel, a tremendous amount of information can be sent at once.

To finalize it is important to recall that the IEEE 802.11a, IEEE 802.11b and the IEEE 802.11g use the same Medium Access Control (MAC) layer technology, CSMA/CA, for controlling the channel access.

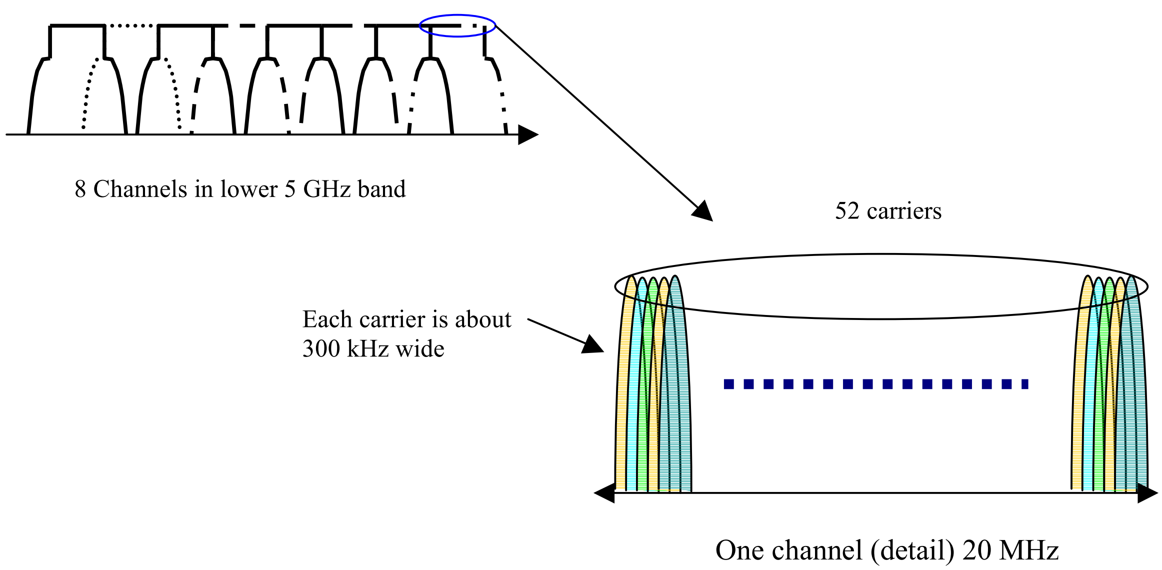

Figure 2.15 There are 8 non-overlapping channels in IEEE 802.11a.

Chapter 3

Mobile Radio Propagation

The mobile radio channel places fundamental limitation on the performance of wireless communications systems. The transmission path between the transmitter and the receiver can vary from simple line-of-sight (LOS) to on that is severely obstructed by objects. Unlike wired channels that are stationary and predictable, radio channels are extremely random and do not offer easy analysis.
Modeling the radio channel has historically been one of the most difficult parts of mobile radio system design, and is typically done in a statistical fashion, based on measurements made specifically for an intended communication system or spectrum allocation, [15].

In this chapter a review of the radio propagation path loss is presented with emphasis on mathematical models in scenarios where there is no line of sight (LOS) between transmitter and receiver and small scale propagation effects such as fading are predominant.

3.1 Introduction to Radio Wave Propagation

Propagation models have traditionally focused on predicting the average received signal strength at a given distance from the transmitter, as well as the variability of the signal strength in close spatial proximity to a particular location. Propagation models that predict the mean signal strength for an arbitrary transmitter–receiver separation distance are useful in estimating the radio coverage area of a transmitter and are called large-scale propagation models, since the characterize signal strength over a large transmitter – receiver separation distances (several hundreds of thousands of meters). On the other hand, propagation model that characterize the rapid fluctuations of the received signal strength over a very short travel distances (a few wavelengths) or short time duration (on the order of seconds) are called small-scale or *fading* models [15].

As mobile moves over very small distances, the instantaneous received signal strength may fluctuate rapidly giving rise to small-scale fading; such is the case of wireless LAN network. The reason for this is that the received signal is a sum of many contributions coming form different directions. Since the phases are random, the sum of the contributions varies widely; it obeys a Rayleigh fading distribution. In small-scale fading the received signal power may vary by as much as three or four orders of magnitude (30 to 40 dB) when the receiver is moved by only a fraction of wavelength. As the mobile moves away from the transmitter over much larger distances, the local average received signal will gradually decrease, and it is the local average signal level that is predicted by large-scale propagation models [15]. Typically, the local average received power is computed by averaging signal measurements over a track of 5 λ to 40 λ.

3.2 Free Space Propagation Model

The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line of sight path between them. As with most large-scale radio wave propagation models, the free space model predicts that the received power decays as a function of the transmitter – receiver separation distance raised to some power. The free space power received by a receiver antenna, which is separated from a radiating transmitter antenna by a distance d, is given by the Friss free space Equation, [15].

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \qquad (3.1)$$

where P_t is the transmitted power, $P_r(d)$ is the received power which is a function of the transmitter – receiver separation, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, d is the transmitter – receiver separation distance in meters, L is the system loss factor not related to propagation, and λ is the wavelength in meters. The gain of an antenna is related to its effective aperture, A_e, by

$$G = \frac{4\pi A_e}{\lambda^2}. \qquad (3.2)$$

The effective aperture A_e is related to the physical size of the antenna, and λ is related to the carrier frequency by

$$\lambda = \frac{c}{f} = \frac{2\pi c}{w_c}, \qquad (3.3)$$

where f is the carrier frequency in Hertz, w_c is the carrier frequency in radians per second, and c is the speed of light given in meters/s. The miscellaneous losses L ($L \geq 1$) are usually due to transmission line attenuation, filter losses, and antenna losses in the communication system. A value of $L = 1$ indicates no loss in the system hardware, [15].

It is common to express Equation (3.1) as the local-mean power of the transmitted signal at the receiver. In such case, Equation (3.1) may be written as:

$$P_d(d) = A \cdot d^{-n} \cdot P_t, \qquad (3.4)$$

where n is the path loss exponent and it is equal to 2 in the free space model an equal to 4 for indoor channels in picocells systems as in wireless LANs.

3.3 Small-Scale Fading and Multipath

Small-scale fading, or simply *fading*, is used to describe the rapid fluctuation of the amplitudes, phases or multipath delays of a radio signal over a short period of time or travel distance, so that large-scale path loss effects may be ignored [15].

Fading is caused by interference between two or more version of the transmitted signal which arrive at the receiver at slightly different times. These waves, called multipath waves, combine at the receiver antenna to give a resultant signal which can vary widely in amplitude an phase, depending on the distribution of the intensity and relative propagation time of the waves and the bandwidth of the transmitted signal.

If objects in the radio channel are static, and motion is considered to be only due to that of the mobile, then fading is purely a spatial phenomenon. The spatial variations of the resulting signal are seen as temporal variation by the receiver as it moves through the multipath field. Due to the constructive and destructive effects of multipath waves summing at various pints in space, a receiver moving at high speed can pass through several fades in a small period of time. In a more serious case, a receiver may stop at a particular location at which the receiver signal is in a deep fade. Maintaining good communications can then become very difficult, although passing vehicles or people walking in the vicinity of the mobile can often disturb the field pattern, thereby diminishing the likelihood of the received signal remaining in a deep null for a long period of time.

Many physical factors in the radio propagation channel influence small-scale fading. These include the following:

- Multipath propagation.- The presence of reflecting objects and scatters in the channel creates a constantly changing environment that dissipates the signal energy in amplitude, phase, and time. These effects result in multiple versions of the transmitted signal that arrive at the receiving antenna, displaced with respect to on another in time and spatial orientation. The random phases and amplitudes of the different multipath components cause fluctuations in signal strength, thereby inducing small-scale fading, signal distortion, or both.
- Speed of the mobile.- The relative motion between the base station and the mobile results in random frequency modulation due to different Doppler shifts on each of the multipath components. Doppler shift will be positive or negative depending on whether the mobile receiver is moving toward or away form the base station.
- Speed of surrounding object.- If objects in the radio channel are in motion, they induce a time varying Doppler shift on multipath components. If the surrounding objects move at a grater rate than the mobile, then this effect

dominates the small-scale fading. Otherwise, motion of surrounding objects may be ignored, and only the speed of the mobile need to be considered.

3.3.1 Rayleigh Distribution

The received signal at a mobile will rarely have a direct line of sight to a transmitter. It is the sum of the signals formed by the transmitted signal scattered by randomly placed obstruction imposing different attenuation and phases on the resultant signals. It is plausible to suppose that the phases of the scattered waves are uniformly distributed from 0 to 2π radians and that amplitudes and phases are statistically independent form each other [16]. Consequently, we may expect that at a certain instant the waves will be in phase, producing large amplitude (constructive interference), whereas at another instant they will be out of phase, producing a small amplitude (destructive interference).

In mobile radio channels, the Rayleigh distribution is commonly used to describe the statistical time varying nature of the received envelope. It is well known that the envelope of the sum of two quadrature Gaussian noise signals obeys a Rayleigh distribution, a formal demonstration can be found in [16].

In other words, when there is no line of sight between the transmitter and the receiver, the received complex envelope, $z(t) = |r(t)|$, has a Rayleigh probability density function at any time t [4], given by:

$$f_r(r) = \frac{r}{\sigma^2}\exp\left\{-\frac{r^2}{2\sigma^2}\right\}, \quad 0 \le r \le \infty , \tag{3.5}$$

were r is the received signal amplitude.
The second moment (average power of the signal) is:

$$E[r^2] = 2\sigma^2 = p_o . \tag{3.6}$$

Thus, Equation (3.5) can be expressed in terms of the signal amplitude and the average power of the signal as:

$$f_r(r) = \frac{2r}{p_o}\exp\left\{-\frac{r^2}{p_o}\right\} , \quad 0 \le r \le \infty . \tag{3.7}$$

This type of fading is called *Rayleigh fading* and agrees very well with empirical observation for microcellular applications, as in wireless networks. Rayleigh fading usually applies to any scenario where there is no line of sight between the transmitter and the receiver antennas.

Equation (3.7) gives us the pdf of the received signal amplitude, but in a radio propagation and interference analysis we need to work with the received signal's power and not its amplitude. We are now interested in finding the pdf of the received instantaneous power.

The probability density function of the received instantaneous power $z^2(t) = |r(t)|^2$ is calculated using a random variable transformation.
Let P be the instantaneous power at the receptor, then:

$$P = r^2,$$
$$r = \sqrt{P}.$$

The pdf for the instantaneous power is obtained by using the following random variable transformation:

$$f_y(y) = f_x(x)\left|\frac{dx}{dy}\right|.$$

This gives us:

$$f_P(P) = \frac{2r}{p_o}\exp\left\{-\frac{r^2}{p_o}\right\}\left|\frac{dr}{dP}\right|_{r=\sqrt{P}},$$
$$= \frac{2\sqrt{P}}{p_o}\exp\left\{\frac{-P}{p_o}\right\}\left|\frac{1}{2\sqrt{P}}\right|,$$

$$f_P(P) = \frac{1}{p_o}\exp\left\{\frac{-P}{p_o}\right\}\ ,\quad P > 0. \tag{3.8}$$

Thus the received instantaneous power follows is an exponential probability distribution function.

With the theory of chapters 2 and 3 and Equation (3.8) and some probability background we can now begin to develop an IEEE 802.11 capacity analysis under the influence of co-channel interference.

Chapter 4

Capture Effect in Wireless Systems under Rayleigh Fading

In classical analysis of random access protocols (ideal channel consideration) it is assumed that all the frames involved in a collision are destroyed. This is an unrealistic assumption in mobile radio environment because of the differences in power levels of the transmitted signals at the receiver introduced by the deterministic path attenuation, shadowing and multipath fading. Due to the capture effect, a frame with the strongest received signal strength can be correctly decoded at the receiver even in the presence of simultaneous transmission of multiple stations. Capture effect is feasible in an indoor environment consisting of low-power transmitting stations [3], i.e. in a wireless LAN.

In this chapter both frame capture and hidden station effects are analytically considered from the perspective of Rayleigh fading on the radio channel. Their impact and the interference problem analysis in IEEE 802.11 systems are analyzed in terms of the throughput and the delay of stations in Chapter 5.

4.1 Capture Model under Rayleigh Fading

The IEEE 802.11 radio channels are exposed to multipath fading, which primarily results in increase of frame-error probability, but also introduces both the hidden terminal and the capture effect as mentioned in Chapter 2. Recalling the hidden node problem mentioned in chapter 2 (see Figure 2.4); in a real world scenario station A would not be able to sense the transmission of station B because the instantaneous signal power received at station A due to station B would be small enough so the receiver of station A would think is noise and the same will happen to station B with the received signal from station A. As a consequence they will both transmit and a collision could probably occur diminishing their throughput and increasing their delay. Station A and station B can not detect each other due to the Rayleigh fading. Notice that a collision would “probably” occur, which means that even thought both stations transmit at the same time there is a *capture effect* in where the transmitted signal with the highest instantaneous power could be correctly received. This assumption is reasonable in the presence of powerful codes, as those used in actual wireless systems [3].

As can be seen, with a proper model which takes in count the multipath radio channel in IEEE 802.11 systems, both the hidden node problem and the capture effect will be modeled as a natural result of the analysis, which is one of the major contributions of this work.

A natural application of IEEE 802.11 systems are on indoor environments. This indoor environment produces in most of the cases a non line of sight transmission, so a great number of signals are reflected. Experimental analysis show that the coverage area of an IEEE 802.11 system is around 100 meters in a free space, and around 60 m in an indoor environment [6]; with this measures and the mentioned assumptions a transmitted signal experiences a Rayleigh fading in an indoor application.

For a station in a IEEE 802.11 system, at a distance r from the Access Point, which means the envelope of transmitted signal is Rayleigh faded; its instantaneous received power has a pdf given by Equation (3.8), and is exponentially distributed:

$$f_P(P) = \frac{1}{p_o} e^{-\frac{P}{p_o}}, \ P > 0. \quad (4.1)$$

Where p_o represent the local mean power of the transmitted frame at the receiver. The local mean power is determined by Equation (3.4):

$$p_o = A \cdot r^{-\alpha} \cdot P_T,$$

where $A \cdot r^{-\alpha}$ is the deterministic path-loss law, and P_T is the transmitted signal power. Constants A and P_T are assumed to be identical for all transmitted frames and the path loss exponent is assumed to be $\alpha = 4$. So we have:

$$p_o = A \cdot r^{-4} \cdot P_T. \quad (4.2)$$

Let P_i be the received instantaneous power of the i^{th} interfering station.
And let P_u be the received instantaneous power of the desired user (desired station). “Notice that the i^{th} interfering station can be any station from the Basic Service Set and it can also be any other station that belongs to other non identified Basic Service Set (a station that belongs to other IEEE 802.11 that is overlapped with the desired system)”

The instantaneous Signal to Noise Ratio (SNR) can be expressed as:

$$SNR = \frac{P_u}{P_{ThermalNoise} + \sum_{i=1}^{\eta} P_i},$$

where there are η interfering stations.

Assuming that the instantaneous thermal noise power, $P_{ThermalNoise}$, is small enough to be insignificant compared with the interfering instantaneous power signals. So,

$$SNR = \frac{P_u}{\sum_{i=1}^{\eta} P_i}. \tag{4.3}$$

Let's rename the SNR by γ, so that:

$$\gamma = \frac{P_u}{\sum_{i=1}^{\eta} P_i}. \tag{4.4}$$

We define the *capture probability*, $P_{capture}$, as the probability that γ falls above (exceeds) a receiver threshold for correctly detection, β, where β can be seen as the capture threshold.

For the case when in an IEEE 802.11 system only the desired station is transmitting (assuming that there could more stations in the system but none of them are going to transmit, thus there is no interference), the probability of capture is:

$$P_{capture}(P_u \geq \beta) = \int_{\beta}^{\infty} f_P(P_u)dP_u \ . \tag{4.5}$$

The above Equation specifies the probability that the received instantaneous power is greater than the receiver threshold, β, and where $f_P(P_u)$ is the pdf of the received instantaneous power of the desired user in a Rayleigh faded channel. Substituting (4.1) in (4.5) we get:

$$P_{capture}(P_u \geq \beta) = \int_{\beta}^{\infty} f_P(P_u)dP_u = \frac{1}{p_o} e^{-\frac{P_u}{p_o}} \cdot \frac{1}{-\frac{1}{p_o}} = -e^{-\frac{P_u}{p_o}}\Big|_{\beta}^{\infty}.$$

Thus,

$$P_{capture}(P_u \geq \beta) = e^{-\frac{\beta}{p_o}} \ . \tag{4.6}$$

Equation (4.6) is an important result and it will be widely use for the throughput and delay analysis in Chapter 5.

For the case when there are η interfering stations, we have $SNR = \gamma = \frac{P_u}{\sum_{i=1}^{\eta} P_i}$.

We are interested in the capture probability, that is, the probability that $\gamma \geq \beta$ given that we have η interfering stations at a distance r_i form the receiver:
(It is important to notice that IEEE 802.11 systems don't have power control)

$$\text{Probability of capture} = \text{Prob}\left\{\gamma \geq \beta \mid r_u, r_1, ..., r_\eta\right\}, \qquad \gamma = 0, 1, 2, ... \tag{4.7}$$

Which means that the probability of capture of my sending frame is the probability that my SNR exceeds the threshold detection, β, given that I know the distances of al the stations affecting the transmission.

From (4.7) we can establish the following relation for the capture probability:

$$\text{Prob}\left\{\gamma \geq \beta \mid r_u, r_1, ..., r_\eta\right\} = \text{P}\left\{P_1 \geq 0\right\} \text{P}\left\{P_2 \geq 0\right\} \text{P}\left\{P_3 \geq 0\right\} ... \text{P}\left\{P_\eta \geq 0\right\} \text{P}\left\{P_u \geq \beta(P_1 + ... + P_\eta)\right\} \tag{4.8}$$

The right side of Equation (4.8) is explained as follows: the probability that a receiver captures a transmitted frame from the desired user given that there are η interfering stations and that I know their distances relative to the receiver station is equal to the probability that the number one interfering station is transmitting in the same time slot and that the number two interfering station is transmitting in the same time slot and that the number three interfering station is transmitting in the same time slot and that the η interfering station is transmitting in the same time slot and that the desired user transmits and its instantaneous received power is greater than the threshold β and than the other interfering stations.

This analysis is based under the assumption of mutual statistical independence, i.e., the signal transmitted by station 1 is attenuated differently than the signal transmitted by station 2, this is because there are different obstacles in the transmitter – receiver paths. A second assumption is made in supposing that the instantaneous received power remains constant in a given time slot. This assumption is valid since the time slot duration is very small.

Also, an immediate validation questioning on (4.8) can be realized when using IEEE 802.11 systems. Equation (4.8) says that all the interfering stations are transmitting at the same time the desired user transmits. This is by far an unrealistic statement, but the analysis is not finished yet. We necessary have to know the probability of transmission of each of the interfering stations, τ_i, which will be obtained in Chapter 5 and with these and the fundamental assumption made by [1] and [2] of transmission independence in the medium when the system is in a state of *saturation*, which is experimentally reached when there are more than 10 station involved in the system, we can make use of a binomial probability density function to calculate the probability of capture when there are i potential interfering frames using the probability of transmission of the stations as the probability of success (arrival) in the binomial pdf.

Continuing with the analysis of Equation (4.8) and using (4.1) we have:

$$\text{Prob}\{\gamma \geq \beta / r_u, r_1, ..., r_\eta\} = \int_0^\infty f_{P_1}(P_1)dP_1 \int_0^\infty f_{P_2}(P_2)dP_2 \cdots \int_0^\infty f_{P_\eta}(P_\eta)dP_\eta \int_{\beta(P_1+\cdots+P_\eta)}^\infty f_{P_u}(P_u)dP_u$$

$$= \int_0^\infty f_{P_1}(P_1)dP_1 \int_0^\infty f_{P_2}(P_2)dP_2 \cdots \int_0^\infty f_{P_\eta}(P_\eta)dP_\eta \int_{\beta(P_1+\cdots+P_\eta)}^\infty \frac{1}{p_{ou}} e^{-\frac{P_u}{p_{ou}}} dP_u$$

$$= \int_0^\infty f_{P_1}(P_1)dP_1 \int_0^\infty f_{P_2}(P_2)dP_2 \cdots \int_0^\infty f_{P_\eta}(P_\eta)dP_\eta \cdot \frac{1}{p_{ou}} e^{-\frac{P_u}{p_{ou}}}(-P_{ou}) \Bigg|_{\beta(P_1+\cdots+P_\eta)}^\infty$$

$$= \int_0^\infty f_{P_1}(P_1)dP_1 \int_0^\infty f_{P_2}(P_2)dP_2 \cdots \int_0^\infty f_{P_\eta}(P_\eta)dP_\eta \cdot e^{-\beta \sum_{i=1}^{\eta} \frac{P_i}{p_{ou}}}$$

$$= \int_0^\infty f_{P_1}(P_1)dP_1 \int_0^\infty f_{P_2}(P_2)dP_2 \cdots \int_0^\infty \frac{1}{p_{o\eta}} e^{-\frac{P_\eta}{p_{o\eta}}} \cdot e^{-\beta \sum_{i=1}^{\eta-1} \frac{P_i}{p_{ou}}} \cdot e^{-\beta \frac{P_\eta}{p_{ou}}} dP_\eta$$

$$= \int_0^\infty f_{P_1}(P_1)dP_1 \int_0^\infty f_{P_2}(P_2)dP_2 \cdots \frac{e^{-\beta \sum_{i=1}^{\eta-1} \frac{P_i}{p_{ou}}}}{p_{o\eta}} \int_0^\infty e^{-P_\eta \left(\frac{p_{ou}+\beta p_{o\eta}}{p_{o\eta} p_{ou}}\right)} dP_\eta$$

$$= \int_0^\infty f_{P_1}(P_1)dP_1 \int_0^\infty f_{P_2}(P_2)dP_2 \cdots \frac{e^{-\beta \sum_{i=1}^{\eta-1} \frac{P_i}{p_{ou}}}}{p_{o\eta}} \cdot \left[\frac{p_{o\eta} p_{ou}}{p_{ou} + \beta p_{o\eta}}\right] \cdot e^{-P_\eta \left(\frac{p_{ou}+\beta p_{o\eta}}{p_{o\eta} p_{ou}}\right)} \Bigg|_0^\infty$$

$$= \int_0^\infty f_{P_1}(P_1)dP_1 \int_0^\infty f_{P_2}(P_2)dP_2 \cdots e^{-\beta \sum_{i=1}^{\eta-1} \frac{P_i}{p_{ou}}} \cdot \left[\frac{p_{ou}}{p_{ou} + \beta p_{o\eta}}\right] \cdot e^{-P_\eta \left(\frac{p_{ou}+\beta p_{o\eta}}{p_{o\eta} p_{ou}}\right)} \Bigg|_0^\infty$$

$$=\int_0^\infty f_{P_1}(P_1)dP_1\int_0^\infty f_{P_2}(P_2)dP_2\cdots e^{-\beta\sum_{i=1}^{\eta-1}\frac{P_i}{p_{ou}}}\cdot\left[\frac{1}{1+\beta\frac{p_{o\eta}}{p_{ou}}}\right]\cdot e^{-P_\eta\left(\frac{p_{ou}+\beta p_{o\eta}}{p_{o\eta}p_{ou}}\right)}\Bigg|_0^\infty$$

$$=\int_0^\infty f_{P_1}(P_1)dP_1\int_0^\infty f_{P_2}(P_2)dP_2\cdots e^{-\beta\sum_{i=1}^{\eta-1}\frac{P_i}{p_{ou}}}\cdot\left[\frac{1}{1+\beta\frac{p_{o\eta}}{p_{ou}}}\right]$$

$$=\int_0^\infty f_{P_1}(P_1)dP_1\int_0^\infty f_{P_2}(P_2)dP_2\cdots\int_0^\infty f_{P_{\eta-1}}(P_{\eta-1})dP_{\eta-1}e^{-\beta\sum_{i=1}^{\eta-1}\frac{P_i}{p_{ou}}}\cdot\left[\frac{1}{1+\beta\frac{p_{o\eta}}{p_{ou}}}\right]$$

$$=\int_0^\infty f_{P_1}(P_1)dP_1\int_0^\infty f_{P_2}(P_2)dP_2\cdots e^{-\beta\sum_{i=1}^{\eta-2}\frac{P_i}{p_{ou}}}\cdot\left[\frac{1}{1+\beta\frac{p_{o\eta}}{p_{ou}}}\right]\int_0^\infty\frac{1}{p_{o\eta-1}}e^{-\frac{P_{\eta-1}}{p_{o\eta-1}}}e^{-\beta\frac{P_{\eta-1}}{p_{ou}}}dP_{\eta-1}$$

$$=\int_0^\infty f_{P_1}(P_1)dP_1\int_0^\infty f_{P_2}(P_2)dP_2\cdots e^{-\beta\sum_{i=1}^{\eta-2}\frac{P_i}{p_{ou}}}\cdot\left[\frac{1}{1+\beta\frac{p_{o\eta}}{p_{ou}}}\right]\frac{1}{p_{o\eta-1}}\int_0^\infty e^{-P_{\eta-1}\left(\frac{p_{ou}+\beta p_{o\eta-1}}{p_{ou}p_{o\eta-1}}\right)}dP_{\eta-1}$$

$$=\int_0^\infty f_{P_1}(P_1)dP_1\int_0^\infty f_{P_2}(P_2)dP_2\cdots e^{-\beta\sum_{i=1}^{\eta-2}\frac{P_i}{p_{ou}}}\cdot\left[\frac{1}{1+\beta\frac{P_{o\eta}}{p_{ou}}}\right]\frac{1}{p_{o\eta-1}}\left[\frac{p_{o\eta-1}p_{ou}}{p_{ou}+\beta p_{o\eta-1}}\right]$$

$$=\int_0^\infty f_{P_1}(P_1)dP_1\int_0^\infty f_{P_2}(P_2)dP_2\cdots e^{-\beta\sum_{i=1}^{\eta-2}\frac{P_i}{p_{ou}}}\cdot\left[\frac{1}{1+\beta\frac{p_{o\eta}}{p_{ou}}}\right]\left[\frac{1}{1+\beta\frac{P_{o\eta-1}}{p_{ou}}}\right].$$

By induction, Prob $\{\gamma\geq\beta/r_o,r_1,...,r_\eta\}$ has a closed form expression:

$$\text{Prob}\left\{\gamma \geq \beta / r_u, r_1, ..., r_\eta\right\} = \prod_{i=1}^{\eta} \frac{1}{1 + \beta \dfrac{p_{oi}}{p_{ou}}}. \tag{4.9}$$

Where p_{oi} is the average power of the i^{th} interfering station given by

$$p_{oi} = A \cdot r_i^{-4} \cdot P_T, \tag{4.10}$$

and p_{ou} is the average power of the desired user given by

$$p_{ou} = A \cdot r_u^{-4} \cdot P_T. \tag{4.11}$$

Substituting (4.10) and (4.11) in (4.9) we have a final closed form expression of the capture probability given that we know al the distances with respect the receiving station:

$$\text{Prob}\left\{\gamma \geq \beta / r_u, r_1, ..., r_\eta\right\} = \prod_{i=1}^{\eta} \frac{1}{1 + \beta \left(\dfrac{r_i}{r_u}\right)^{-4}}. \tag{4.12}$$

Where r_i is the distance of the i^{th} interfering station to the receiver (the receiver is the station to who the desired user intents to transmit a frame) and r_u is the distance of the desired user to its desired receiver.

As mentioned in this chapter, for the IEEE 802.11 CSMA/CA algorithm we cannot use directly the probability of capture defined by Equation (4.12), because it assumes all stations are transmitting at the same time in the time slot.

In IEEE 802.11, the time is divided in time slots, and each particular station transmits with a particular τ_i in a time slot ($0 \leq t_{slot} \leq t$). We are interested in the probability that in this time slot no users interfere with the transmission, or the probability that only 1 user interfere with the transmission, or the probability of 2 users interfere with the transmission, …, or the probability that η users interfere simultaneously, or the combination of any of the above. A classical approach to find this probability is to sum the probabilities of the contribution of each interfering station with the combination of any one using a binomial probability density function. To use the binomial probability function, we must know the probability of success and the probability of failure. In this case, the probability of success is the probability of transmission of any interfering station, τ_i, and the probability of failure is 1 - τ_i.

In an IEEE 802.11 real world scenario, each station transmits with its own transmission probability τ_i and it is dependent of its space localization, as it will be shown in Chapter 5.

For illustration purposes two situations are analyzed:

1. All the interfering stations transmit with the same probability, τ .
2. Each interfering station has its own probability of transmission, τ_i .

1. All the interfering stations transmit with the same probability, τ .

If we assume that all the stations transmit with the same probability, τ , the probability of capture will be the following:

We define $R(i) = R_i$ as the probability that i interfering frame generates in an observed time slot, thus

$$R(i) = R_i = \binom{\eta}{i} \tau^i (1-\tau)^{\eta-i} . \tag{4.13}$$

Where η are all the IEEE 802.11 *interfering* stations operating in the same frequency band (note that an AP is also a station and it can also cause interference) and it also include stations belonging to other IEEE 802.11 systems working in the same frequency band (channel), so that η does not include the transmitting station; only the interfering ones. τ is the probability of transmission that an interference occurs in the receptor to which the desired station is sending a frame to

For a system where all stations have the same probability of transmission, the probability of capture of a frame sent by the desired user at distance r_u from the receiver given that we know the all the distances of all the interfering stations to the receiver and the receiver threshold, β , is

Probability of capture = Pcapture $\{\beta, r_u, r_1, r_2, ..., r_\eta\}$.

The probability of capture is given by:

Pcapture $\{\beta, r_u, r_1, r_2, ..., r_\eta\}$=P{of transmission of interfering station 1 in the time slot}•Prob $\{\gamma \geq \beta / r_u, r_1\}$

+P{of transmission of interfering station 1 and interfering station 2 in the time slot}•Prob $\{\gamma \geq \beta / r_u, r_1, r_2\}$

.
.
.

+P{of transmission of any interfering combination in the time slot}•Prob $\{\gamma \geq \beta / r_u, r_1, r_2\}$

.
.
.

+P{of transmission of interfering station 1 and 2 and 3…and η^{th} station in the time slot}•Prob $\{\gamma \geq \beta / r_u, r_1, r_2, r_3, ..., r_\eta\}$

$$\text{P}_{\text{capture}}\{\beta, r_u, r_1, r_2, ..., r_\eta\} = \sum_{i=1}^{\eta} R_i \cdot \text{Prob}\{\gamma \geq \beta / r_u, r_1, r_2, ..., r_i\} . \tag{4.14}$$

Using Equation (4.12),

$$\text{P}_{\text{capture}}\{\beta, r_u, r_1, r_2, ..., r_\eta\} = \sum_{i=1}^{\eta} R_i \cdot \prod_{k=1}^{i} \frac{1}{1+\beta\left(\frac{r_k}{r_u}\right)^{-4}} . \quad (4.15)$$

Under the assumption that each station transmits with the same probability, τ, we can find the probability of capture using equations (4.13), (4.14) and (4.15) by just knowing all the distances relative to the receiver.

As mentioned above, in a IEEE 802.11 real world scenario we will have different probabilities of transmission for each station, thus the probability of success, τ, of the binomial pdf in Equation 4.13 can not be applied directly. For these reason we use another approach but an equivalent solution for the calculation of the probability of capture, this will be show below

2. Each interfering station has its own probability of transmission, τ_i.

Let Pcapture_u denote the probability of capture of a frame sent by station u to a receiver. For the case when we have η interfering stations, and each station has its own probability of transmission, τ_i, the probability of capture can be written as,

$$\text{Pcapture}_\text{u} = 1 - \prod_{i=1}^{\eta} \left(1 - \tau_u \cdot \tau_i \cdot \left(\frac{1}{1+\beta\left(\frac{r_i}{r_u}\right)^{-4}} \right) \right) . \quad (4.16)$$

By calculating the probability of capture this way, we relate all the probability of transmission of the stations and we avoid doing the combinations of interfering transmissions.

Equation (4.16) will be the probability of capture used for the saturation throughput and expected delay analysis in Chapter 5.

Chapter 5

Saturation Throughput and Expected Delay under Co-Channel Interference

In this chapter, we concentrate on the performance evaluation of the DCF scheme for the IEEE 802.11 system in terms of the throughput and the expected delay and its impact under the presence of co-channel interference, Rayleigh fading and capture; with the assumption of finite number of stations, always having a packet available for transmission. In other words, operating in *saturation* conditions (when the system handles traffic patterns that correspond to the maximum load the network can support in stable conditions), i.e., the transmission queue of each station is assumed to be always nonempty (always wanting to transmit).

This chapter is outlined as follows. In Section 5.1 the concept of Saturation Throughput is defined and we concentrate in calculating the stationary probability of transmission of each station, τ , the stationary probability of collision, p , and the stationary probability of sensing the channel busy, p_b , for both ideal and non ideal channel conditions. The analysis is based on a discrete time Markov chain. These probabilities are used in Section 5.2 and in Section 5.3 for calculating the Saturation Throughput and the expected delay, both under co-channel interference, Rayleigh fading and transmission capture.

5.1 The System Model

The model used for this analysis is based on the Saturation Throughput. This is a fundamental performance Figure defined as the limit reached by the system throughput as the offered load increases, and represents the maximum load that the system can carry in stable conditions.

It is well known that several random access schemes exhibit an unstable behavior [1]. As the offered load increases the throughput grows up to a maximum value, referred as the *maximum throughput*. However, further increases of the offered load lead to an eventually significant decrease in the system throughput. This results in the practical impossibility to operate the random access scheme at its maximum throughput for a long period of time. This can be seen as an instability problem.

The IEEE 802.11 protocol is known to exhibit some form of instability. In [1] an IEEE 802.11 ideal channel simulation was done, in which the offered load increased linearly with the simulation time. For 20 stations, the results returned that the measured throughput followed closely the measured offered load for the first seconds of simulation, while it dropped asymptotically to a fixed value in the further seconds. This asymptotic throughput value is referred in [1] as the saturation throughput, and represents the system throughput in overload conditions.

The analysis is divided in three subsections. In subsection 5.1.1, the MAC behavior of a single station is studied with a Markov model and the stationary probability τ_i that a station transmits a packet in a generic (randomly chosen) slot time is obtained. This probability does not depend on the access mechanism (i.e., Basic or RTS/CTS) employed. In subsection 5.1.2 the calculation of the probability of collision and the probability of sensing the channel busy are computed for the ideal channel case and in subsection 5.1.3 these three probabilities are again calculated for the Rayleigh fading channel.

5.1.1 Packet Transmission Probability

Consider a fixed number n of contending stations. In saturation conditions, each station has immediately a packet available for transmission, after the completion of each successful transmission. Moreover, being all packets consecutive, each packet needs to wait for a random backoff time before transmitting.

Let's first give a brief review of the transmission procedure for the IEEE 802.11 CSMA/CA given in Chapter 2 before presenting the Markov chain model given by [1] and [2].

According to the CSMA/CA protocol, a station having a frame to transmit must initially listen to the channel if another station is transmitting. If no transmission take place for a distributed interframe space (DIFS) time interval, the minimum duration of inactivity for considering the medium free, the transmission may not proceed. If the medium is busy, the station has to wait until the end of the current transmission. It will then wait for an additional DIFS time, and then generate a random delay before transmitting its frame (backoff procedure explained in chapter 2). This delay is uniformly chosen in the range (0, $w-1$) which is called *contention window*. If there is no other transmission before this period expires, the station will transmit its frame. If there is no other transmission before this time period expires, the station will transmit its frame. If there are transmission from other stations during this time period, the station will freeze its backoff counter until the end of the transmission. Then, the station resumes its counting after a DIFS time. At the first transmission attempt, $w = W_{\min}$ where $W_{\min} = W$ is the minimum size of the contention window. After each unsuccessful transmission, w is doubled up to a maximum value $W_{\max} = 2^m W$. The backoff counter uses as time the duration a station needs to detect transmission of a frame from any other station. This time interval is called ‘slot time’ and accounts for the propagation delay, for the time needed to switch from the receiving to the transmitting state ($Rx\_Tx\_Turnaround\_Time$), and for the time to signal the MAC layer about the state of the channel (*bussy detection time)*. So, the time immediately following an idle DIFS is considered slotted.

Since collisions cannot be detected in a wireless CSMA/CA system, there are two mechanisms to determine the successful reception of a frame. According to the first mechanism, which is called ACK CSMA/CA, the destination station returns an ACK frame immediately following a successfully received frame. ACK is transmitted after a short time space (SIFS), where $t_{SIFS} < t_{DIFS}$. The transmitter reschedules its frame transmission if it does not receive the ACK within a specified $ACK\_Timeout$, or if it detects the transmission of a different frame. In the second mechanism, which is called RTS/CTS CSMA/CA, the station that has a frame to transmit sends a RTS (request to send) frame and the receiving station responds with a CTS (clear to send) frame after SIFS time. The data frame is transmitted after the successful exchange of the RTS and CTS. The RTS frame is retransmitted in case the CTS frame is not received within a predetermined time interval.

Following the considerations of Ref. [1], let $b(t)$ be a stochastic process representing the backoff time counter for a given station at slot time t. It is assumed that each station has $m+1$ stages of backoff delay and that $s(t)$ is the stochastic process representing the backoff stage i at time t, were $0 \le i \le m$. The value of the backoff counter is uniformly chosen in the range ($0, W_i - 1$), where $W_i = 2^i W_{\min}$ and depends on the station's backoff stage i. The bi-dimensional process $\{s(t), b(t)\}$ is a discrete time Markov chain under the assumption that the probability p, that a transmitted frame collides and that the probability p_b, that the channel is busy, are independent to the backoff procedure. *The above assumption become more accurate as W and n get larger (as large as 10 stations [1]).* Thus the key approximation for this model is that, at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant ant independent probability p and senses the medium busy with independent probability p_b. It is intuitive that this assumption results more accurate as long as W and n get larger, as mentioned.

Once independence is assumed, and p is supposed to be a constant value, it is possible to model the bidimensional process $\{s(t), b(t)\}$ with a discrete time Markov chain depicted in Figure 5.1

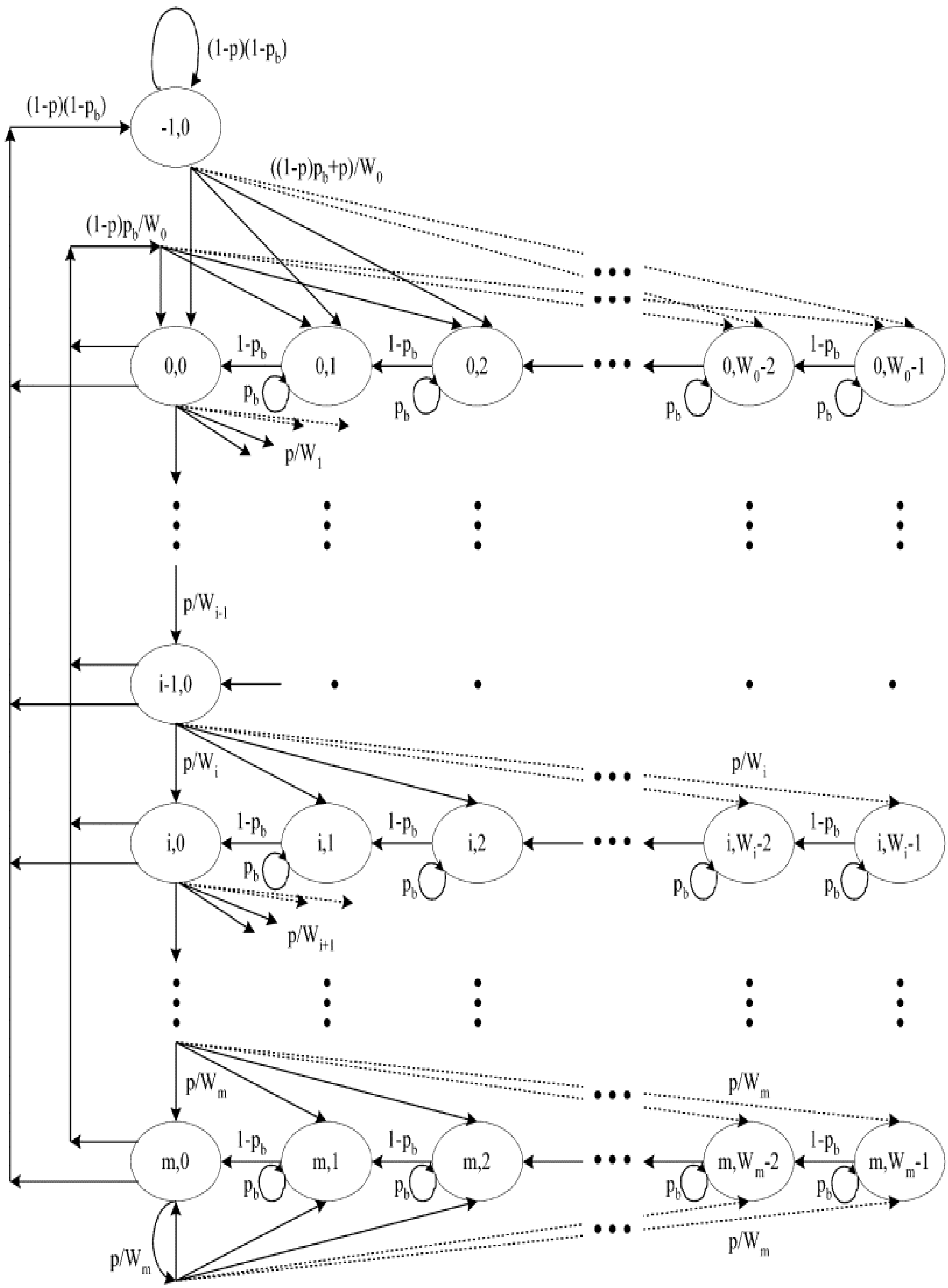

Figure 5.1 The state transition diagram for the Markov chain model.

So, the state of each stations is described by $\{i,k\}$, where i indicates the backoff stage and takes the values ($0,1,...m$) and k indicates the backoff delay and takes values ($0,1,...,W_i-1$) in slot times. In the model proposed by [2], shown in Figure 5.1, there is another state, denoted by {-1, 0}. According to Ref. [17], the backoff procedure is invoked whenever a station has a frame to transmit and finds the medium busy or whenever the transmitting station infers a failed transmission. Whenever the backoff counter is equal to zero, the stations senses that the channel is idle for DIFS time, then the stations transmits without activating the backoff procedure. State {-1, 0} models the above condition. As it will be shown at the end of this subsection, this state is very important for determining the network performance and later the state {-1,0} will be referred as the transmission probability, τ_i, of the i^{th} station.

The state transition diagram of the Markov chain shown in Figure 5.1 has the following transition probabilities:

1. When the channel continues idle after a transmission, the station transmits its frame without entering the backoff procedure. In the next transition probability, that is, when a station is in the state {-1,0} it may stay at the same state if it does not find a fail in its transmission due to a collision or if it finds the medium busy.
$$\text{P}\{-1,0\,|\,-1,0\}=(1-p)(1-p_b)\,. \tag{5.1}$$

2. The station goes to the stage 0 if it transmits a frame and after the transmission, finds the medium busy or if its frame collided. The next transition probability shows the probability of given that a station was in state {-1,0} it will pass to the first stage of the backoff procedure and chose uniformly a value of 0 to W_0-1, since is the first stage.
$$\text{P}\{0,k\,|\,-1,0\}=\frac{(1-p)p_b+p}{W_0}, \qquad 0\le k\le W_0-1\,. \tag{5.2}$$

3. When a station senses that the channel is busy, the backoff counter freezes, so it stays in the same states.
$$\text{P}\{i,k\,|\,i,k\}=p_b, \qquad 1\le k\le W_i-1,\ 0\le i\le m\,. \tag{5.3}$$

4. The backoff counter decrements when the station senses the channel idle.
$$\text{P}\{i,k\,|\,i,k+1\}=1-p_b, \quad 0\le k\le W_i-2\ \ 0\le i\le m\,. \tag{5.4}$$

5. When a station is in the last state of the backoff counter (any $\{i,0\}$), the station will try to transmit, if the channel is sensed as busy, the station will reset the backoff counter and return to stage 0 (the first stage of the backoff process).

$$\text{P}\{0,k \mid i,0\} = \frac{(1-p)p_b}{W_0}, \quad 0 \le k \le W_0 - 1,\ 0 \le i \le m. \tag{5.5}$$

6. The station enters into the $\{-1,0\}$ state if it verifies a successful transmission and if it senses the channel idle.

$$\text{P}\{-1,0 \mid i,0\} = (1-p)(1-p_b), \qquad 0 \le i \le m. \tag{5.6}$$

7. If a station is in stage $i-1$ and transmits, and if the transmission is unsuccessful, the station will assume a collision occurred and will enter to stage i.

$$\text{P}\{i,k \mid i-1,0\} = \frac{p}{W_i}, \qquad 0 \le k \le W_i - 1,\ 1 \le i \le m. \tag{5.7}$$

8. When a station has reached the last stage of backoff procedure it will remain at it as long as there are unsuccessful transmissions. This means that when a station through unsuccessful transmissions gets to the last stage, it will remain there until a successful transmission occurs.

$$\text{P}\{m,k \mid m,0\} = \frac{p}{W_m}, \qquad 0 \le k \le W_m - 1. \tag{5.8}$$

Having the transition probabilities, the next step is to obtain the steady state probabilities.

Let $b_{i,k} = \lim_{t\to\infty} \text{P}\{s(t)=i, b(t)=k\}$ be the stationary distribution of the Markov chain, where i, k are integers $-1 \le i \le m$, $0 \le k \le W_i - 1$. Observing that the probability of being in state $b_{3,0}$ is equal to the probability of being in state $b_{2,0}$ and that a collision occurred, this is:

$$b_{3,0} = p \cdot b_{2,0}.$$

In the same way, we have that,

$$b_{2,0} = p \cdot b_{1,0},$$
$$b_{1,0} = p \cdot b_{0,0}.$$

Thus

$$b_{i-1,0} \cdot p = b_{i,0}. \tag{5.9}$$

Thus we have the following relation.

$$b_{i,0} = \lim_{t\to\infty} \text{P}\{s(t)=i, b(t)=0\} = p^i \cdot b_{0,0},\ 0 \le i \le m-1. \tag{5.10}$$

For the last stage, m, we observe that the probability of being in state $b_{m,0}$ and that there has not been any further collision (the case when is the first time the station reaches this stage) is equal to the probability of being in $b_{m-1,0}$ and that a collision occurred. In other words: $b_{m-1,0} \cdot p = (1-p) \cdot b_{m,0}$, and according to (5.10) $(1-p) \cdot b_{m,0} = p^{m-1} \cdot p \cdot b_{0,0}$, hence we can say:

$$b_{m,0} = \lim_{t \to \infty} \mathrm{P}\{ s(t) = m, b(t) = 0 \} = \frac{p^m}{1-p} \cdot b_{0,0} . \tag{5.11}$$

To obtain the probability of being in state $b_{i,k}$ we notice that for a station to be in this state it first had to had been in state $b_{i-1,0}$ and a collision must have occurred, having this occurred the station will be in the i^{th} stage, so the probability of being in the k^{th} stage is equal to $(1-\frac{k}{W_i})$. From this, we can obtain the probability of being in state $b_{i,k}$,

$$(1-p_b) \cdot b_{i,k} = \left(1 - \frac{k}{W_i}\right) \cdot b_{i-1,0} \cdot p .$$

Using Equation (5.9)

$$b_{i,k} = \left(\frac{W_i - k}{W_i}\right) \cdot \frac{1}{(1-p_b)} \cdot b_{i,0}, \quad 0 \le i \le m, \quad 1 \le k \le W_i - 1 . \tag{5.12}$$

To find the probability of being in state $b_{0,0}$ we have to notice that for being in this state the channel must be busy or the channel must not be busy but a collision must occur. Thus,

$$(1-p_b) \cdot b_{0,0} = (p_b + p \cdot (1-p_b)) \cdot b_{-1,0} ,$$

$$b_{0,0} = \frac{p_b + p \cdot (1-p_b)}{(1-p_b)} \cdot b_{-1,0} . \tag{5.13}$$

We are interested in finding the probability of being in state $b_{-1,0}$, this is, the probability of transmission. We first note that we have that the sum of all the chain states must be equal to one, thus,

$$\sum_{i=1}^{m} \sum_{k=0}^{W_i-1} b_{i,k} = 1 . \tag{5.14}$$

Extracting the probability $b_{-1,0}$ of the above sum,

$$b_{-1,0} + \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} = 1 . \tag{5.15}$$

Using Equation (5.12), Equation (5.10) and $W_i = 2^i \cdot W$, we have,

$$b_{-1,0} + \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} \frac{W_i - k}{W_i} \cdot \frac{1}{(1-p_b)} \cdot p^i \cdot b_{0,0} = 1 ,$$

$$b_{-1,0} + \frac{1}{(1-p_b)} \sum_{i=0}^{m} p^i \cdot b_{0,0} \sum_{k=0}^{W_i-1} \frac{2^i \cdot W - k}{2^i \cdot W} = 1$$

Using Equation (5.11),

$$b_{-1,0} + \frac{1}{(1-p_b)} \sum_{i=0}^{m-1} p^i \cdot b_{0,0} \sum_{k=0}^{W_i-1} \frac{2^i \cdot W - k}{2^i \cdot W} + \frac{p^m}{(1-p)} \cdot \frac{1}{(1-p_b)} \cdot b_{0,0} = 1 . \quad (5.16)$$

Using Equation (5.13),

$$b_{-1,0} + \frac{1}{(1-p_b)} \sum_{i=0}^{m-1} p^i \cdot \frac{p_b + p\cdot(1-p_b)}{(1-p_b)} \cdot b_{-1,0} \sum_{k=0}^{W_i-1} \frac{2^i \cdot W - k}{2^i \cdot W} + \frac{p^m}{(1-p)} \cdot \frac{1}{(1-p_b)} \cdot \frac{p_b + p\cdot(1-p_b)}{(1-p_b)} \cdot b_{-1,0} = 1 \quad (5.17)$$

Factorizing $b_{-1,0}$ from Equation (5.17),

$$b_{-1,0} \cdot \left[1 + \frac{1}{(1-p_b)} \sum_{i=0}^{m-1} p^i \cdot \frac{p_b + p\cdot(1-p_b)}{(1-p_b)} \sum_{k=0}^{W_i-1} \frac{2^i \cdot W - k}{2^i \cdot W} + \frac{p^m}{(1-p)} \cdot \frac{1}{(1-p_b)} \cdot \frac{p_b + p\cdot(1-p_b)}{(1-p_b)} \right] = 1 ,$$

$$b_{-1,0} = \frac{1}{\left[1 + \frac{1}{(1-p_b)} \sum_{i=0}^{m-1} p^i \cdot \frac{p_b + p\cdot(1-p_b)}{(1-p_b)} \sum_{k=0}^{W_i-1} \frac{2^i \cdot W - k}{2^i \cdot W} + \frac{p^m}{(1-p)} \cdot \frac{1}{(1-p_b)} \cdot \frac{p_b + p\cdot(1-p_b)}{(1-p_b)} \right]} ,$$

$$b_{-1,0} = \frac{2\cdot(1-p_b)^2 \cdot (1-2p)\cdot(1-p)}{2\cdot(1-p_b)^2 \cdot (1-2\cdot p)\cdot(1-p) + \left(p_b + p\cdot(1-p_b)\right)\cdot(1-2\cdot p)\cdot(W+1) + p\cdot W \cdot \left(p_b + p\cdot(1-p_b)\right)\cdot\left(1-(2\cdot p)^m\right)} \quad (5.18)$$

If in Equation (5.18) the values of W, m, p and p_b are known, we can calculate the steady state probabilities of the Markov chain. We know that the values of W and m are known, but the probabilities p and p_b must be calculated. Let τ be the probability that any given station transmits during a slot time. We know that a station transmit when the backoff counter reaches zero in any stage, therefore,

$$\tau = \sum_{i=-1}^{m} b_{i,0} = b_{-1,0} + \sum_{i=0}^{m-1} b_{i,0} + b_{m,0} . \quad (5.19)$$

Substituting equations (5.10), (5.11) into (5.19) and using (5.13) and (5.18), we have,

$$\tau = \frac{2\cdot(1-p_b)\cdot(1-2\cdot p)}{2\cdot(1-p_b)^2(1-p) + \left(p_b + p\cdot(1-p_b)\right)\cdot(1-2\cdot p)\cdot(W+1) + p\cdot W \cdot \left(p_b + p\cdot(1-p_b)\right)\cdot(1-(2\cdot p)^m)} . \quad (5.20)$$

Equation (5.20) is an important result because it gives us the probability of transmission of any station and the only unknown parameters are p and p_b, which depend of the medium and are different for every station.

5.1.2 Calculation of p, p_b and τ in one WLAN cell under ideal channel conditions.

Consider an IEEE 802.11 WLAN system as shown if Figure 5.2. Under ideal channel conditions there is no fading, nor interference from other IEEE 802.11 systems. Since there is no fading, the distances of the stations form the access point are careless, thus, all stations transmit with the *same* probability, τ. Since there is no fading for this case, it is considered that the stations in the inner circle can be heard by the access point, and anything outside this circle is not considered. In general, τ depends on the conditional collision probability p, and in the conditional busy medium probability p_b which are still unknown.

In the ideal channel case, a transmitted frame collides when two or more stations transmit during a slot time, so the probability p that a transmitted frame collides is given by

$$p = 1 - (1-\tau)^{\eta-1}. \tag{5.21}$$

The channel is detected busy when at least one station transmits during a slot time, and thus, the probability p_b that the channel is busy is given by

$$p_b = 1 - (1-\tau)^{\eta}. \tag{5.22}$$

The fundamental independence assumption given above implies that each transmission "sees" the system in the same state, i.e., in steady state. At steady state, each remaining station transmits a packet with probability τ.

Is we substitute equations (5.21) and (5.22) in (5.20), we obtain a nonlinear system of three unknowns τ, p and p_b, and in function of various parameters that we know (W, m and η). The nonlinear system can be solved using numerical techniques or with a mathematical software like Mathematica.

As seen, in this ideal channel case we can obtain a final expression to compute the probability of transmission of a station in a WLAN transmits, just in terms of the number of users η that there are within a WLAN.

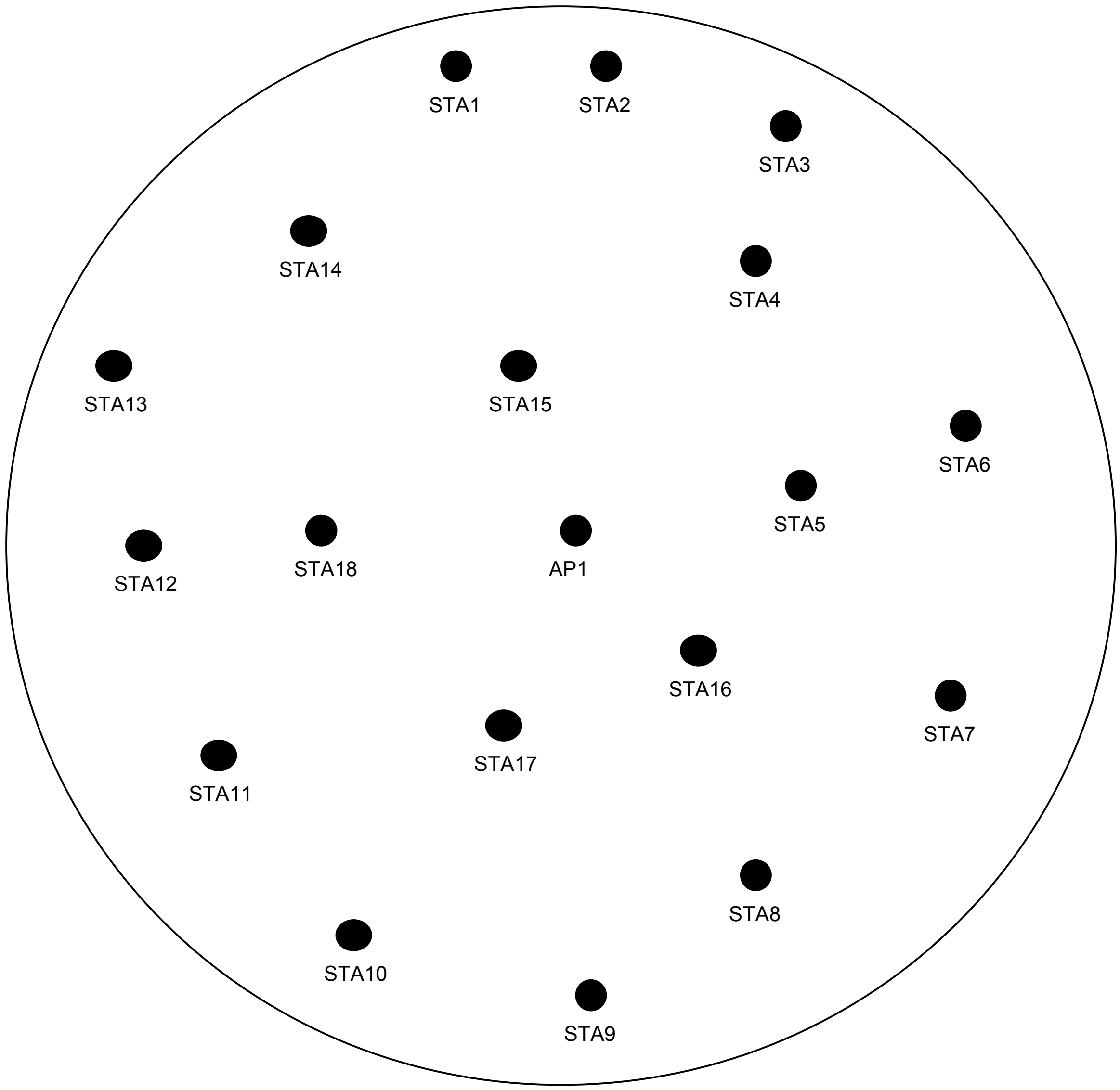

Figure 5.2 An IEEE 802.11 WLAN with a fixed number of stations η

5.1.3 Calculation of p, p_b and τ for any given station under Rayleigh Fading and Co-Channel Interference in a multicell IEEE 802.11 wireless system.

Consider a mutlciell IEEE 802.11 WLAN system as shown in Figure 5.3. This system consists of three different LANs all operating in the same frequency band. Each WLAN has its own Access Point (AP), and each AP has a fixed number of stations under its control. We define some nomenclature for this scenario.

- **APu** Refers to the Access Point of the u^{th} WLAN system operating in the same frequency band.
- STA$_{u,n}$ Refers to the Station belonging to the u^{th} WLAN system. And n is a label for station identification on the u^{th} WLAN system.
- η_u Is the total number of station belonging to the u^{th} WLAN system. Note that an Access Point is also a Station but for terms of nomenclature **APu** $\notin \eta_u$.
- η Is the total number of stations of all the WLAN systems. ($\eta = \eta_1 + \eta_2 + ... + \eta_u +$ **AP 1** $+$ **AP 2** $+ ...$ **+AP u**)

In this scenario it is considered that Rayleigh fading exits, all stations (including the Access Point) transmit with the same local mean power and the probabilities p, p_b and τ are to be calculated. We are interested in finding these three probabilities for each of the stations (including the AP), since as we will see, this probabilities are in function of all of the distances of the stations relative to the receiving station. We define some nomenclature for this purpose,

- $p_{u,n}$ Refers to the probability that station n of the WLAN u encounters a collision.
- $p_{b(u,n)}$ Refers to the probability that the station n of the WLAN u senses the channel as busy.
- $\tau_{u,n}$ Refers to the probability that the station n of the WLAN u transmit.

It's important to notice in Figure 5.3 that the circle representing a WLAN coverage is not drawn. Compared with Figure 5.3, Figure 5.2 does have a circle representing the cell coverage, which is a simplification meaning that all the stations inside the circle are the only ones considered to be in range and also there was no channel fading consideration. In the case when Rayleigh fading and interference is considered, we will be working with the probability of detecting a signal, thus the simplification of the circles is not needed since it will appear naturally when the mathematical model is presented.

Suppose we are interested in calculating the probability of transmission of the $STA_{1,1}$. According to Equation (5.20), the probability of transmission of $STA_{1,1}$ is

$$\tau_{1,1}=\frac{2\cdot(1-p_{b(1,1)})\cdot(1-2\cdot p_{1,1})}{2\cdot(1-p_{b(1,1)})^2(1-p_{1,1})+\left(p_{b(1,1)}+p_{1,1}\cdot(1-p_{b(1,1)})\right)\cdot(1-2\cdot p_{1,1})\cdot(W+1)+p_{1,1}\cdot W\cdot\left(p_{b(1,1)}+p_{1,1}\cdot(1-p_{b(1,1)})\right)\cdot(1-(2\cdot p_{1,1})^m)} \tag{5.23}$$

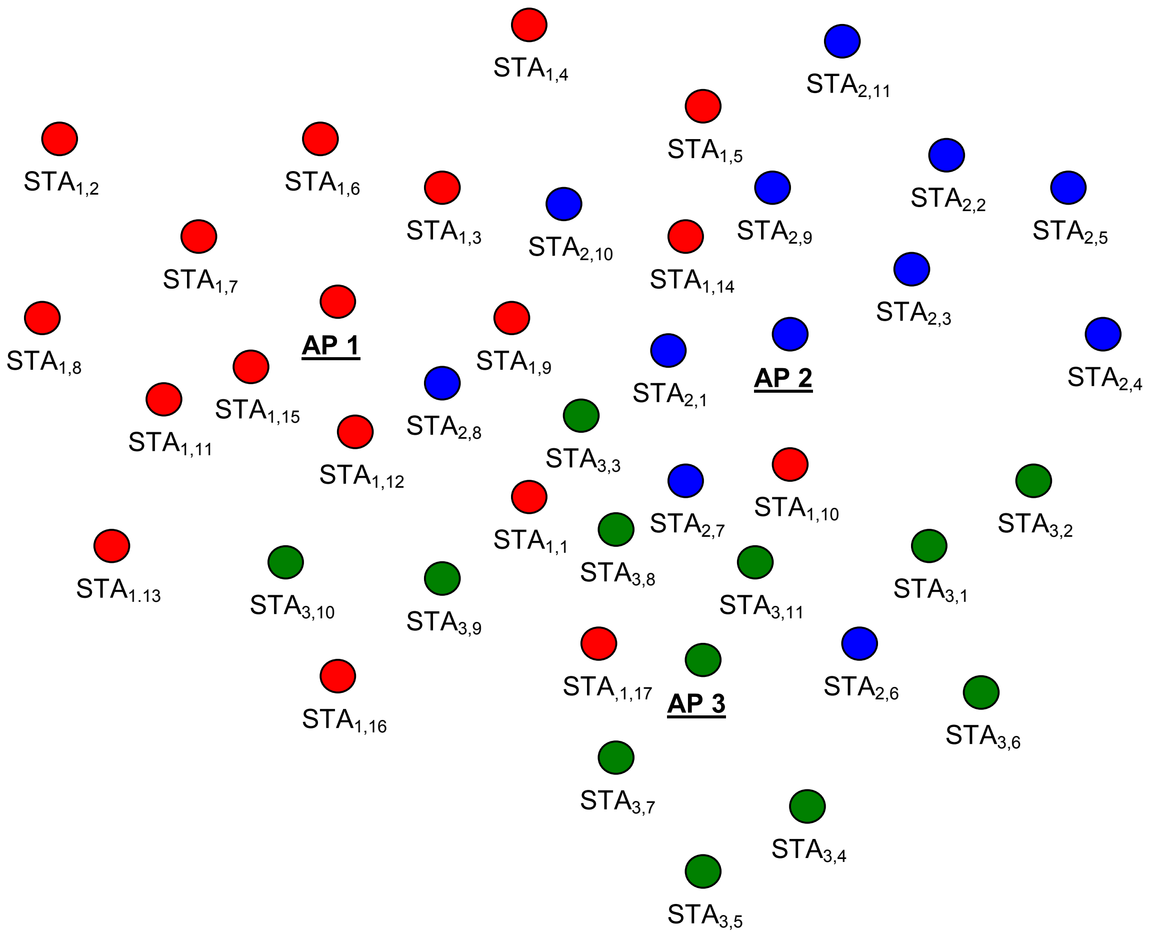

Figure 5.3 Three IEEE 802.11 WLANs operating in the same frequency band, making a total of η stations

Since m and W are known, Equation (5.23) is in function of $p_{1,1}$ and $p_{b(1,1)}$. For these reason we have to find an Equation for $p_{1,1}$ and $p_{b(1,1)}$ that can solve the system of non linear equations and finally obtain the probability of transmission of $STA_{1,1}$. At first instance, it can be seen that we would only need three Equation for solving for the three unknown variables ($\tau_{1,1}$, $p_{1,1}$ and $p_{b(1,1)}$), but as it will be shown next, we will need a total of $3\cdot\eta$ equations to solve for $3\cdot\eta$ unknown variables.

Under the fundamental independence assumption given in section 4.1.1, the probability that a transmitted packet by $STA_{1,1}$ encounters a collision means that the frame was corrupted by interference at the receptor. This probability can be written as:

$$p_{1,1} = 1-\{[1-\tau_{1,2}\cdot P_{capture}(P_{1,2}\geq\beta)]\cdot[1-\tau_{1,3}\cdot P_{capture}(P_{1,3}\geq\beta)]\cdot[1-\tau_{1,4}\cdot P_{capture}(P_{1,4}\geq\beta)]\cdots$$
$$\cdots[1-\tau_{1,\eta_1}\cdot P_{capture}(P_{receptor}\geq\beta)]\cdot[1-\tau_{receptor}]\}\cdot\{[1-\tau_{2,1}\cdot P_{capture}(P_{2,1}\geq\beta)]\cdot[1-\tau_{2,2}\cdot P_{capture}(P_{2,2}\geq\beta)]\cdots$$
$$\cdots[1-\tau_{2,\eta_2}\cdot P_{capture}(P_{2,\eta_2}\geq\beta)]\cdot[1-\tau_{AP2}\cdot P_{capture}(P_{AP2}\geq\beta)]\}\{[1-\tau_{3,1}\cdot P_{capture}(P_{3,1}\geq\beta)]\cdot[1-\tau_{3,2}\cdot P_{capture}(P_{3,2}\geq\beta)]\cdots$$
$$\cdots[1-\tau_{3,\eta_3}\cdot P_{capure}(P_{\eta_3}\geq\beta)]\cdot[1-\tau_{AP3}\cdot P_{capture}(P_{AP3}\geq\beta)]\} \quad (5.24)$$

Using Equation (4.6)

$$p_{1,1} = 1-\{[1-\tau_{1,2}\cdot e^{-\frac{\beta}{P_{o(1,2)}}}]\cdot[1-\tau_{1,3}\cdot e^{-\frac{\beta}{P_{o(1,3)}}}]\cdot[1-\tau_{1,4}\cdot e^{-\frac{\beta}{P_{o(1,4)}}}]\cdots[1-\tau_{1,\eta_1}\cdot e^{-\frac{\beta}{P_{o(1,\eta_1)}}}]\cdot[1-\tau_{receptor}]\}\cdot$$
$$\{[1-\tau_{2,1}\cdot e^{-\frac{\beta}{P_{o(2,1)}}}]\cdots[1-\tau_{2,\eta_2}\cdot e^{-\frac{\beta}{P_{o(2,\eta_2)}}}]\cdot[1-\tau_{AP2}\cdot e^{-\frac{\beta}{P_{o(AP2)}}}]\}\cdot\{[1-\tau_{3,1}\cdot e^{-\frac{\beta}{P_{o(3,1)}}}]\cdots[1-\tau_{3,\eta_3}\cdot e^{-\frac{\beta}{P_{o(3,\eta_3)}}}][1-\tau_{AP3}\cdot e^{-\frac{\beta}{P_{o(AP3)}}}]\}$$
$$(5.25)$$

In (5.25) $P_{o(u,n)}$ and $P_{o(APu)}$ are the received local mean power at the receptor, due to $STA_{u,n}$ and AP u, respectively, given by Equation (4.2), thus

$$p_{o(u,n)} = A\cdot r^{-4}_{(u,n),Rx}\cdot P_T\ , \quad (5.26)$$

$$p_{o(APu)} = A\cdot r^{-4}_{(APu),Rx}\cdot P_T\ , \quad (5.27)$$

where $r^{-4}_{(u,n),Rx}$ is the distance from station $STA_{u,n}$ to the desired receptor (Rx) and r^{-4}_{APu-Rx} is the distance from the AP u to the desired receptor (Rx). In this case the desired receptor is the Access Point 1 (AP 1), thus for the calculation of $p_{1,1}$, the probability of transmission of the desired receptor expressed in Equation (5.25) is:

$$\tau_{receptor} = \tau_{AP1}$$

Using the last relation, Equation (4.6) can be rewritten as:

$$p_{1,1} = 1-\{[1-\tau_{1,2}\cdot e^{-\frac{\beta}{P_{o(1,2)}}}]\cdot[1-\tau_{1,3}\cdot e^{-\frac{\beta}{P_{o(1,3)}}}]\cdot[1-\tau_{1,4}\cdot e^{-\frac{\beta}{P_{o(1,4)}}}]\cdots[1-\tau_{1,\eta_1}\cdot e^{-\frac{\beta}{P_{o(1,\eta_1)}}}]\cdot[1-\tau_{AP1}]\}\cdot$$
$$\{[1-\tau_{2,1}\cdot e^{-\frac{\beta}{P_{o(2,1)}}}]\cdots[1-\tau_{2,\eta_2}\cdot e^{-\frac{\beta}{P_{o(2,\eta_2)}}}]\cdot[1-\tau_{AP2}\cdot e^{-\frac{\beta}{P_{o(AP2)}}}]\}\cdot\{[1-\tau_{3,1}\cdot e^{-\frac{\beta}{P_{o(3,1)}}}]\cdots[1-\tau_{3,\eta_3}\cdot e^{-\frac{\beta}{P_{o(3,\eta_3)}}}][1-\tau_{AP3}\cdot e^{-\frac{\beta}{P_{o(AP3)}}}]\}$$

(5.28)

The probability that the channel is sensed busy by station $STA_{1,1}$ (the transmitter) can be written as:

$$p_{b(1,1)} = 1-\{[1-\tau_{transmitter}]\cdot[1-\tau_{1,2}\cdot P_{capture}(P_{1,2}\geq\beta)]\cdot[1-\tau_{1,3}\cdot P_{capture}(P_{1,3}\geq\beta)]\cdots$$
$$\cdots[1-\tau_{1,\eta_1}\cdot P_{capture}(P_{1,\eta_1}\geq\beta)]\cdot[1-\tau_{AP1}\cdot P_{capture}(P_{AP1}\geq\beta)]\}\cdot\{[1-\tau_{2,1}\cdot P_{capture}(P_{2,1}\geq\beta)]\cdot[1-\tau_{2,2}\cdot P_{capture}(P_{2,2}\geq\beta)]\cdots$$
$$\cdots[1-\tau_{2,\eta_2}\cdot P_{capture}(P_{2,\eta_2}\geq\beta)]\cdot[1-\tau_{AP2}\cdot P_{capture}(P_{AP2}\geq\beta)]\}\cdot\{[1-\tau_{3,1}\cdot P_{capture}(P_{3,1}\geq\beta)][1-\tau_{3,2}\cdot P_{capture}(P_{3,2}\geq\beta)]\cdots$$
$$\cdots[1-\tau_{3,\eta_3}\cdot P_{capture}(P_{3,\eta_3}\geq\beta)]\cdot[1-\tau_{AP3}\cdot P_{capture}(P_{AP3}\geq\beta)]\}\,, \quad (5.29)$$

where, for this case,

$$\tau_{transmitter} = \tau_{1,1}\,.$$

Again, using Equation (4.6) we have the following relation:

$$p_{b(1,1)} = 1-\{[1-\tau_{1,1}]\cdot[1-\tau_{1,2}\cdot e^{\frac{-\beta}{P_{o(1,2)}}}]\cdot[1-\tau_{1,3}\cdot e^{\frac{-\beta}{P_{o(1,3)}}}]\cdots[1-\tau_{1,\eta_1}\cdot e^{\frac{-\beta}{P_{o(1,\eta_1)}}}]\cdot[1-\tau_{AP1}\cdot e^{\frac{-\beta}{P_{o(1,AP1)}}}]\}\cdot$$
$$\{[1-\tau_{2,1}\cdot e^{\frac{-\beta}{P_{o(2,1)}}}]\cdot[1-\tau_{2,2}\cdot e^{\frac{-\beta}{P_{o(2,2)}}}]\cdots[1-\tau_{2,\eta_2}\cdot e^{\frac{-\beta}{P_{o(2,\eta_2)}}}]\cdot[1-\tau_{AP2}\cdot e^{\frac{-\beta}{P_{o(AP2)}}}]\}\cdot$$
$$\{[1-\tau_{3,1}\cdot e^{\frac{-\beta}{P_{o(3,1)}}}]\cdot[1-\tau_{3,2}\cdot e^{\frac{-\beta}{P_{o(3,2)}}}]\cdots[1-\tau_{3,\eta_3}\cdot e^{\frac{-\beta}{P_{o(3,\eta_3)}}}]\cdot[1-\tau_{AP3}\cdot e^{\frac{-\beta}{P_{o(AP3)}}}]\} \quad ,\eta_1\neq 1$$

(5.30)

In (5.30) $P_{o(u,n)}$ is the received local mean power at $STA_{1,1}$ due to the other $STA_{u,n}$ stations and $P_{o(APu)}$ is the received local mean power at $STA_{1,1}$ (the transmitter), due to the AP u's access points. The relation are given by Equation (4.2), thus

$$p_{o(u,n)} = A\cdot r_{(u,n),Tx}^{-4}\cdot P_T\,, \quad (5.31)$$
$$p_{o(APu)} = A\cdot r_{(APu),Tx}^{-4}\cdot P_T\,, \quad (5.32)$$

where $r_{(u,n).Tx}^{-4}$ is the distance from station $STA_{u,n}$ to the transmitter (Tx), in this case the transmitter is $STA_{1,1}$, and $r_{(APu,)TX}^{-4}$ is the distance from the AP u to the transmitter (Tx).

From Equation (5.28) and (5.30) it can be seen that both probability $p_{1,1}$ and $p_{b(1,1)}$ depend on the probability of transmission, $\tau_{u,n}$, of all of the other stations. Thus to solve for $\tau_{1,1}$ we also need to solve for al of the $\tau_{u,n}$. But to solve for $\tau_{u,n}$ we need to have all the $p_{u,n}$ and $p_{b(u,n)}$ of all the station. For these reason we have a nonlinear system of $3\cdot\eta$ equations with $3\cdot\eta$ unknown variables, in were we only know how many stations are and the distance of each station relative to all the others. For these reason we can generalize the solution of the probability of transmission of any station, $\tau_{u,n}$, given that we have u overlapping WLANs and n stations inside each WLAN by only knowing the coordinates of each station.

For convenience let $\tau_{u,n}$, $p_{u,n}$ and $p_{b(u,n)}$ be the probabilities associated with a station ($STA_{u,n}$); and let τ_{APu}, p_{APu} and $p_{b(APu)}$ be the probabilities associated with an Access Point. These probabilities can be generalized with the following equations:

Form (5.23) we can generalize as:

$$\tau_{u,n} = \frac{2\cdot(1-p_{b(u,n)})\cdot(1-2\cdot p_{u,n})}{2\cdot(1-p_{b(u,n)})^2(1-p_{u,n})+K\cdot(1-2\cdot p_{u,n})\cdot(W+1)+p_{u,n}\cdot W\cdot K\cdot(1-(2\cdot p_{u,n})^m)} \tag{5.33}$$

In (5.33) $\tau_{u,n}$ is the probability of transmission of any $STA_{u,n}$ and $K = \left(p_{b(u,n)} + p_{u,n}\cdot(1-p_{b(u,n)})\right)$.

From (5.28) the probability that a frame sent by any $STA_{u,n}$ encounters a collision is:

$$p_{u,n} = 1-\left\{\prod_{i=1}^{L}\prod_{j=1}^{\eta_i}(1-\tau_{i,j}\cdot e^{\frac{-\beta}{P_{o(i,j),APu}}})\right\}\left\{\prod_{k=1}^{L}(1-\tau_{APk}\cdot e^{\frac{-\beta}{P_{o(APk),APu}}})\right\}\left\{\frac{1-\tau_{APu}}{1-\tau_{u,n}\cdot e^{\frac{-\beta}{P_{o(u,n),APu}}}}\right\}\left\{\frac{1}{1-\tau_{APu}\cdot e^{\frac{-\beta}{P_{o(APu),APu}}}}\right\} \tag{5.34}$$

From Equation (5.30) we can generalize for the probability that any $STA_{u,n}$ senses the channel busy:

$$p_{b(u,n)} = 1 - \left\{ \prod_{i=1}^{L} \prod_{j=1}^{\eta_i} (1 - \tau_{i,j} \cdot e^{\frac{-\beta}{P_{o(i,j),(u,n)}}}) \right\} \left\{ \prod_{k=1}^{L} (1 - \tau_{APk} \cdot e^{\frac{-\beta}{P_{o(APk),(u,n)}}}) \right\} \left\{ \frac{1 - \tau_{u,n}}{1 - \tau_{u,n} \cdot e^{\frac{-\beta}{P_{o(u,n),(u,n)}}}} \right\} \quad (5.35)$$

Where L is the total number of $AP's$ and,

$$P_{o(u,n),APu} = A \cdot r_{(u,n),APu}^{-4} \cdot P_T , \quad (5.36)$$

$$P_{o(APk),APu} = A \cdot r_{(APk),APu}^{-4} \cdot P_T , \quad (5.37)$$

$$P_{o(i,j),APu} = A \cdot r_{(i,j),APu}^{-4} \cdot P_T , \quad (5.38)$$

$$P_{o(APk),(u,n)} = A \cdot r_{(APk),(u,n)}^{-4} \cdot P_T , \quad (5.39)$$

$$P_{o(i,j),(u,n)} = A \cdot r_{(i,j),(u,n)}^{-4} \cdot P_T , \quad (5.40)$$

The probability of transmission of any access point, APu, can also be generalized from Equation (5.23) as:

$$\tau_{APu} = \frac{2 \cdot (1 - p_{b(APu)}) \cdot (1 - 2 \cdot p_{APu})}{2 \cdot (1 - p_{b(APu)})^2 (1 - p_{APu}) + B \cdot (1 - 2 \cdot p_{APu}) \cdot (W + 1) + p_{APu} \cdot W \cdot B \cdot (1 - (2 \cdot p_{APu})^m)} \quad (5.41)$$

Where $B = \left(p_{b(APu)} + p_{APu} \cdot (1 - p_{b(APu)}) \right)$.

In (5.41) the probability of transmission of any access point, τ_{APu}, depends on the probability that a data frame sent by an AP encounters a collision, p_{Apu} and on the probability of sensing the channel busy, $p_{b(APu)}$. The probability that an access point encounters a collision is slightly different from the probability that a station encounters a collision, since any station $STA_{u,n}$ is only interested on the data transmitted to the access point, i.e., it's interested on the probability that a collision occurs at the AP receptor; but the access points are interested on the data transmitted to any of the stations, $STA_{u,n}$,, thus Equation (5.34) must take account that the access point will encounter a collision we it transmits to any $STA_{u,n}$, Equation (5.34) is modified for an access point as:

$$p_{APu} = \sum_{l=1}^{\eta_u} \left\{ \left\{ 1 - \left\{ \prod_{i=1}^{L} \prod_{j=1}^{\eta_i} (1-\tau_{i,j} \cdot e^{\frac{-\beta}{P_{o(i,j),(u,l)}}}) \right\} \left\{ \prod_{k=1}^{L} (1-\tau_{APk} \cdot e^{\frac{-\beta}{P_{o(APk),(u,l)}}}) \right\} \left\{ \frac{1-\tau_{u,l}}{1-\tau_{APu} \cdot e^{\frac{-\beta}{P_{o(APu),(u,l)}}}} \right\} \left\{ \frac{1}{1-\tau_{u,l} \cdot e^{\frac{-\beta}{P_{o(u,l),(u,l)}}}} \right\} \right\} \cdot \{P[u,l]\} \right\} \tag{5.42}$$

where $P[u,l]$ is the probability that the destination of the packet is the station $STA_{u,l}$. If the stations around the AP are distributed following a uniform distribution and under our fundamental independence assumption, we can use,

$$P[u,l] = \frac{1}{\eta_u} \tag{5.43}$$

Thus, Equation (5.42) can be rewritten as,

$$p_{APu} = \frac{1}{\eta_u} \cdot \sum_{l=1}^{\eta_u} \left\{ 1 - \left\{ \prod_{i=1}^{L} \prod_{j=1}^{\eta_i} (1-\tau_{i,j} \cdot e^{\frac{-\beta}{P_{o(i,j),(u,l)}}}) \right\} \left\{ \prod_{k=1}^{L} (1-\tau_{APk} \cdot e^{\frac{-\beta}{P_{o(APk),(u,l)}}}) \right\} \left\{ \frac{1-\tau_{u,l}}{1-\tau_{APu} \cdot e^{\frac{-\beta}{P_{o(APu),(u,l)}}}} \right\} \left\{ \frac{1}{1-\tau_{u,l} \cdot e^{\frac{-\beta}{P_{o(u,l)(u,l)}}}} \right\} \right\} \tag{5.44}$$

Equation (5.44) gives us the generalized probability that a frame sent by an access point encounters a collision. The probability that an access point senses the channel busy is written in the same way as Equation (5.35):

$$p_{b(APu)} = 1 - \left\{ \prod_{i=1}^{L} \prod_{j=1}^{\eta_i} (1-\tau_{i,j} \cdot e^{\frac{-\beta}{P_{o(i,j),APu}}}) \right\} \left\{ \prod_{k=1}^{L} (1-\tau_{APk} \cdot e^{\frac{-\beta}{P_{o(APk),APu}}}) \right\} \left\{ \frac{1-\tau_{APu}}{1-\tau_{APu} \cdot e^{\frac{-\beta}{P_{o(APu),APu}}}} \right\} \tag{5.45}$$

and,

$$P_{o(i,j),(u,l)} = A \cdot r_{(i,j),(u,l)}^{-4} \cdot P_T \,, \tag{5.46}$$

$$P_{o(APk),(u,l)} = A \cdot r_{(APk),(u,l)}^{-4} \cdot P_T \,, \tag{5.47}$$

$$P_{o(APu),(u,l)} = A \cdot r_{(APu),(u,l)}^{-4} \cdot P_T \,, \tag{5.48}$$

$$P_{o(i,j),(APu)} = A \cdot r_{(i,j),(APu)}^{-4} \cdot P_T \,, \tag{5.49}$$

$$P_{o(Apk),APu} = A \cdot r_{(APk),APu}^{-4} \cdot P_T \,. \tag{5.50}$$

With the use of equations (5.33), (5.34), (5.35), (5.41), (5.44) and (5.45) and supposing we know all the distances of the stations and AP relative to each other we can get the probability of transmission of any station, $STA_{u,n}$, and of any access point, APu, by solving the nonlinear set of equations.

These results are valid for scenarios were the channel is affected by Rayleigh fading and Co-channel interference and the CSMA/CA algorithm is used.

5.2 Saturation Throughput Analysis

In this section we introduce the analysis of the throughput, according to the model seen in the last section.

In Section 5.2.1 we derive the Saturation Throughput for ideal channel conditions in a similar way as [2]. In Section 5.2.2 we obtain the Saturation Throughput for Rayleigh fading channels and in section 5.2.3 we obtain the Saturation Throughput for Rayleigh fading channels and with the capture effect.

5.2.1 Saturation Throughput for ideal channel conditions

The throughput is the rate at which the system transmits data from the sender to the receiver. Let S be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits. According to the model used by [2], we assume that each transmission, whether it is successful or not, is a renewal process, thus it is sufficient to compute the throughput during a single renewal interval between two consecutive transmissions. The system state alternates between idle periods (I) in which no user transmits packets and busy periods (B) in which at least one user transmits a packet. Let U be the time spent in useful transmission during regeneration cycle. The throughput S is expressed as:

$$S = \frac{E[U]}{E[B] + E[I]}.$$

Equivalently, the throughput can be expressed as:

$$S = \frac{E[\textit{time used for successful tranmisssion in an interval}]}{E[\textit{lenght between two consecutive transmissions}]}.$$

For *ideal channel* conditions, the system throughput can be rewritten as:

$$S = \frac{P_s E[P]}{E[\psi] \cdot (1 - p_b) + P_s T_s + (p_b - P_s) T_c}, \tag{5.51}$$

where $E[P]$ is the average payload length, T_s is the average time that the channel is captured with a successful transmission, T_c is the average time that the channel is captured by stations which collide, P_s is the probability that a transmission is successful and $E[\psi]$ is the mean value of the random variable ψ which represents the number of consecutive idle slot times before a transmission takes place, due to the backoff algorithm.

The average payload length $E[P]$ is defined by the pdf of the payload length. Here, we assume that all frames are of the same fixed size, $E[P] = P$ where P can be calculated by the number of bits that the frame payload contains and the channel bit rate.

The values of T_s and T_c depend on the channel access method and are the basic (ACK) and RTS-CTS access methods. For the ACK CSMA/CA access method the values T_s and T_c can be computed (according to [1]) as

$$\left.\begin{aligned} T_s^{ack} &= H + P + \delta + SIFS + ACK + \delta + DIFS \\ T_c^{ack} &= H + P + \delta + DIFS \end{aligned}\right\}, \tag{5.52}$$

where $H = PHY_{hdr} + MAC_{hdr}$, that is the physical header plus the MAC header of the frame, and δ is the propagation delay.

For the RTS-CTS CSMA/CA access method, the values of T_s and T_c may be computed as

$$\left.\begin{aligned} T_s^{rcts} &= RTS + \delta + SIFS + CTS + \delta + SIFS + H + P + \delta + SIFS + ACK + \delta + DIFS \\ T_c^{rcts} &= RTS + \delta + DIFS \end{aligned}\right\}. \tag{5.53}$$

In Equation (5.51) the most important parameter is the probability of success, P_s. This probability is different form the probability of transmission τ, since if a station transmits does not mean that the transmission will be correctly received at the destination.

We are know interested in finding this probability of success, P_s, for the ideal channel case.

Consider an ideal channel consisting of n contending stations, including the AP and where there are no other stations associated with other AP's interfering with our system (see Figure 5.2).

For the ideal channel, all the station have the same probability of transmission, τ. For a slot to be successful in the system, only a single transmission must take place within it. This means that either all backlogged users remain silent and a single new user transmits, or a single backlogged user transmits while no new packet is generated. Given that there are i backlogged users this can be stated as

$$P_s(i) = \textit{Prob}[\textit{Successful slot / } i \textit{ users in backlog}]$$
$$= (1-v)^i \cdot (n-i)\cdot\tau\cdot(1-\tau)^{n-i-1} + i\cdot v\cdot(1-v)^{i-1}\cdot(1-\tau)^{n-i}. \qquad 5.54$$

Where v is the probability of transmission of a backlogged station.

As a special case, consider a situation in which we do not distinguish between backlogged packets and new packets, i.e., we set $v=\tau$. Substituting this into Equation 5.54 yields

$$P_s = n\cdot\tau(1-\tau)^{n-1}, \qquad (5.55)$$

indicating that the probability of success is independent of i. This result is, of course, not surprising since if we cease to distinguish between backlogged transmission and new transmissions we cannot expect the probability of success depend on the number of backlogged users.

In a similar way, since we are calculating the saturation throughput, we will be working with the assumption that we cannot distinguish between backlogged transmissions and new ones, thus with Equation (5.55) we can continue the calculation of the saturation throughput for the ideal channel case.

The probability of success given in (5.55) is somewhat incomplete for describing the behavior in a CSMA/CD protocol. This was done on purpose for the reason of making more understandable the assumption of transmission independence between station and that in saturation we can not distinguish between new user s and backlogged ones.

The probability of success of the system for the CSMA/CA is calculated as

$$P_s = \textit{Prob[successful transmission period]}$$

$$= \textit{Prob}\begin{bmatrix}\text{single arrival in last mini - slot before} & \\ \text{the transmission period} & \end{bmatrix} \text{| some arrivals}$$

$$= \frac{\textit{Prob[single arrival in a mini slot]}}{\textit{Prob[some arrivals in a mini slot]}},$$

thus

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \qquad (5.56)$$

For the individual station throughput, the probability of success of an individual station is

$$P_s = 1 \cdot \tau(1-\tau)^{n-1}. \tag{5.57}$$

The mean number $E[\psi]$ of consecutive idle slot time before a transmission takes place can be found by noting that its pdf is geometrically distributed, thus,

$$E[\psi] = \frac{1}{p_b} - 1 . \tag{5.58}$$

Since $E[\psi]$ is measured in slot times, the values of P, T_s and T_c are also measured in slot times. Note that p_b, is the probability that the channel is in reality busy, not that the station sense the channel busy; for the ideal channel case this two probabilities are the same because there is no hidden terminal problem, nor fading. Using equations (5.52), (5.56) and (5.58) in (5.51) we can get the system throughput for the ACK CSMA/CA mechanism. And using (5.53), (5.56) and (5.58) in (5.51) we can get the system throughput for the RTS-CTS CSMA mechanism. The same equations are used for the calculation of the throughput for a single station just by using Equation (5.57) instead of (5.56).

5.2.2 Saturation Throughput under Rayleigh fading channels

For the Rayleigh fading channel case in Figure 5.3, each $STA_{u,n}$ will have different probability of success, P_s, depending on the location of each station, for this reason we define the following nomenclature:

$P_{s(u,n)}$ is the probability that $STA_{u,n}$ transmits a frame successfully.

$P_{s(APu)}$ is the probability that APu transmits a frame successfully.

$P_{sChannel}$ is the probability that there is a successful transmission in the channel due to any station or AP. In other words, $P_{sChannel}$ is the sum of all the probabilities of success in the channel.

We are interested in finding the throughput of each station. Since each station and AP will have different probability of success, they all will have different throughput. For the Rayleigh fading channel case in Figure 5.3 we have for the probability of success of station $STA_{1,1}$ the following relation,

$$P_{s(1,1)} = \left\{\tau_{1,1} \cdot e^{\frac{-\beta}{P_{o(1,1),AP1}}}\right\}\left\{1-\tau_{1,2} \cdot e^{\frac{-\beta}{P_{o(1,2),AP1}}}\right\}\cdots\left\{1-\tau_{1,\eta_1} \cdot e^{\frac{-\beta}{P_{o(1,\eta_1),AP1}}}\right\}\left\{1-\tau_{2,1} \cdot e^{\frac{-\beta}{P_{o(2,1),AP1}}}\right\}\cdots\left\{1-\tau_{2,\eta_2} \cdot e^{\frac{-\beta}{P_{o(2,\eta_2),AP1}}}\right\}$$
$$\left\{1-\tau_{3,1} \cdot e^{\frac{-\beta}{P_{o(3,1),AP1}}}\right\}\cdots\left\{1-\tau_{3,\eta_3} \cdot e^{\frac{-\beta}{P_{o(3,\eta_3),AP1}}}\right\}\left\{1-\tau_{AP2} \cdot e^{\frac{-\beta}{P_{o(AP2),AP1}}}\right\}\left\{1-\tau_{AP3} \cdot e^{\frac{-\beta}{P_{o(AP3),AP1}}}\right\}\{1-\tau_{AP1}\}$$

(5.59)

Again, the above probability can be generalized for any station $STA_{u,n}$ as follows:

$$P_{s(u,n)} = \left\{ \tau_{u,n} \cdot e^{\frac{-\beta}{P_{o(u,n),APu}}} \right\} \left\{ \prod_{i=1}^{L}\prod_{j=1}^{\eta_i} \left\{ 1-\tau_{i,j}\cdot e^{\frac{-\beta}{P_{o(i,j),APu}}} \right\} \right\} \left\{ \prod_{k=1}^{L} \left\{ 1-\tau_{APk}\cdot e^{\frac{-\beta}{P_{o(APk),APu}}} \right\} \right\} \left\{ \frac{\{1-\tau_{APu}\}}{\left(1-\tau_{u,n}\cdot e^{\frac{-\beta}{P_{o(u,n),APu}}}\right)\left(1-\tau_{APu}\cdot e^{\frac{-\beta}{P_{o(APu),APu}}}\right)} \right\}$$

(5.60)

Now, for the access points,

$$P_{s(APu)} = \frac{1}{\eta_u}\sum_{l=1}^{\eta_u} \left\{ \left[\tau_{APu}\cdot e^{\frac{-\beta}{P_{o(APu),(u,l)}}} \right] \left[\prod_{i=1}^{L}\prod_{j=1}^{\eta_i} \left(1-\tau_{i,j}\cdot e^{\frac{-\beta}{P_{o(i,j),(u,l)}}} \right) \right] \left[\prod_{k=1}^{L} \left(1-\tau_{APk}\cdot e^{\frac{-\beta}{P_{o(APk),(u,l)}}} \right) \right] \left[\frac{\left(1-\tau_{u,l}\right)}{\left(1-\tau_{u,l}\cdot e^{\frac{-\beta}{P_{o(u,l),(u,l)}}}\right)\left(1-\tau_{APu}\cdot e^{\frac{-\beta}{P_{o(APu),(u,l)}}}\right)} \right] \right\}$$

(5.61)

The probability of a successful transmission in the channel, $P_{sChannel}$, is

$$P_{sChannel} = \sum_{u=1}^{L}\sum_{n=1}^{\eta_u} P_{s(u,n)} + \sum_{k=1}^{L} P_{s(APk)} . \quad (5.62)$$

For the Rayleigh fading channel case, the mean number of consecutive idle slot time before a transmission takes place can be found by noting that its pdf is geometrically distributed, thus,

$$E[\psi] = \frac{1}{p_{bChannel}} - 1 , \quad (5.63)$$

where $p_{bChannel}$ is the probability that the channel is in reality busy. As mentioned before, if a station senses the channel busy, doesn't mean that the channel is in reality busy. The channel can be busy even thought that a station senses that it is not, this is due to the hidden terminal problem and the channel fading.

The probability that the channel is in reality busy, $p_{bChannel}$, is

$$p_{bChannel} = 1-\prod_{u=1}^{L}\prod_{n=1}^{\eta_u}\left[1-\tau_{u,n}\cdot\left(1-\prod_{i=1}^{L}\prod_{j=1}^{\eta_i}\left(1-e^{\frac{-\beta}{P_{o(u,n),(i,j)}}}\right)\cdot\prod_{k=1}^{L}\left(1-e^{\frac{-\beta}{P_{o(APk),(u,n)}}}\right)\cdot\frac{1}{1-e^{\frac{-\beta}{P_{o(u,n),(u,n)}}}}\right)\right]\cdot$$
$$\prod_{z=1}^{L}\left[1-\tau_{APz}\cdot\left(1-\prod_{a=1}^{L}\prod_{b=1}^{\eta_a}\left(1-e^{\frac{-\beta}{P_{o(APz),(u,n)}}}\right)\cdot\prod_{c=1}^{L}\left(1-e^{\frac{-\beta}{P_{o(APk),(APc)}}}\right)\cdot\frac{1}{1-e^{\frac{-\beta}{P_{o(APz),(APz)}}}}\right)\right]$$

(5.64)

Finally, the individual saturation throughput can be found in a similar way as in Equation (5.51). Let $S_{u,n}^{bas}$ and $S_{u,n}^{rcts}$ be the saturation throughput of station STA$_{u,n}$ for the basic access mechanism and for the RTS/CTS mechanism, respectively, and let S_{APu}^{bas} and S_{APu}^{rcts} be the saturation throughput of APu for the basic access mechanism and for the RTS/CTS mechanism, respectively, thus

$$S_{u,n}^{bas} = \frac{P_{s(u,n)}\cdot E[P]}{E[\Psi]\cdot(1-p_{bChannel})+P_{sChannel}\cdot T_s^{ack}+(p_{bChannel}-P_{sChannel})\cdot T_c^{ack}},$$

(5.65)

$$S_{u,n}^{rcts} = \frac{P_{s(u,n)}\cdot E[P]}{E[\Psi]\cdot(1-p_{bChannel})+P_{sChannel}\cdot T_s^{rcts}+(p_{bChannel}-P_{sChannel})\cdot T_c^{rcts}},$$

(5.66)

$$S_{APu}^{bas} = \frac{P_{s(APu)}\cdot E[P]}{E[\Psi]\cdot(1-p_{bChannel})+P_{sChannel}\cdot T_s^{ack}+(p_{bChannel}-P_{sChannel})\cdot T_c^{ack}},$$

(5.67)

$$S_{APu}^{rcts} = \frac{P_{s(APu)}\cdot E[P]}{E[\Psi]\cdot(1-p_{bChannel})+P_{sChannel}\cdot T_s^{rcts}+(p_{bChannel}-P_{sChannel})\cdot T_c^{rcts}}.$$

(5.67)

The system saturation throughput for each WLAN (for the u^{th} WLAN) is

$$SystemThroughput_u^{bas} = \sum_{n=1}^{\eta_u} S_{u,n}^{bas} + S_{APu}^{bas}, \quad u = 1,2,...,L, \tag{5.68}$$

$$SystemThroughput_u^{rcts} = \sum_{n=1}^{\eta_u} S_{u,n}^{rcts} + S_{APu}^{rcts}, \quad u = 1,2,...,L. \tag{5.69}$$

Finally, the channel Saturation Throughput is

$$ChannelThroughput^{bas} = \sum_{u=1}^{L} SystemThroughput_u^{bas}, \tag{5.70}$$

$$ChannelThroughput^{rcts} = \sum_{u=1}^{L} SystemThroughput_u^{rcts}. \tag{5.71}$$

5.2.3 Saturation Throughput under Rayleigh fading channels and the Capture Effect

In Chapter 4 we obtained the probability of capture (Equation 4.16). Let $Pcapture_{u,n}$ be the probability of capture of STA$_{u,n}$ and $Pcapture_{APu}$ be the probability of capture of APu. Thus,

$$Pcapture_{u,n} = 1 - \prod_{i=1}^{L}\prod_{j=1}^{\eta_i}\left[1 - \tau_{u,n}\cdot\tau_{i,j}\cdot\left(\frac{1}{1+\beta\cdot\left(\frac{P_{o(APu),(i,j)}}{P_{o(APu),(u,n)}}\right)^{-4}}\right)\right]\cdot\left[\prod_{k=1}^{L}\left(1-\tau_{u,n}\cdot\tau_{APk}\cdot\left(\frac{1}{1+\beta\cdot\left(\frac{P_{o(APu),(APk)}}{P_{o(APu),(u,n)}}\right)^{-4}}\right)\right)\right]\cdot$$
$$\frac{1}{1-\tau_{u,n}\cdot\tau_{u,n}\cdot\frac{1}{1+\beta\cdot\left(\frac{P_{o(APu),(u,n)}}{P_{o(APu),(u,n)}}\right)^{-4}}}\cdot\frac{1}{1-\tau_{u,n}\cdot\tau_{APu}\cdot\frac{1}{1+\beta\cdot\left(\frac{P_{o(APu),(APu)}}{P_{o(APu),(u,n)}}\right)^{-4}}} \tag{5.72}$$

$$Pcapture_{APu} = 1 - \frac{1}{\eta_u}\sum_{l=1}^{\eta_u}\left\{\prod_{i=1}^{L}\prod_{j=1}^{\eta_i}\left(1-\tau_{APu}\tau_{i,j}\left(\frac{1}{1+\beta\cdot\left(\frac{P_{o(i,j),(u,l)}}{P_{o(APu),(u,l)}}\right)^{-4}}\right)\right)\prod_{k=1}^{L}\left(1-\tau_{APu}\tau_{APk}\left(\frac{1}{1+\beta\cdot\left(\frac{P_{o(APk),(u,l)}}{P_{o(APu),(u,l)}}\right)^{-4}}\right)\right)\right.$$
$$\left.\frac{1}{1-\tau_{APu}\cdot\tau_{u,l}\cdot\frac{1}{1+\beta\cdot\left(\frac{P_{o(u,l),(u,l)}}{P_{o(APu),(u,l)}}\right)^{-4}}}\frac{1}{1-\tau_{APu}\cdot\tau_{APu}\cdot\frac{1}{1+\beta\cdot\left(\frac{P_{o(APu),(u,l)}}{P_{o(APu),(u,l)}}\right)^{-4}}}\right\} \tag{5.73}$$

We are now interested in finding the probability of a successful transmission when we have the capture phenomenon. Let $P_{sCapture(u,n)}$ be the probability of a successful transmission of station STA$_{u,n}$ when the probability of capture is considered; and let $P_{sCapture(APu)}$ be the probability of a successful transmission of APu when the probability of capture is considered. These probabilities are given by,

$$P_{sCapture(u,n)} = P_{s(u,n)} + P_{capture(u,n)}\,, \tag{5.74}$$

$$P_{sCapture(APu)} = P_{s(APu)} + P_{capture(APu)}\,. \tag{5.75}$$

And the channel probability of success is given by,

$$P_{sCaptureChannel} = \sum_{u=1}^{L}\sum_{n=1}^{\eta_u} P_{sCapture(u,n)} + \sum_{k=1}^{L} P_{sCapture(APk)}\,. \tag{5.76}$$

The individual, systems and channel saturation throughputs can be again calculated by using these new probabilities of success in equations (5.65) through (5.71)

5.3 Delay Analysis

In this section the expected delay of each station is calculated. The structure is the same as the last section. We first calculate the expected delay on ideal channel conditions, then we continue with the calculation of the expected delay on a Rayleigh fading channel and we conclude the chapter with the calculation of the expected delay taking into account the capture phenomenon.

5.3.1 Delay analysis on ideal channel conditions

Frame delay is defined as the time elapsed between the generation of a frame and its successful reception. Let D be the random variable representing the frame delay and $E[D]$ its mean value. The mean frame delay can be found by the following relation [2]:

$$E[D] = E[N_c]\left(E[BD] + T_c + T_o\right) + \left(E[BD] + T_s\right), \tag{5.77}$$

where $E[N_c]$ is the number of collision of a frame until its successful reception, $E[BD]$ is the average backoff delay that a station chooses before accessing the channel under busy channel conditions, T_o is the time that a station has to wait when its frame transmission collides, before sensing the channel again. Finally, times T_s and T_c are given by equations (5.52) and (5.53) respectively.

The average number of collision before transmitting a frame can be calculated by using the probability P_s that a transmission is successful. If the probability P_s is known, then the retransmission follows a geometric pdf, and the average number of retransmission is [2],

$$E[N_c] = \frac{1}{P_s} - 1\,. \tag{5.78}$$

The average backoff delay depends on the value of its counter and the duration the counter freezes when the station detects transmission from other stations. Considering that the counter of a station is at state $b_{i,k}$, then a time interval of k slot times is needed for the counter to reach state 0, without taking into account the time the counter is stopped. This time interval is denoted by the random variable X and its average is given by

$$E[X] = \sum_{i=0}^{m} \sum_{k=1}^{W_i - 1} k b_{i,k}\ ,$$

based on equations (5.10), (5.11) and (5.12) we get that [2]

$$E[X] = \frac{b_{0,0}}{6(1-p_b)} \frac{W^2(1-p-3p(4p)^m)+4p-1}{(1-4p)(1-p)} . \tag{5.79}$$

We denote by F the time that the counter of a station freezes. When the counter freezes, it remains stopped for the duration of a transmission. This duration depends on the transmission success. So, in order to calculate the average time $E[F]$ that the counter remains stopped, we have to find $E[N_{Fr}]$, the average number of time that a station detects transmission form other stations before its counter reaches state 0. Based on $E[X]$, the average backoff delay of each station and on $E[\psi]$, the mean number of consecutive idle slot times before a transmission proceeds, then [2]

$$E[N_{Fr}] = \frac{E[X]}{\max(E[\psi],1)} - 1 ,$$

and

$$E[F] = E[N_{Fr}](P_s T_s + (p_b - P_s)T_c). \tag{5.80}$$

From equations (5.79) and (5.80), we have that

$$E[BD] = E[X] + E[N_{Fr}](P_s T_s + (p_b - P_s)Tc). \tag{5.81}$$

Finally, the time T_o depends on the access method and equals

$$T_o = \begin{cases} SIFS + ACK\_timeout \\ SIFS + CTS\_timeout \end{cases} . \tag{5.82}$$

Substituting equations (5.82), (5.81) and (5.78) into Equation (5.77), we can calculate the mean frame delay for a station under ideal channel conditions.

5.3.2 Delay analysis on Rayleigh fading channels

In a Rayleigh fading channel we will have different expected delays for each station due to its space location. We continue with the same nomenclature as in the last sections.

The procedure to find the expected delay is the same as in ideal channel case. We just have to be careful on identifying the probabilities that are related to each individual station and the probabilities that are related to the whole channel. The expected values defined on the ideal channel case are the same in this section, we just add the labels u, n and AP_u as we have been using them to refer to stations and access points. The probabilities for both basic access mechanism and RTS/CTS are:

$$E[X]_{u,n} = \frac{b_{0,0(u,n)}}{6(1-p_{b(u,n)})} \frac{W^2(1-p_{u,n}-3p_{u,n}(4p_{u,n})^m)+4p_{u,n}-1}{(1-4p_{u,n})(1-p_{u,n})} \tag{5.83}$$

$$E[X]_{APu} = \frac{b_{0,0(APu)}}{6(1-p_{b(APu)})} \frac{W^2(1-p_{APu}-3p_{APu}(4p_{APu})^m)+4p_{APu}-1}{(1-4p_{APu})(1-p_{APu})}, \tag{5.84}$$

$$E[N_{Fr}]_{u,n} = \frac{E[X]_{u,n}}{\max(\frac{1}{p_{b(u,n)}}-1,1)} - 1, \tag{5.85}$$

$$E[N_{Fr}]_{APu} = \frac{E[X]_{APu}}{\max(\frac{1}{p_{b(APu)}}-1,1)} - 1, \tag{5.86}$$

$$E[F_{bas}]_{u,n} = E[N_{Fr}]_{u,n} \cdot (P_{sChannel} \cdot T_s^{bas} + (p_{bChannel} - P_{sChanel}) \cdot T_c^{bas}), \tag{5.87}$$

$$E[F_{bas}]_{APu} = E[N_{Fr}]_{APu} \cdot (P_{sChannel} \cdot T_s^{bas} + (p_{bChannel} - P_{sChanel}) \cdot T_c^{bas}), \tag{5.88}$$

$$E[F_{rcts}]_{u,n} = E[N_{Fr}]_{u,n} \cdot (P_{sChannel} \cdot T_s^{rcts} + (p_{bChannel} - P_{sChanel}) \cdot T_c^{rcts}), \tag{5.89}$$

$$E[F_{rcts}]_{APu} = E[N_{Fr}]_{APu} \cdot (P_{sChannel} \cdot T_s^{rcts} + (p_{bChannel} - P_{sChanel}) \cdot T_c^{rcts}), \tag{5.90}$$

$$E[N_c]_{u,n} = \frac{1}{P_{s(u,n)}} - 1, \tag{5.91}$$

$$E[N_c]_{APu} = \frac{1}{P_{s(APu)}} - 1, \tag{5.92}$$

$$E[BD]_{u,n}^{bas} = E[X]_{u,n} + E[N_{Fr}]_{u,n} \cdot (P_{sChannel} \cdot T_s^{bas} + (p_{bChannel} - P_{sChannel}) \cdot T_c^{bas}), \tag{5.93}$$

$$E[BD]_{u,n}^{rcts} = E[X]_{u,n} + E[N_{Fr}]_{u,n} \cdot (P_{sChannel} \cdot T_s^{rcts} + (p_{bChannel} - P_{sChannel}) \cdot T_c^{rcts}), \tag{5.94}$$

$$E[BD]_{APu}^{bas} = E[X]_{APu} + E[N_{Fr}]_{APu} \cdot (P_{sChannel} \cdot T_s^{bas} + (p_{bChannel} - P_{sChannel}) \cdot T_c^{bas}), \tag{5.95}$$

$$E[BD]_{APu}^{rcts} = E[X]_{APu} + E[N_{Fr}]_{APu} \cdot (P_{sChannel} \cdot T_s^{rcts} + (p_{bChannel} - P_{sChannel}) \cdot T_c^{rcts}), \tag{5.96}$$

$$E[D]_{u,n}^{bas} = E[N_c]_{u,n} \cdot (E[BD]_{u,n}^{bas} + T_c^{bas} + T_o^{bas}) + (E[BD]_{u,n}^{bas} + T_s^{bas}), \tag{5.97}$$

$$E[D]_{APu}^{bas} = E[N_c]_{APu} \cdot (E[BD]_{APu}^{bas} + T_c^{bas} + T_o^{bas}) + (E[BD]_{APu}^{bas} + T_s^{bas}), \tag{5.98}$$

$$E[D]_{u,n}^{rcts} = E[N_c]_{u,n} \cdot (E[BD]_{u,n}^{rcts} + T_c^{rcts} + T_o^{rcts}) + (E[BD]_{u,n}^{rcts} + T_s^{rcts}), \quad (5.99)$$

$$E[D]_{APu}^{rcts} = E[N_c]_{APu} \cdot (E[BD]_{APu}^{rcts} + T_c^{rcts} + T_o^{rcts}) + (E[BD]_{APu}^{rcts} + T_s^{rcts}). \quad (5.100)$$

For the capture effect consideration, we just have to change the $P_{sChannel}$ with the $P_{sCaptureChannel}$ and we obtain the expected delay for each station using equations 5.83 through 5.100.

Chapter 6

Voice Over 802.11

Voice over 802.11 is voice over IP used to transport voice over wireless Ethernet. Voice over Internet Protocol (VoIP) is one of the fastest growing Internet applications today and it has two fundamental benefits compared with voice over traditional telephone networks. First, by exploiting advanced voice-compression techniques and bandwidth sharing in packet-switched networks, VoIP can dramatically improve bandwidth efficiency. Second, it facilitates the creation of new services that combine voice communication with other media and applications such as video, white boarding and file sharing. At the same time, driven by huge demands for portable access, the wireless local area network (WLAN) market is taking off quickly. Due to its convenience, mobility, and high-speed access, WLAN represents an important future trend for “last-mile” Internet access.

This chapter presents a review of Voice over Wireless LAN and important characteristics and issues related to its system capacity are presented.

6.1 Background on Voice over Internet Protocol

The first process in an IP voice system is the digitization of the speaker’s voice (PCM digitization). The next step (and the first step when the user is on a handset connected to a geteway using a digital PSTN connection) is typically the suppression of unwanted signals and compression of the voice signal. This has tow stages. First, the system examines the recently digitized information to determine if it contains a voice signal or only ambient noise and discards any packets that do no contain speech. Second, complex algorithms are employed to reduce the amount of information that must be sent to the other party. Sophisticated CODECS enable noise suppression and compression of voice streams.

Following compression, voice must be packetized and VoIP protocols added. Some storage of data occurs during the process of collecting voice data, since transmitter must wait for a certain amount of voice data to be collected before it is combined to form a packet ant transmitted via the network. Protocols are added to the packet to facilitate its transmission across the network. In example, each packet will need to contain the address of its destination, a sequencing number in case the packets do not arrive in the proper order, and additional data for error checking. Because IP is a protocol designated to interconnect networks of varying kinds, substantially more processing is required than in smaller networks. The network addressing system can often be very complex, requiring a process of

encapsulating one packet inside another and as data move along, repackaging, readdressing, and reassembling the data is required.
When each packet arrives at the destination computer, its sequencing is checked to place the packets in the proper order. A decompression algorithm is used to restore the data to their original form, and clock synchronization and delay-handling techniques are used to ensure proper spacing. Because data packets are transported via the network by variety of routes, they do no arrive at their destination in order. To correct this, incoming packets are stored for a time in a jitter buffer to wait for late-arriving packets. The length of time in which data are held in a jitter buffer varies depending on the characteristics of the network.

6.2 Interference Issues and QoS on Vo802.11 Wireless Networks

If Vo802.11 networks are to be a viable bypass of the PSTN, the must deliver a subscriber experience comparable to or better than that of the PSTN. This is especially important with regard to voice services. The concern many have when it comes to replacing the copper wires or fiber cables of the PSTN with the air wave of 802.11 is that the air wave, given that they are not as controllable or predictable as copper wire or fiber cables, will deliver an inferior QoS or may be susceptible to interference form other emitter in the electromagnetic spectrum.

Voice is a challenging medium to deliver in packet-switched networks. QoS in wired VoIP networks remains a topic of almost endless discussion. Given the emphatic focus on QoS in wired packet networks, one of the foremost concerns regarding Vo802.11 is that it cannot deliver the QoS necessary for intelligible voice quality.

What is commonly thought when refereeing to QoS in a wireless network actually has to do with interference from other transmission sources. An immediate concern is a profusion of wireless appliances in day-to-day use such as garage door openers, microwave ovens, and cordless phones. Many of these household appliances do not operate on the same frequency as 802.11 or the power of their emission is to low or too distant to interfere with 802.11 traffic.

A wide variety of other devices (bar-code scanners, industrial lighting, industrial heaters, and home microwave ovens) also use the same frequencies. Because WLANs operate at fairly low power levels, the actual risk of interference with other devices is relatively slight but it does exist. As the popularity of such WLANs has increased, situations have developed in which such interferences have indeed become an issue.

6.3 Importance of QoS on 802.11 Networks

When the suggestion is made that 802.11 networks and associated protocols could potentially replace the PSTN as we know it, one of the first considerations is to provide an alternative to the primary service for which the PSTN was built: voice. The primary objection to carry voice over the Internet Protocol, the primary means of transmitting voice over a packet network, is that the QoS of an IP network is inadequate to deliver intelligible voice to the subscriber. The limitations of an IP network to deliver adequate QoS for voice and video include latency, jitter and packet loss. By delivering adequate QoS for voice service, 802.11 presents an alternative to the PSTN's voice services.

To deliver voice quality that compares to the PSTN, a network operator must minimize latency, jitter, and packet loss on a Vo802.11 network.

6.4 Latency in Wireless Networks

The biggest threat to an IP network is latency, or delay of the delivery of packets via the network. *Latency* is defined as the time it takes for the network to respond to a user command. If latency is high, causing noticeable delays in downloading Web pages, then the experience feels nothing al all like broadband, no matter how high the data rates are. Low latency (less than 50 ms) is a requirement that must be met if the mass-market adoption for wireless services and devices is to be successful.

The latency experienced by the wireless user has a number of contributing sources:

- Air link processing.- The time necessary to convert user data to air link packets (code, modulate, and frame user data) and transmit it.
- Propagation.- The time necessary for a signal to travel a distance between the base station and the subscriber device and vice versa.
- Network transmission.- The time necessary to send the packet across the backhaul and backbone networks, including routing and protocol processing delays and transmission time.
- Far-end processing.- The time required for processing by the far-end servers and other devices.
- Application being used and the user device.

The sum of these latencies must be minimized to ensure a positive end-user experience. Because of the many contributing sources in wired networks, there is little room for latency contributed by the wireless system.

Latency can also be thought of as the time it takes from data send-off on one end to data retrieval on the other end (from one user to the other).
Latency is crucial to the broadband experience because the Internet is based on TCP. TCP requires the recipient of packet to acknowledge its receipt. If the sender does not receive a receipt in a certain amount of time (milliseconds), then TCP assumes that the connection is congested and slows down the rate at which it

sends packets. TCP is very effective in dealing with congestion on the wired networks.

A system's ability to efficiently handle a large user population depends significantly on its ability to service many small TCP/IP messages per unit time and, hence, to multiplex many active data users within a given cell. Hence, high latency translates directly into lower system capacity for serving data users, which equates to higher cost.

6.5 QoS on Vo802.11 Networks

As wired service providers and network administrator have found, voice is the hardest service to provision on an IP network.

6.5.1 Measuring voice quality in Vo802.11

As the VoIP industry matured, means of measuring voice quality come on the market. Currently, two tests are available that provide a metric for voice quality. The first is a holdover from the circuit-switched voice industry known as the mean opinion score (MOS). The other has emerged with the rise in popularity of VoIP and is known as perceptual speech quality measurement (PSQM).

MOS

The mean opinion score is a measurement technique defined in ITU-T P.800 and it's based on the opinions of many testing volunteers who listen to a sample of voice traffic and rate the quality of that transmission. The volunteers rate the voice sample from 1 to 5 with 5 being "excellent" and 1 being "bad". The voice samples are then awarded a mean opinion score or "MOS". A MOS of 4 is considered "toll quality", that is, equal to the PSTN.

PSQM

Another means of testing voice quality in Vo802.11 networks is known as perceptual speech quality measurement. It is based on ITU-T Recommendation P.861, which specifies a model to map actual audio signals to their representations inside the head of a human. Voice quality consists of a mix of objective and subjective parts and varies widely among the different coding schemes and the types of network topologies used for transport.

6.5.2 Detractors on Voice Quality in Vo802.11 Networks

Latency, jitter, packet loss, and echo detract from good voice quality in an 802.11 network. With proper engineering, the impact of these factors on voice quality can be minimized and voice quality equal to or better than that of the PSTN can be achieved on 802.11 networks. With proper engineering, the impact of these factors on voice quality can be minimized and voice quality equal or better than that of the PSTN can be achieved on 802.11 networks.

Countering Latency on Vo802.11 Networks

Voice as a wireless IP application presents unique challenges for 802.11 networks. Primary among these is acceptable audio quality resulting from minimized network latency (also known as delay) in a mixed voice and data environment. Ethernet, wired or wireless was not designed for real-time streaming media or guaranteed packet delivery. Congestion on the wireless network, without traffic differentiation, can quickly render voice unusable. QoS measures must be taken to ensure that voice packet delay stays under 100 ms.

Voice signal processing at the sending and receiving ends, which includes the time required to encode or decode the voice signal form the analog or digital form into the voice-coding scheme selected from the call and vice versa, adds to the delay. Compressing the voice signal will also increase the delay. The grater the compression the grater the delay.

On the transmitting side, packetization delay is another factor that must be accounted for in the calculations. The packetization delay is the time it takes to fill a packet with data. The larger de packet size, the more time is required. Using shorter packet sizes can shorten this delay but will increase the overhead because more packets have to be sent, all containing similar information in the header. Balancing voice quality, packetization delay, and bandwidth utilization efficiency is very important to the service provider.

Latency is the greatest factor degrading the Vo802.11 QoS. Latency less than 100 ms does not affect “toll quality” voice. However, latency of grater than 120 ms is discernible to most callers, and at 150 ms the voice quality is noticeably impaired, resulting in less than a toll-quality communication. The challenge of Vo802.11 service providers and their vendors is to get the latency of any conversation on their network to not exceed 100 ms [18]. Humans are intolerant of speech delays of more than about ***250 ms***. ITU-T G.114 specifies that delay is not to exceed 150 ms one way or 300 ms round trip. The dilemma is that while elastic applications (e-mail for example) can tolerate a fair amount of delay, the usually try to consume every bit of network capacity they can. In contrast, voice applications need only small amounts of the network, but that amount has to be available immediately. [18]

The delay experienced in a call occurs on the transmitting side, in the network, and on the receiving side. Most of the delay on the transmitting side is due to codec delay and processing delay. In the network, most of the delay stems from transmission time (serialization and propagation) and router queuing time. Finally, the jitter buffer depth, processing, and, in some implementations, polling intervals add to the delay on the receiving side.

The delay introduced by the speech coder can be divided into algorithmic and processing delay. The algorithmic delay occurs due to framing for block processing, since the encoder produces a set of bits representing a block of speech samples. Furthermore, many coders using block processing also have a lock-ahead function that requires a buffering of future speech samples before a block is encoded. This adds to the algorithmic delay. Processing delay is the amount of time it takes to encode and decode a block of speech samples.

Dropped Packets

In Vo802.11 networks, a percentage of the packets can be lost or delayed, especially during periods of congestion. Also, some packets are discarded due to errors that occurred during transmission. Lost, delayed, and damaged packets result in substantial deterioration of voice quality. In conventional error correction techniques used in other protocols, incoming blocks of data containing errors are discarded, and the receiving computer requests the retransmission of the packet. Thus, the message that is finally delivered to the user is exactly the same as the message that originated. Because Vo802.11 systems are time sensitive and cannot wait for retransmission, more sophisticated error detection and correction systems are used to create sound to fill in the gaps. This process stores a portion of the incoming speaker's voice, then, using complex algorithm to approximate the contents of the missing packets, new sound information is created to enhance the communication. Thus, the sound heard by the receiver is not exactly the sound transmitted, but rather portions of it have been created by the system to enhance the delivered sound.

Most of the packet losses occur in the routers, either due to high router load or high link load. In both situations, packets in the queues might be dropped. Another source of packet loss is errors in the transmission links, resulting in CRC errors for the packet. Configuration errors and collision might also result in packet losses. In nonreal-time applications, packet losses are solved at the protocol layer by retransmission (TCP). For telephony this is not a viable solution since retransmitted packets would arrive too late and be of no use.

Jitter

Jitter occurs because packets have varying transmission times. It is caused by different queuing time in the routers and possibly by different routing paths. The jitter results in unequal time spacing between the arriving packets and requires a jitter buffer to ensure smooth, continuous playback of the voice stream.

The chief correction for jitter is to include an adaptive jitter buffer. The jitter buffer described in the solution above is a fixed jitter buffer. An improvement above that is an adaptive jitter buffer that can dynamically adjust to accommodate for the high levels of delay that can be encountered in wireless networks.

Factors Affecting QoS in Vo802.11 Networks

The four most important network parameters for effective transport of Vo802.11 traffic are bandwidth, delay, jitter, echo, and packet loss. This presents a challenge for network designer who must first focus on these issues in order to deliver the best QoS possible.

Improving QoS in IP Routers and Gateways

End-to-end delay is the time required for a signal generated at the caller’s mouth to reach the listener’s ear. Delay is the impairment that receives the most attention in the media gateway industry. It can be corrected via functions contained in the IP network routers, the VoIP gateway, and in engineering in the IP network. The shorter the end-to-end delay, the better the perceived quality and overall user experience.

Sources of Delay: IP Routers

Packet delay is primarily determined by the buffering, queuing, and switching or routing delay of the IP routers. Packet capture delay is the time required to receive the entire packet before processing and forwarding it through the router. This delay is determined by the packet length, link layer operating parameters, and transmission speed. Using short packets over high-speed networks can easily shorten the delay. Vo802.11 networks use packetization rates to balance connection bandwidth efficiency and packet delay.

This chapter explained QoS consideration for Vo802.11. QoS on a Vo802.11 can be engineered to be as good as a PSTN. As with any engineering issue, overcoming shortcomings is merely a matter of good engineering. With the right mix of QoS measures, Vo802.11 networks can deliver voice quality as good the PSTN.

Chapter 7

Numerical Results

We now present numerical results for the expected delay, delay variance, their respective cumulative distribution functions and the system throughput under saturation and determine the spatial, traffic and system capacity for the transmission of voice over WLAN under the influence of co channel interference. Extensive numerical simulations were conducted to achieve the above objective.

This chapter is divided in two main different scenarios. The first one involves the simulation results for the case when there is only one WLAN, i.e., one access point and a finite number of stations. Analyzing this scenario we determine the maximum number of stations, the bit rate at which they must be operating and the maximum coverage area so that voice over WLAN can be achieved. Once obtained the best possible way to transmit VoWLAN in the single WLAN scenario we can part form there to analyze the co channel interference scenario, i.e., one WLAN with an access point and its corresponding number of stations all surrounded by other WLAN's with their respective access points and stations with the objective of finding the conditions where they can all coexist together and don't cause enough impact to degrade the performance of the VoWLAN transmission.

7.1 WLAN scenario 1: One WLAN with a finite number of stations.

For the purpose of having a more detailed analysis this section is divided in subsections. Each one corresponding to different scenarios having the following variables: signal to noise radio for correct signal detection (receiver sensitivity for lowest level signal reception), bit rate, radius of coverage and number of stations. We also have some fixed variables, which include the voice packet payload and the transmission power of the access point and the stations. Also the coordinates of the stations are randomly distributed following a uniform distribution over the coverage area and the access point is located at the origin. We then plot the results for the expected delay, its jitter (also referred as the standard deviation of the expected delay), the maximum delay of an access point and a station and the system throughput for both Basic Access Mechanism and the Request Mechanism.

Fixed Variables:

- **Transmission Power.** The transmission power is assumed to be the maximum allowed by the FCC, which is ***1 Watt***.

- **Packet Payload.** Depending on the codec used the typical packet payload for VoIP ranges from 10 to 30 Bytes. For all the scenarios, simulations are made with the G.729 codec. As a general review of the codec, the G.729 provides a toll quality speech with only moderate processing requirements and delay time. It performs well In the presence of random bit errors. It's based on the Code Excited Linear Prediction Model and Conjugate-Structure Algebraic CELP (CS-CELP). It's used on visual telephony, wireless communications and digital satellite communication systems. Table 7.1 gives general information about this codec. The following protocol header assumptions are used for the calculation of the total packet payload: Compressed Real time Protocol (cRTP) IP/UDP/RTP header of 2 Bytes and a 6 Bytes of Multilink Point to Point Protocol (MP). Using this assumptions we calculate the Total Packet Size:

  Total Packet Size (Bytes) = (MP header of 6 Bytes) + (compressed IP/UDP/RTP header of 2 Bytes) + (voice payload of 20 Bytes) = 28 Bytes.

  Total Packet Size (bits) = (28 Bytes) * 8 bits = ***224 bits.***

Table 7.1. Codec used characteristics.

Codec & Bit Rate (Kbps)	Codec Sample Size (Bytes)	Codec Sample Interval (ms)	Mean Opinion Score	Voice Payload Size (Bytes)	Voice Payload Size (ms)
G.729 (8 Kbps)	10 Bytes	10 ms	3.92	20 Bytes	20 ms

Simulation Variables:

- **Receiver's sensitivity for correct signal detection (in dB).** For the simulations numerical results, 6, 8 and 10 dB are used to compare how the receivers sensitivity affects the capacity of VoWLAN.
- **Channel Bit Rate.** The channel bit rates used for simulations results are: 5, 11 and 54 Mbps.
- **Coverage radiuses.** For the coverage radiuses it is assumed that an Access Point is located at the origin and all the stations are located inside this coverage radius. The radiuses are: 10, 20 and 30 meters.
- **Number of Stations.** The number of stations varies from 5 to 18 stations.

Desired Results:

The results we expect to obtain are:

- Access Point Expected Delay using the Basic Access Mechanism.
- Access Point Expected Delay using the Request to Send Mechanism.
- Stations expected delay using the Basic Access Mechanism.
- Stations expected delay using the Request to Send Mechanism.

- System Throughput using the Basic Access Mechanism.
- System Throughput using the Request to Send Mechanism.
- Access Point Delay Variance using the Basic Access Mechanism.
- Access Point Delay Variance using the Request to Send Mechanism.
- Stations Delay Variance using the Basic Access Mechanism.
- Stations Delay Variance using the Request to Send Mechanism.
- System Throughput Variance using the Basic Access Mechanism.
- System Throughput Variance using the Request to Send Mechanism.

All result with their respective simulation variables.

In the following subsections, the general simulation results for the first scenario is presented and at the last subsection a review of the best case scenarios for the transmission of VoWLAN will be presented with high detail as well as their respective cumulative distribution functions.

7.1.1 Scenario: Signal to Noise Ratio = 6 dB at 5.5 Mbps

Figure 7.1 and 7.2 show the expected Delay of the Access Point and Stations and the System Throughput for a coverage radius of 10 meters and with a receiver sensitivity of 6 dB operating at 5.5 Mbps.

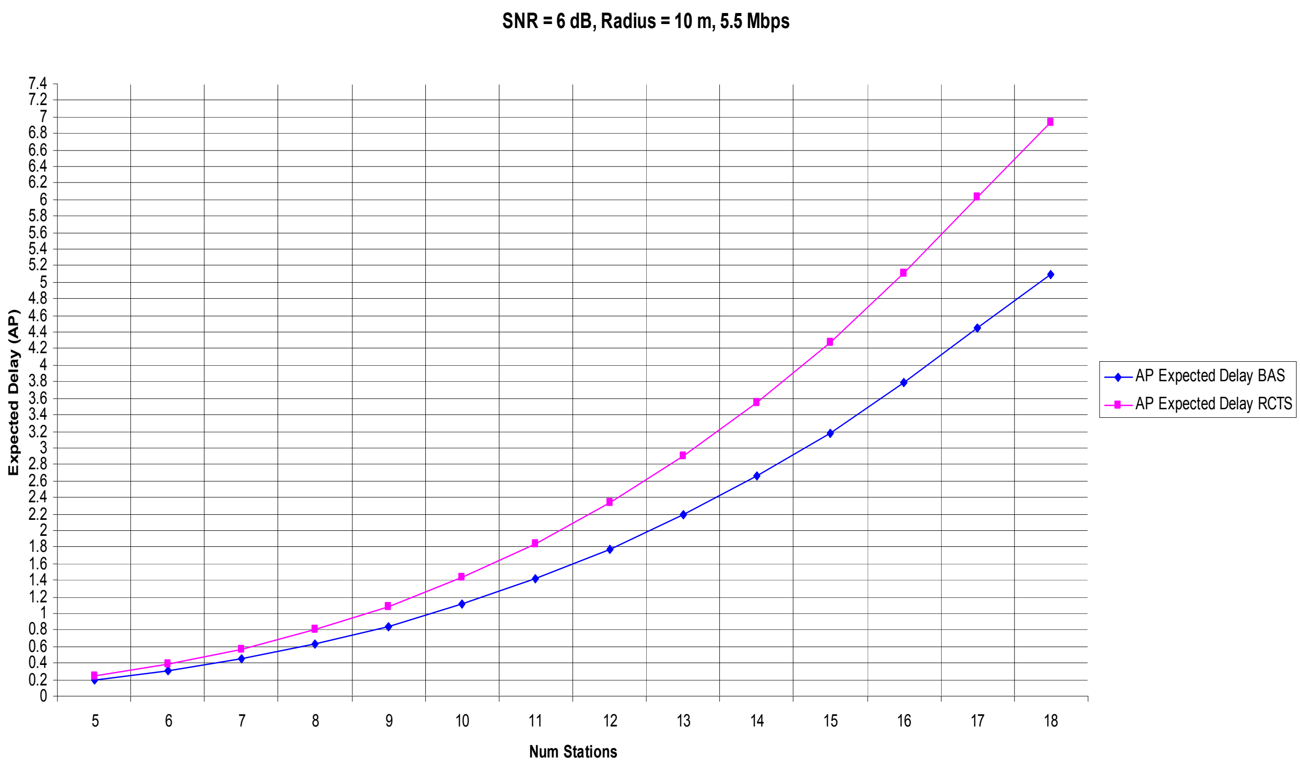

Figure 7.1. Access Point Expected Delay for SNR = 6 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

- System Throughput using the Basic Access Mechanism.
- System Throughput using the Request to Send Mechanism.
- Access Point Delay Variance using the Basic Access Mechanism.
- Access Point Delay Variance using the Request to Send Mechanism.
- Stations Delay Variance using the Basic Access Mechanism.
- Stations Delay Variance using the Request to Send Mechanism.
- System Throughput Variance using the Basic Access Mechanism.
- System Throughput Variance using the Request to Send Mechanism.

All result with their respective simulation variables.

In the following subsections, the general simulation results for the first scenario is presented and at the last subsection a review of the best case scenarios for the transmission of VoWLAN will be presented with high detail as well as their respective cumulative distribution functions.

7.1.1 Scenario: Signal to Noise Ratio = 6 dB at 5.5 Mbps

Figure 7.1 and 7.2 show the expected Delay of the Access Point and Stations and the System Throughput for a coverage radius of 10 meters and with a receiver sensitivity of 6 dB operating at 5.5 Mbps.

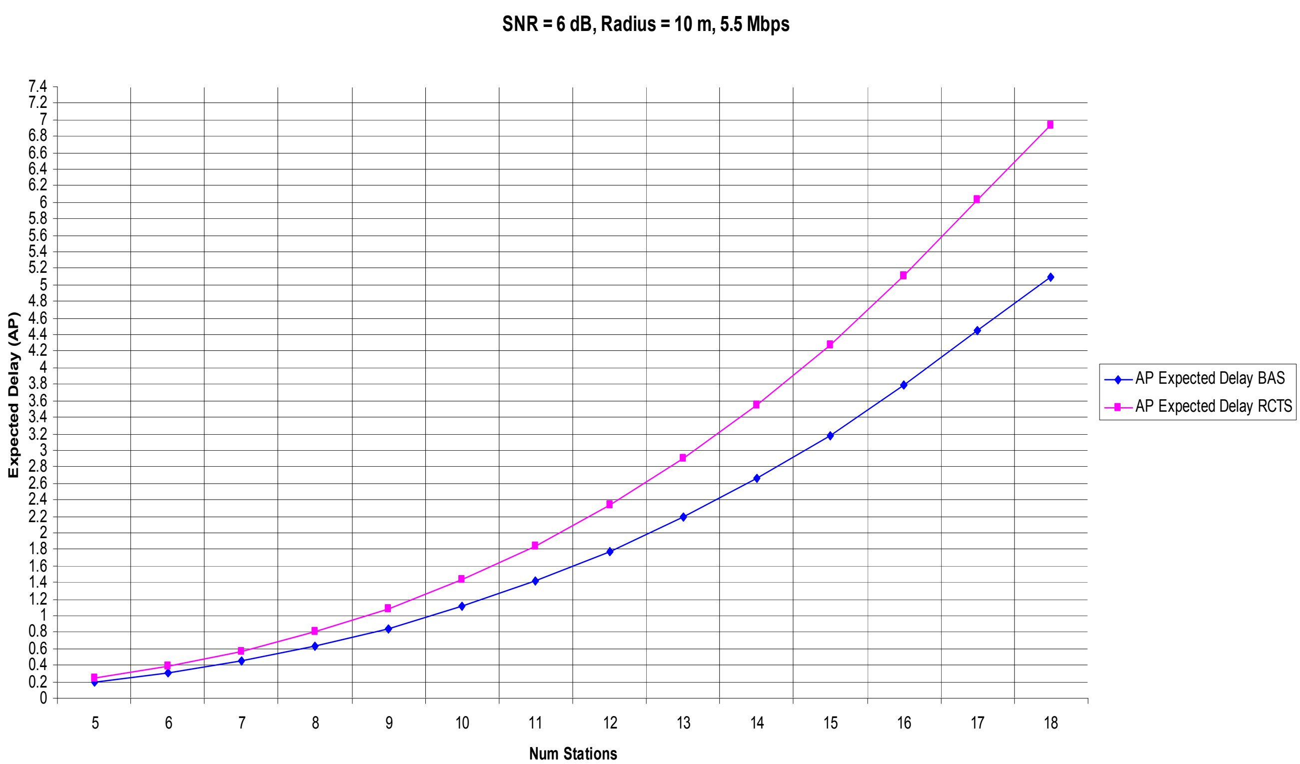

Figure 7.1. Access Point Expected Delay for SNR = 6 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

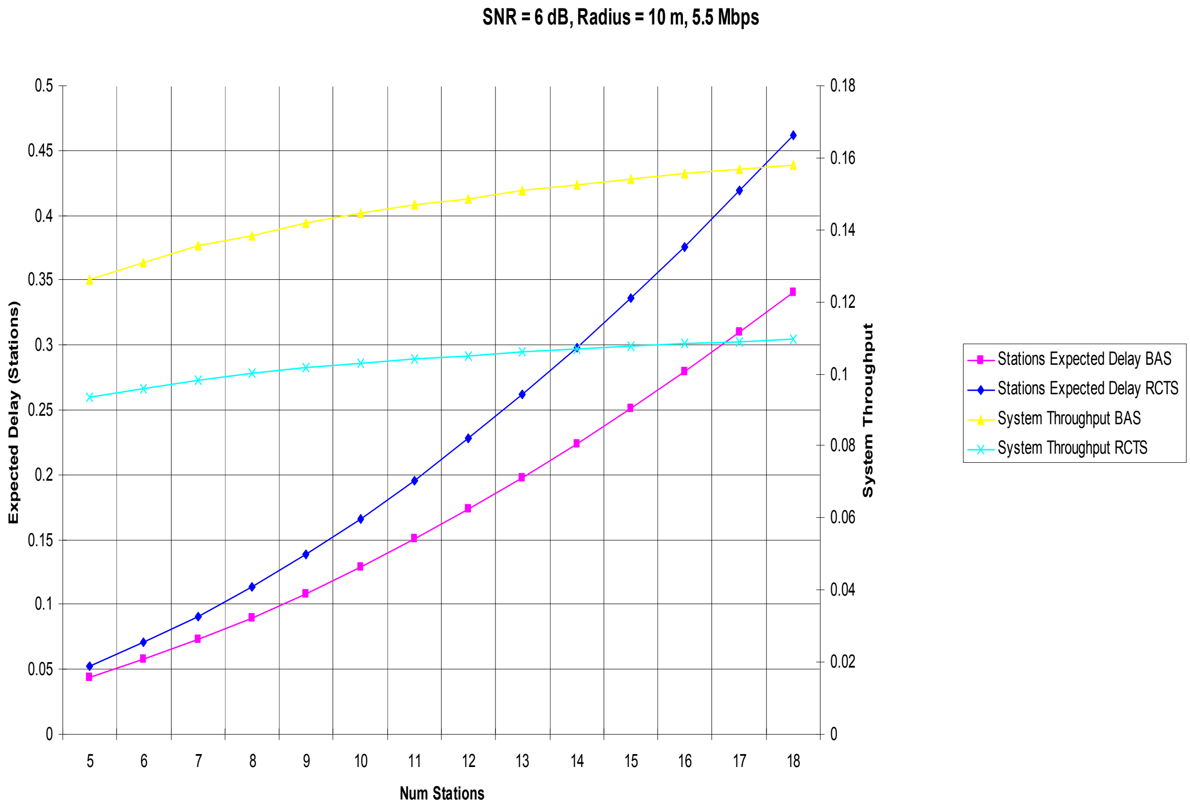

Figure 7.2. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 10 m, at 5.5 Mbps

As it can be seen in both figures, the Basic Access mechanism has less delay than the Request to Send mechanism, this is because the Basic Access mechanism doesn't reserve the channel so it doesn't waste time on it. Also the packet payload is smaller in size compared with the MAC and the Physical header used in transmission and is about the same size of the request to send packet and of the clear to send packet. This causes that the BAS mechanism is better suited for the transmission of VoWLAN.

Figure 7.2 shows in average the maximum number of stations that can be put in the system so that the delay is below of 200 ms. As can be seen the maximum number of stations are 13. So, in average, if we have 13 stations randomly distributed inside a radius of 10 meters, each station will have an average delay of less than 200 ms. The reason of the increased delay as the number of stations increases is because as the number of stations increases the probability of sensing the channel busy and the probability of collisions also increases and the stations will enter more frequently the exponential backoff contention time. This case can be seen as the uplink connection.

For the case of the downlink connection (transmission from the Access Point to a station), Figure 7.1 show that only 5 stations can be supported for an average delay less than 200 ms.

In the case of the system throughput (effective data channel utilization), again the BAS mechanism has a better performance than the RCTS mechanism and it's again due to the packet payload. Even though the channel utilization is really poor (less than 16 %).

As a preliminary conclusion it can be seen that for these scenario, only five stations can be handled correctly for the transmission of VoWLAN.

Just by it self, the average delay doesn't gives us enough information of the complete situation. For this reason in figures 7.3 and 7.4 the variance for this same scenario is shown.

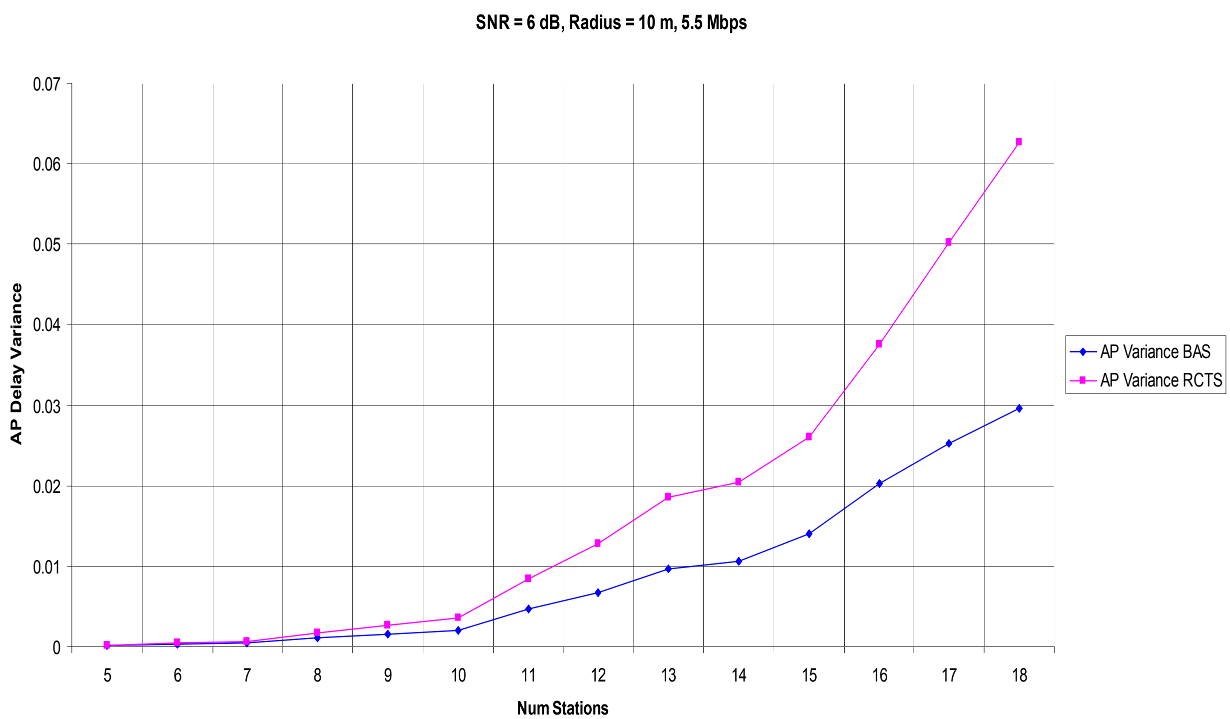

Figure 7.3. AP Delay Variance for SNR = 6 dB, Radius = 10 m, at 5.5 Mbps

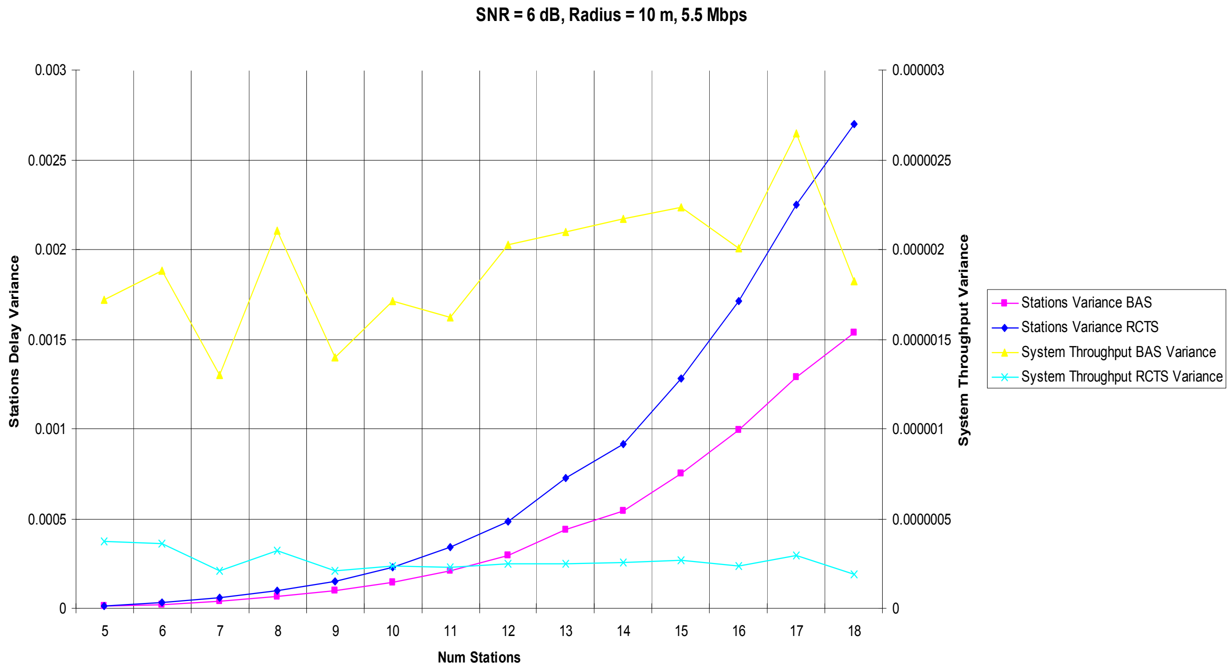

Figure 7.4. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 10 m, at 5.5 Mbps

In Figure 7.4 the stations delay variance for both BAS and RCTS mechanism is shown. Even though the stations delay variance is very small, it increases as the number of stations increases. The reason for this is the distance and the path loss factor. As more stations are put around the access point, some of them will be located at the border of the coverage area and they will suffer a little bit of the of the channel fading thus they will have to retransmit. Also the capture effect gives a little more advantage to the stations near de access point, but as can be seen, the variance of the delay is not relay significant.

The delay variance of the RCTS mechanism is grater than the delay variance of the BAS one. The reason is also due to the distance and that the RCTS has a grater delay, a grater probability of sensing the channel busy and will have to wait a little bit more time in the backoff stages and thus will have a grater variance.

The same thing occurs in the uplink. Figure 7.3 shows how the variance of the access point increases as the number of stations increases. It is also important to notice that the delay variance of the access point is grater than the delay variance of the stations. The reason for this is that the access point delay between two consecutive transmission is small but it has to be multiplied by a factor of N, were N is the number of stations so that the access point has to make N transmission before transmitting the next packet to the first station it transmitted to.

The system throughput variance for both the BAS and RCTS mechanism is really small. The BAS mechanism has a grater variance than the RCTS mechanism the reason is that when the RCTS mechanism requests to reserve the channel and the access point responds with the clear to send all the station listen it, and thus make the throughput to be more stable in all the stations, but even though the average throughput is smaller. In the other hand, in the BAS mechanism the channel is not reserved and that makes that some stations have a higher throughput than other ones.

In figures 7.5 to 7.8 the coverage radius is changed to 20 meters and all the other variables remain the same.

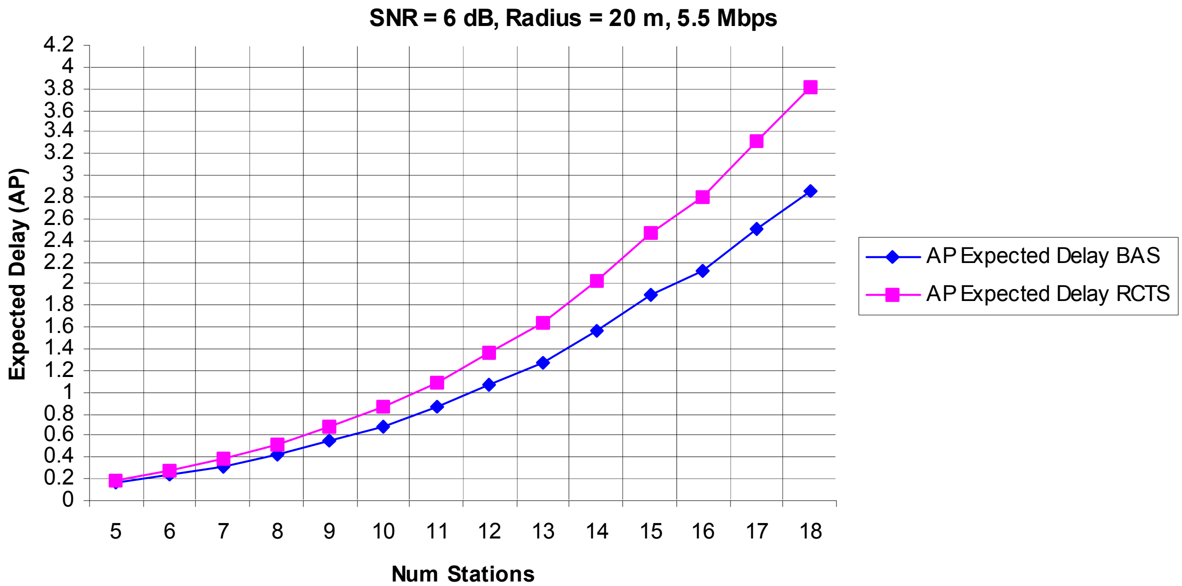

Figure 7.5. Access Point Expected Delay for SNR = 6 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

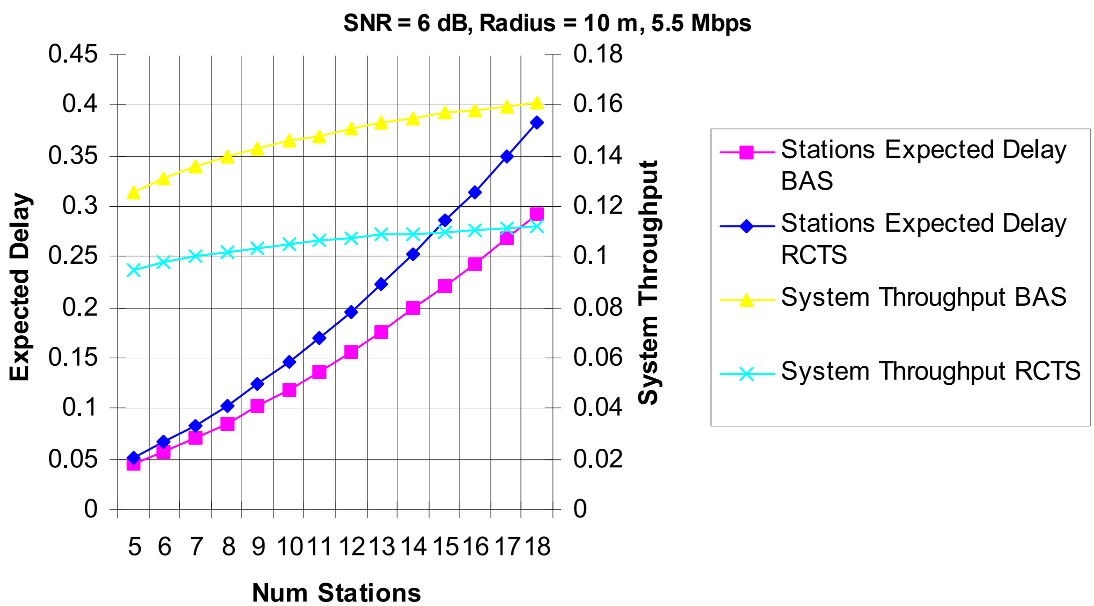

Figure 7.6. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

In Figure 7.6 is shown how there is an improvement of one station over the 10 meters radius coverage. We now have 15 stations below the 200 ms threshold compared with the 13 stations that we had on the 10 meters radius. The reason of this improvement is that as the coverage are has been increased, the probability of the stations of sensing the channel busy has been relaxed so that the stations are distributed more separated from each other and they do not enter the exponential backoff so frequently, also they are no to far form the access point so that the transmission can be captured correctly.
The system throughput is slightly above the 10 meters case. There is a very slight improvement and it is allowed due to the delay of two consecutive transmission is slightly less, thus there is a little bit more time to allow a few other transmissions, thus the channel utilization is slightly more utilized. Also and more important is that the coverage radius is grater and some stations will be placed farther than others, even though this stations still have a small delay, their throughput will be slightly less. The stations that are nearer the AP will have a higher transmission probability of success, so as the AP. This higher probability of success is because the stations are nearer the AP and they also have the advantage of the capture phenomenon, will rise their individual throughputs and rise the system throughput.

In Figure 7.5 there are still 5 stations below the 200 ms threshold. Even though we have one more station below the 200 ms, the access point still limits us in the uplink transmission. But we now have the advantage of a larger area were the stations can be placed beside the one more station of capacity.

The variance for this scenario is shown in Figure 7.7 and 7.8

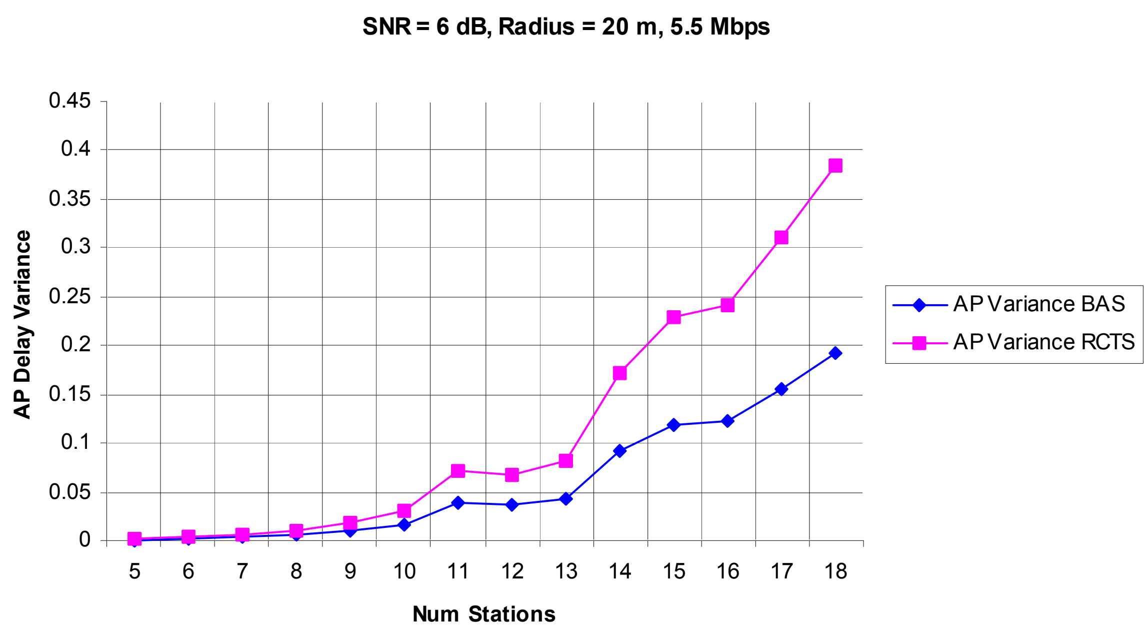

Figure 7.7. AP Delay Variance for SNR = 6 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

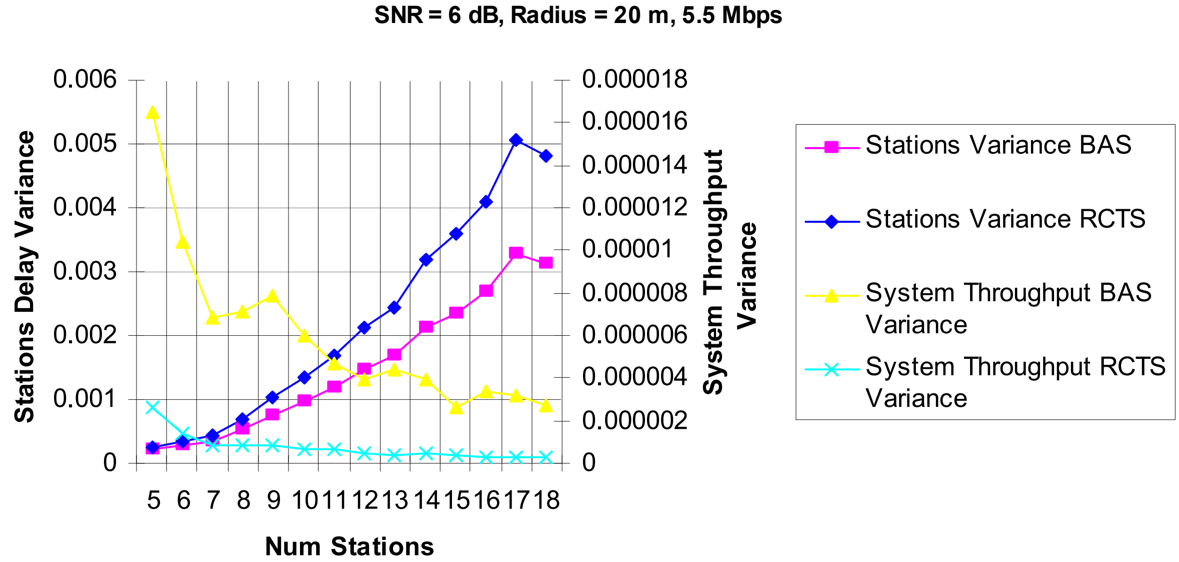

Figure 7.8. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

As expected, the delay variance for the radius of coverage of 20 m is somewhat higher than the 10 m radius.

In figures 7.9 to 7.12 the same scenario simulation results are presented but now for a coverage area of 30 meters.

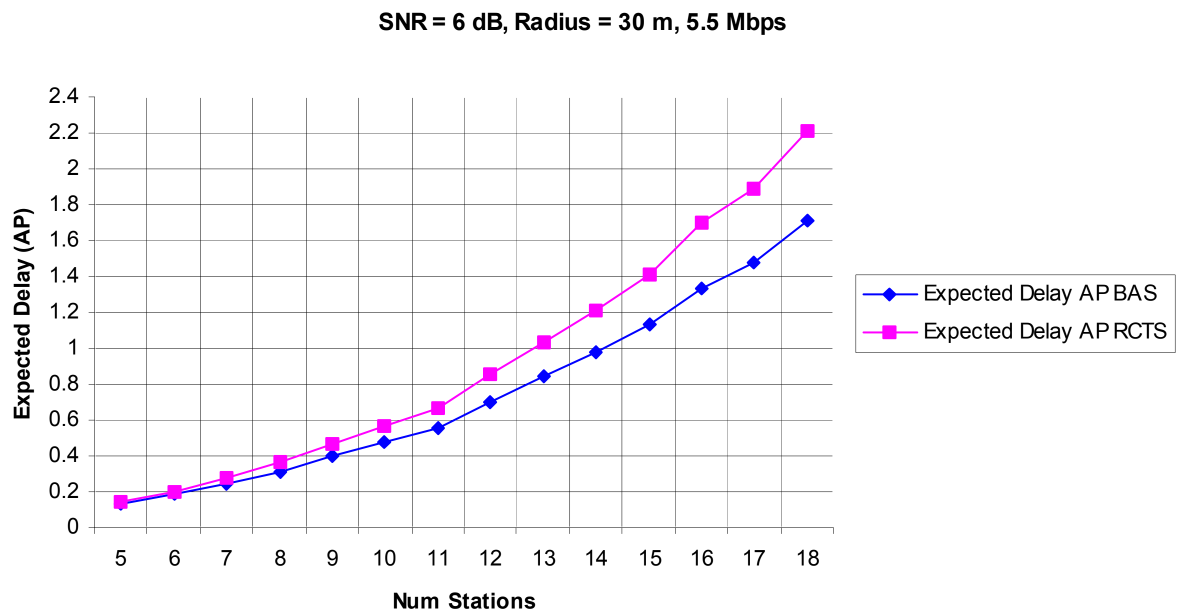

Figure 7.9. AP Expected Delay for SNR = 6 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

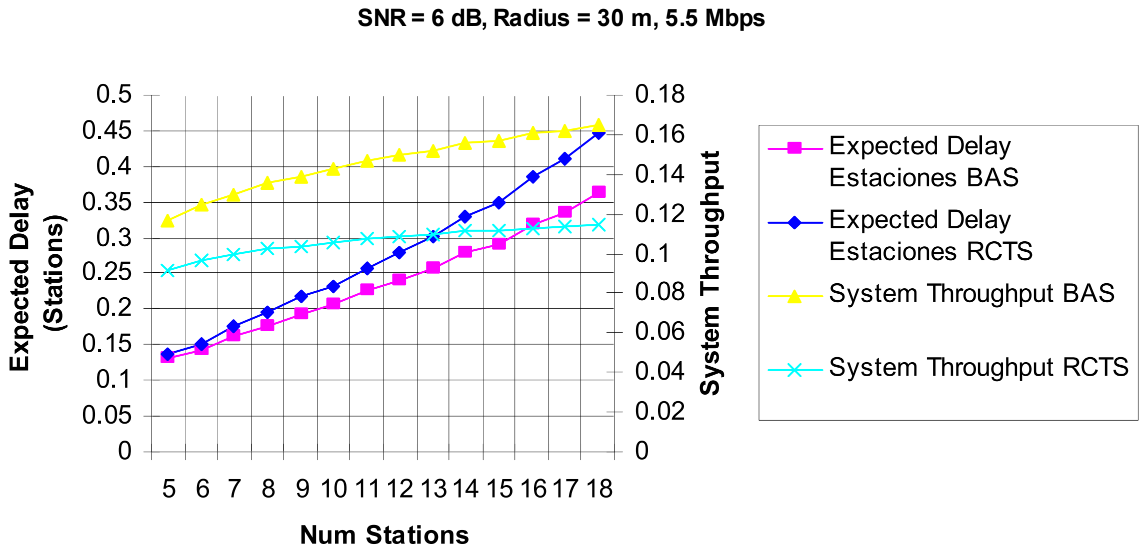

Figure 7.10. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

In Figure 7.9 we now have 6 stations below the 200 ms threshold for the downlink transmission, but Figure 7.10 shows that the number of stations below the 200 ms threshold for the uplink transmission has diminished to 9. This is because the radius of coverage is larger and some stations can be placed through the border of the area of coverage and the AP wont detect their transmission correctly due to the channel fading so they will have to retransmit after passing through the exponential backoff.

The system throughput is highly above the 20 m case. Although the delay is much grater in the 30 m case, the data is still being transmitted due to the stations nearer the AP.

The results for the variance are presented in figures 7.11 and 7.12. As it can be seen, the delay variance on the AP in Figure 7.11 has increased with respect to the 20 m radius of coverage. But the delay variance of the stations in Figure 7.12 is much more higher and it wont be suitable for the transmission of VoWLAN. For example, when there are only 5 stations in the system, the stations delay variance is of 0.0614 and the standard deviation is of 247 ms. With this high standard deviation VoWLAN is not possible in this scenario.

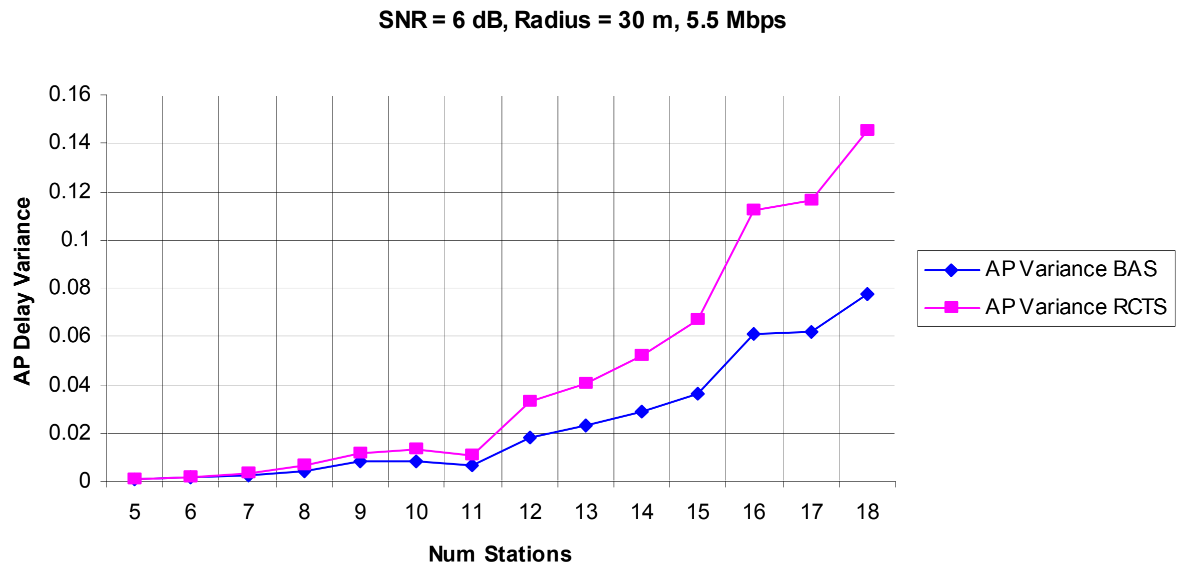

Figure 7.11. AP Delay Variance for SNR = 6 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

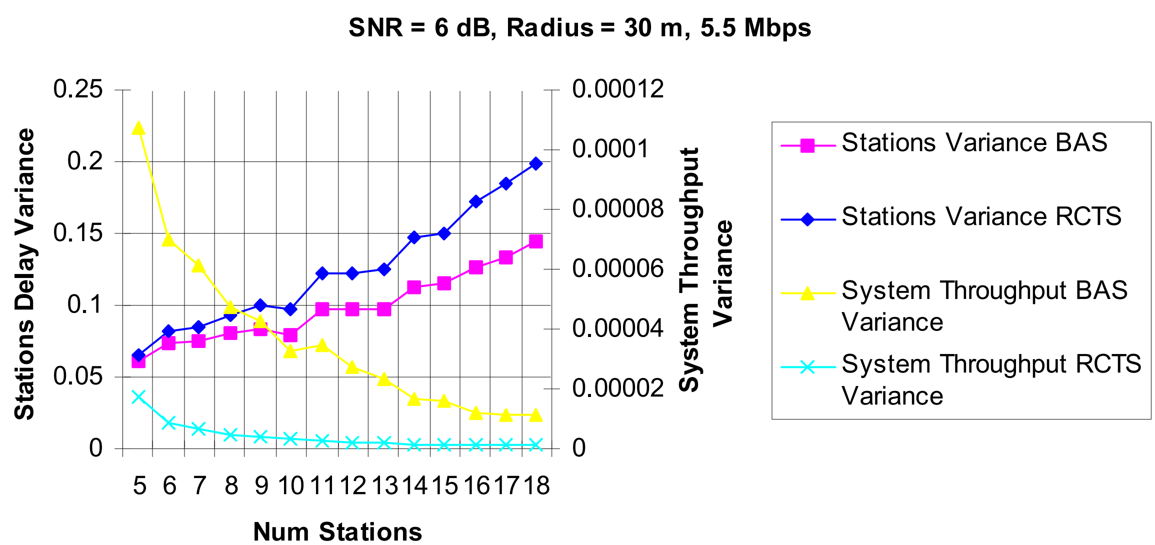

Figure 7.12. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

7.1.2 Scenario: Signal to Noise Ratio = 6 dB at 11 Mbps

Figure 7.13 and 7.14 show the expected Delay of the Access Point and Stations and they System Throughput for a coverage radius of 10 meters and with a receiver sensitivity of 6 dB operating at 11 Mbps.

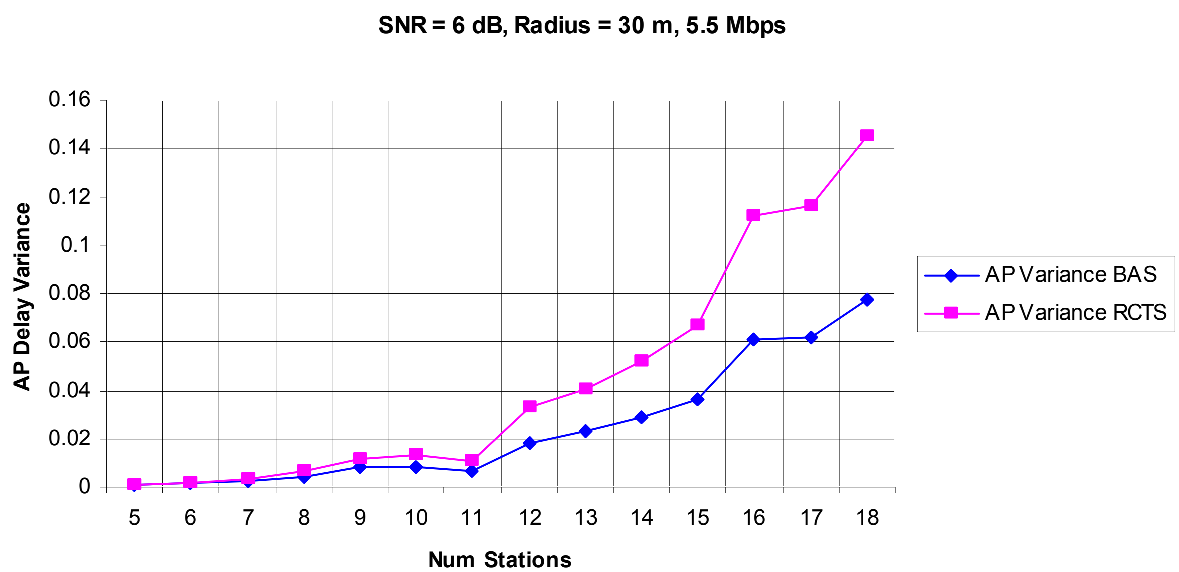

Figure 7.11. AP Delay Variance for SNR = 6 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

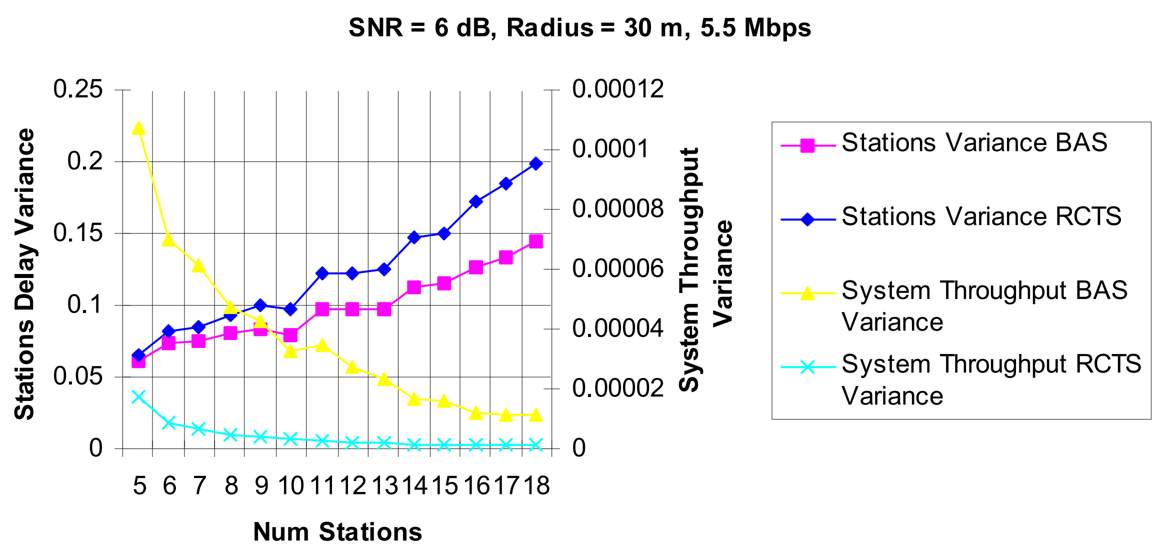

Figure 7.12. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

7.1.2 Scenario: Signal to Noise Ratio = 6 dB at 11 Mbps

Figure 7.13 and 7.14 show the expected Delay of the Access Point and Stations and they System Throughput for a coverage radius of 10 meters and with a receiver sensitivity of 6 dB operating at 11 Mbps.

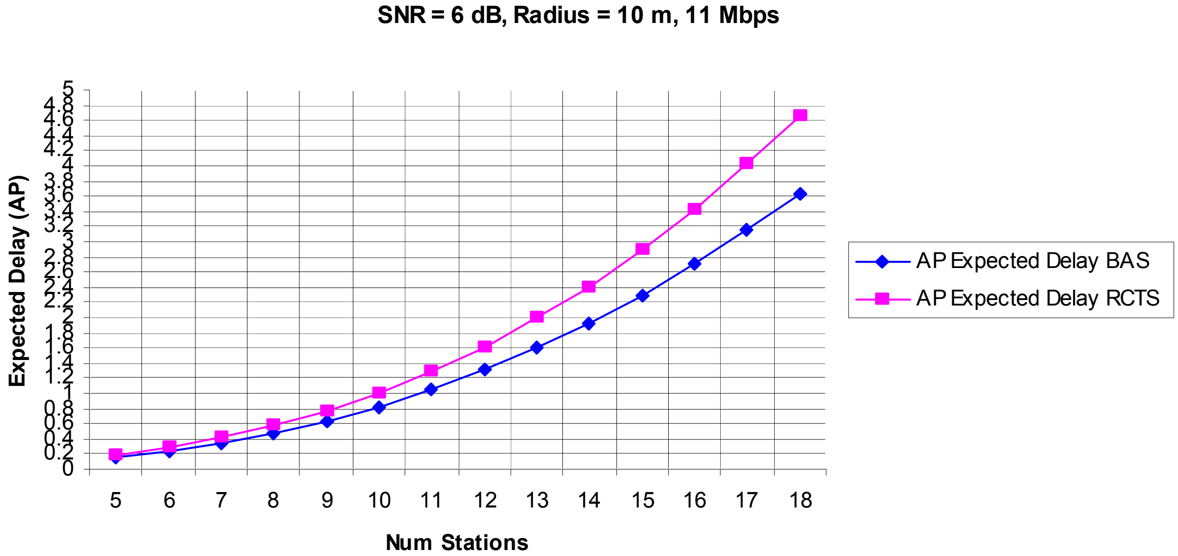

Figure 7.13. AP Expected Delay for SNR = 6 dB, Radius = 10 m, Bit Rate = 11 Mbps

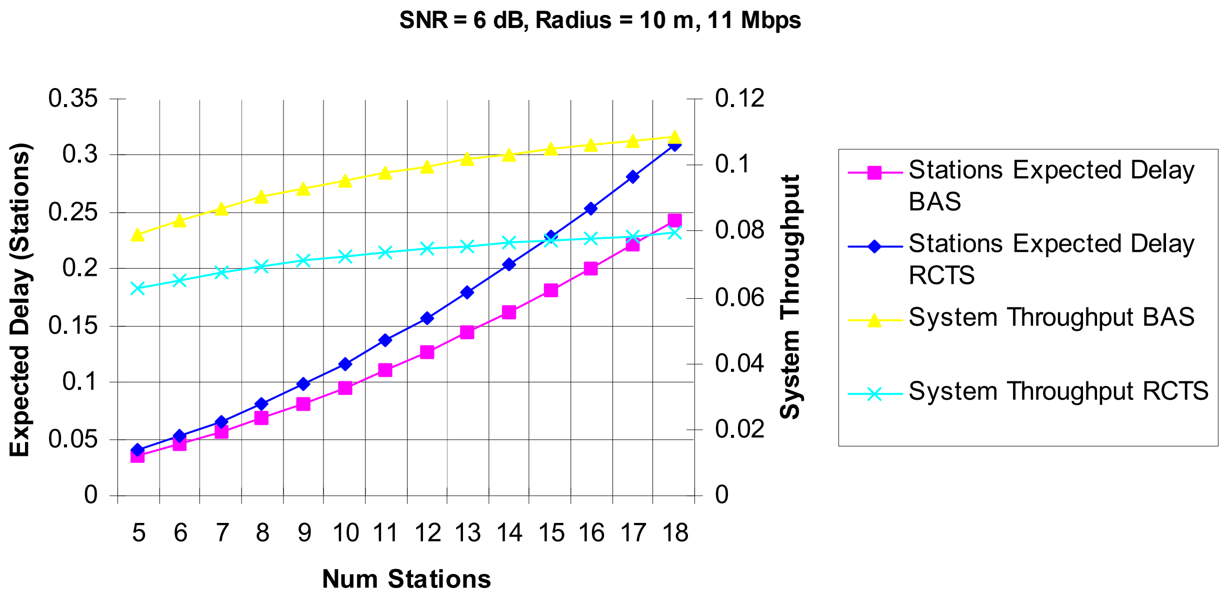

Figure 7.14. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 10 m, Bit Rate = 11 Mbps

Figure 7.13 shows the expected delay of the AP. It can be seen that there can only be 5 stations supported in the system to accomplish the 200 ms threshold. (downlink condition)

In Figure 7.14 the stations expected delay and the system throughput simulations results are shown. Due to the increase in the bit rate, the system can support 15 stations for the uplink transmission, its an increase of 2 stations compared with the 5.5 Mbps bit rate. But still, the problem remains with the downlink, and the for the VoWLAN effective transmission, only 5 stations can be placed.
In Figure 7.14 is also shown that the system throughput has decreased in both mechanisms with respect to the 5.5 Mbps. The reason is that the duration of the DIFS, SIFS and slot time is independent of the channel bit rate, while the frame transmission time decreases as the channel bit rate increases. So the portion of the time the system spends on DIFS, SIFS and backoff delay during a frame transmission increases as the channel bit rate increases, causing a throughput degradation.

In Figure 7.15 and 7.15 the AP and stations delay variance are shown as well as the system throughput variance.

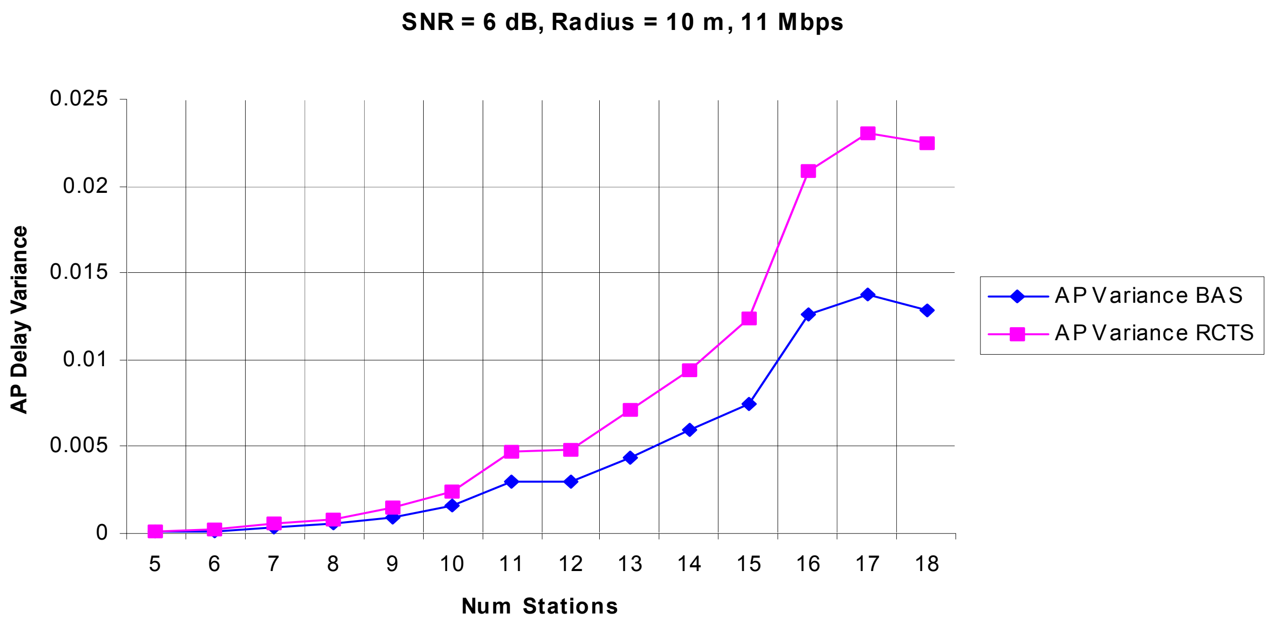

Figure 7.15. AP Delay Variance for SNR = 6 dB, Radius = 10 m, Bit Rate = 11 Mbps

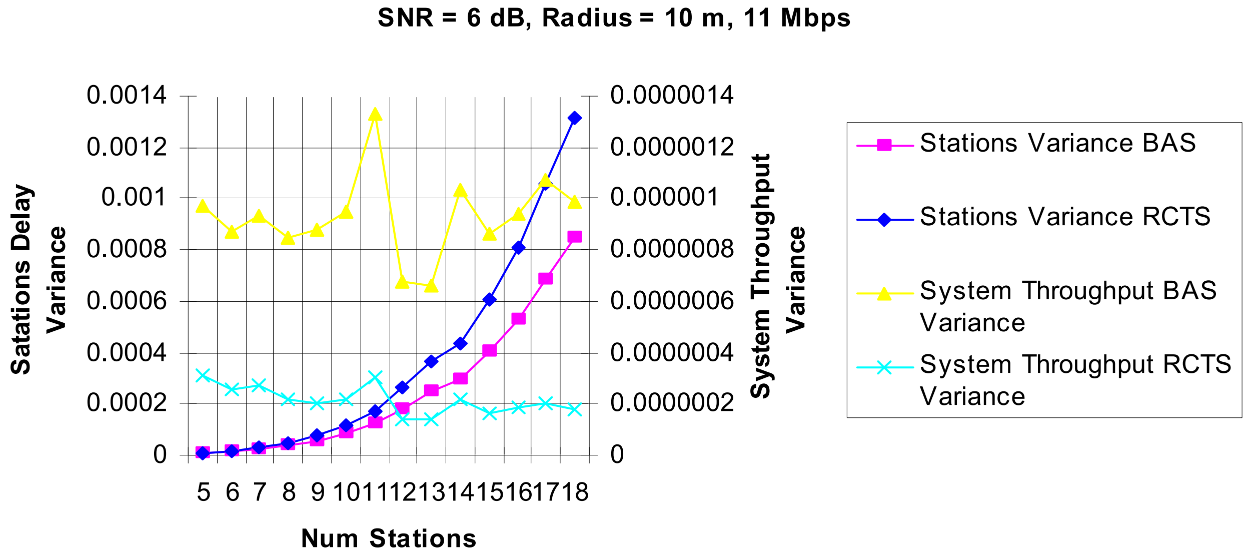

Figure 7.16. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 10 m, Bit Rate = 11 Mbps

Figures 7.15 and 7.16 show the same behavior that has been presented for the variance and the difference relates in the exact values. The exact values will be discussed in the last subsection of this part with high detail.

In Figures 7.17 to 7.20, the corresponding graphs for the case when the radius is 20 meters is presented.

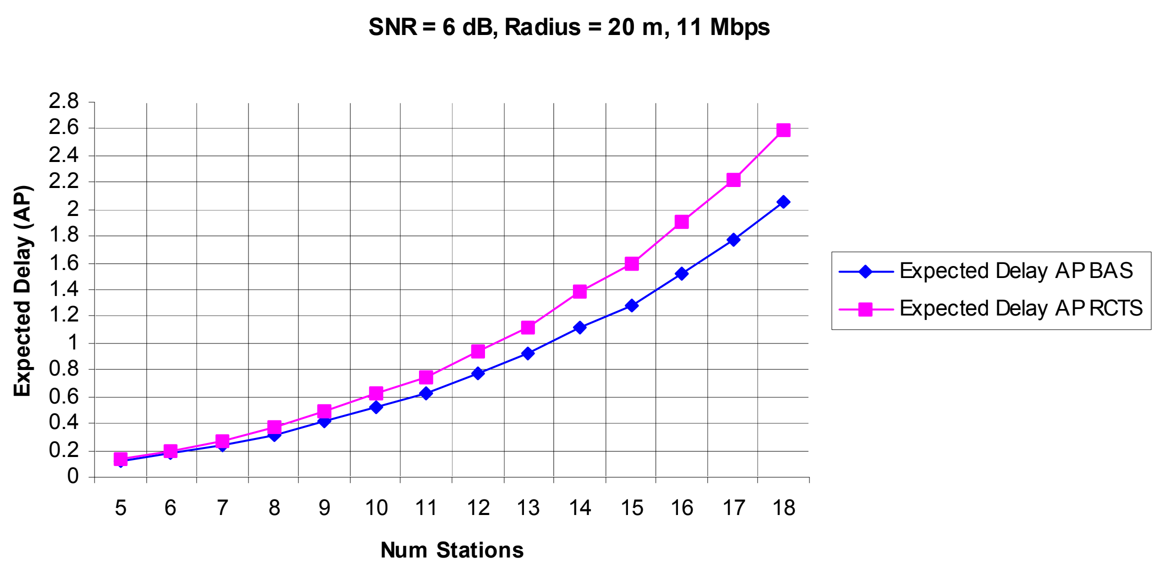

Figure 7.17. AP Expected Delay for SNR = 6 dB, Radius = 20 m, Bit Rate = 11 Mbps

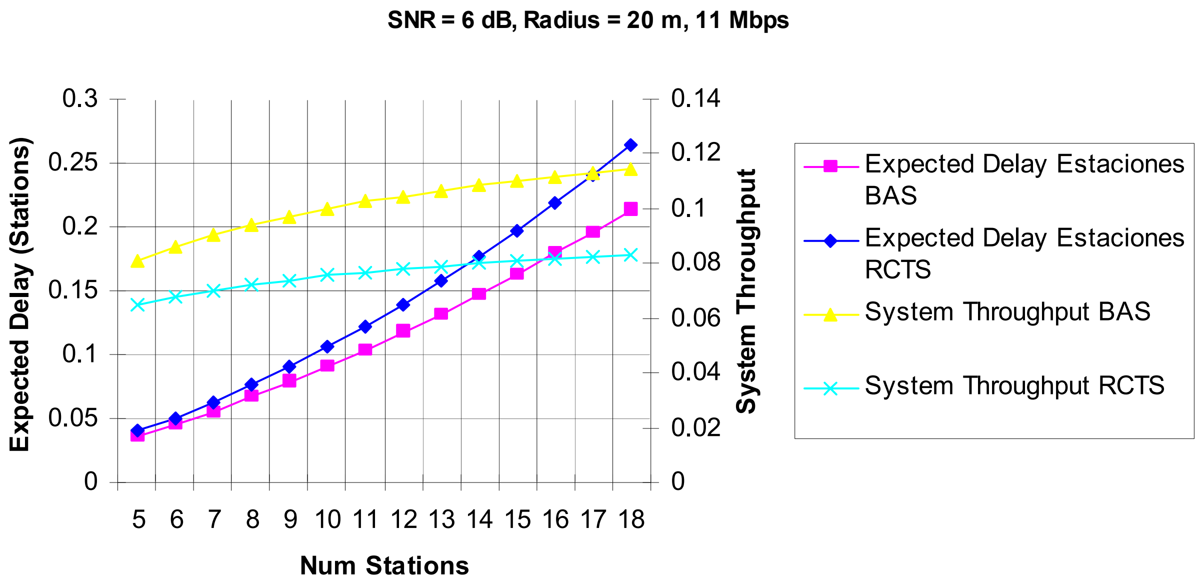

Figure 7.18. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 20 m, Bit Rate = 11 Mbps

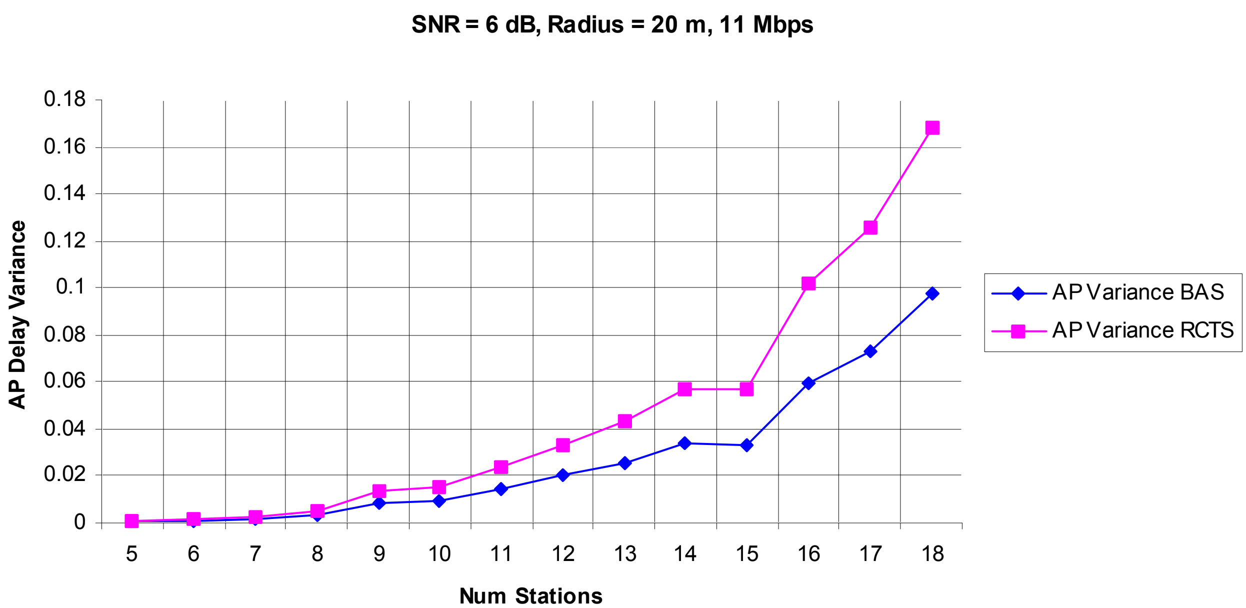

Figure 7.19. AP Delay Variance for SNR = 6 dB, Radius = 20 m, Bit Rate = 11 Mbps

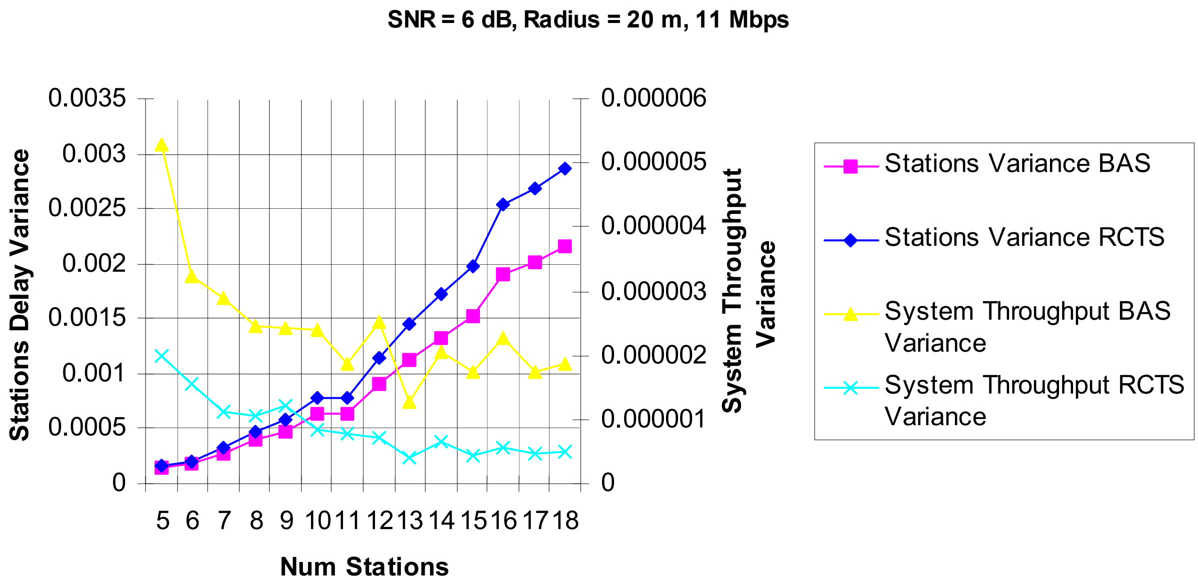

Figure 7.20. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 20 m, Bit Rate = 11 Mbps

For this scenario the maximum number of stations that can be supported in the uplink is 17 stations, this is that with 17 stations distributed through an area of coverage of radius equal to 20 m they will have an average delay below the 200 ms. But the uplink transmission requires that it can only be 6 stations so that the AP would have an average delay below 200 ms.
The details of the variance, maximum delay and cdf's will be analyzed with detail in the last subsection.

Figures 7.21 to 7.24 show the average delay of the access point and the stations; as well as their respective variance and the system throughput.

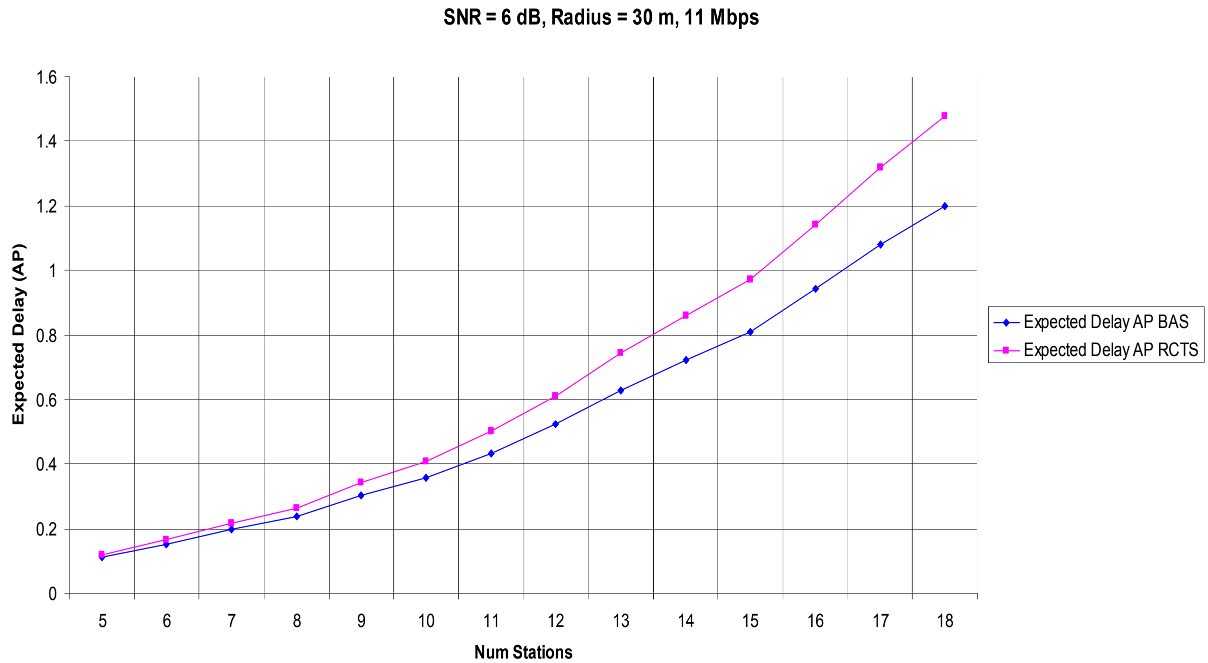

Figure 7.21. AP Expected Delay for SNR = 6 dB, Radius = 30 m, Bit Rate = 11 Mbps

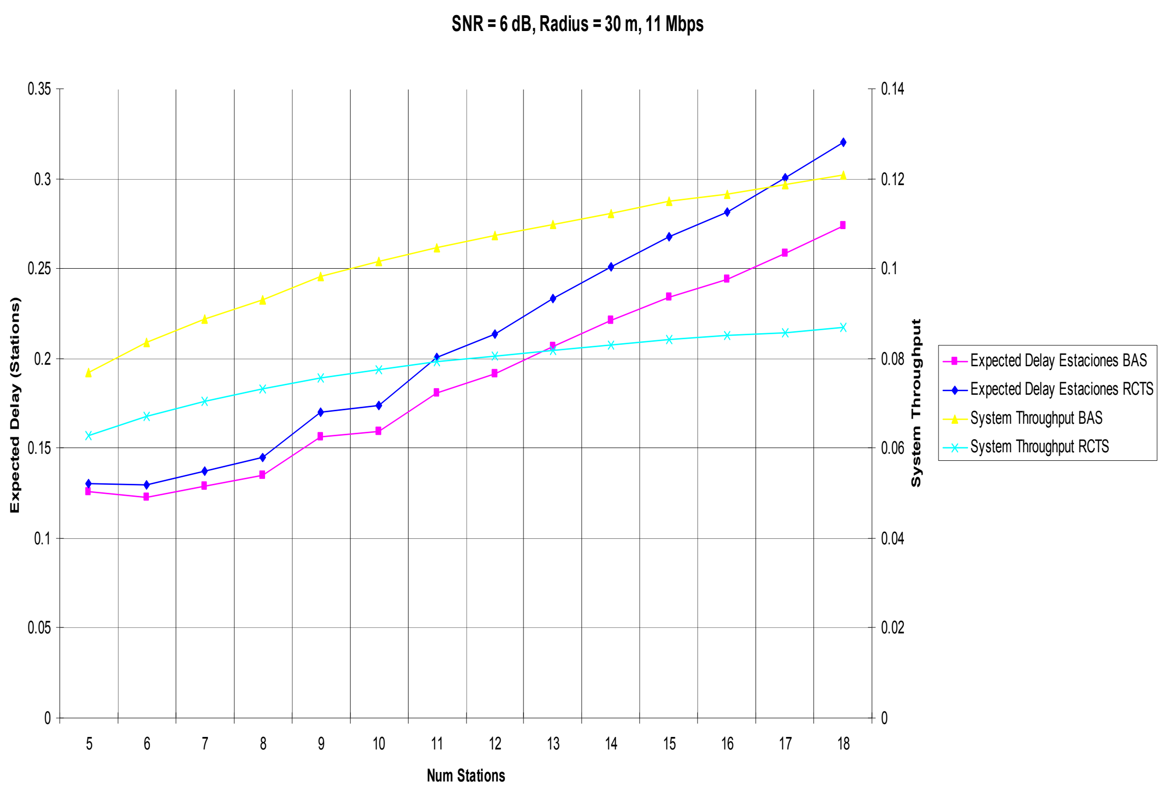

Figure 7.22. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 30 m, Bit Rate = 11 Mbps

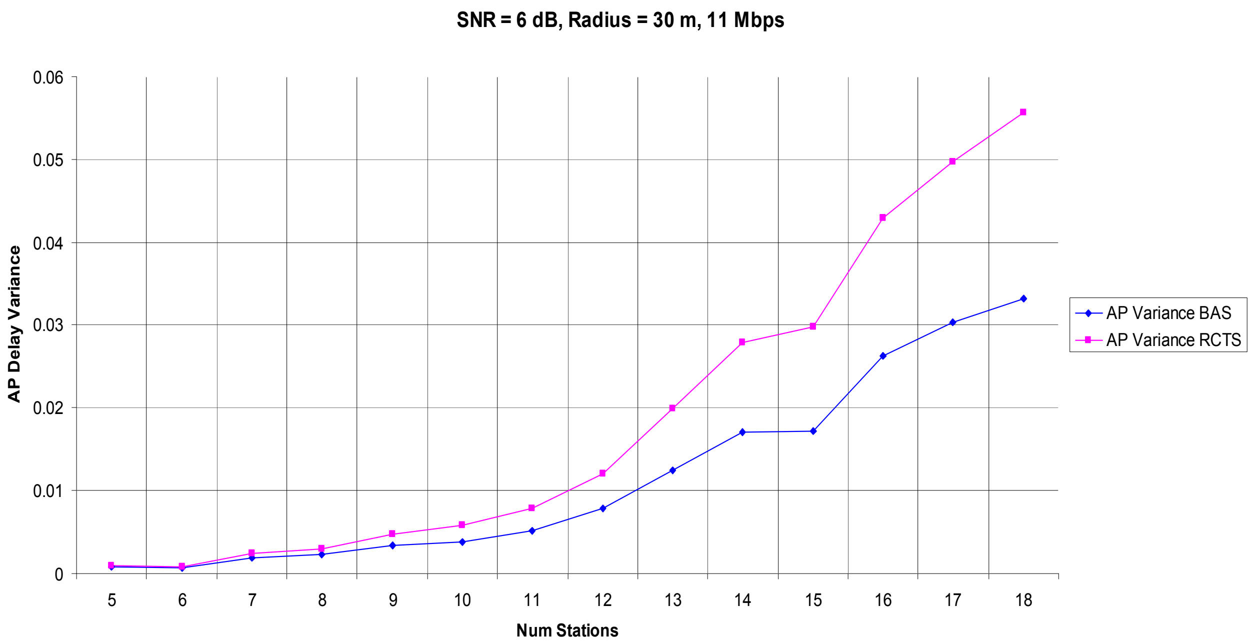

Figure 7.23. AP Delay Variance for SNR = 6 dB, Radius = 30 m, Bit Rate = 11 Mbps

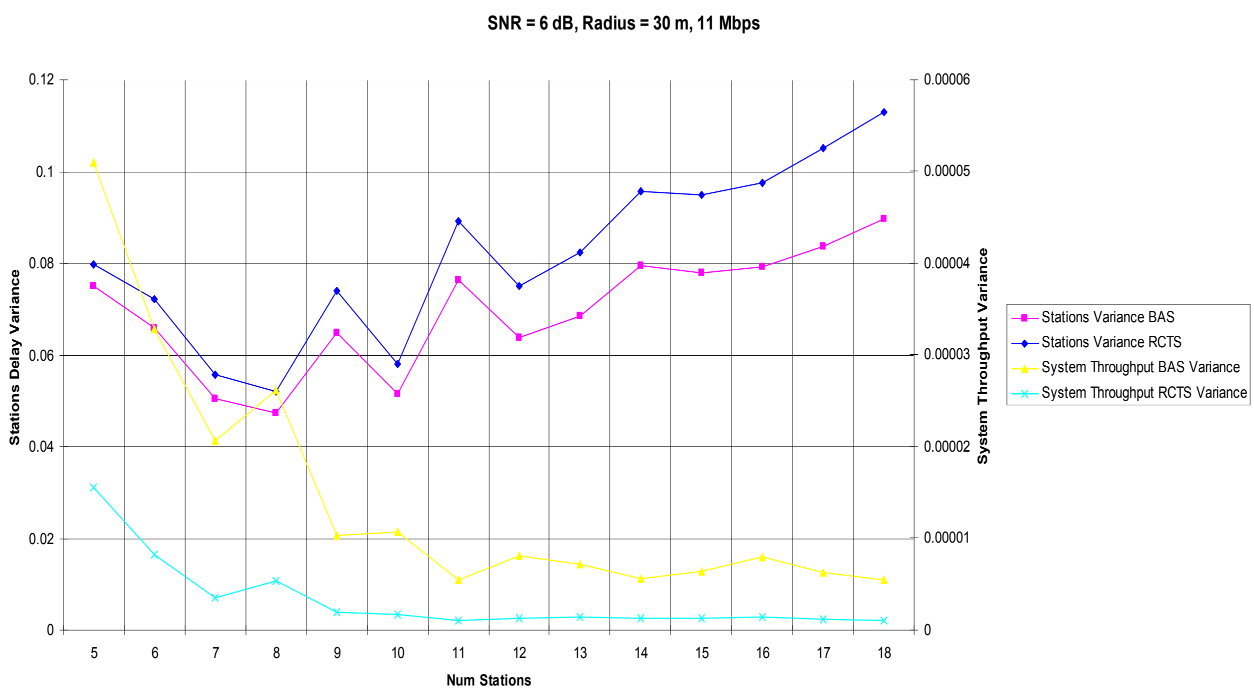

Figure 7.24. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 30 m, Bit Rate = 11 Mbps

In figures 7.21 and 7.22 the expected delay of the AP and of the stations are shown. For the downlink transmission, it can be seen that the AP will be below the

200 ms threshold only if the number of stations is less than 7. But for the uplink, if we have 7 or 6 or 5 stations, the average expected delay is highly above the 200 ms threshold. As a preliminary conclusion, for the radius of 30 m it is not possible the transmission of VoWLAN.
More details about the delay variance will be shown with more detail in the last subsection.

7.1.3 Scenario: Signal to Noise Ratio = 6 dB at 54 Mbps

Figure 7.25 and 7.28 show the expected Delay of the Access Point and Stations and they System Throughput for a coverage radius of 10 meters and with a receiver sensitivity of 6 dB operating at 54 Mbps.

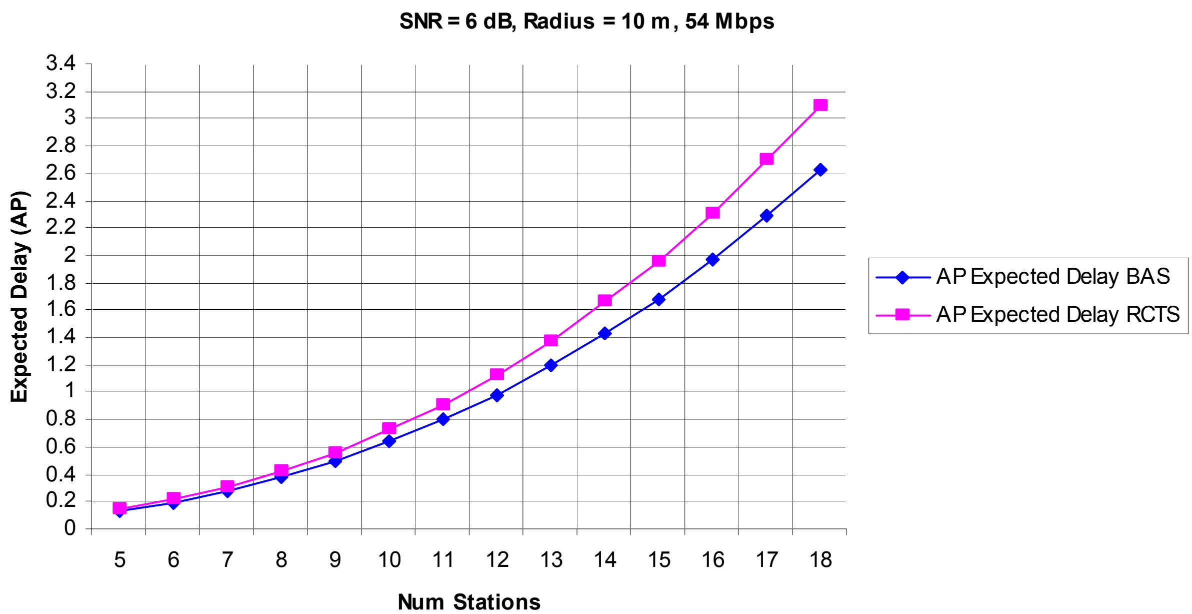

Figure 7.25. AP Expected Delay for SNR = 6 dB, Radius = 10 m, Bit Rate = 54 Mbps

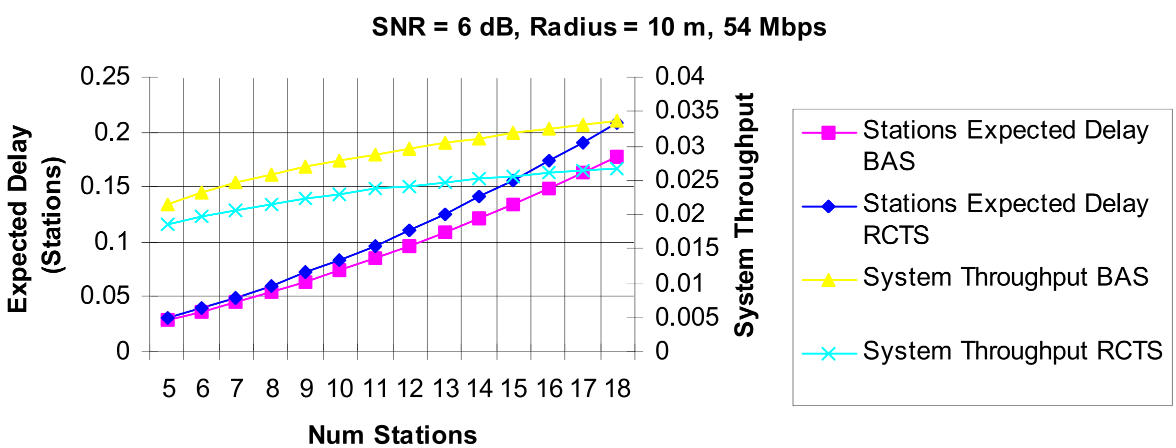

Figure 7.26. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 10 m, Bit Rate = 54 Mbps

200 ms threshold only if the number of stations is less than 7. But for the uplink, if we have 7 or 6 or 5 stations, the average expected delay is highly above the 200 ms threshold. As a preliminary conclusion, for the radius of 30 m it is not possible the transmission of VoWLAN.
More details about the delay variance will be shown with more detail in the last subsection.

7.1.3 Scenario: Signal to Noise Ratio = 6 dB at 54 Mbps

Figure 7.25 and 7.28 show the expected Delay of the Access Point and Stations and they System Throughput for a coverage radius of 10 meters and with a receiver sensitivity of 6 dB operating at 54 Mbps.

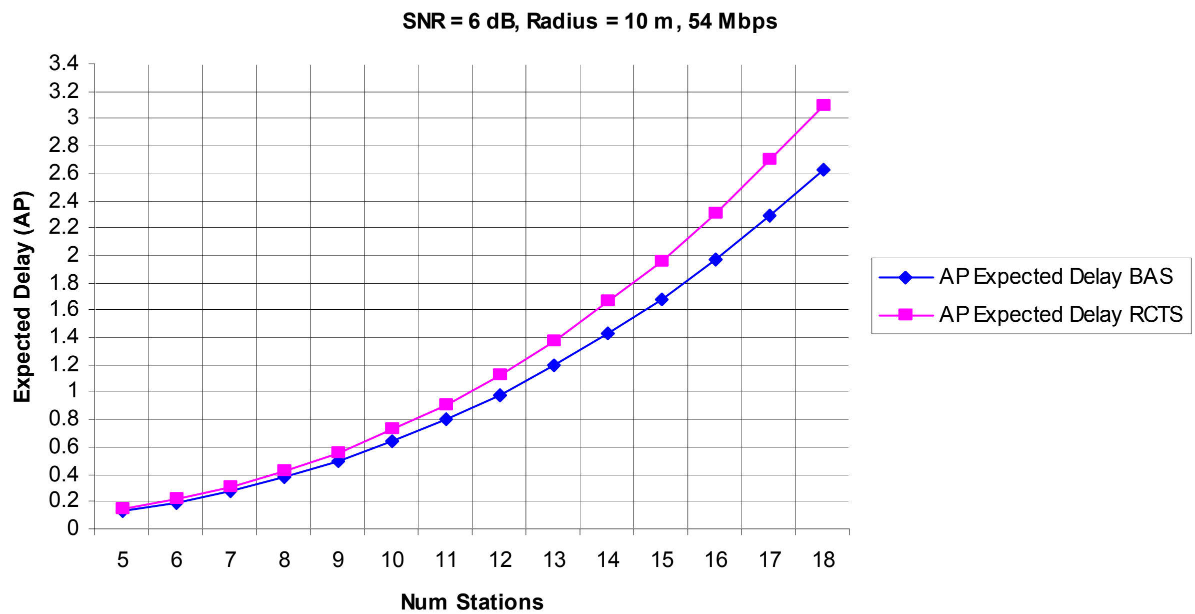

Figure 7.25. AP Expected Delay for SNR = 6 dB, Radius = 10 m, Bit Rate = 54 Mbps

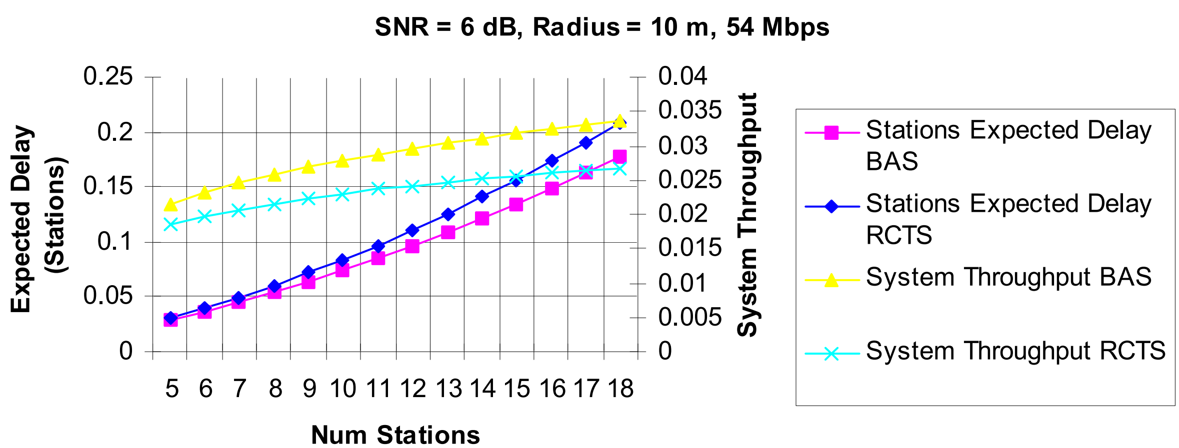

Figure 7.26. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 10 m, Bit Rate = 54 Mbps

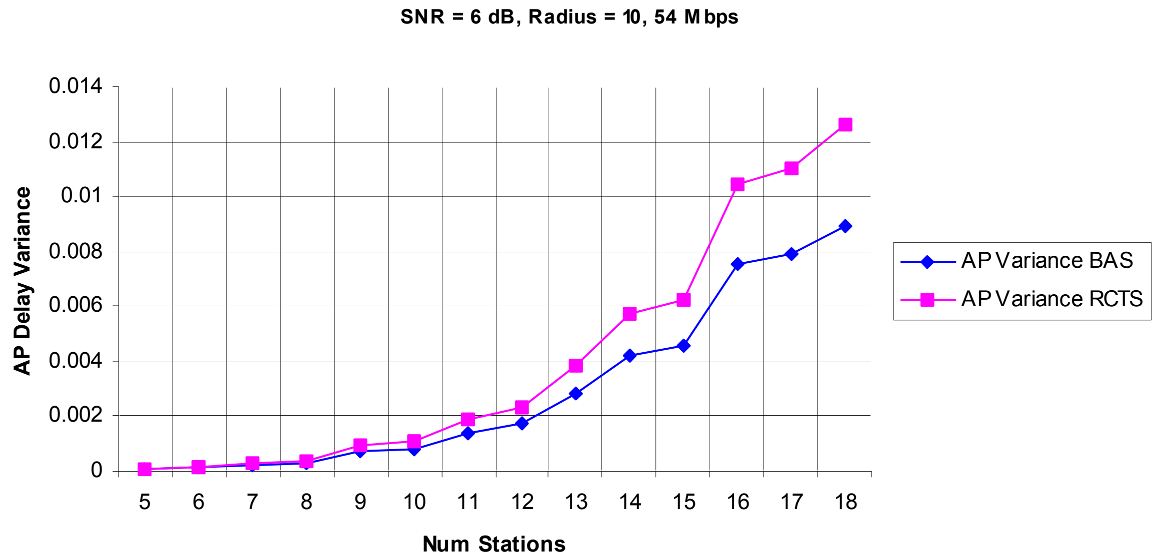

Figure 7.27. AP Delay Variance for SNR = 6 dB, Radius = 10 m, Bit Rate = 54 Mbps

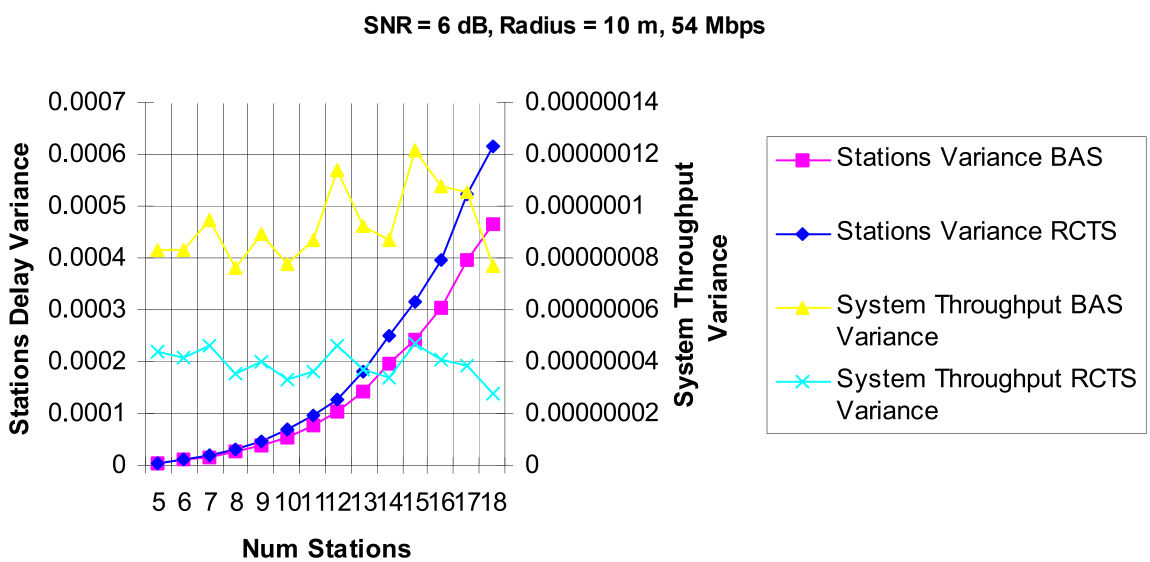

Figure 7.28. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 10 m, Bit Rate = 54 Mbps

In figures 7.25 and 7.26 is shown the expected delay of the AP and stations as well as the system throughput. In this case we can se that we now can handle 18 stations in for the uplink transmission, which are below de 200 ms threshold. But in the same way as the other cases, the downlink transmission limits us in capacity. The AP can now handle 6 stations (one more stations compared with the 11 Mbps in the same scenario).

As expected and in the same way that happened to the 11 Mbps bit rate, the System Throughput went down. The reason is the same as mentioned, as the bit rate increases, the system throughput will go down due to the DIFS, SIFS, the slot time and the exponential backoff.

The variance of the stations and of the AP follows the same pattern as the last scenarios. It can be seen in Figure 7.27 that for a system with 6 stations, the AP delay variance is of 0.000116771 and its standard deviation is of 0.01080 seconds. In Figure 7.25 the average delay of the AP is of 0.193161 seconds. Adding the average delay with the standard deviation of the delay we find de maximum delay of the AP for this scenario. The maximum delay would be 203 ms. Which is in the threshold limit to transmit VoWLAN.

As a preliminary result, it is possible to transmit VoWLAN in this scenario having 6 operating stations. A deep analysis will be shown in the last subsections.

In figures 7.29 to 7.32 it is shown the case when the radius of coverage is of 20 meters. As it can be seen in Figure 7.29 and 7.30, there is improvement in the number of stations below the 200 ms threshold. In the uplink transmission, 19 stations can be supported and will be working below the 200 ms threshold. But, as it has been occurring, the downlink transmission limits the capacity of the system to 7 stations, an improvement of one station over the 10 meters radius of coverage. In Figure 7.31, the AP delay variance is shown to be 0.00099452, so its standard deviation is 0.03154 s. In Figure 7.29, the average delay of the AP is of 189 ms, giving a maximum delay of 220 ms. In this case, the AP is still inside the threshold for transmitting VoIP. In Figure 7.30, for 7 stations, the average delay of each one is of 45 ms. And the standard deviation can be obtained form Figure 7.32 and is of 14 ms, giving a maximum delay of 59 m, which is inside the VoWLAN delay limit. This scenario is the best that suits the transmission of VoWLAN.

More details will be shown in the last subsection.

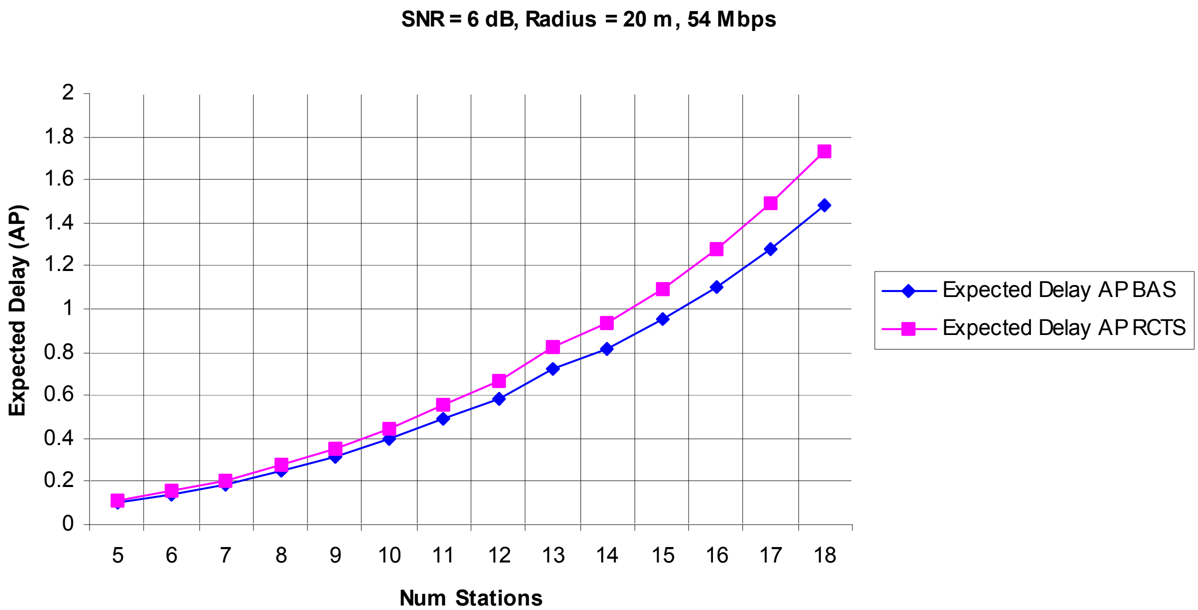

Figure 7.29. AP Expected Delay for SNR = 6 dB, Radius = 20 m, Bit Rate = 54 Mbps

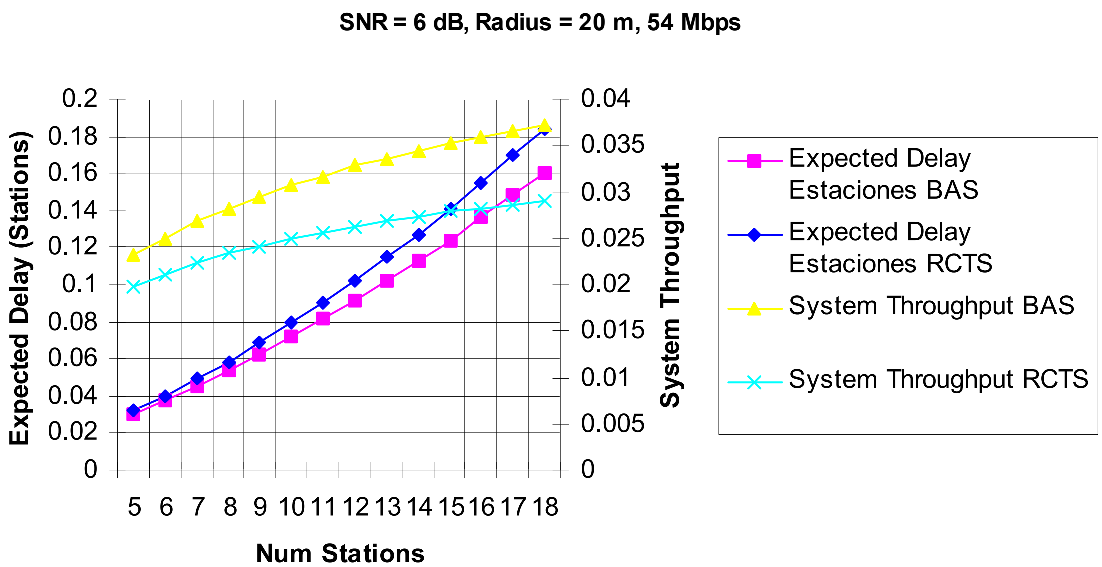

Figure 7.30. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 20 m, Bit Rate = 54 Mbps

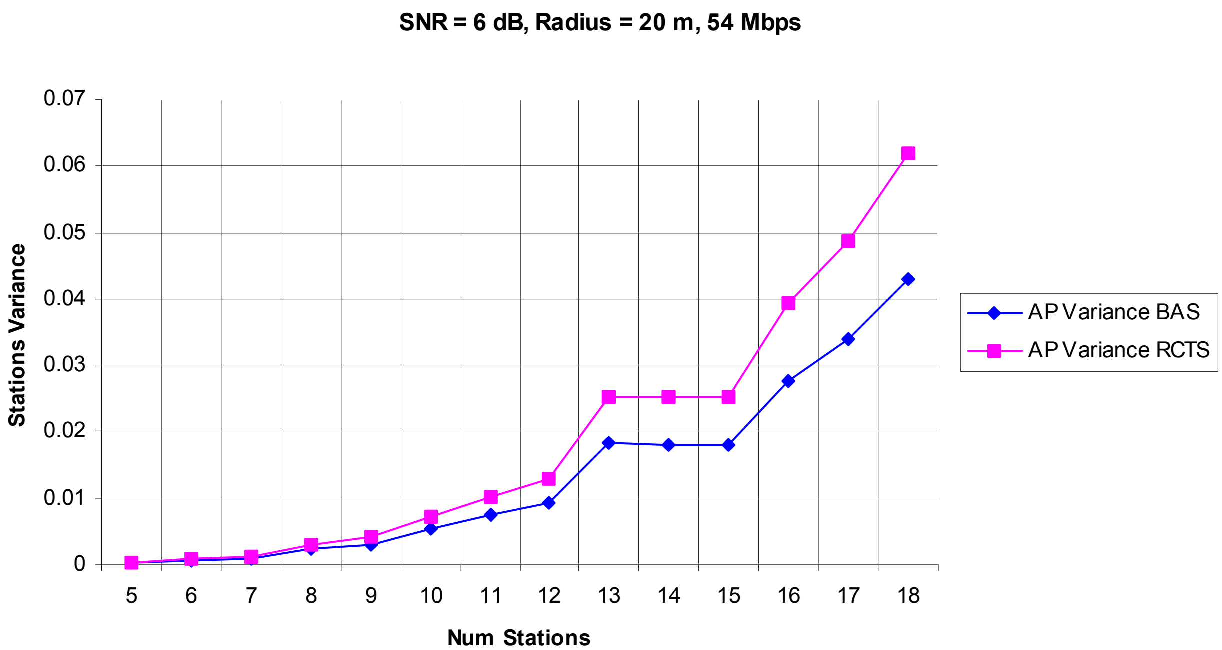

Figure 7.31. AP Delay Variance for SNR = 6 dB, Radius = 20 m, Bit Rate = 54 Mbps

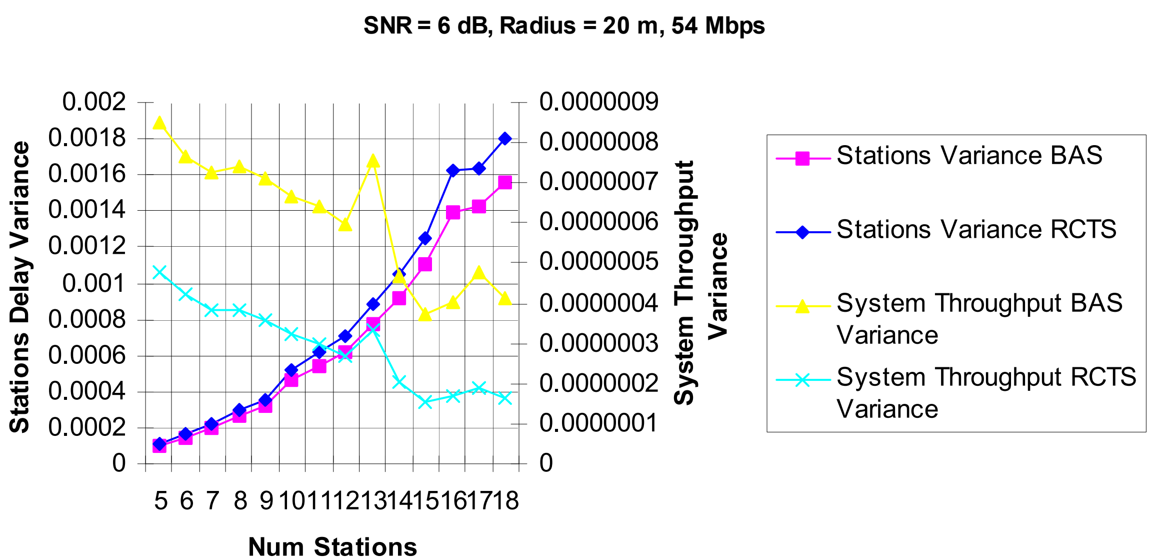

Figure 7.32. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 20 m, Bit Rate = 54 Mbps

In figures 7.33 to 7.36 the AP and stations expected delay and delay variance numerical simulation results are shown for a radius of 30 meters, as well as the system throughput and its variance.

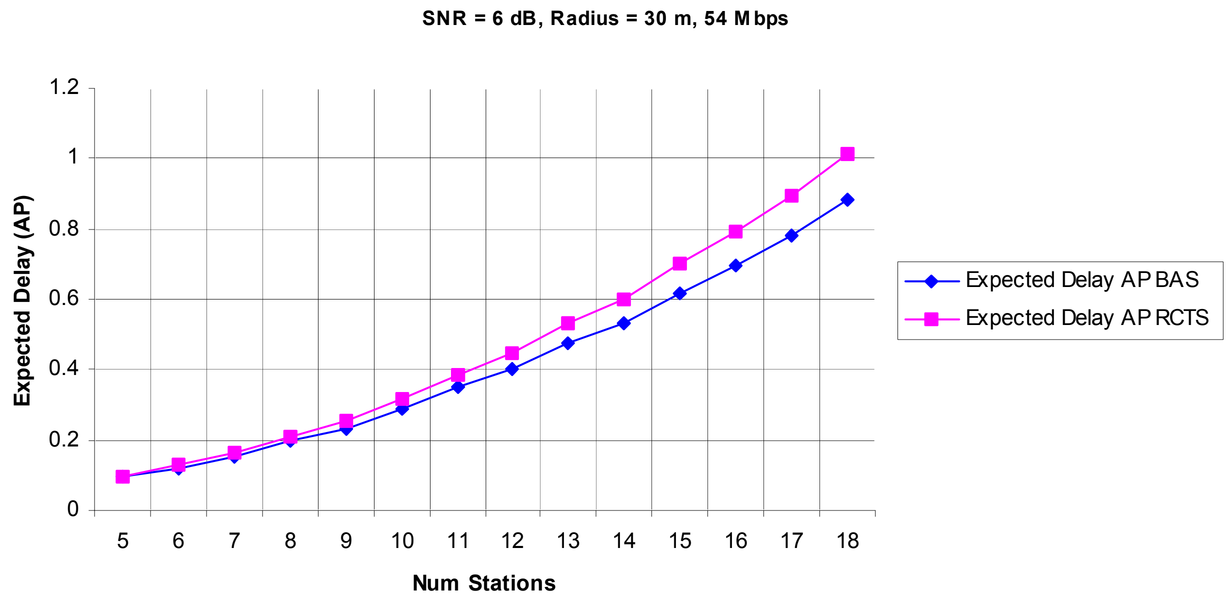

Figure 7.33. AP Expected Delay for SNR = 6 dB, Radius = 30 m, Bit Rate = 54 Mbps

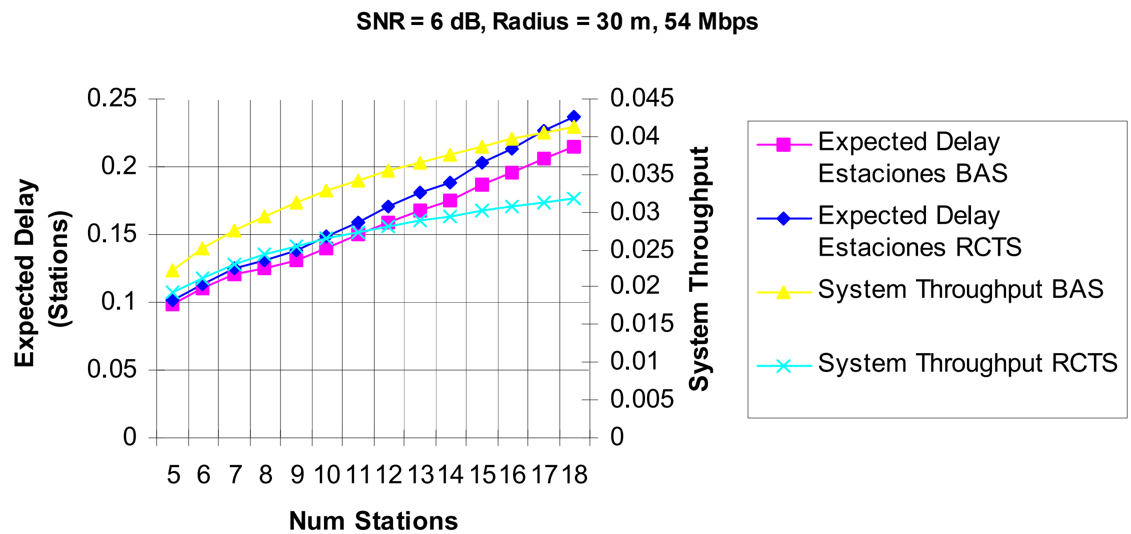

Figure 7.34. Stations Expected Delay and System Throughput for SNR = 6 dB, Radius = 30 m, Bit Rate = 54 Mbps

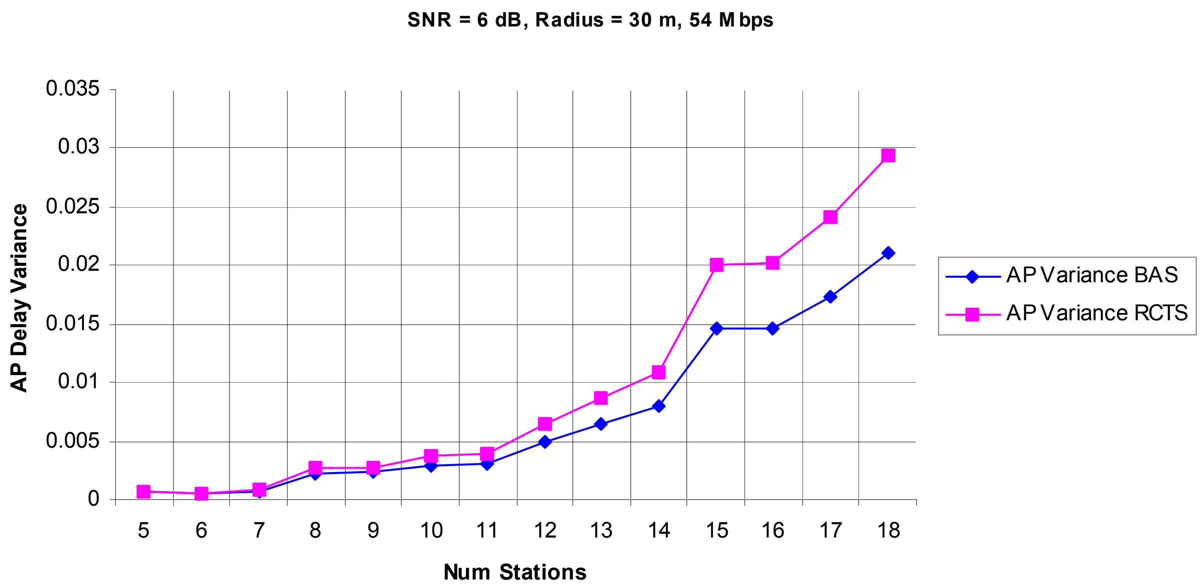

Figure 7.35. AP Delay Variance for SNR = 6 dB, Radius = 30 m, Bit Rate = 54 Mbps

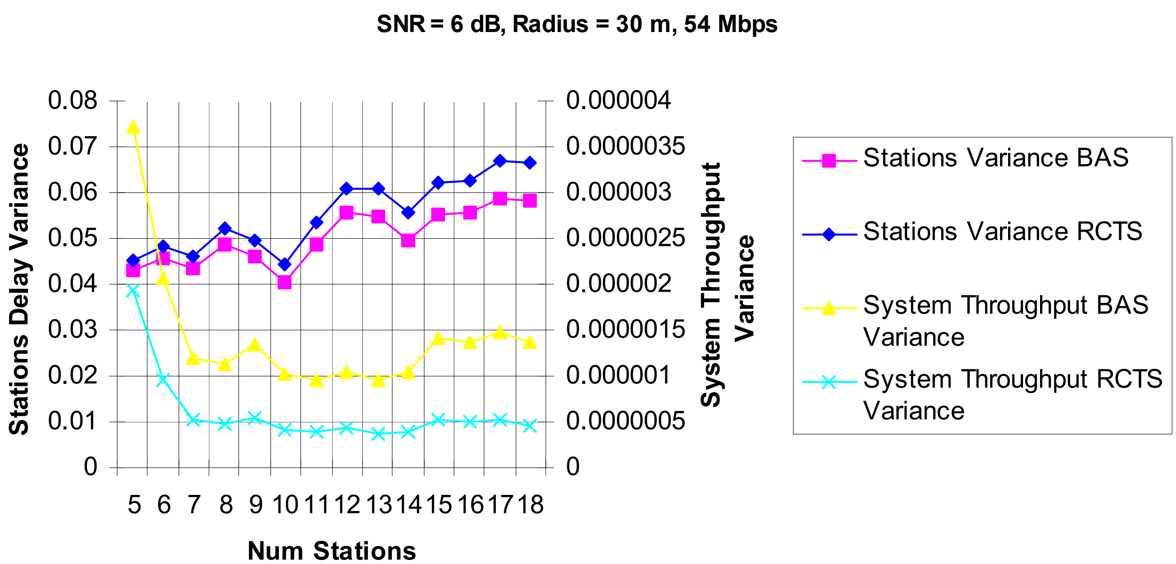

Figure 7.36. Stations Delay Variance and System Throughput Variance for SNR = 6 dB, Radius = 30 m, Bit Rate = 54 Mbps

Looking at Figure 7.33 and 7.34 one could think that for the transmission of VoWLAN 16 station satisfy the 200 ms threshold for the uplink and 8 stations satisfy the conditions for the AP being below de 200 ms threshold for the downlink. So, we could think in picking 8 stations to cover a radius of 30 meters. Also if we look at Figure 7.35 the AP delay variance for 8 stations is of 0.002286, which is not much. But if we look at the delay variance of the stations in Figure 7.36 it is seen that all the variances are above 0.4, so the minimum standard deviation is 200 ms, which is the threshold of the delay. This standard deviations added to the average delay is obviously grater than 250 ms.
As a preliminary conclusion, VoWLAN can not be correctly transmitted for a coverage radius of 30 meters in this scenario.

As mentioned earlier, the system throughput increases as the radius of coverage increases. This is because when the radius of coverage is very big, the stations that are placed by the border have a very poor individual throughput, because the AP won't be able to hear them, thus does stations will have a very big expected delay. But the stations that are near de AP will have big individual throughput because their respective probability of successful transmission will be high also the individual throughput of the AP will be big, because as the AP doesn't hear the stations in the border or hears them very infrequently, its transmission will be dedicated to the nearest to it, thus it will have a high probability of successful transmission. All this together raises de system throughput.

7.1.4 Scenario: Signal to Noise Ratio = 8 dB at 5.5 Mbps

We now change the SNR form 6 to 8 dB and follow the same methodology we've been following.

Figures 7.37 and 7.38 show the AP and stations expected delay. The graphs in both figures follow the same behavior as the SNR = 6 dB. For the uplink transmission delay to be below the 200 ms threshold only 12 stations can be placed in the 10 meters radius. Compared with the 6 dB SNR, we now have 1 station less and is due to the receiver sensitivity to detect the a signal. For the AP to have a delay below the 200 ms, it must have in average 5 stations in the 10 m radius of coverage. The variance shown in Figure 7.39 and 7.40 is not so significant. As a preliminary conclusion, it is possible to have a system with 5 stations and be able to transfer VoWLAN.

Looking at Figure 7.33 and 7.34 one could think that for the transmission of VoWLAN 16 station satisfy the 200 ms threshold for the uplink and 8 stations satisfy the conditions for the AP being below de 200 ms threshold for the downlink. So, we could think in picking 8 stations to cover a radius of 30 meters. Also if we look at Figure 7.35 the AP delay variance for 8 stations is of 0.002286, which is not much. But if we look at the delay variance of the stations in Figure 7.36 it is seen that all the variances are above 0.4, so the minimum standard deviation is 200 ms, which is the threshold of the delay. This standard deviations added to the average delay is obviously grater than 250 ms.
As a preliminary conclusion, VoWLAN can not be correctly transmitted for a coverage radius of 30 meters in this scenario.

As mentioned earlier, the system throughput increases as the radius of coverage increases. This is because when the radius of coverage is very big, the stations that are placed by the border have a very poor individual throughput, because the AP won't be able to hear them, thus does stations will have a very big expected delay. But the stations that are near de AP will have big individual throughput because their respective probability of successful transmission will be high also the individual throughput of the AP will be big, because as the AP doesn't hear the stations in the border or hears them very infrequently, its transmission will be dedicated to the nearest to it, thus it will have a high probability of successful transmission. All this together raises de system throughput.

7.1.4 Scenario: Signal to Noise Ratio = 8 dB at 5.5 Mbps

We now change the SNR form 6 to 8 dB and follow the same methodology we've been following.

Figures 7.37 and 7.38 show the AP and stations expected delay. The graphs in both figures follow the same behavior as the SNR = 6 dB. For the uplink transmission delay to be below the 200 ms threshold only 12 stations can be placed in the 10 meters radius. Compared with the 6 dB SNR, we now have 1 station less and is due to the receiver sensitivity to detect the a signal. For the AP to have a delay below the 200 ms, it must have in average 5 stations in the 10 m radius of coverage. The variance shown in Figure 7.39 and 7.40 is not so significant. As a preliminary conclusion, it is possible to have a system with 5 stations and be able to transfer VoWLAN.

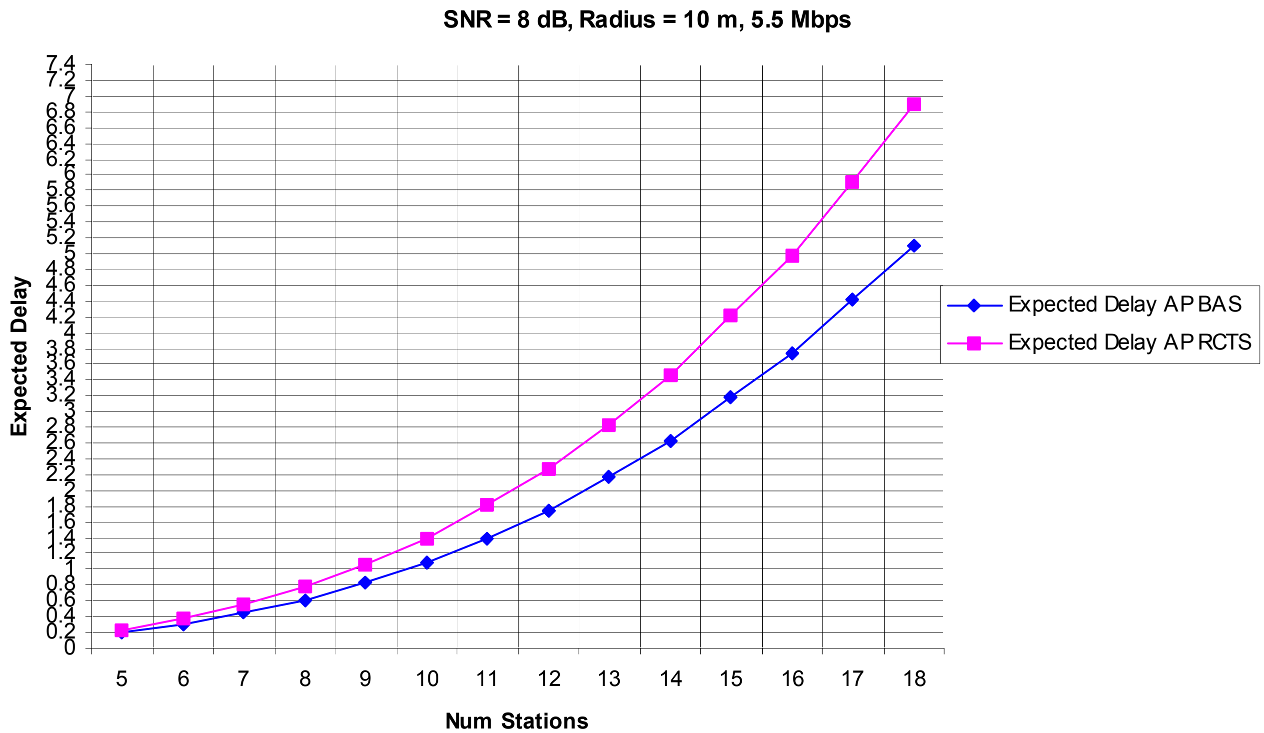

Figure 7.37. AP Expected Delay for SNR = 8 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

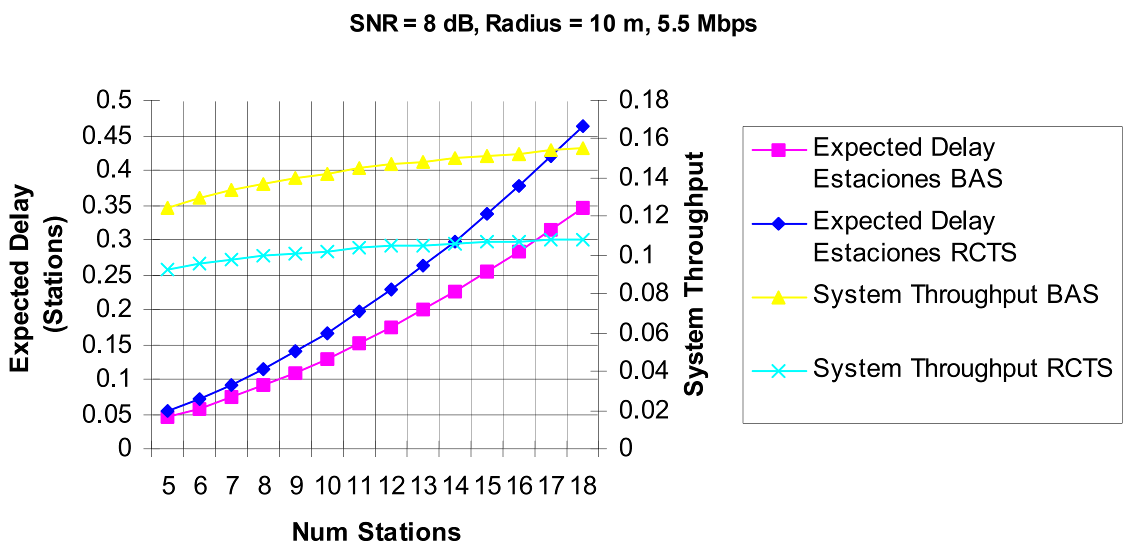

Figure 7.38. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

The details of the maximum delay and variance will be exposed with detail at the last subsection.

The system throughput is slightly lower than the SNR = 6 dB scenario and is due to the receiver sensitivity which means that now the stations have to be closer to the AP for the transmitted signal to be decoded correctly.

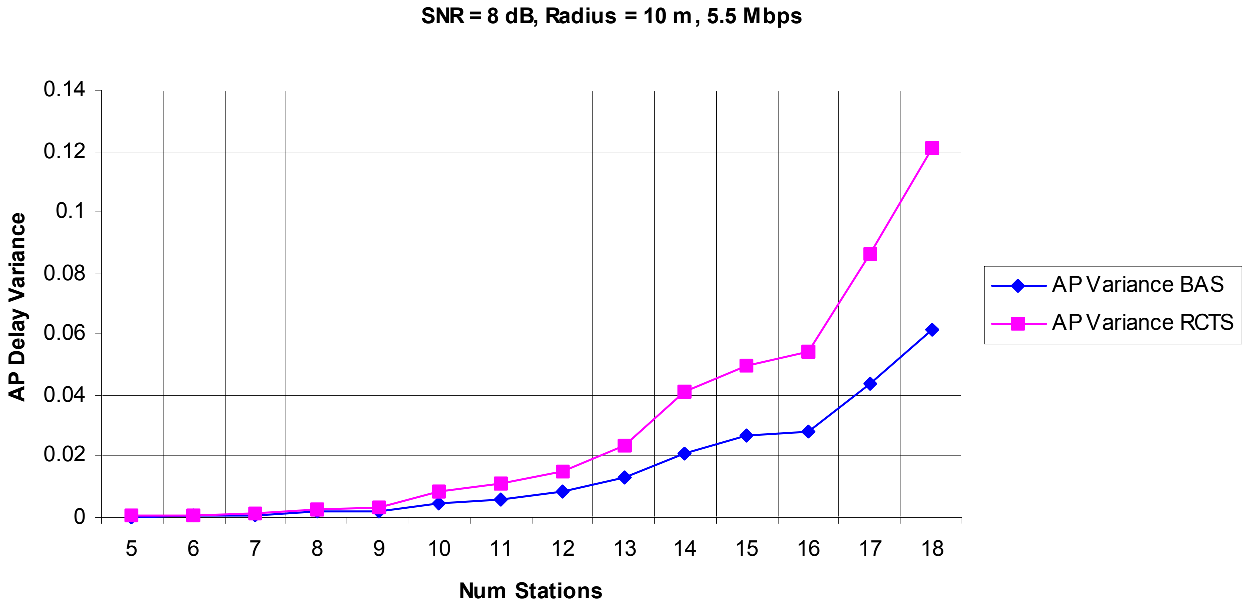

Figure 7.39. AP Delay Variance for SNR = 8 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

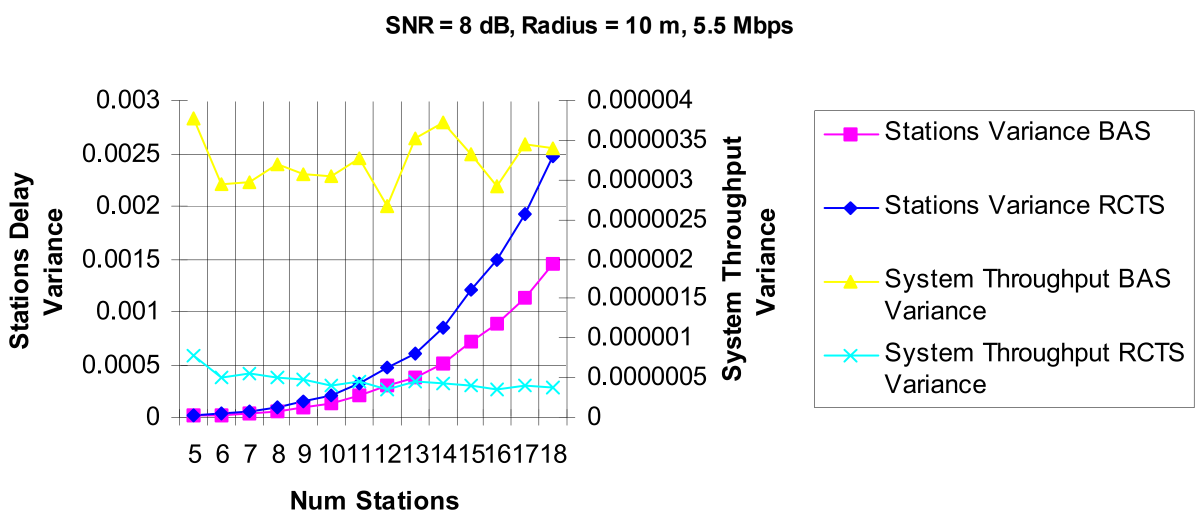

Figure 7.40. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 10 m, Bit Rate = 54 Mbps

Figures 7.41 to 7.44 show the expected delay and the variance delay of the AP and stations as well as the system throughput, for the case when the radius of coverage is 20 meters.

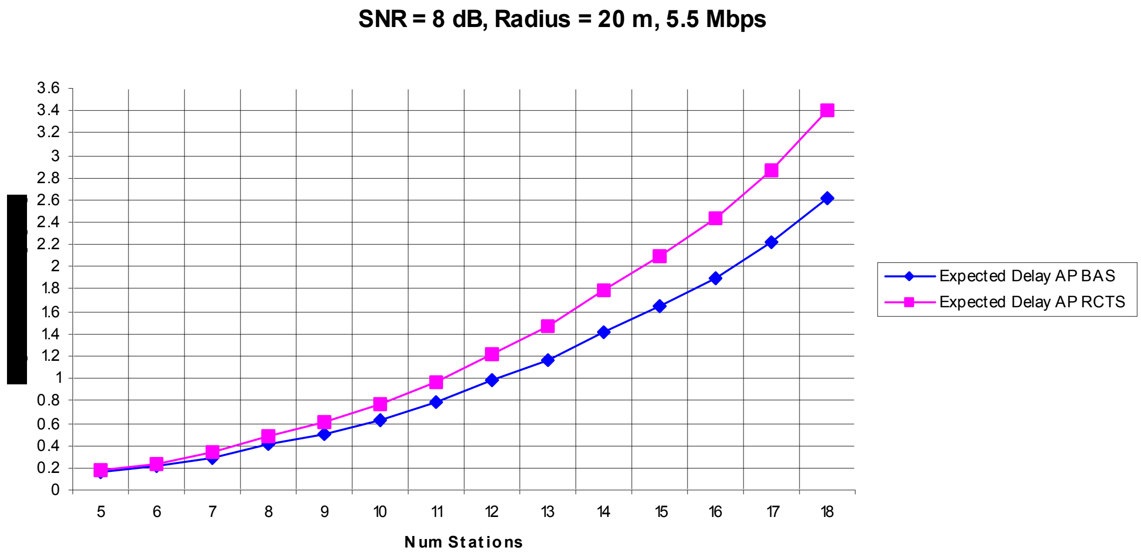

Figure 7.41. AP Expected Delay for SNR = 8 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

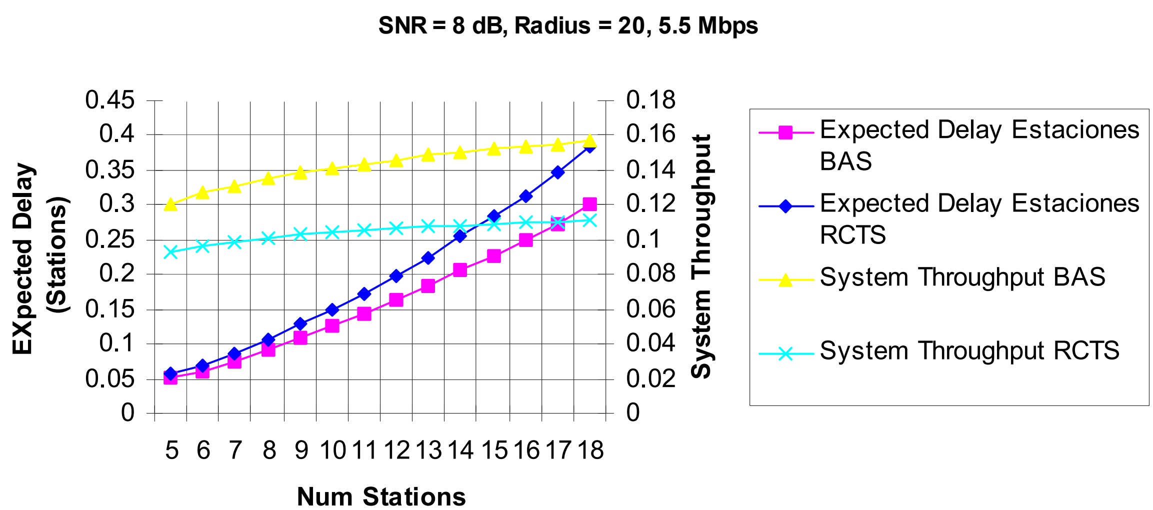

Figure 7.42. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

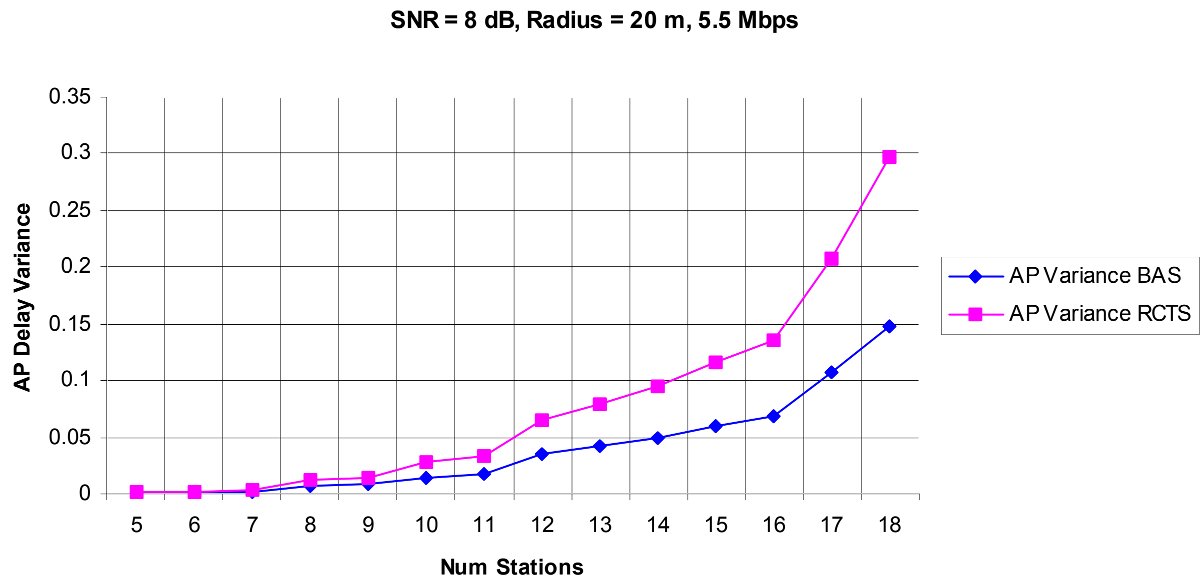

Figure 7.43. AP Delay Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

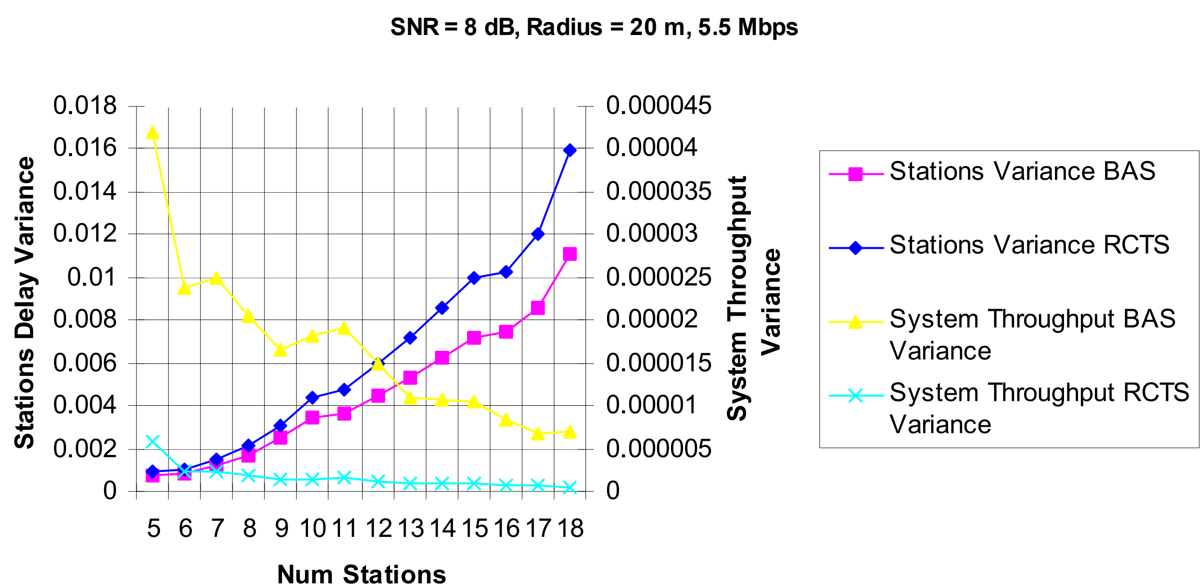

Figure 7.44. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

In Figure 7.41 and 7.42 the expected delay for the 20 meters of coverage is shown. The maximum number of stations the AP can handle to have a delay below 200 ms is 5 (downlink). For this case, the number of stations remains the same as the 10 meter radius.
The standard deviations of the AP when working with 5 stations is of 0.03092 and its average delay is of 155 ms. For the stations, the average delay is 50 ms and the delay standard deviation is of 28 ms. The maximum delay is below the 250 ms for the uplink and for the downlink. As a preliminary conclusion VoIP is possible in this scenario.

Figures 7.45 to 7.48 show the case when we change the radius of coverage to 30 meters.

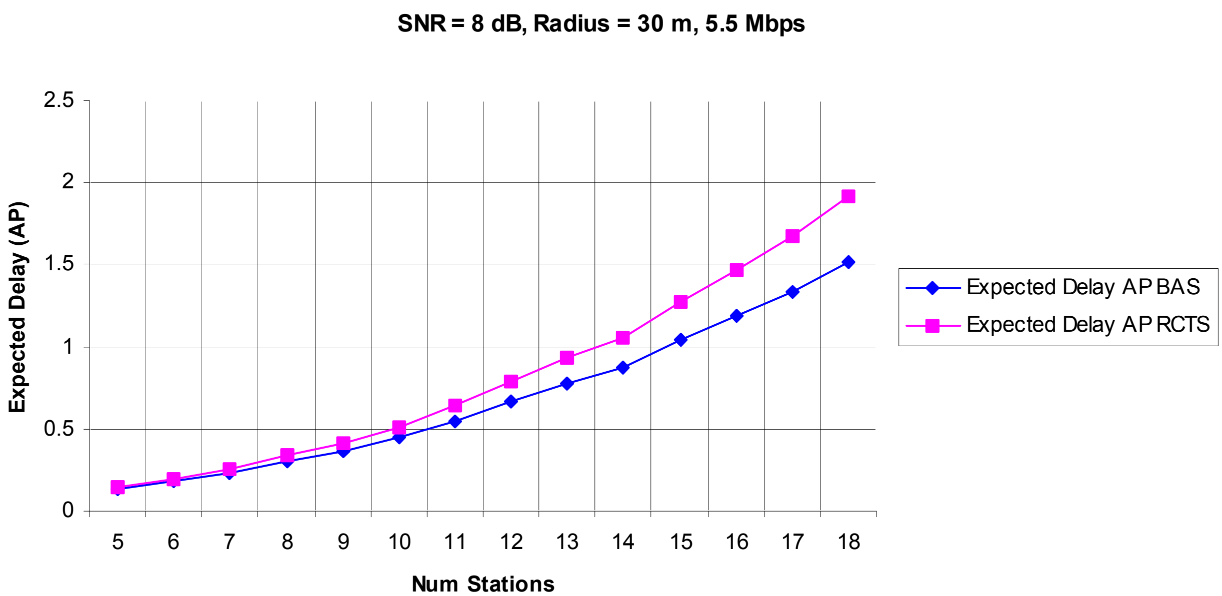

Figure 7.45. AP Expected Delay for SNR = 8 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

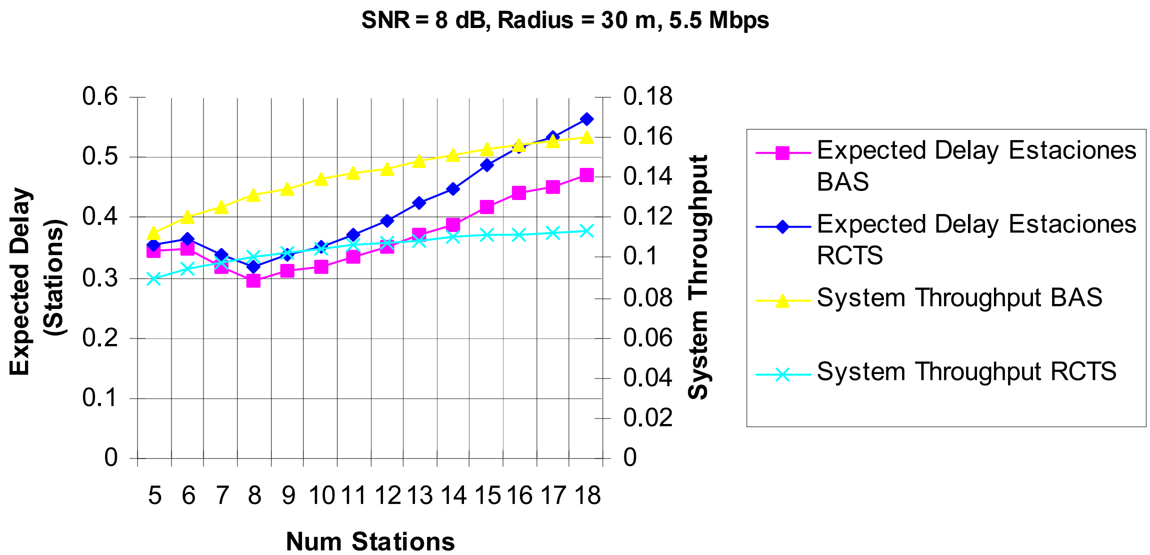

Figure 7.46. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

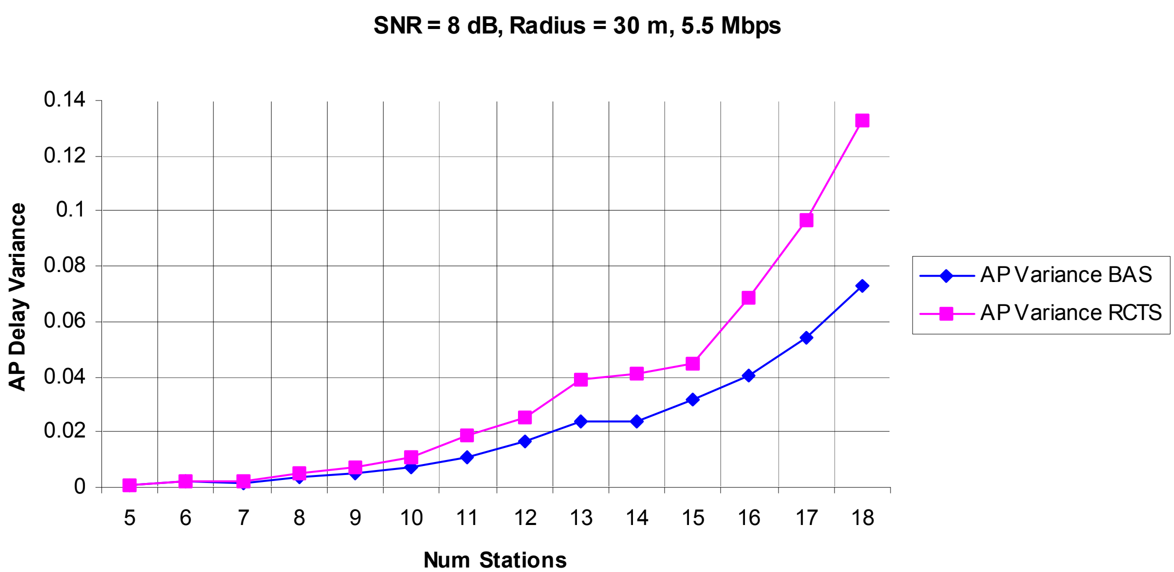

Figure 7.47. AP Delay Variance for SNR = 8 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

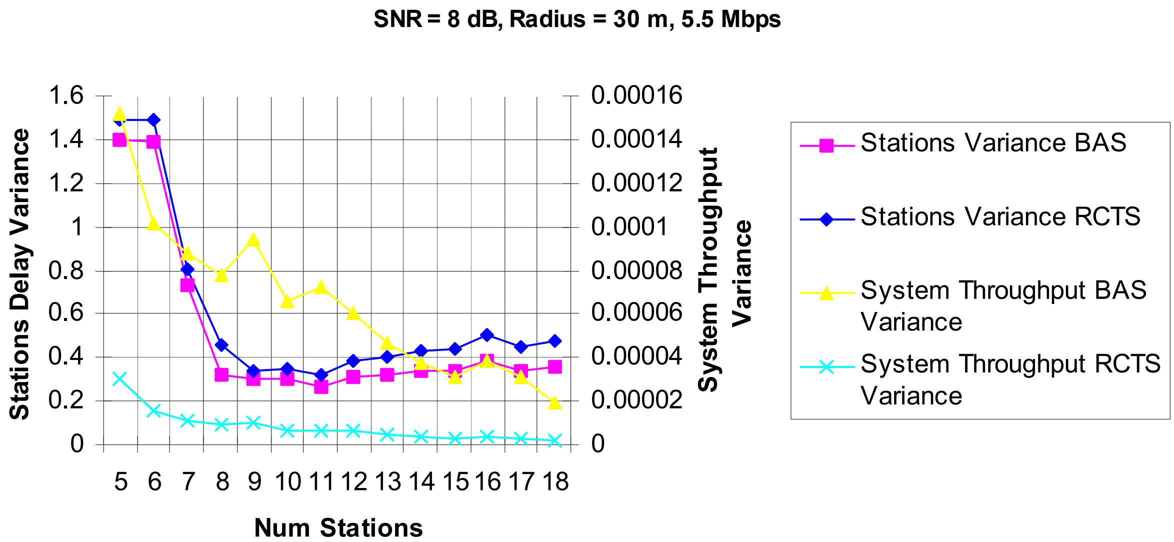

Figure 7.48. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

By directly looking at Figure 4.76 and 4.78 we can se that both the average delay and the delay standard deviation are highly above the 250 ms threshold. As a preliminary conclusion, for this scenario of a radius of 30 meters it is not possible to transmit VoWLAN.

7.1.5 Scenario: Signal to Noise Ratio = 8 dB at 11 Mbps

We now present the numerical simulation result for the case when the receiver sensitivity is of 8 dB and the bit rate at 11 Mbps. Again, we follow the same order of the previous sections.

Figures 7.49 to 7.52 show the numerical results of the AP and stations expected delay and variance and also system throughput behavior is shown.

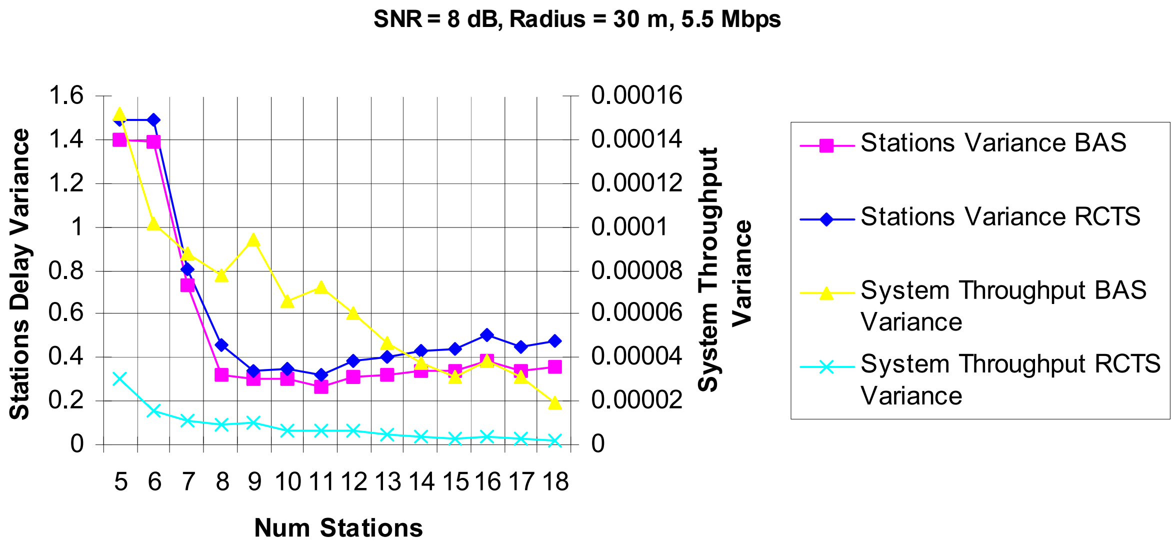

Figure 7.48. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

By directly looking at Figure 4.76 and 4.78 we can se that both the average delay and the delay standard deviation are highly above the 250 ms threshold. As a preliminary conclusion, for this scenario of a radius of 30 meters it is not possible to transmit VoWLAN.

7.1.5 Scenario: Signal to Noise Ratio = 8 dB at 11 Mbps

We now present the numerical simulation result for the case when the receiver sensitivity is of 8 dB and the bit rate at 11 Mbps. Again, we follow the same order of the previous sections.

Figures 7.49 to 7.52 show the numerical results of the AP and stations expected delay and variance and also system throughput behavior is shown.

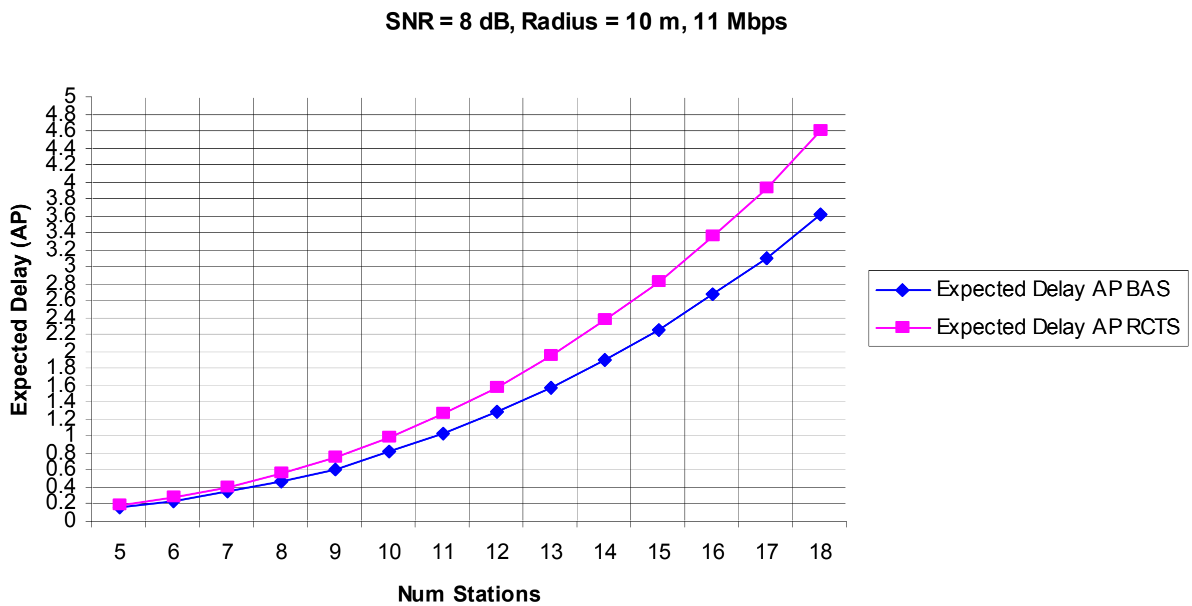

Figure 7.49. AP Expected Delay for SNR = 8 dB, Radius = 10 m, Bit Rate = 11 Mbps

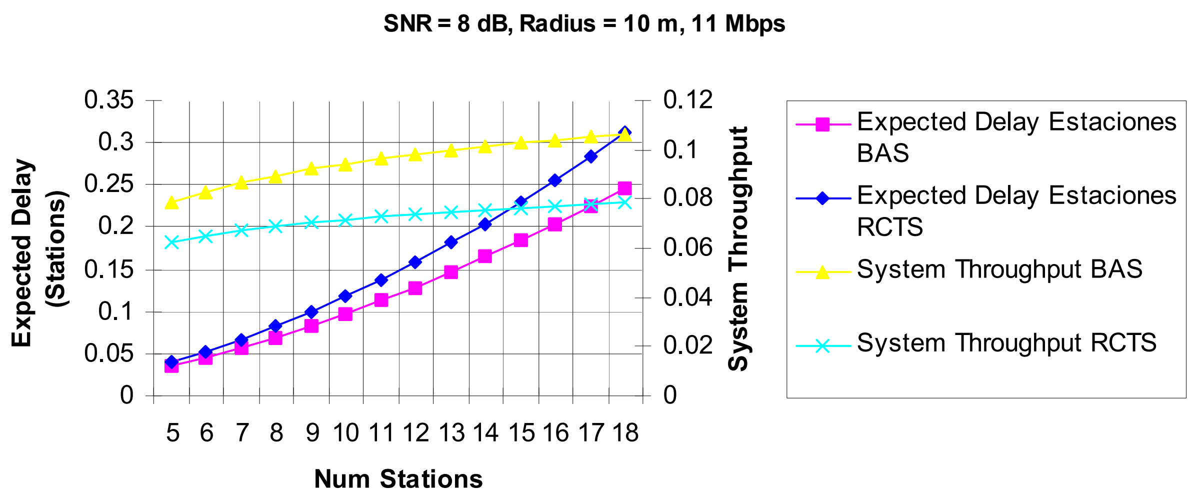

Figure 7.50. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 10 m, Bit Rate = 11 Mbps

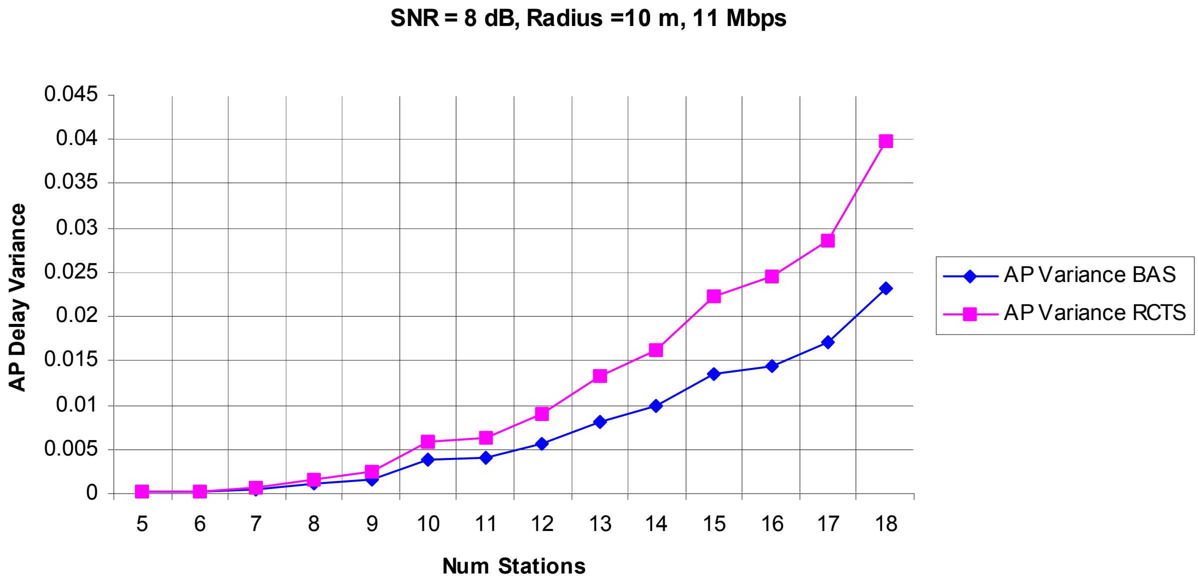

Figure 7.51. AP Delay Variance for SNR = 8 dB, Radius = 10 m, Bit Rate = 11 Mbps

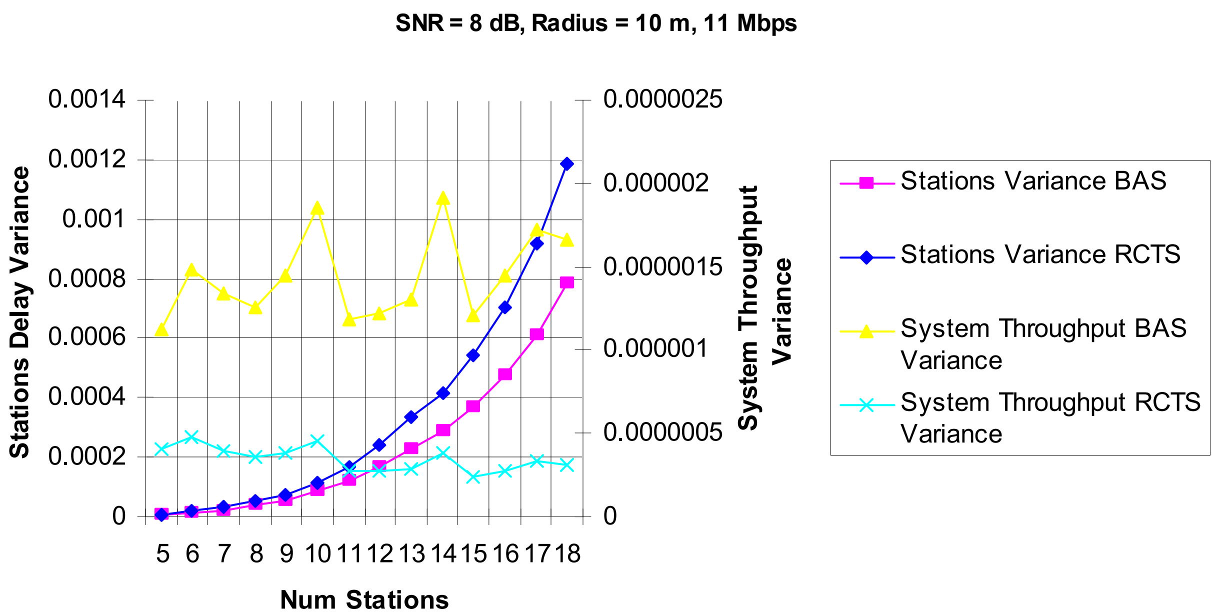

Figure 7.52. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 10 m, Bit Rate = 11 Mbps

In Figure 7.49 and 7.50 shows the expected delay of the AP and the stations. For this scenario we can have a maximum of 5 stations due to the AP limitation. With 5 stations simulations results show that the average delay of the AP is of 155 ms and the standard deviation is of 11 ms. and for the stations, the average delay is of 35 ms and the standard deviation is of 2.6 ms. Thus for this scenario the transmission of VoWLAN is possible with 5 stations.

Figures 7.53 to 7.56 show the case when the radius is increased to 20 meters. In the same manner as the other 20 meters radius scenarios this shows to be the best one that fits for the VoWLAN transmission.

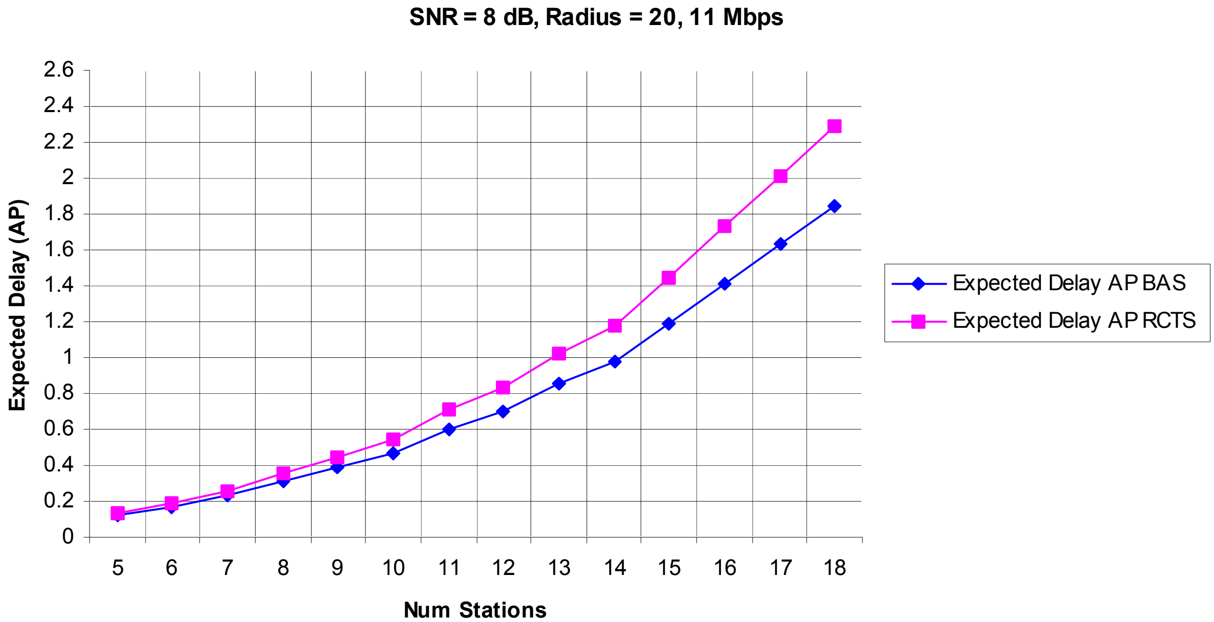

Figure 7.53. AP Expected Delay for SNR = 8 dB, Radius = 20 m, Bit Rate = 11 Mbps

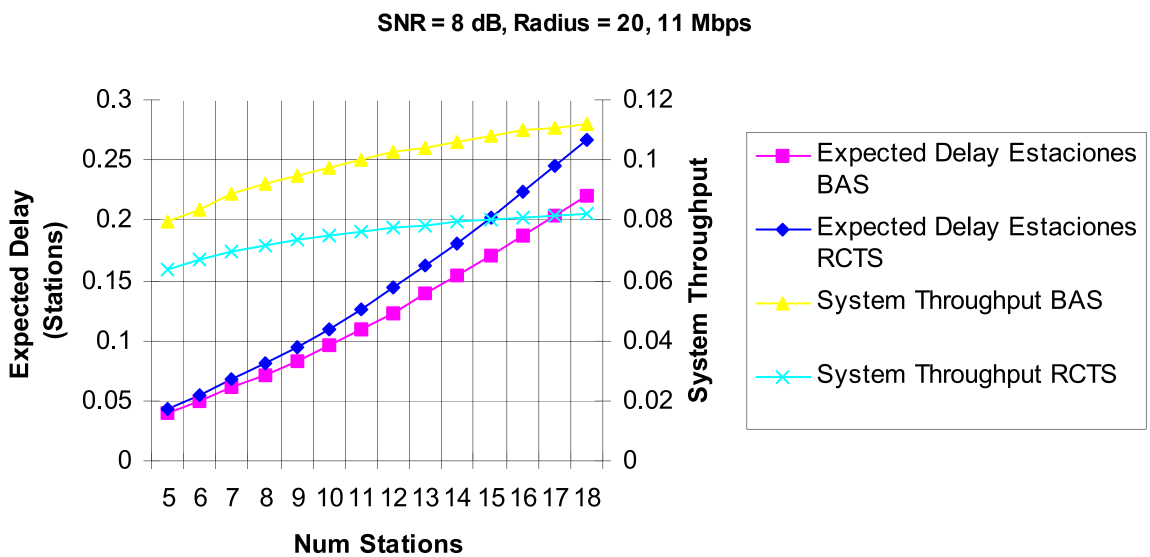

Figure 7.54. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 20 m, Bit Rate = 11 Mbps

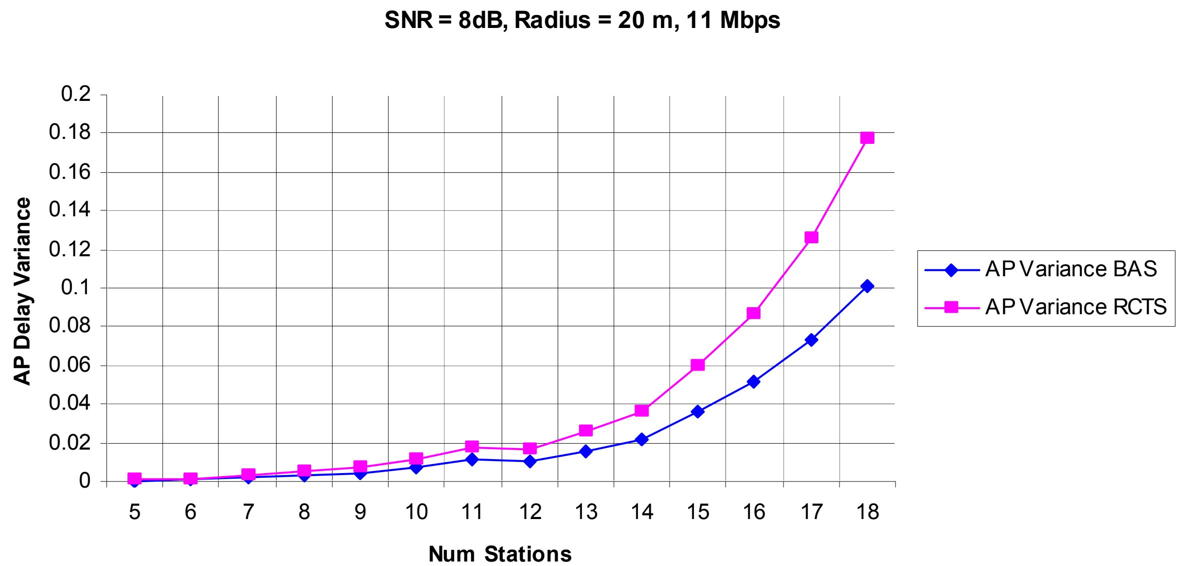

Figure 7.55. AP Delay Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 11 Mbps

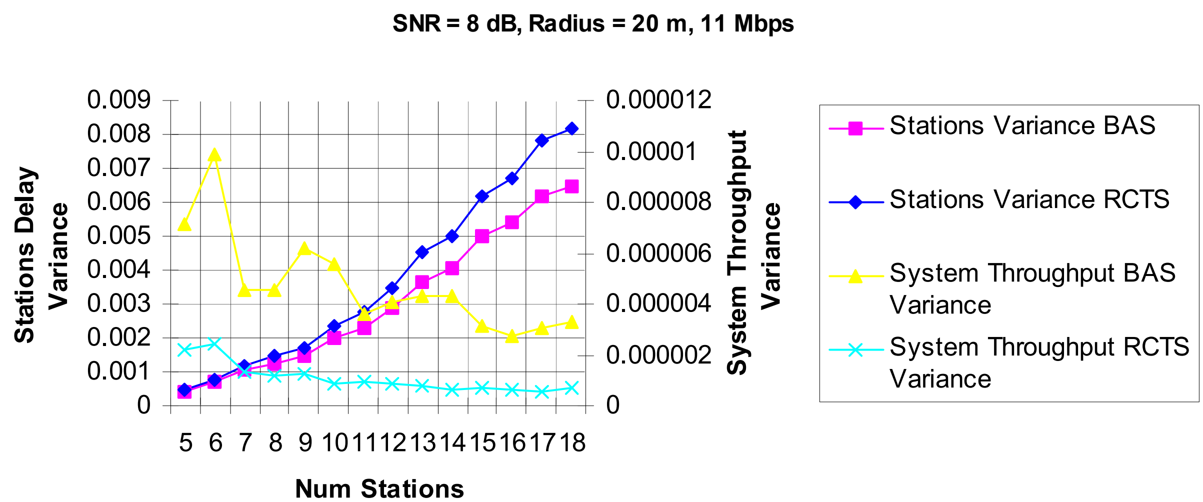

Figure 7.56. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 11 Mbps

From figures 7.53 and 7.54 we can conclude that the maximum number of stations the AP can handle to have a delay below the 200 ms threshold is of 6 stations. In this case, the AP average delay will be of 166 ms with a standard deviation of 31 ms (Figure 7.55), giving a maximum delay of 197 ms. For the stations, the average delay will be of 50 ms and the standard deviation is of 2.6 ms (Figure 7.56) giving a maximum stations delay of 76 ms.

In general, we have an improvement of 1 station over the 10 meters radius. As a preliminary conclusion, it is possible to transmit VoWLAN in this scenario.

Figures 7.57 to 7.60 show the same scenario but with a 30 meters radius of coverage.
Even though in Figure 7.57 it is shown that the AP can handle up to 7 stations and have a delay below the 200 ms threshold, in Figure 7.58 the stations have a threshold above it. As an immediate conclusion it is not possible to transmit VoWLAN when the radius of coverage is of 30 meters or beyond.

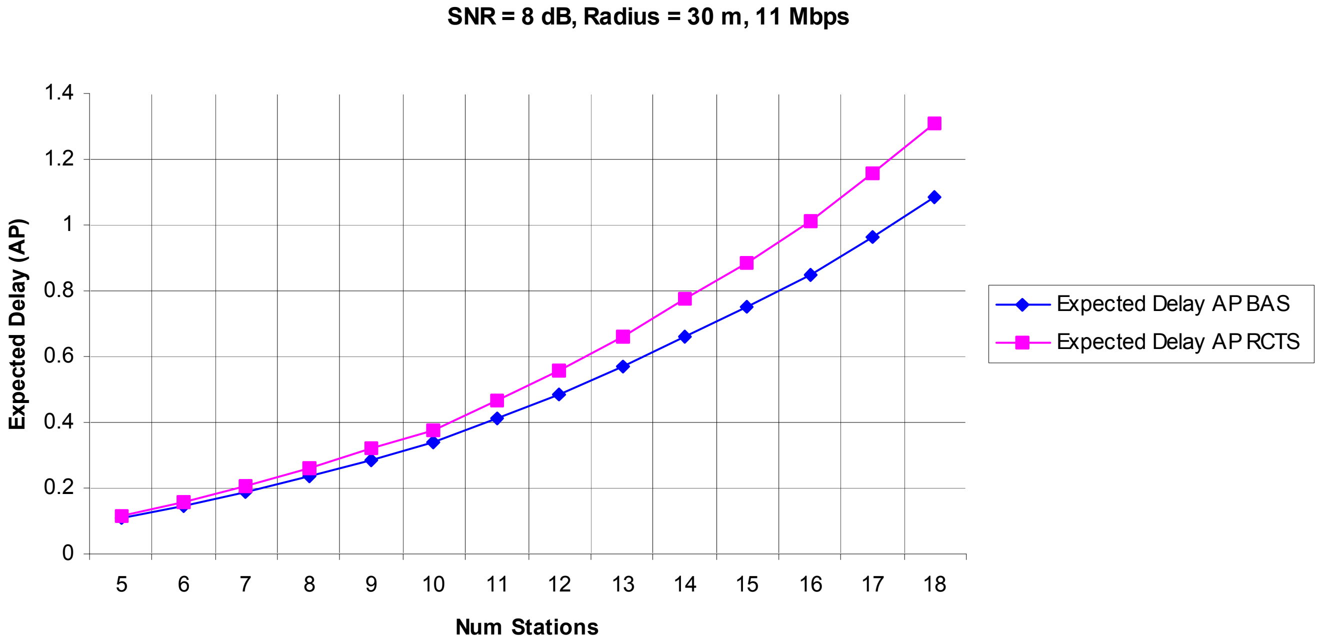

Figure 7.57. AP Expected Delay for SNR = 8 dB, Radius = 30 m, Bit Rate = 11 Mbps

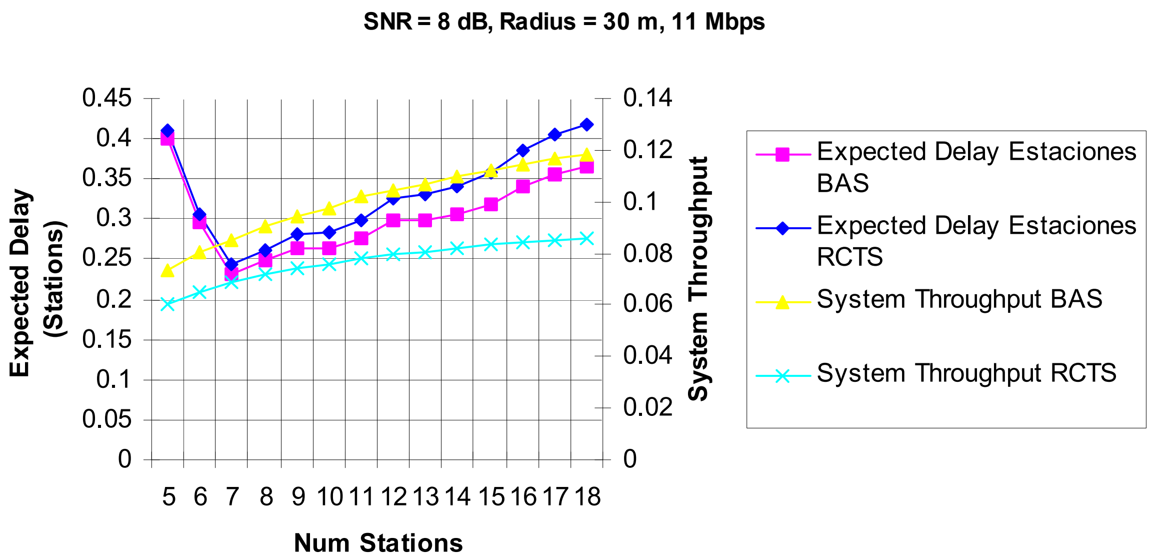

Figure 7.58. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 30 m, Bit Rate = 11 Mbps

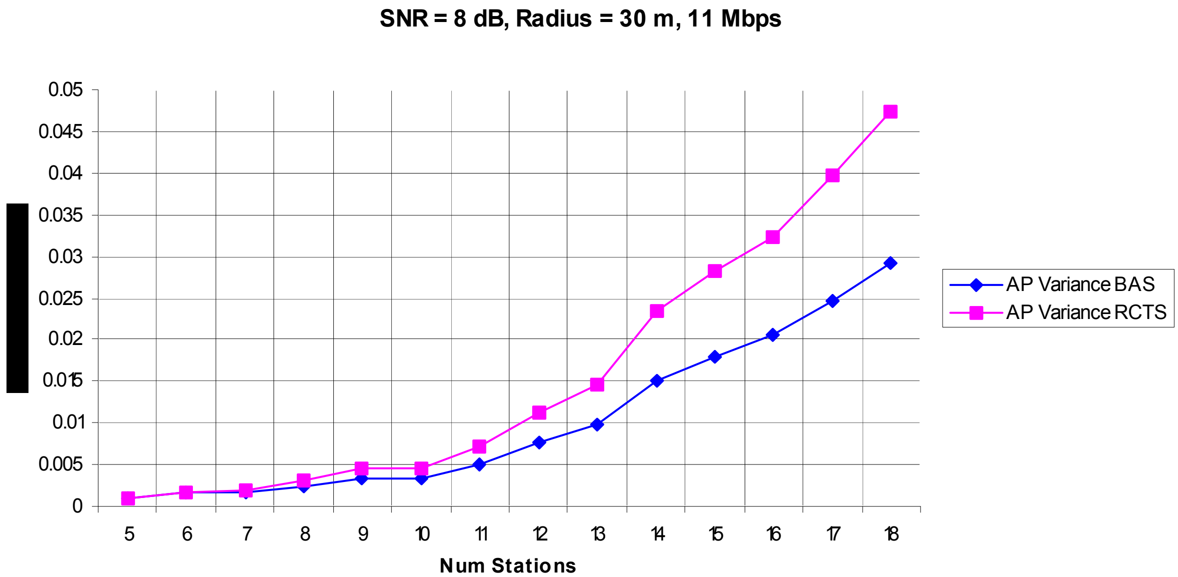

Figure 7.59. AP Delay Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 11 Mbps

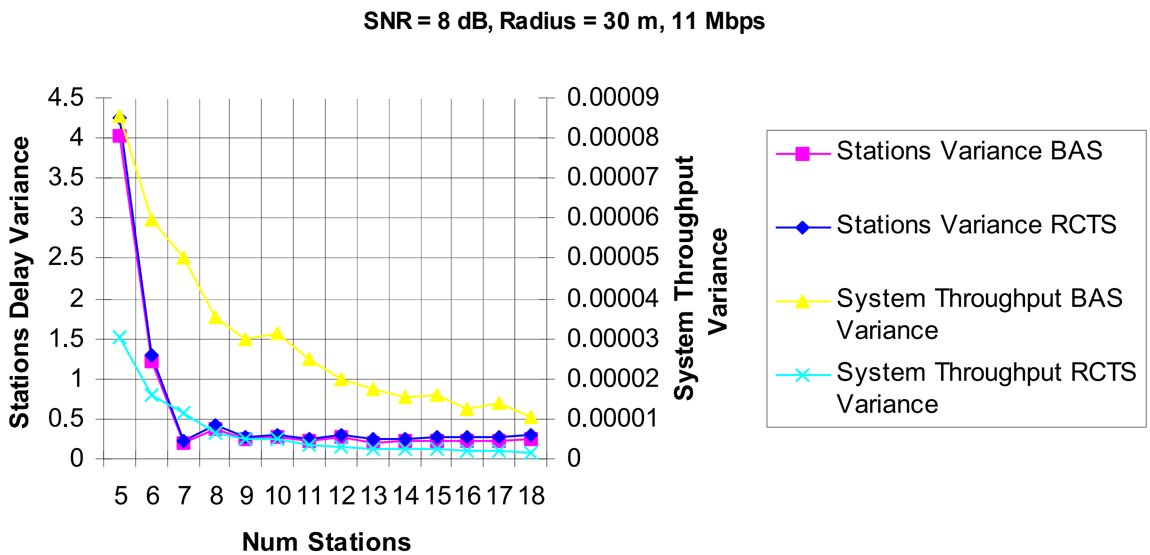

Figure 7.60. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 11 Mbps

7.1.6 Scenario: Signal to Noise Ratio = 8 dB at 54 Mbps

Figures 7.61 to 7.64 shows the expected delay of the AP and stations and their respective variances as well as the system throughput for the case of 54 Mbps bit rate. As it will be seen, the 54 Mbps bit rate has the lowest delay of all the cases and it will prove to be the best suite for the transmission of VoWLAN.

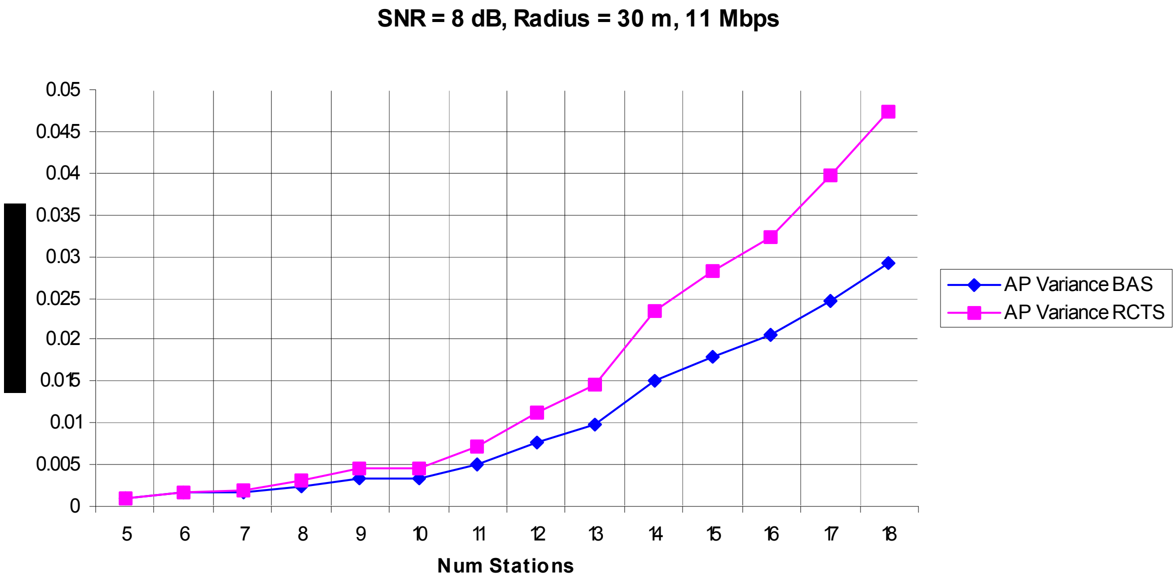

Figure 7.59. AP Delay Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 11 Mbps

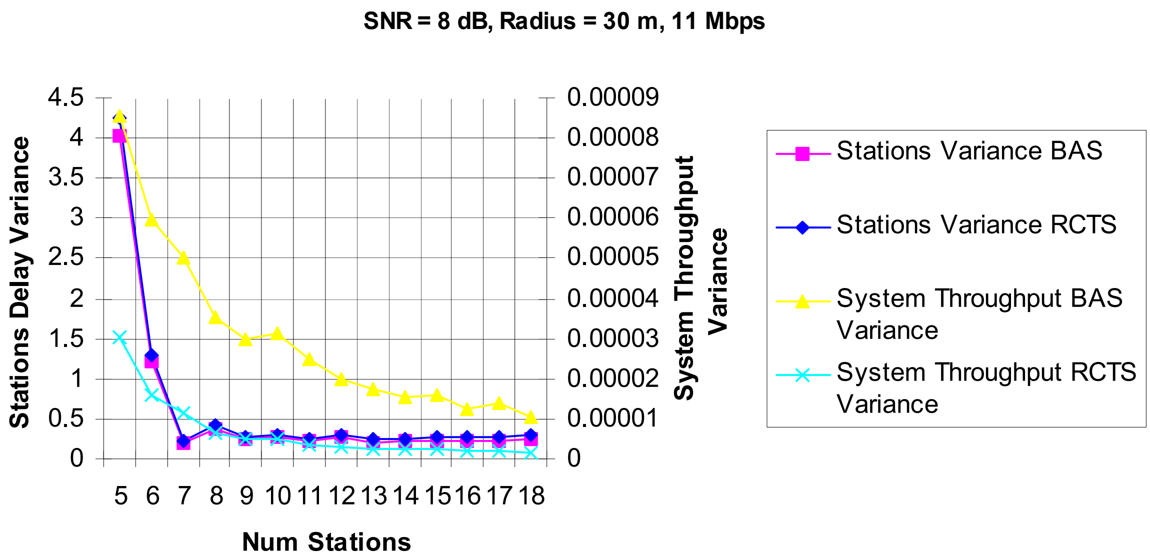

Figure 7.60. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 11 Mbps

7.1.6 Scenario: Signal to Noise Ratio = 8 dB at 54 Mbps

Figures 7.61 to 7.64 shows the expected delay of the AP and stations and their respective variances as well as the system throughput for the case of 54 Mbps bit rate. As it will be seen, the 54 Mbps bit rate has the lowest delay of all the cases and it will prove to be the best suite for the transmission of VoWLAN.

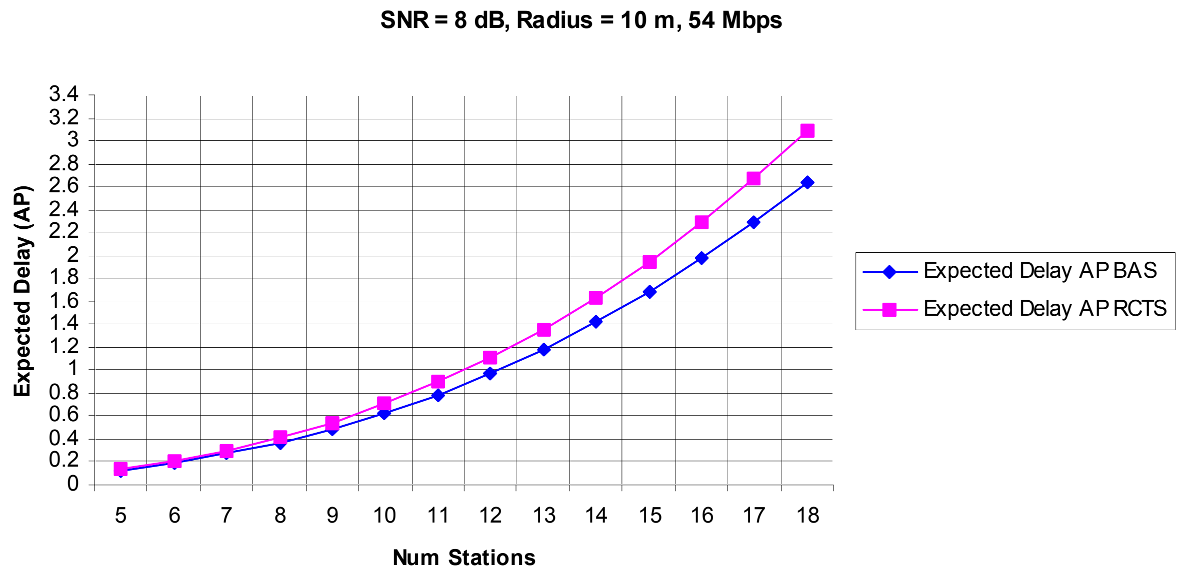

Figure 7.61. AP Expected Delay for SNR = 8 dB, Radius = 10 m, Bit Rate = 54 Mbps

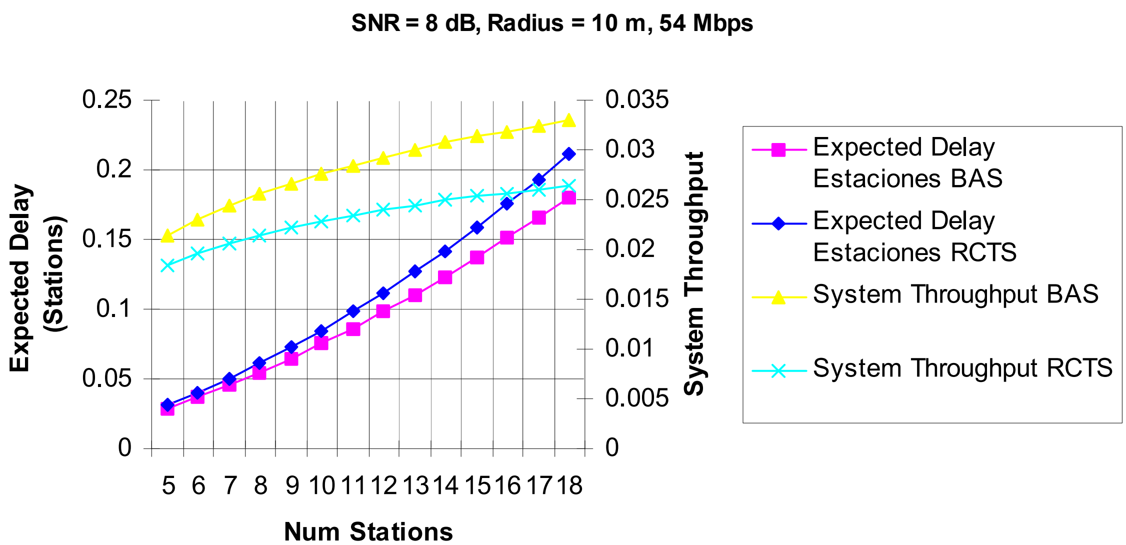

Figure 7.62. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 10 m, Bit Rate = 54 Mbps

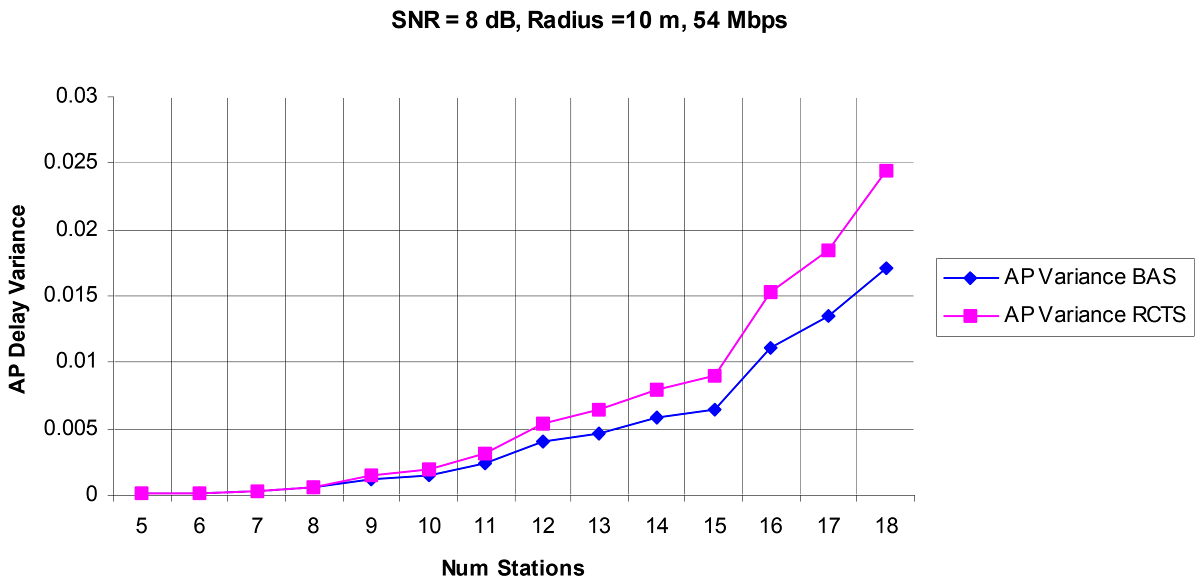

Figure 7.63. AP Delay Variance for SNR = 8 dB, Radius = 10 m, Bit Rate = 54 Mbps

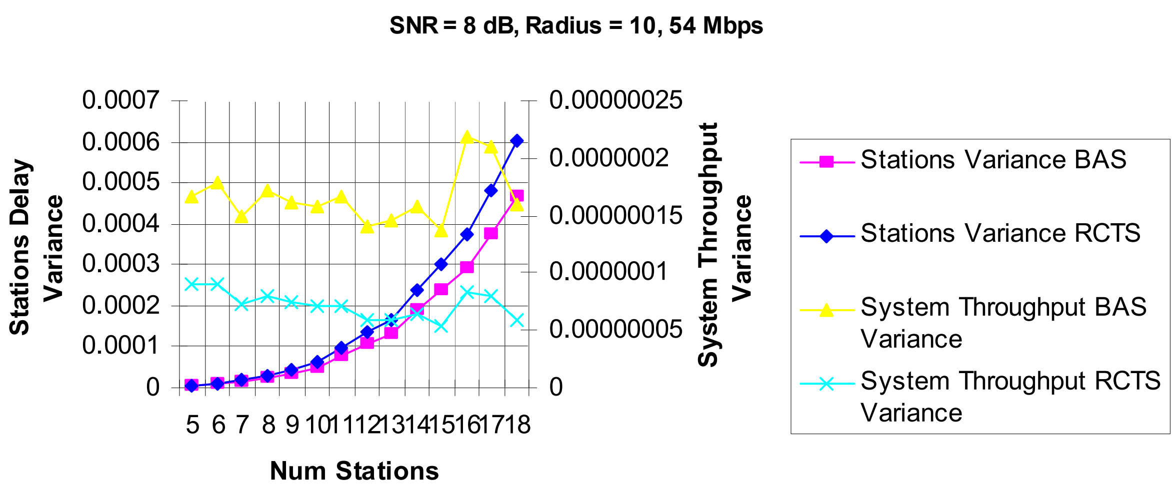

Figure 7.64. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 10 m, Bit Rate = 54 Mbps

Figure 7.61 shows that the maximum number of stations the AP can handle and have an average delay below the 200 ms threshold is 6. With 6 stations, the average delay is of 190 ms and the standard deviation is of 13 ms (see Figure 7.63). For the stations, Figure 7.62 shows that the average delay is of 36 ms and the standard deviation is of 3 ms (see Figure 7.64). For this scenario it is possible to transmit VoWLAN.

Figures 7.65 to 7.68 show the case when the radius changes to 20 meters. It will be shown that for all of the 54 Mbps bit rate scenarios; the 20 meters radius of coverage is the best one to suit the transmission of VoWLAN.

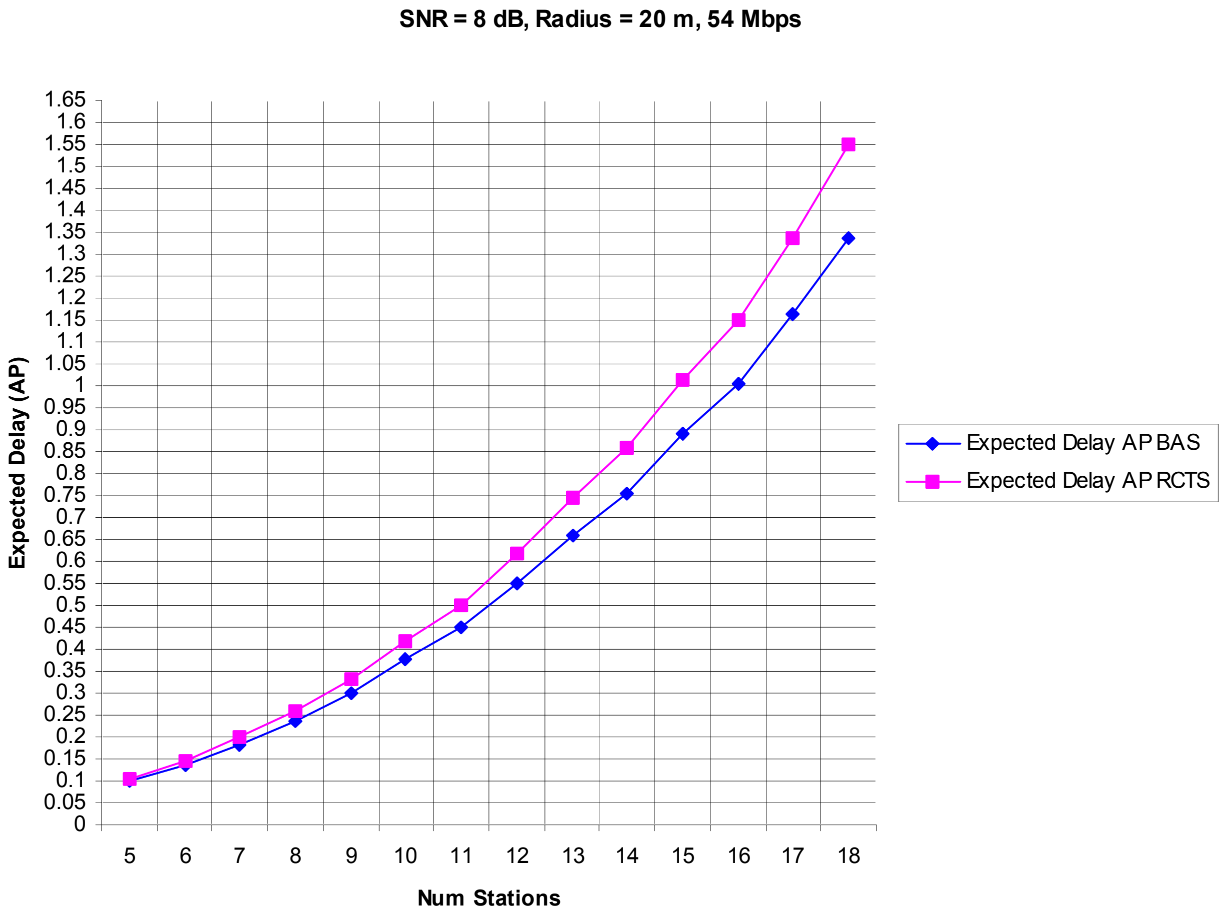

Figure 7.65. AP Expected Delay for SNR = 8 dB, Radius = 20 m, Bit Rate = 54 Mbps

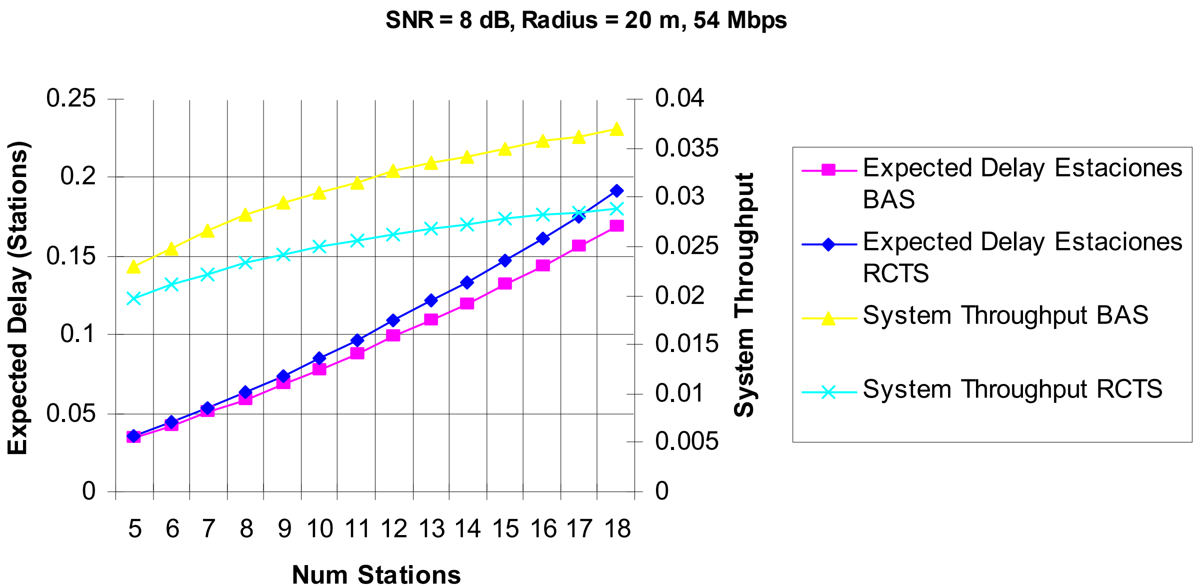

Figure 7.66. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 20 m, Bit Rate = 54 Mbps

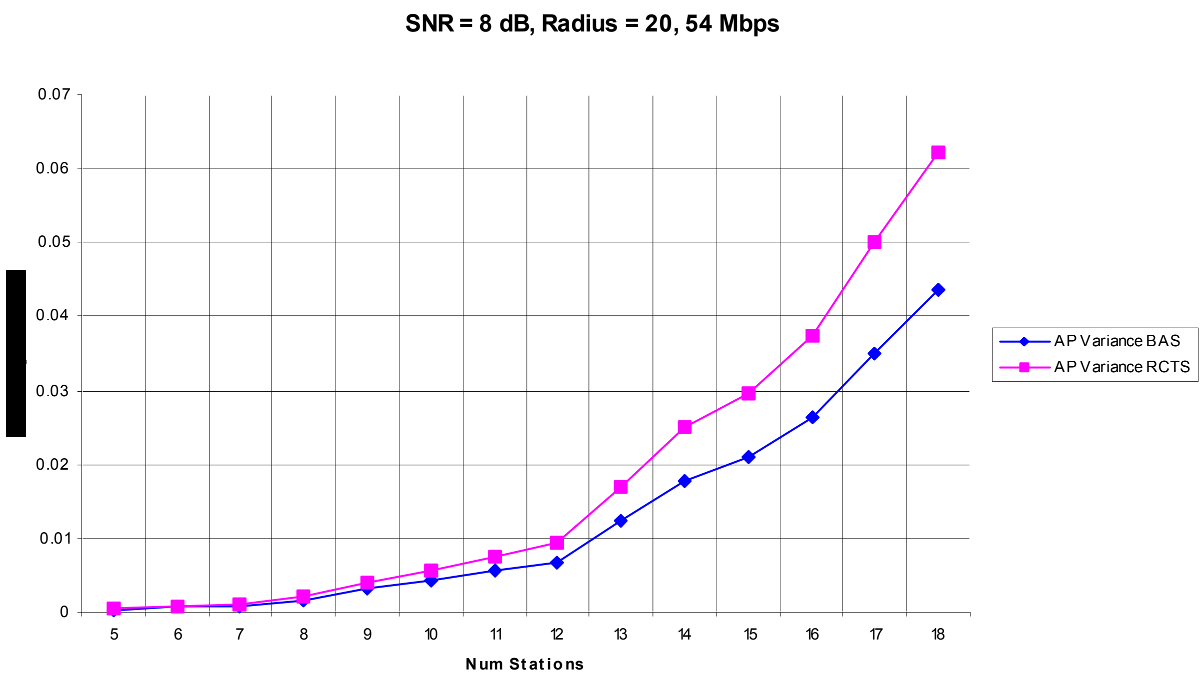

Figure 7.67. AP Delay Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 54 Mbps

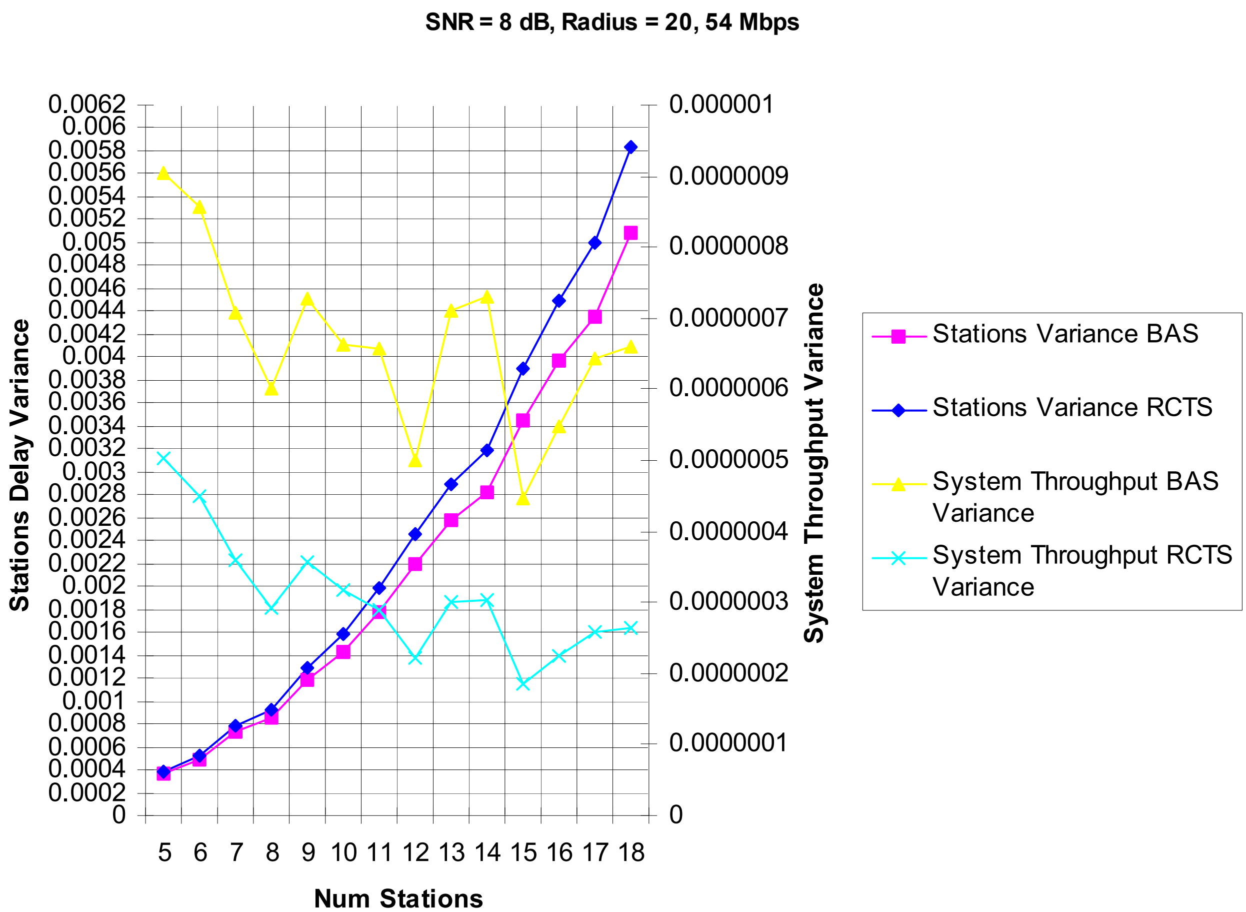

Figure 7.68. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 20 m, Bit Rate = 54 Mbps

Figure 7.65 shows that the maximum number of stations the AP can handle and still be below the 200 ms delay threshold is 7. For 7 stations the average delay of the AP is of 183 ms and the standard deviation is of 29 ms. (see Figure 7.67) For the same number of stations, the stations average delay is of 50 ms with a standard deviation on 26 ms.
For this scenario, the transmission of VoWLAN is possible and is the one with the highest capacity.

Figures 7.69 to 7.72 shows the case when the radius of coverage is changed to 30 meters. For this scenario it is shown that is not possible to transmit VoWLAN due to the large delays.

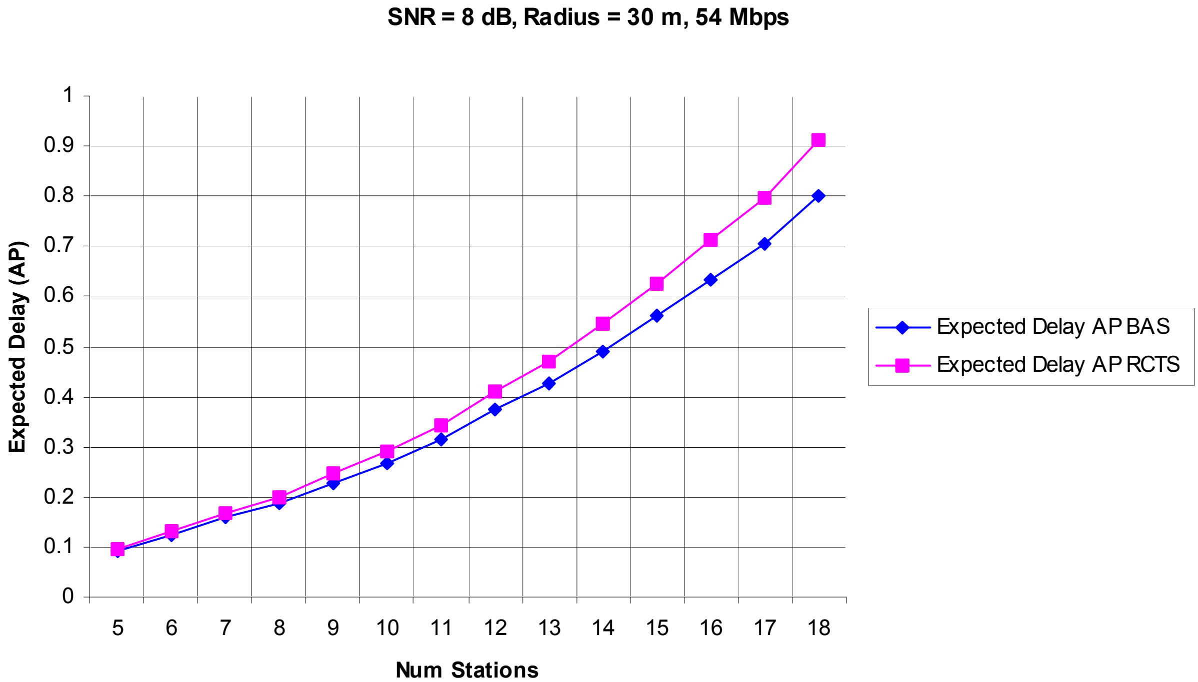

Figure 7.69. AP Expected Delay for SNR = 8 dB, Radius = 30 m, Bit Rate = 54 Mbps

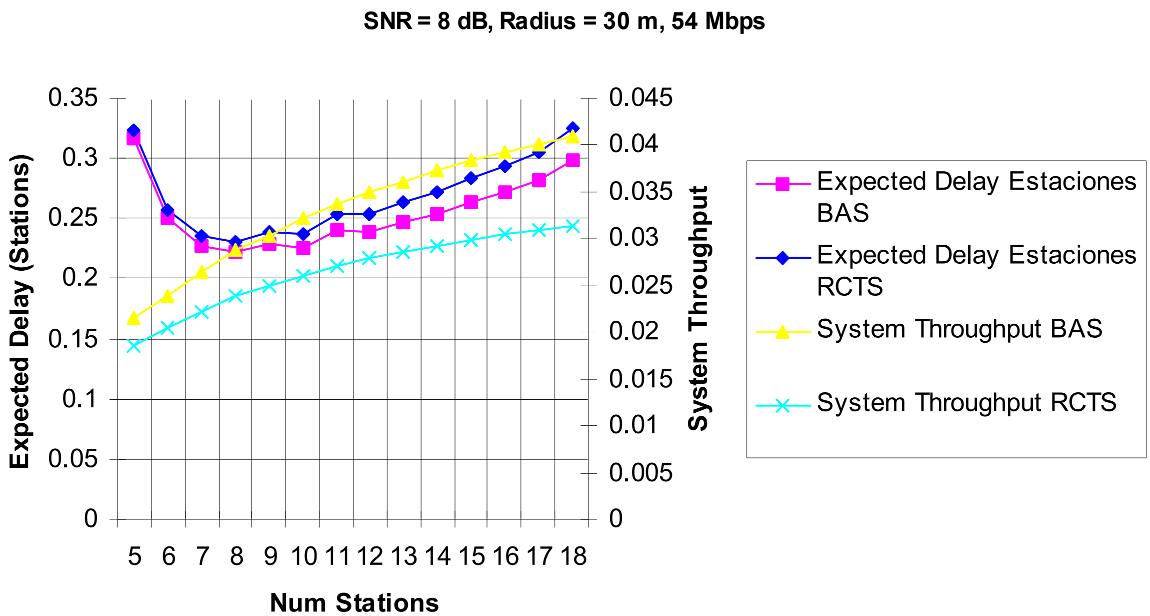

Figure 7.70. Stations Expected Delay and System Throughput for SNR = 8 dB, Radius = 30 m, Bit Rate = 54 Mbps

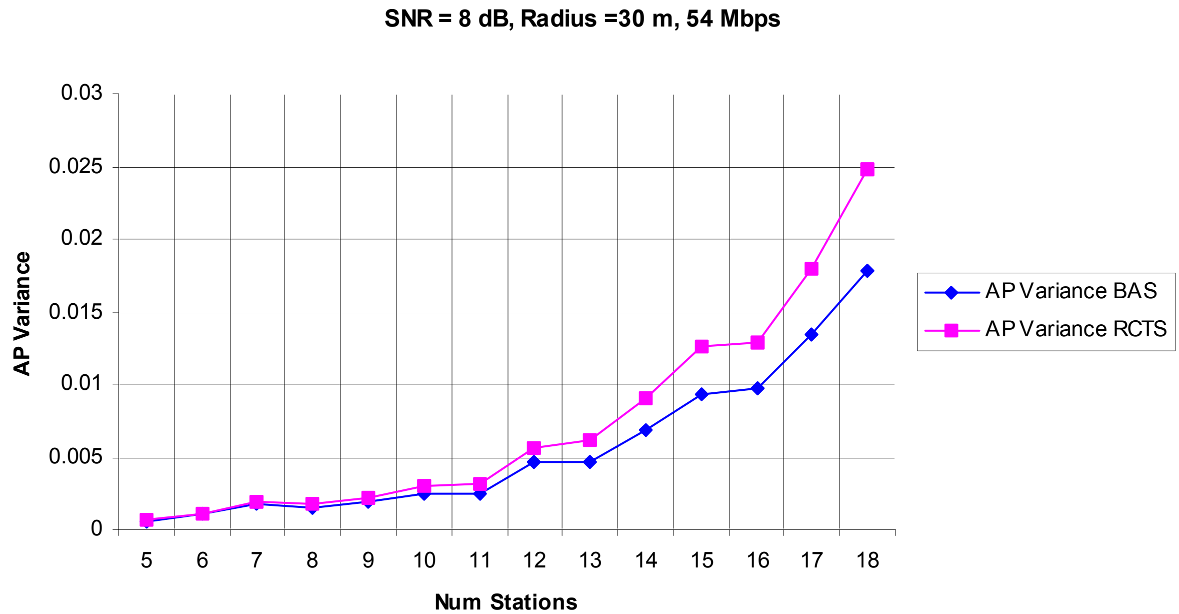

Figure 7.71. AP Delay Variance for SNR = 8 dB, Radius = 30 m, Bit Rate = 54 Mbps

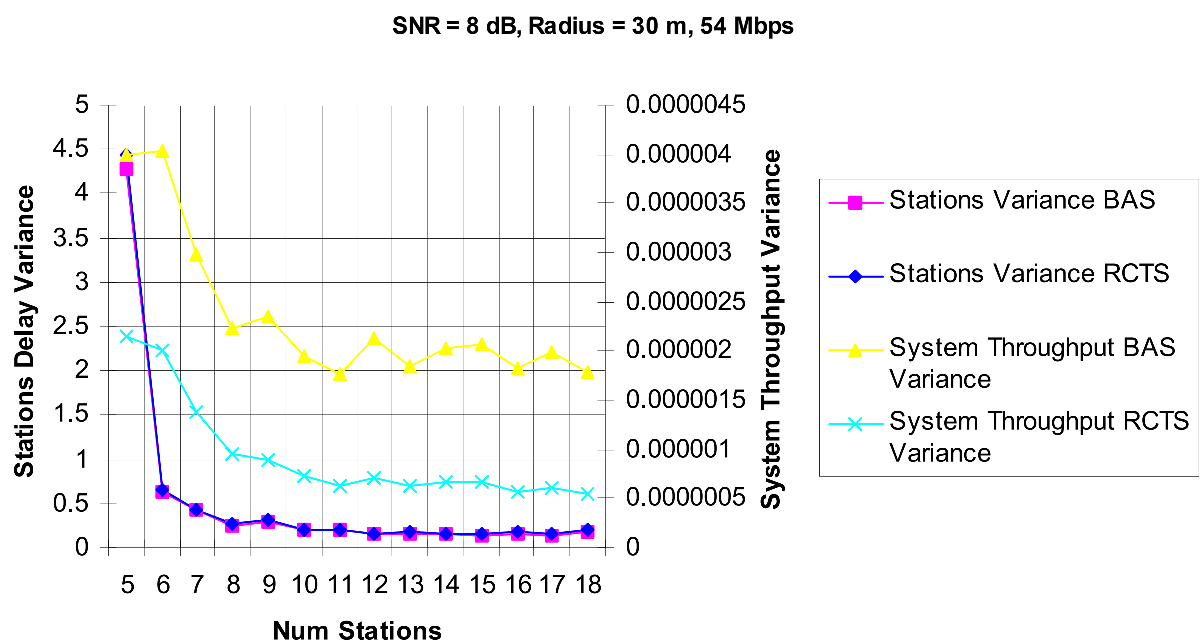

Figure 7.72. Stations Delay Variance and System Throughput Variance for SNR = 8 dB, Radius = 30 m, Bit Rate = 54 Mbps

As can be see in Figure 7.70, the average delay of the stations is above of the 250 ms threshold as well as the delay variance. For this reason, the transmission of VoWLAN for the 30 meters scenario is not possible.

7.1.7 Scenario: Signal to Noise Ratio = 10 dB at 5.5 Mbps

We now present the numerical simulation results for the receiver sensitivity for correct signal reception of 10 dB.

Figures 7.73 to 7.76 show the case when the bit rate is 5.5 Mbps and the coverage radius is of 10 meters.

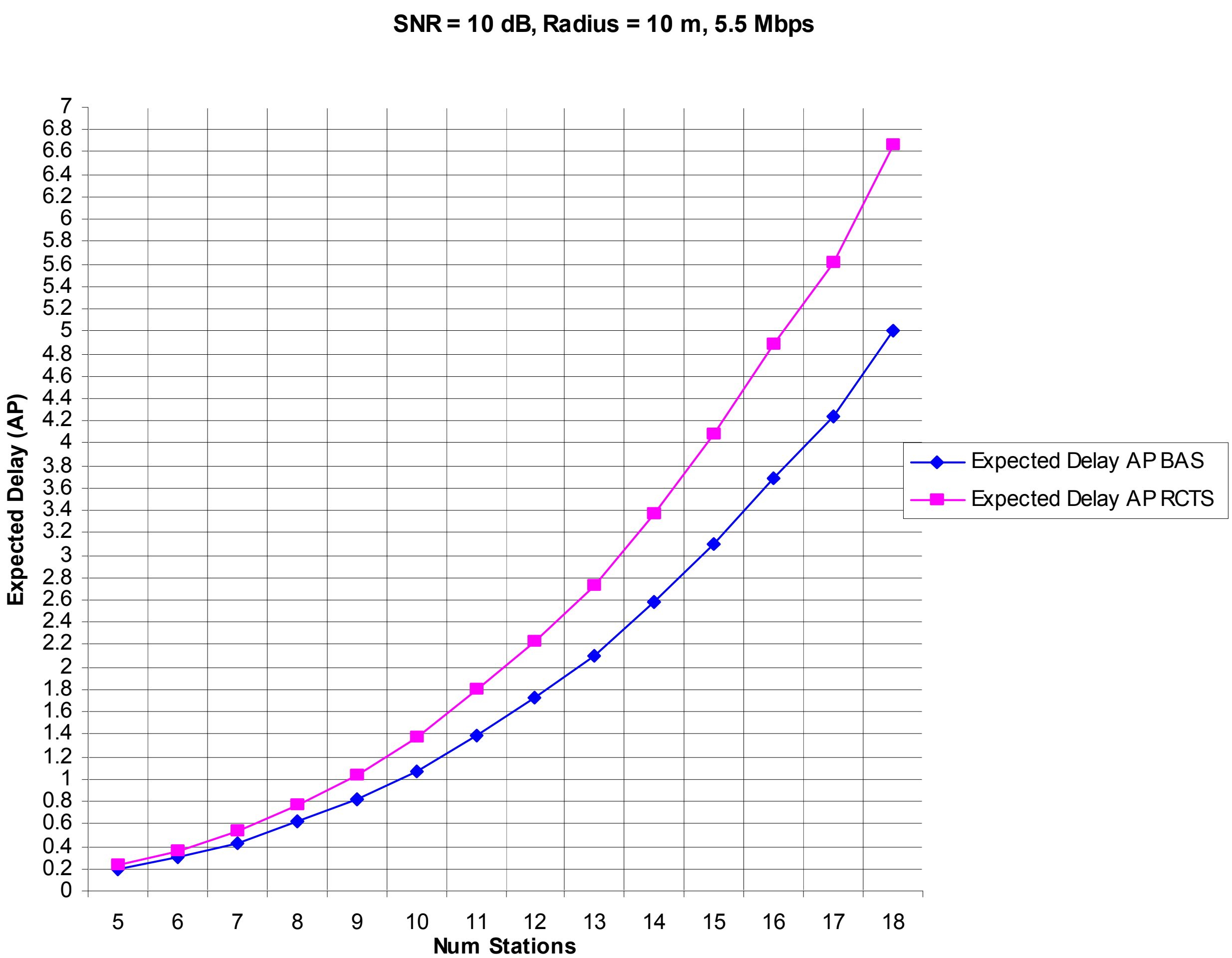

Figure 7.73. AP Expected Delay for SNR = 10 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

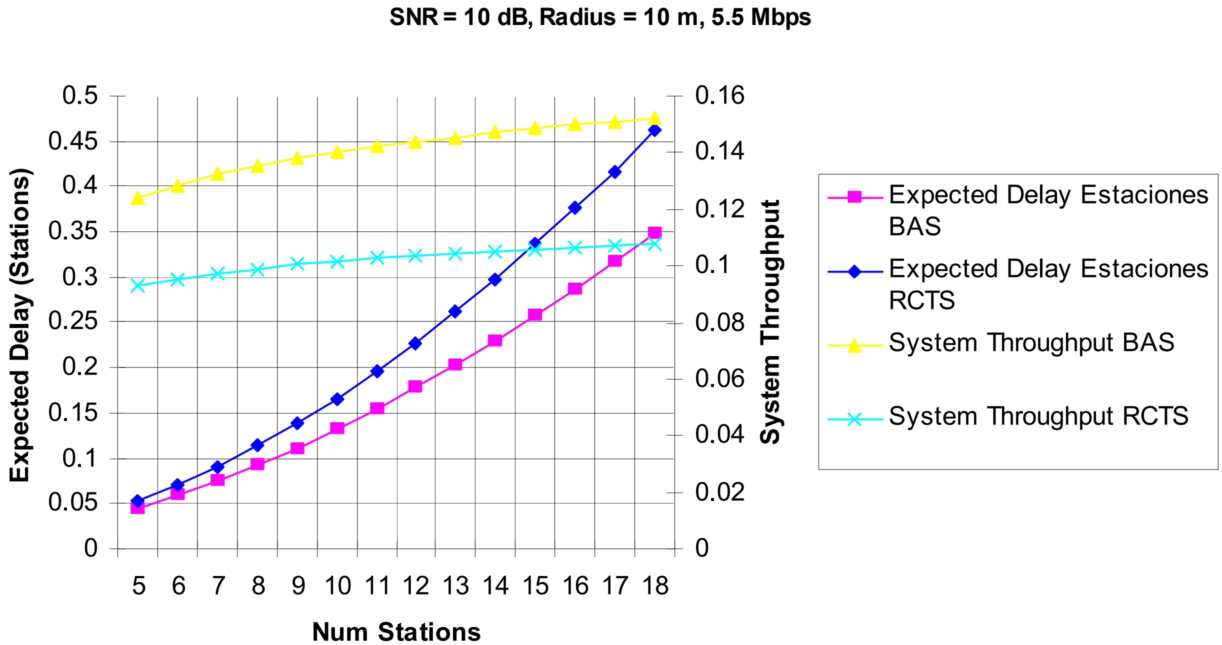

Figure 7.74. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

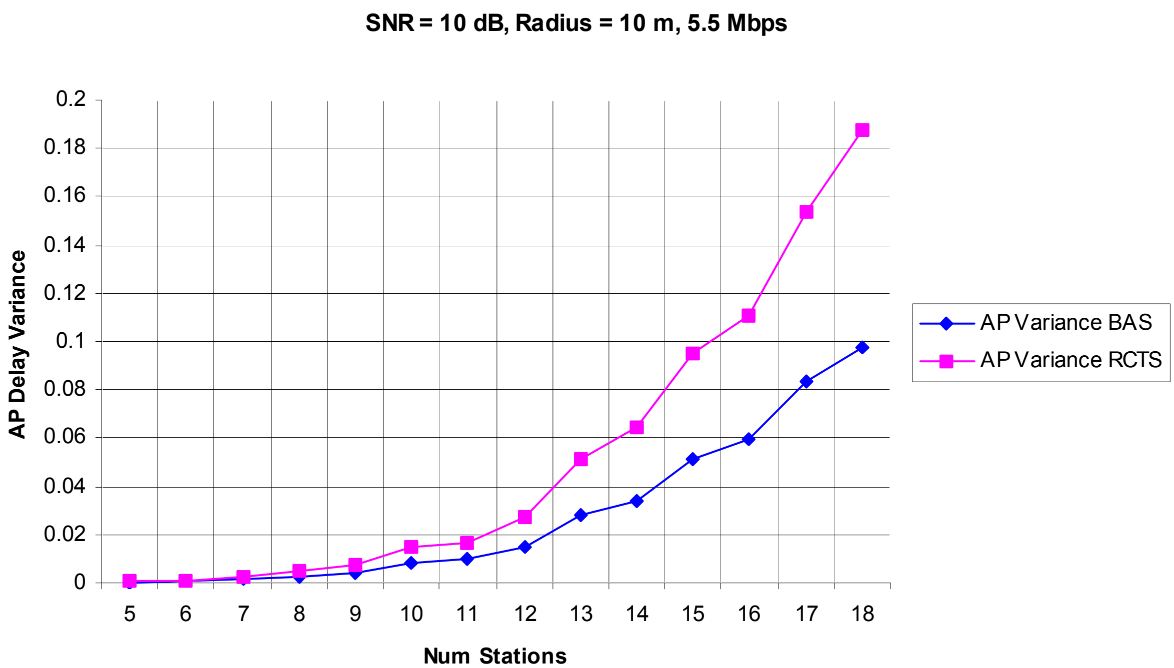

Figure 7.75. AP Delay Variance for SNR = 10 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

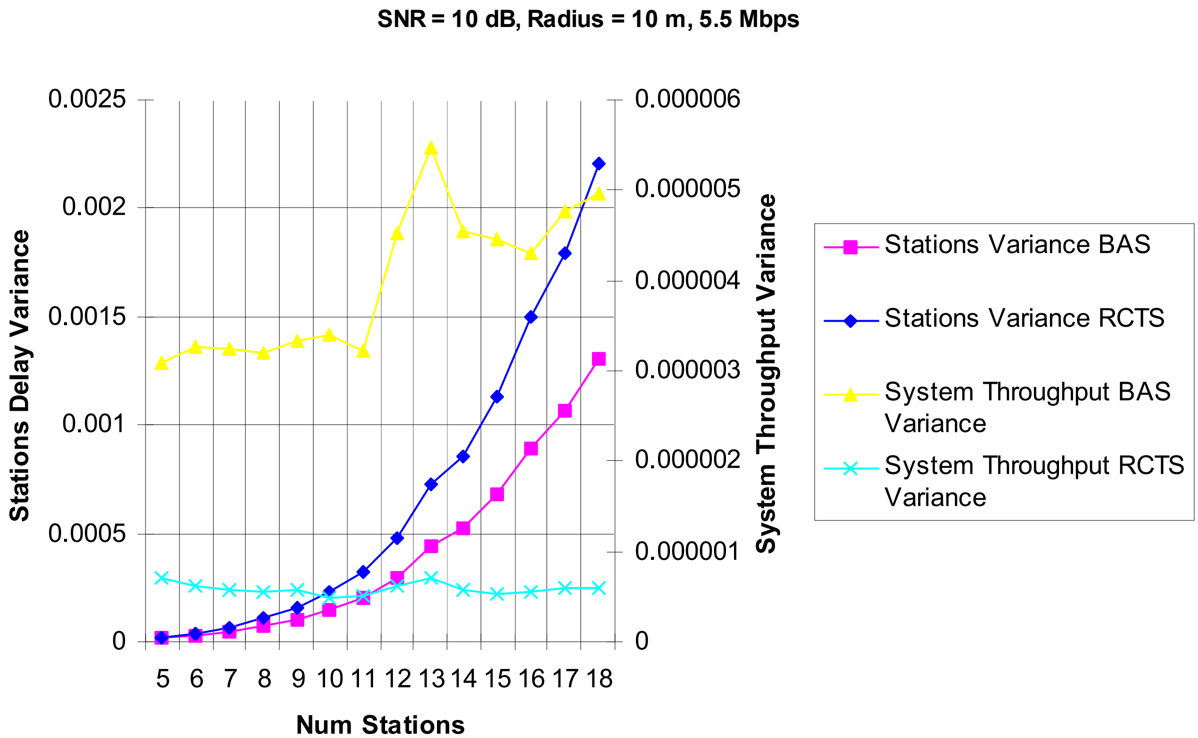

Figure 7.76. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

As can be seen in the graphs, the averages are slightly above compared with the 6 dB and 8 dB receiver's sensitivity. In Figure 7.73 the maximum number of stations below the 200 ms threshold is 5. Compared with the 6 and 8 dB scenarios, even though the number of stations below the 200 ms is same, the average delay is higher, but still in the range. With 5 stations operating in the system, the AP will have an expected delay of 194 ms, and a standard deviation of 18 ms, giving a maximum delay of 212 ms which is still under the maximum tolerable delay of 250 ms. (see figures 7.73 and 7.75) For the case of the stations, each of them will have an average delay of 45 ms and a standard deviation of 38 ms. (see figures 7.74 and 7.76)
For this scenario, the transmission of VoWLAN is possible.

In figures 7.77 to 7.80 the coverage radius has been changed to 20 meters. As all of the 20 meters scenario, it will be shown that is still the best scenario for the transmission of VoWLAN.

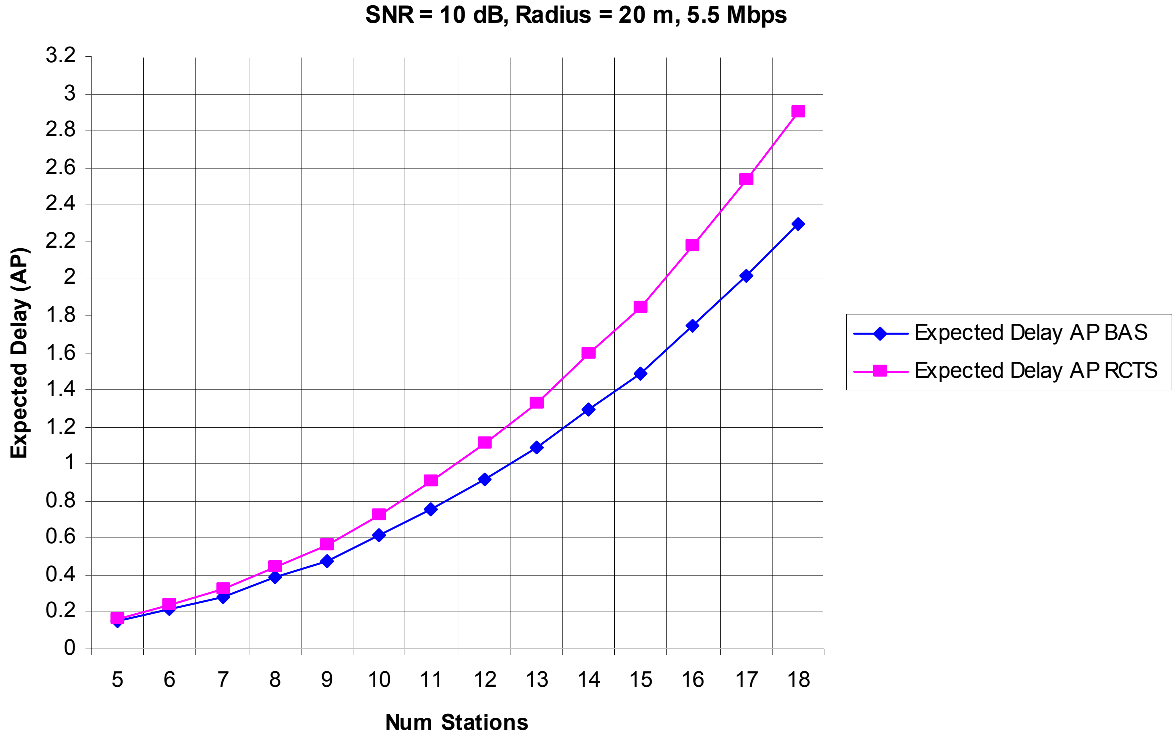

Figure 7.77. AP Expected Delay for SNR = 10 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

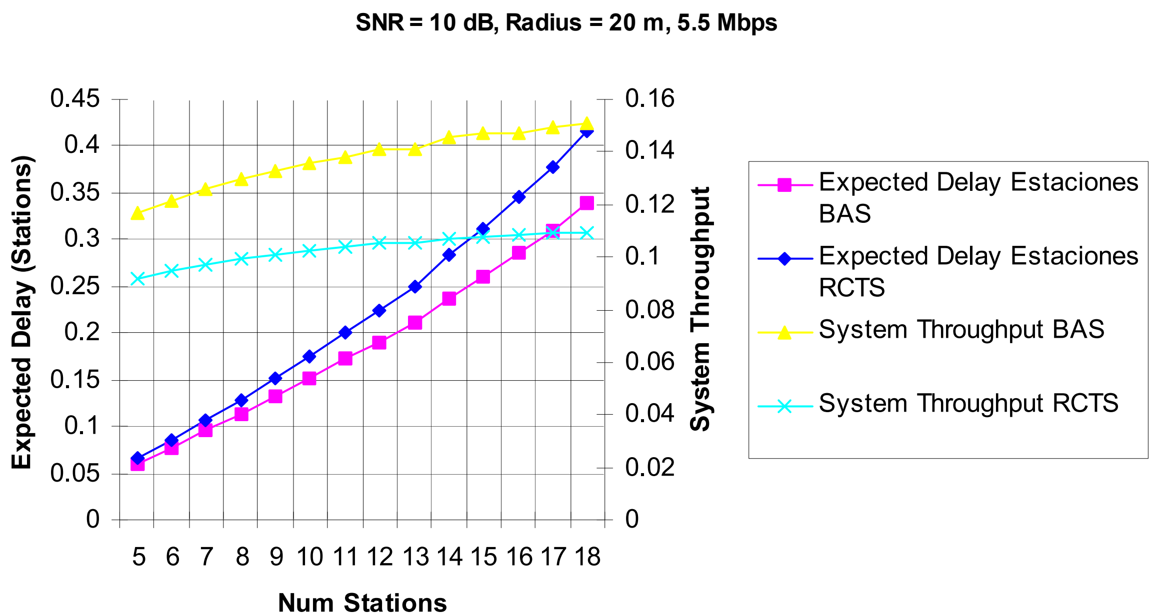

Figure 7.78. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 20 m, Bit Rate = 5.5 Mbps

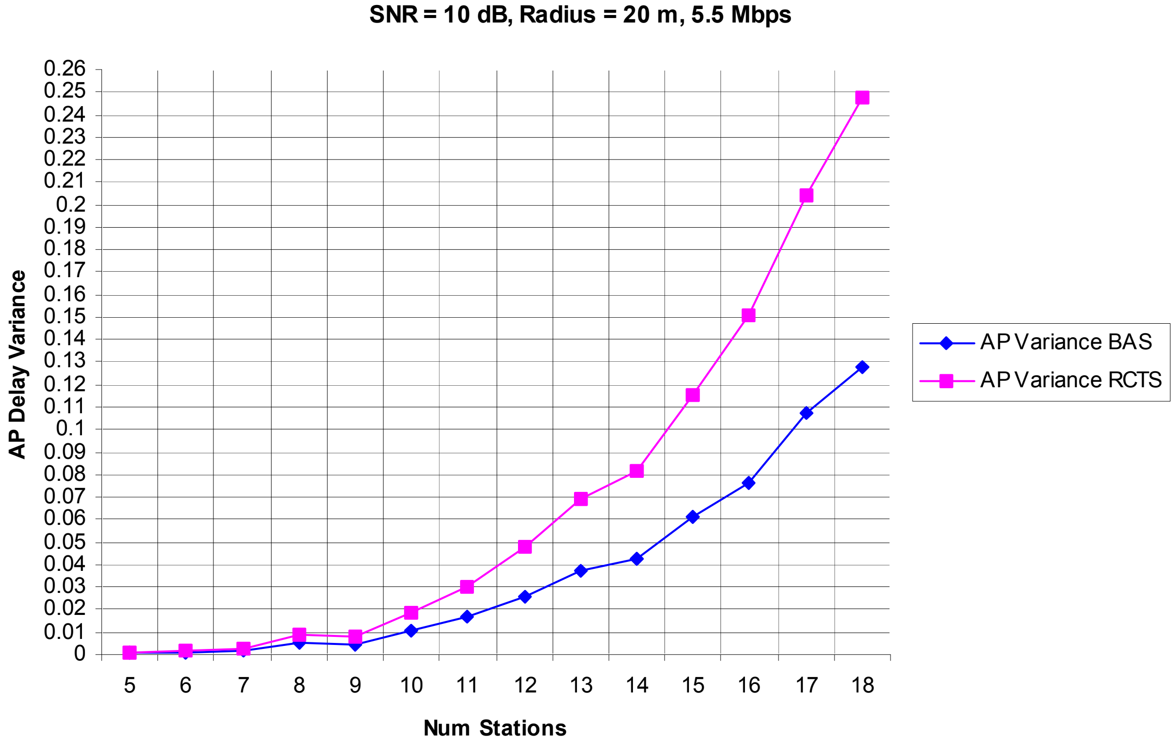

Figure 7.79. AP Delay Variance for SNR = 10 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

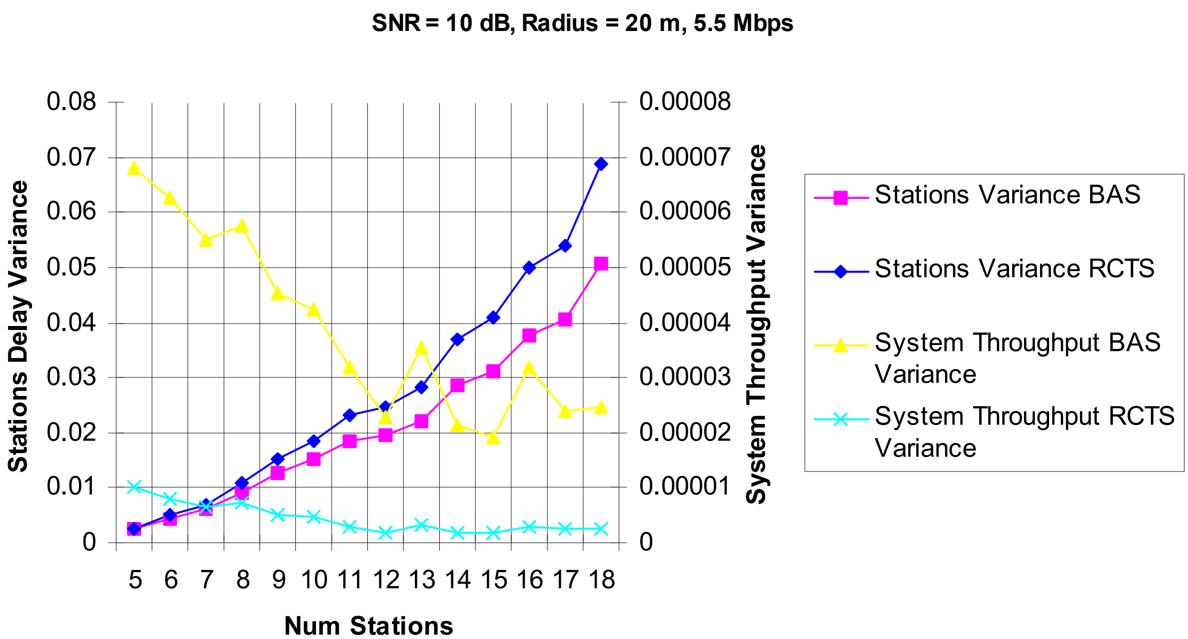

Figure 7.80. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 10 m, Bit Rate = 5.5 Mbps

In Figure 7.77 can be seen that the maximum number of stations the AP can handle is still 5 stations, but with a lower average delay with respect to the 10 meters case. The average delay of the AP when there are 5 stations in the system is 148 ms and the standard deviation is of 26 ms, giving a maximum delay of 174 ms. The stations have an average delay of 60 ms and a standard deviation of 50 ms. As a preliminary conclusion, it is possible to transmit VoWLAN in this scenario.

In figures 7.81 to 7.84 the radius is changed to 30 meters. As in the other cases, it will be seen that in this scenario it is not possible to transmit Vo WLAN.

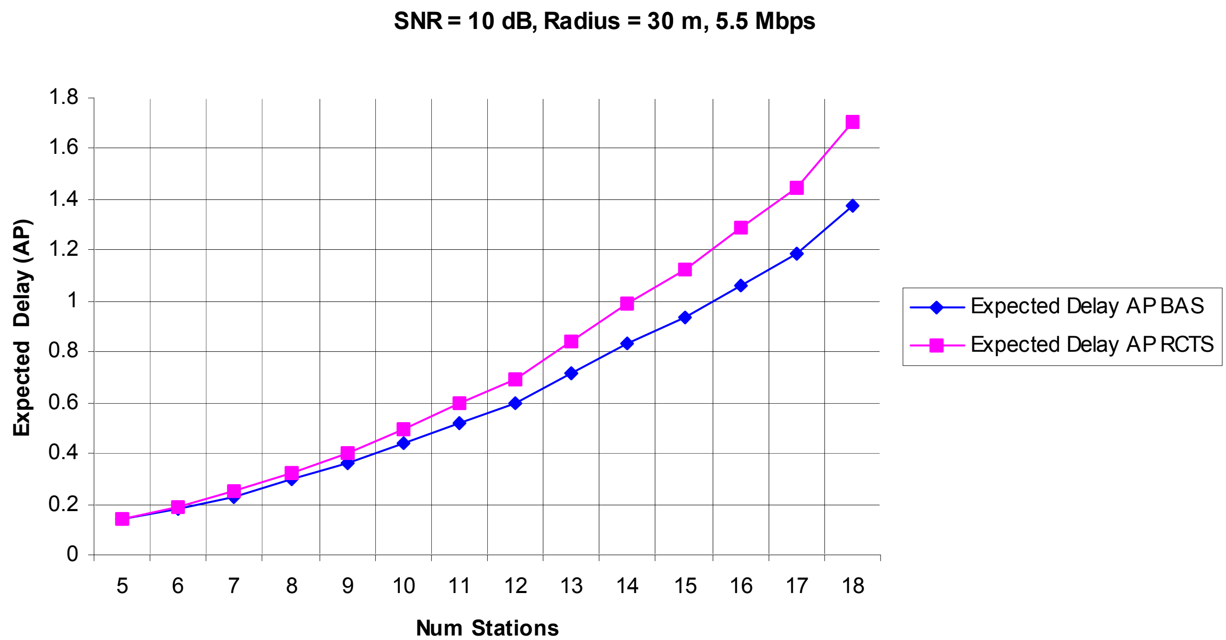

Figure 7.81. AP Expected Delay for SNR = 10 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

In Figure 7.82 can be seen that the average delay is highly above the 250 ms threshold. As an immediate conclusion, it is not possible to transmit VoWLAN when the radius is grater than 30 meters

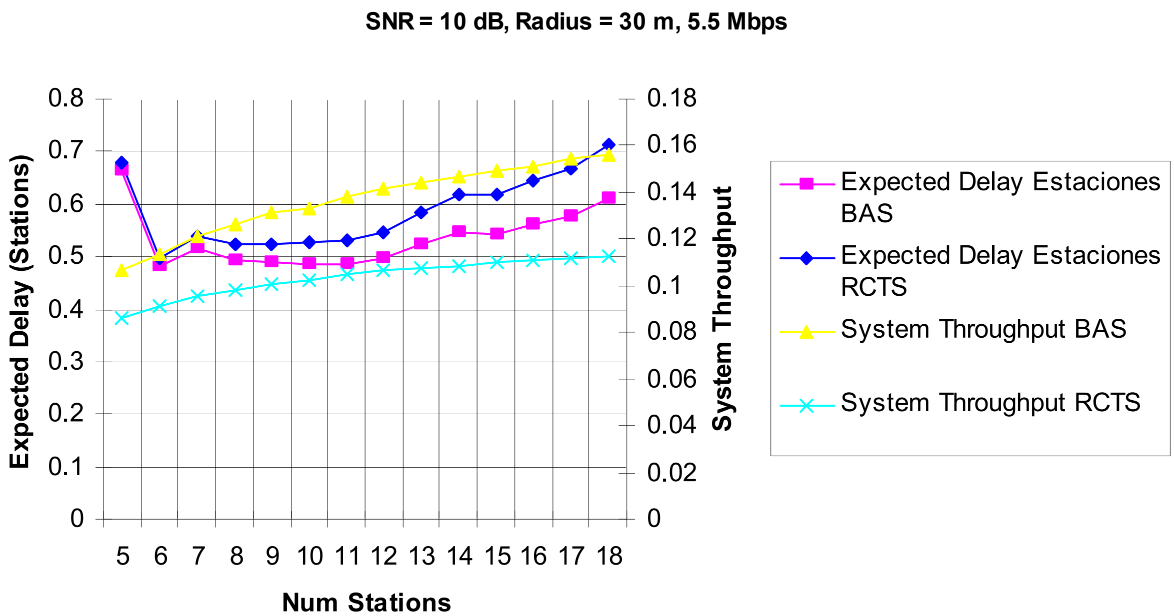

Figure 7.82. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

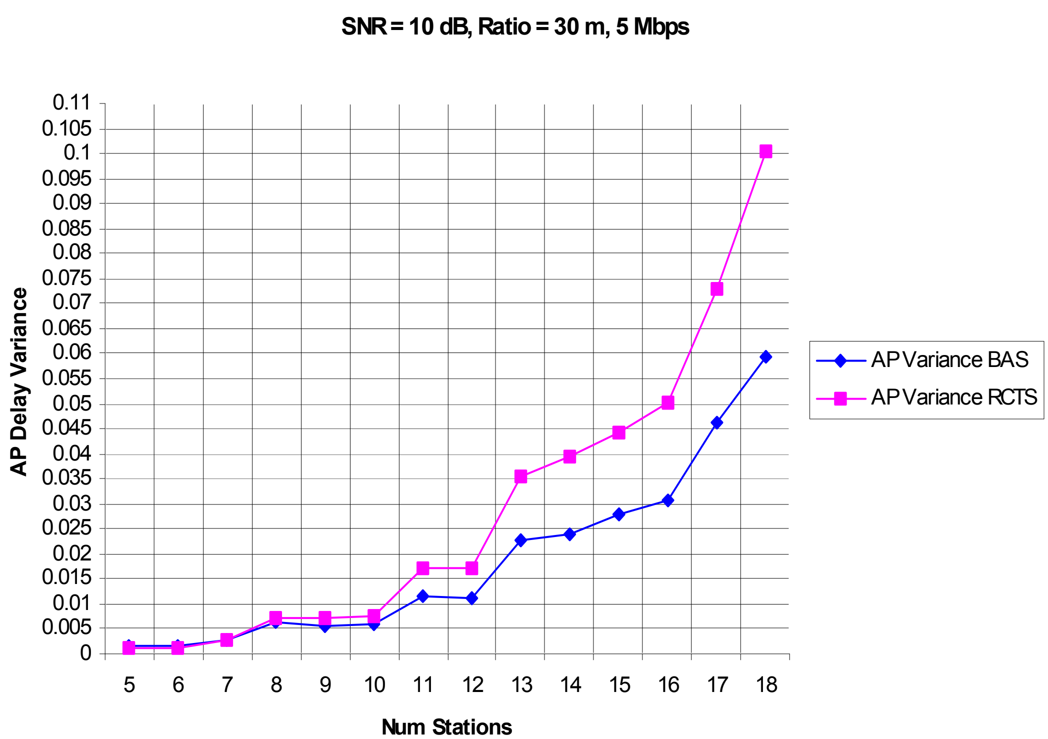

Figure 7.83. AP Delay Variance for SNR = 10 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

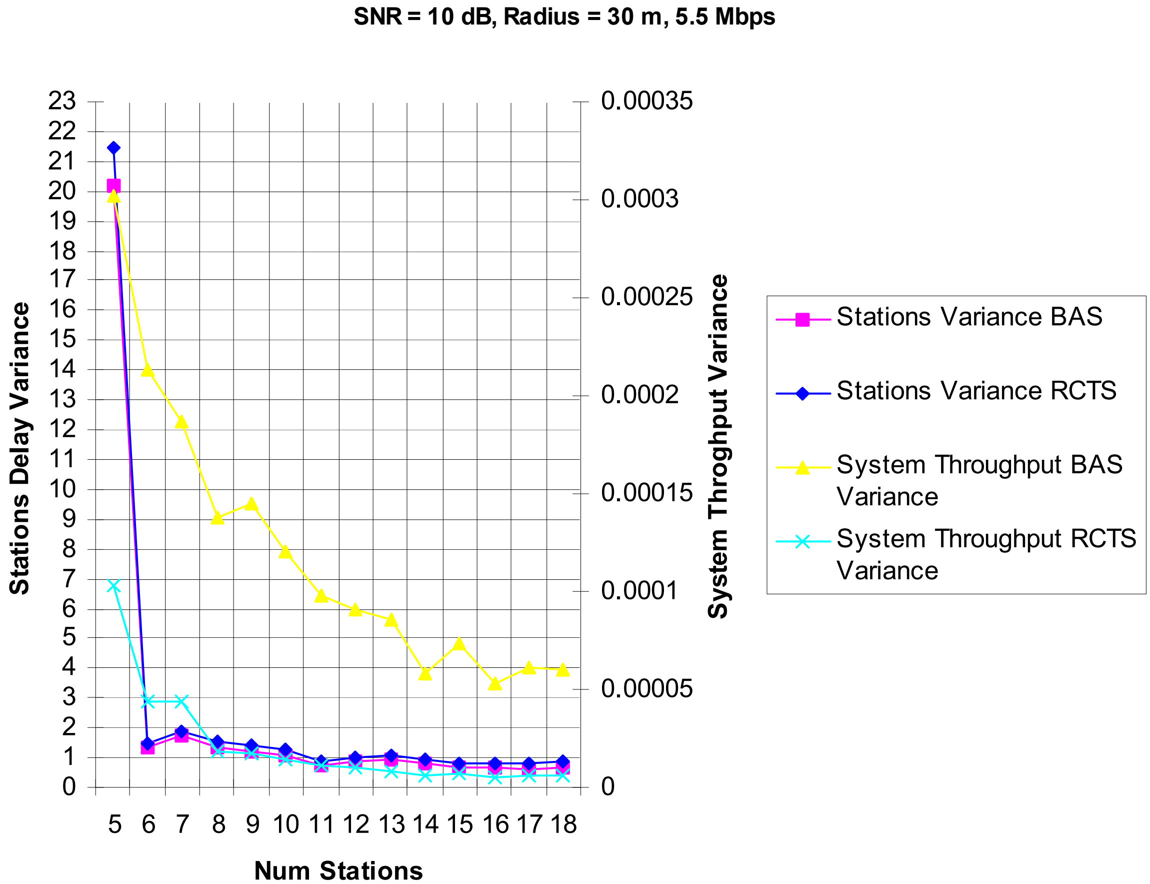

Figure 7.84. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

7.1.8 Scenario: Signal to Noise Ratio = 10 dB at 11 Mbps

We now present the numerical simulations results for the 11 Mbps bit rate. Figures 7.85 to 7.88 shows the AP and stations delay averages and their respective standard deviations as well as the system throughput for the 10 m scenario.

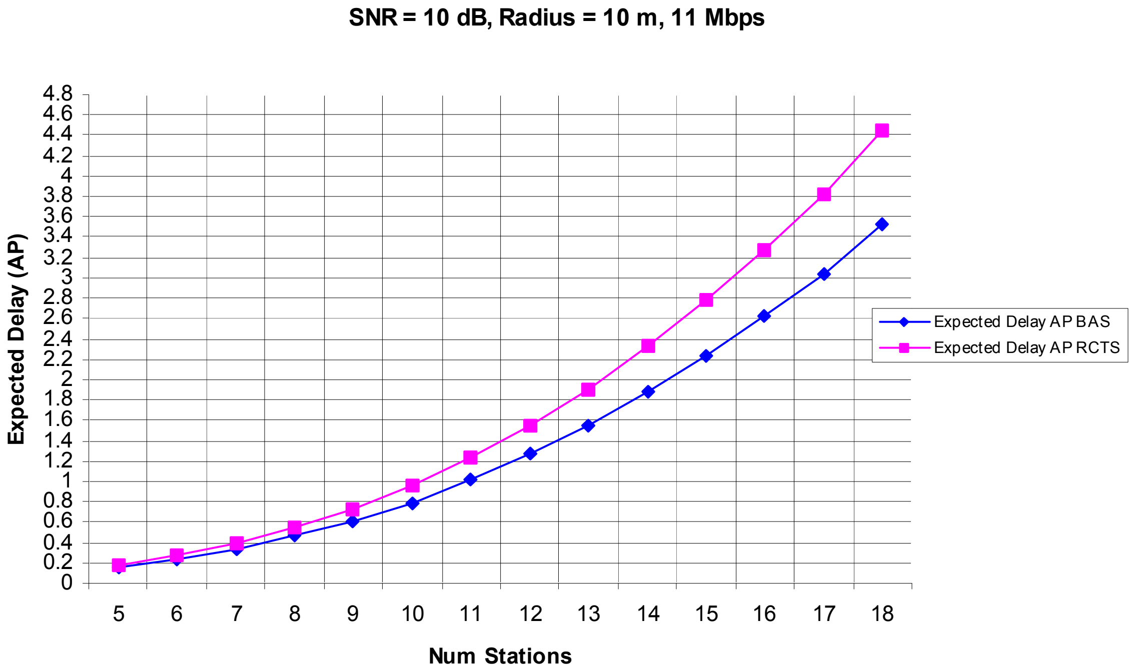

Figure 7.85. AP Expected Delay for SNR = 10 dB, Radius = 10 m, Bit Rate = 11 Mbps

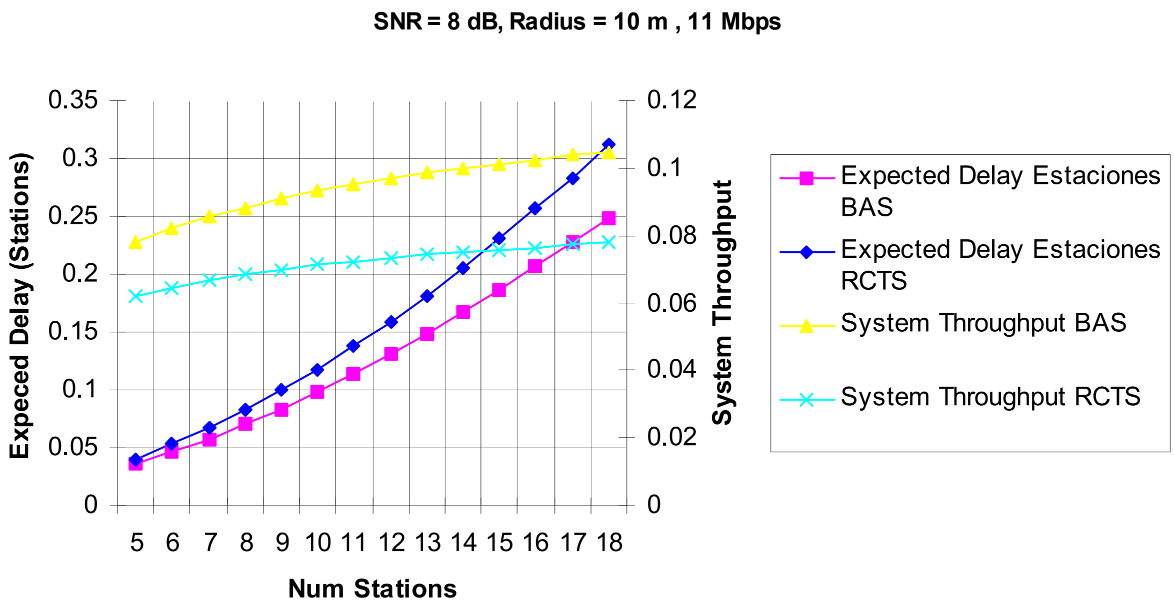

Figure 7.86. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 30 m, Bit Rate = 5.5 Mbps

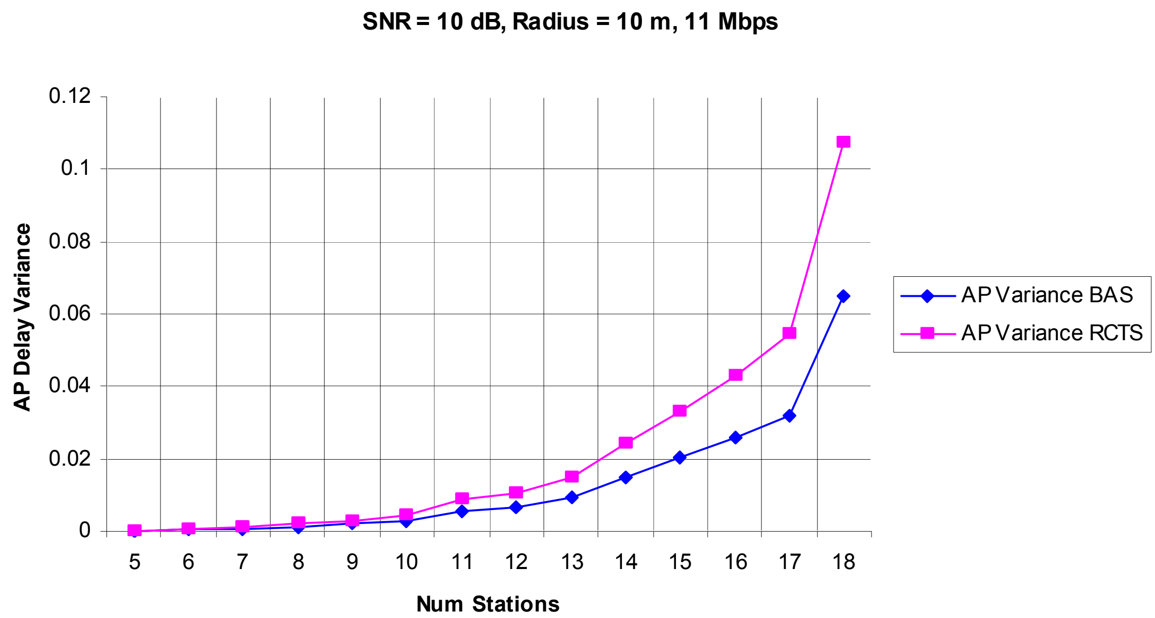

Figure 7.87. AP Delay Variance for SNR = 10 dB, Radius = 10 m, Bit Rate = 11 Mbps

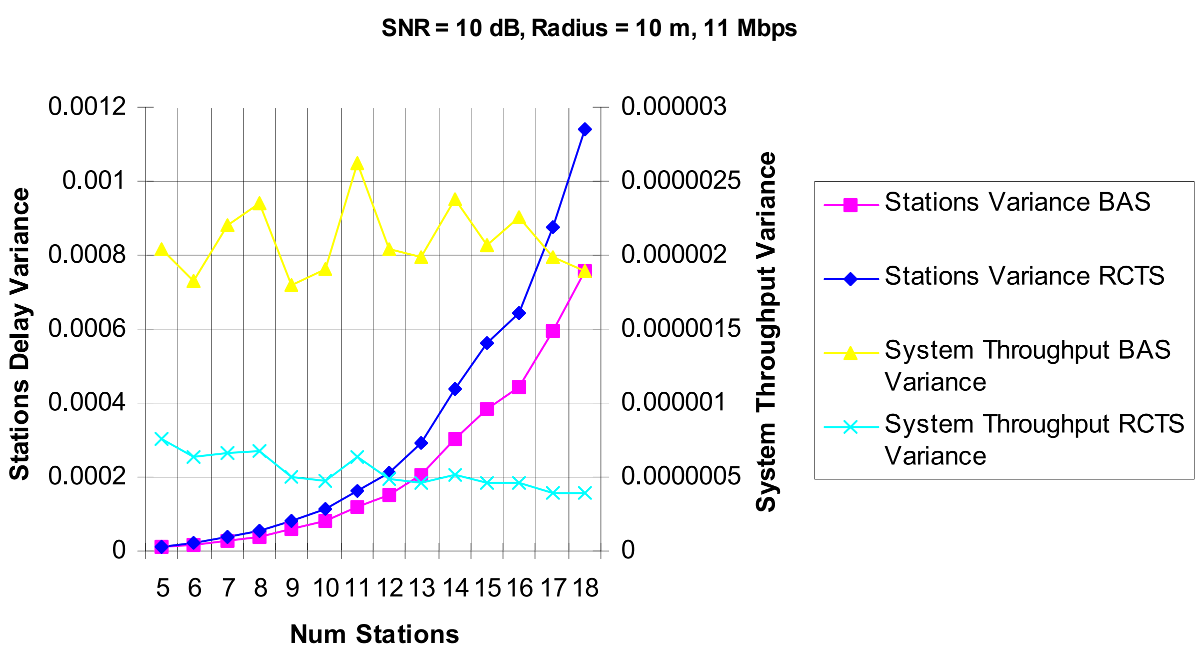

Figure 7.88. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 10 m, Bit Rate = 11 Mbps

For the 10 meter scenario, the maximum number of stations the AP can handle to have an average delay below the 200 ms threshold is 5. (See Figure 7.85) In this case, the AP will have an average delay of 154 ms and a standard deviation of 12 ms (see Figure 7.87). For the stations, the average delay is of 35 ms and the standard deviation is of 3 ms. For this scenario, the transmission of VoWLAN is possible.
Changing the coverage radius to 20 meters, the capacity will have the highest improvement for the 11 Mbps scenario case. Figures 7.89 to 7.92 show the numerical simulation results for this scenario.

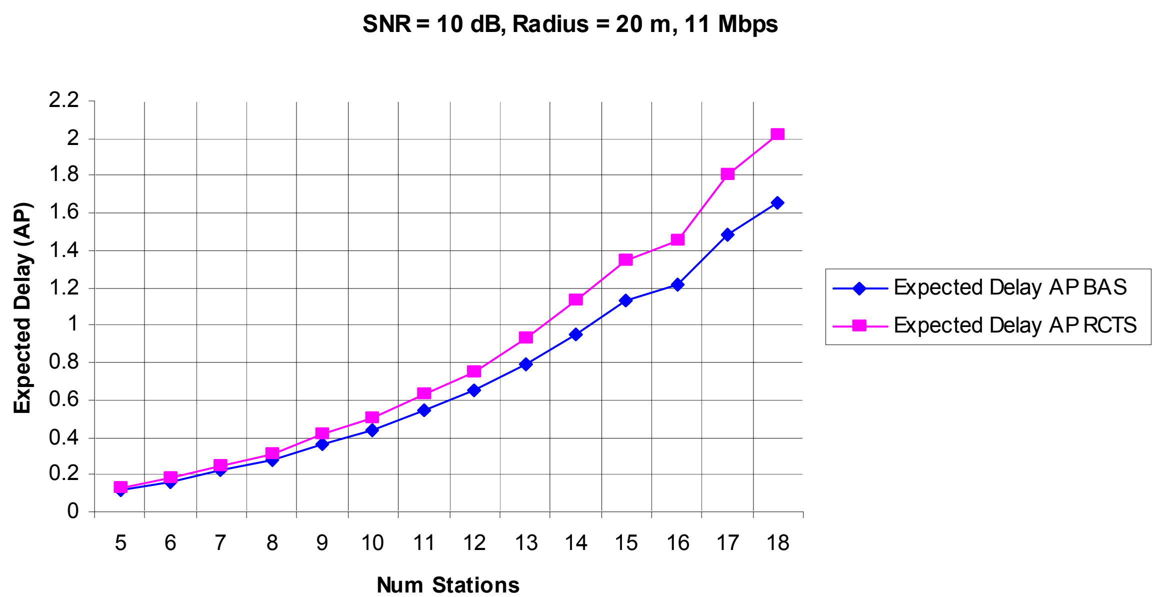

Figure 7.89. AP Expected Delay for SNR = 10 dB, Radius = 20 m, Bit Rate = 11 Mbps

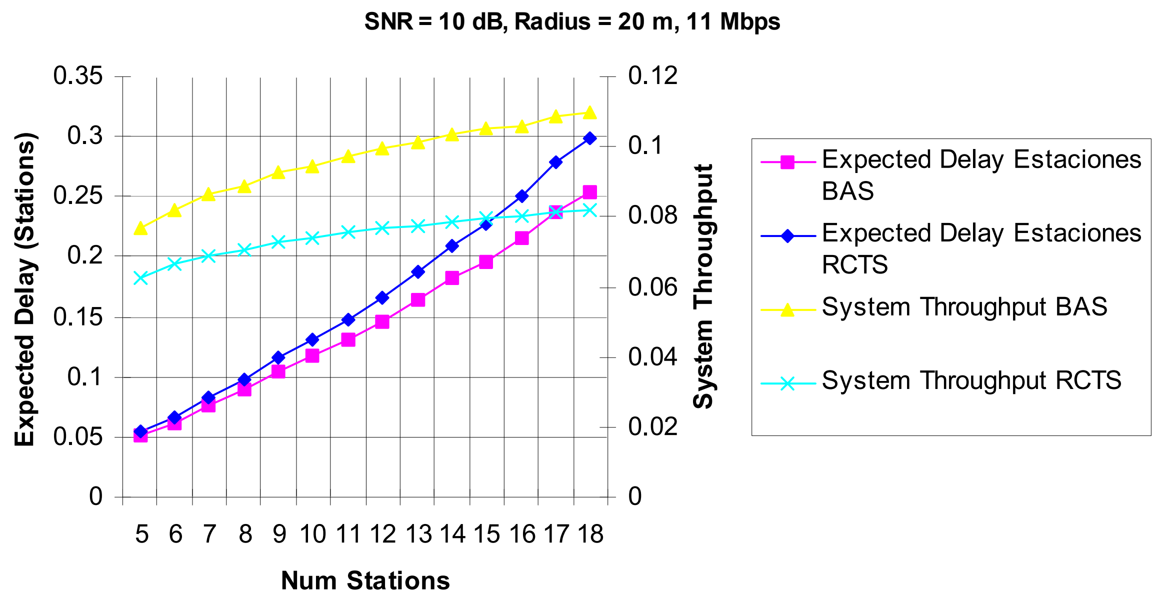

Figure 7.90. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 20 m, Bit Rate = 11 Mbps

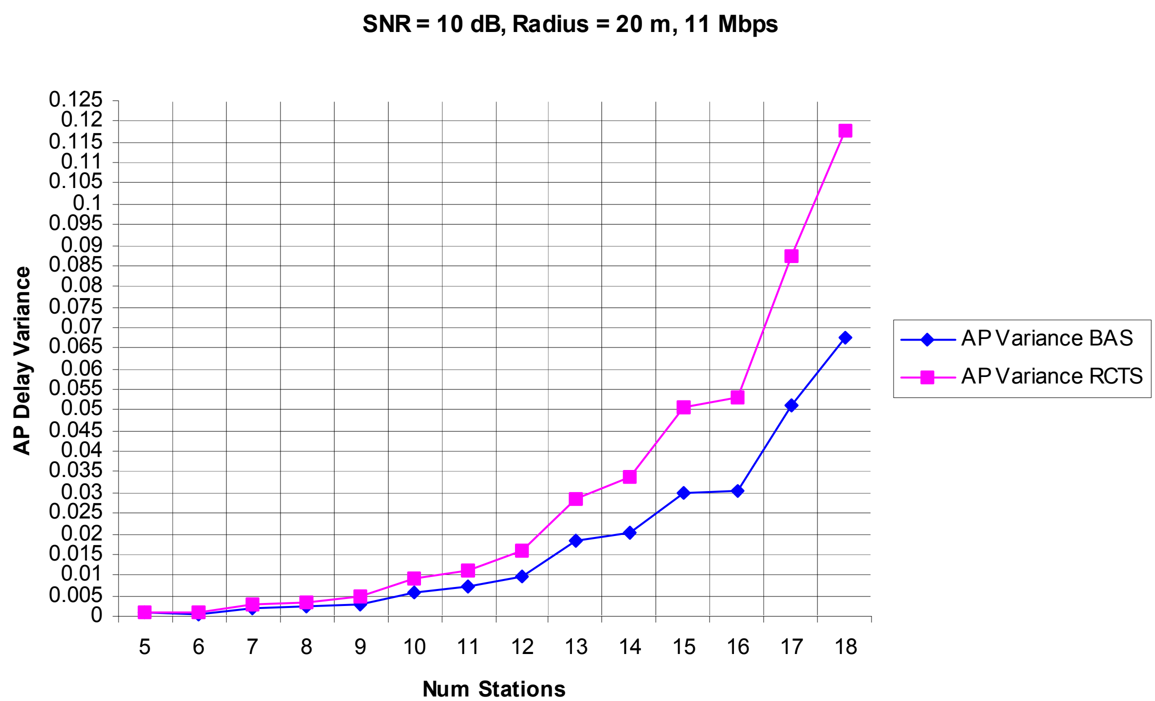

Figure 7.91. AP Delay Variance for SNR = 10 dB, Radius = 20 m, Bit Rate = 11 Mbps

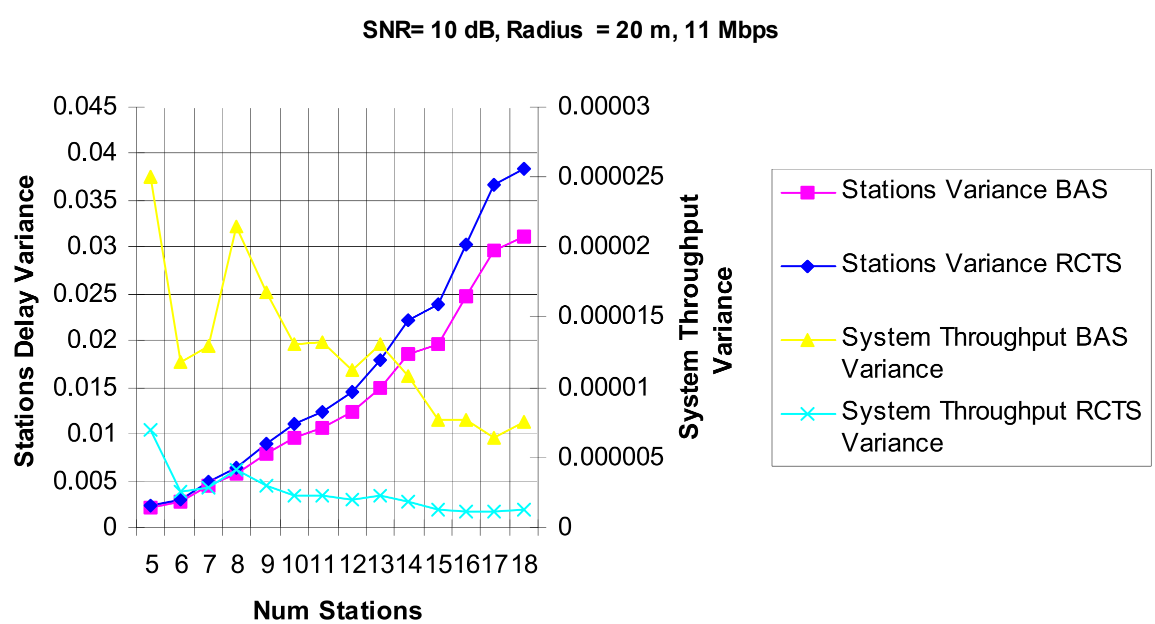

Figure 7.92. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 20 m, Bit Rate = 11 Mbps

For the 20 m radius of coverage, for the AP to have an average delay below the 200 ms threshold, 6 stations are required. Although the number of stations is the same as the 8 dB and one below the 6 dB receivers sensitivity, the delay is slightly higher. With 6 stations the AP has an average delay of 163 ms and a standard deviation of 26 ms. For the same number of station, the stations have an average delay of 62 ms and a standard deviation of 5 ms. With this scenario it is possible to transmit VoWLAN. (See figures 7.90 and 7.92)
For the 30 meters scenario, the results are shown in igures 7.93 to 7.96.

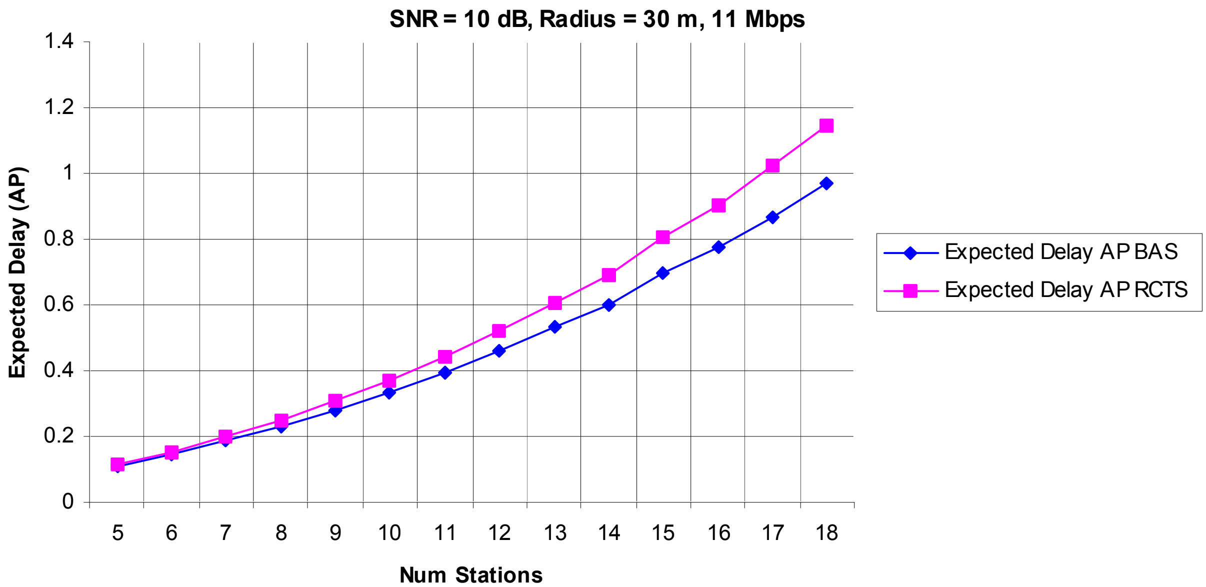

Figure 7.93. AP Expected Delay for SNR = 10 dB, Radius = 30 m, Bit Rate = 11 Mbps

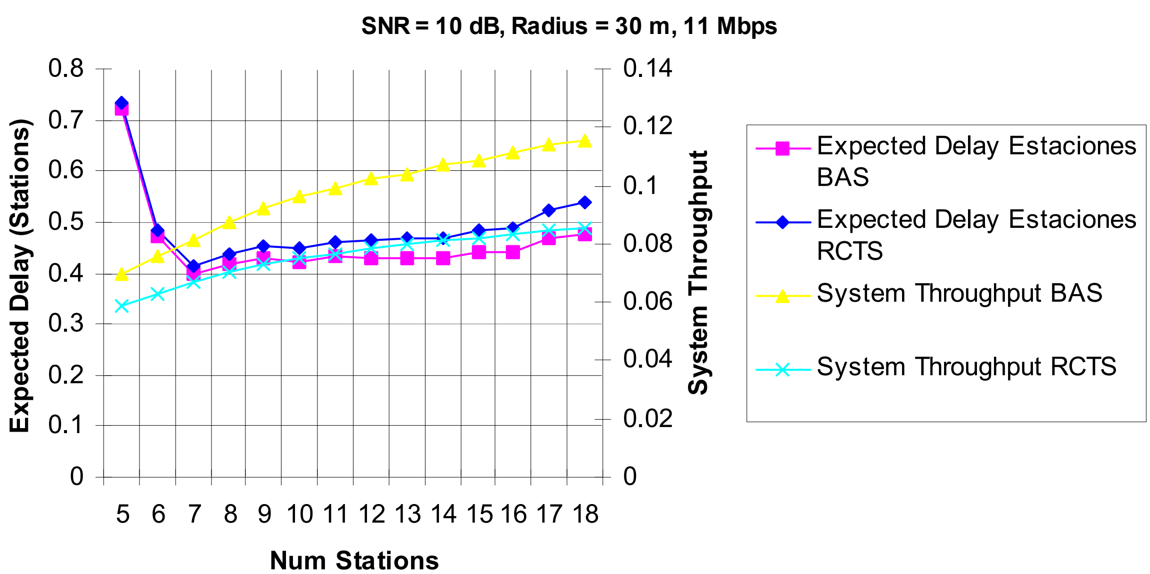

Figure 7.94. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 30 m, Bit Rate = 11 Mbps

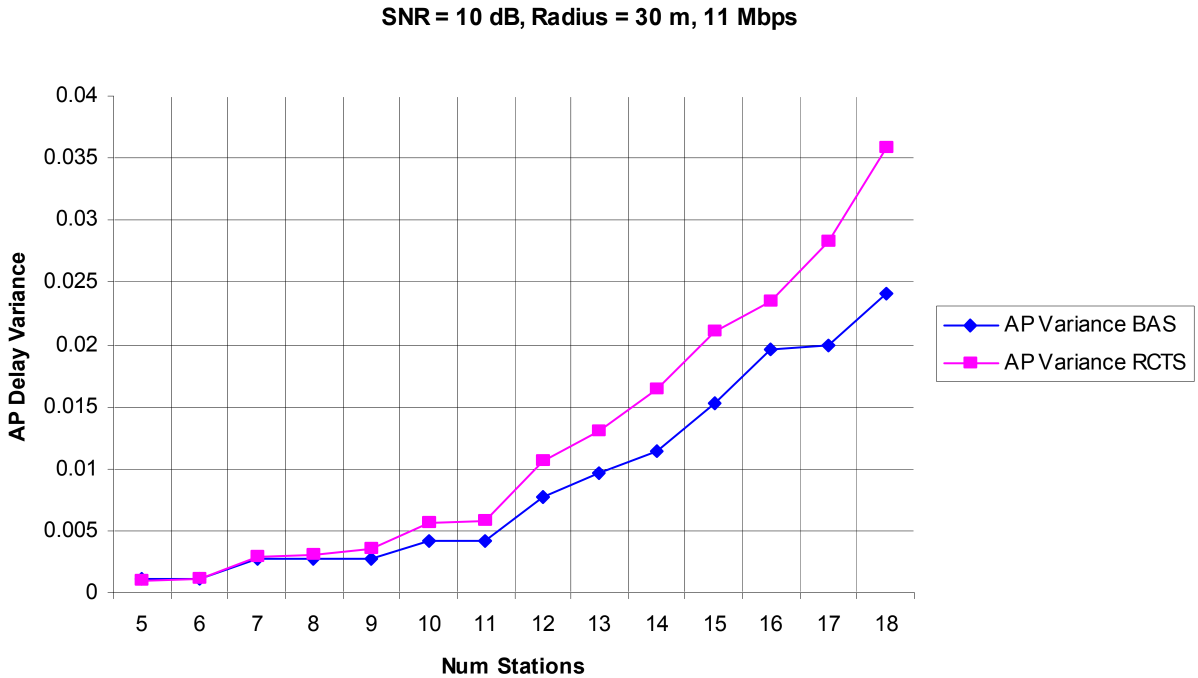

Figure 7.95. AP Delay Variance for SNR = 10 dB, Radius = 30 m, Bit Rate = 11 Mbps

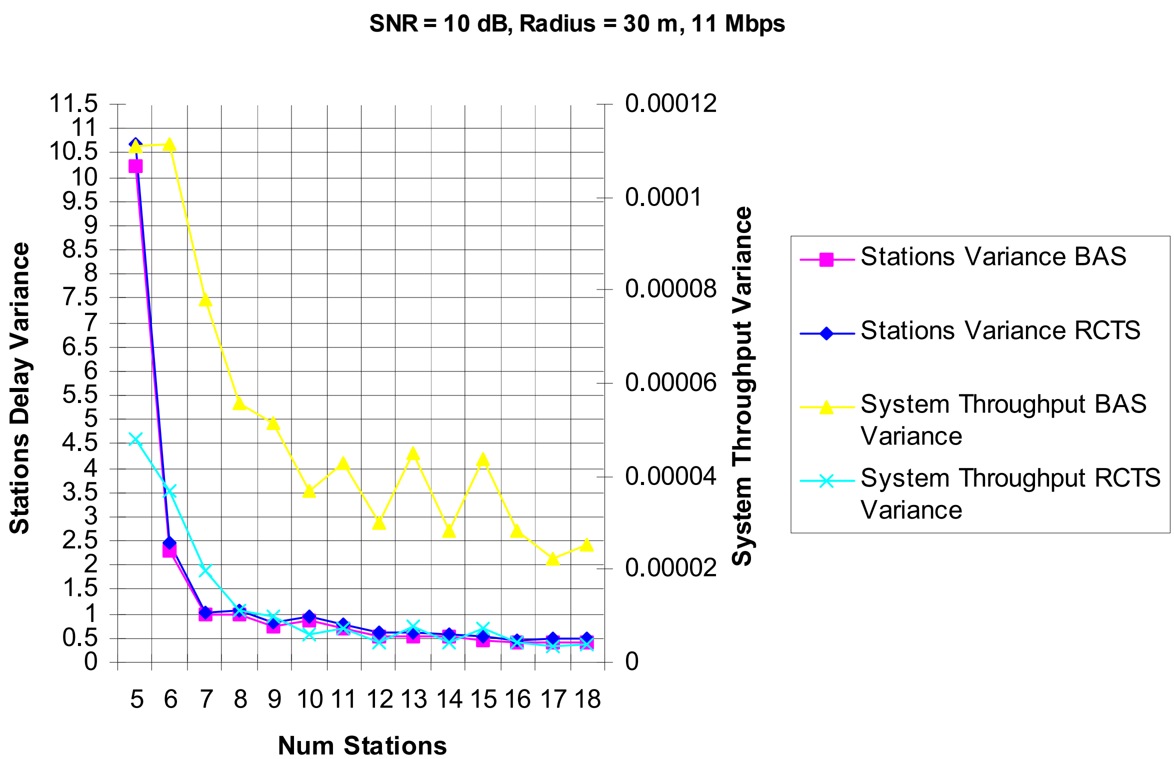

Figure 7.96. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 30 m, Bit Rate = 11 Mbps

It can be seen in Figure 7.94 that the average delay of the stations is above the 250 ms threshold. As an immediate conclusion, VoWLAN cannot be implemented for this scenario.

7.1.9 Scenario: Signal to Noise Ratio = 10 dB at 54 Mbps

We now present the numerical simulations results for the 54 Mbps bit rate.
Figures 7.97 to 7.100 shows the AP and stations delay averages and their respective standard deviations as well as the system throughput for the 10 m scenario.

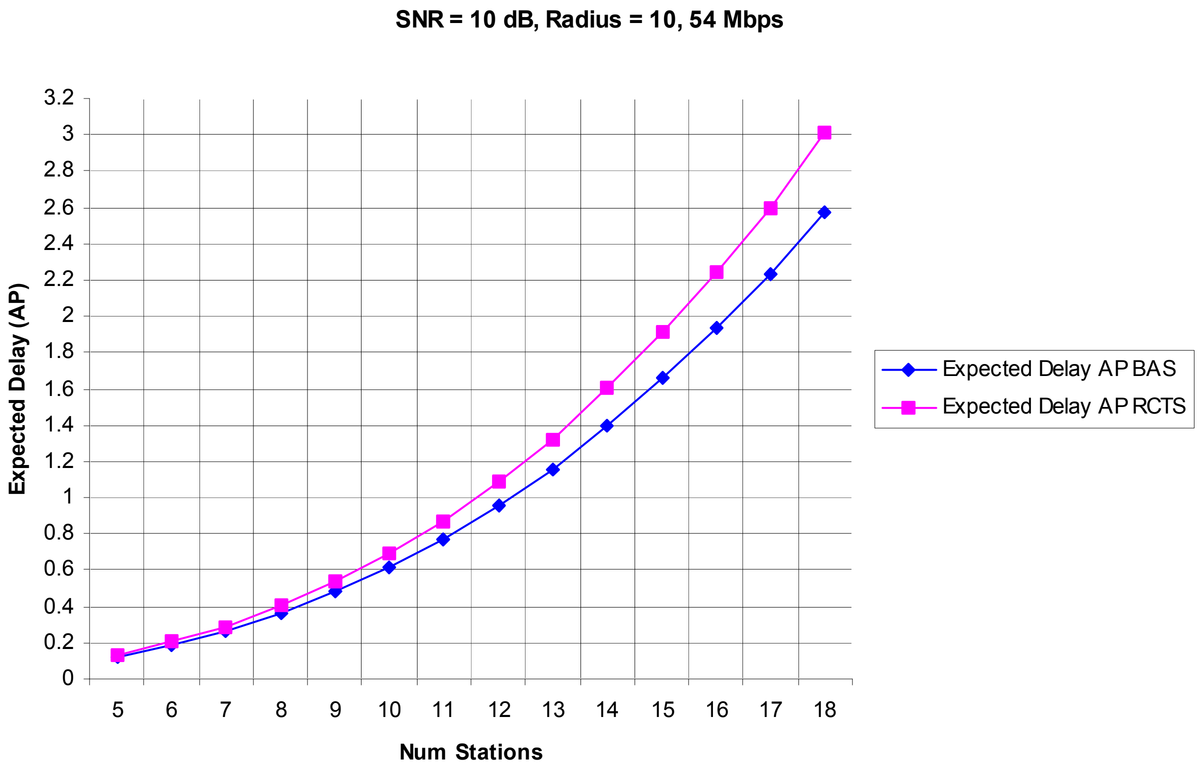

Figure 7.97. AP Expected Delay for SNR = 10 dB, Radius = 10 m, Bit Rate = 54 Mbps

In Figure 7.97 can be seen that the maximum number of stations that can be handled by the AP and have an average delay below the 200 ms threshold is 6. With 6 stations, the average delay of the AP is 188 ms and in Figure 7.99 can be seen that the standard deviations is of 15 ms. For the stations, their average delay is of 37 ms and the standard deviations is of 3 ms. As a preliminary conclusion, for this scenario it is possible to transmit VoWLAN.

It can be seen in Figure 7.94 that the average delay of the stations is above the 250 ms threshold. As an immediate conclusion, VoWLAN cannot be implemented for this scenario.

7.1.9 Scenario: Signal to Noise Ratio = 10 dB at 54 Mbps

We now present the numerical simulations results for the 54 Mbps bit rate.
Figures 7.97 to 7.100 shows the AP and stations delay averages and their respective standard deviations as well as the system throughput for the 10 m scenario.

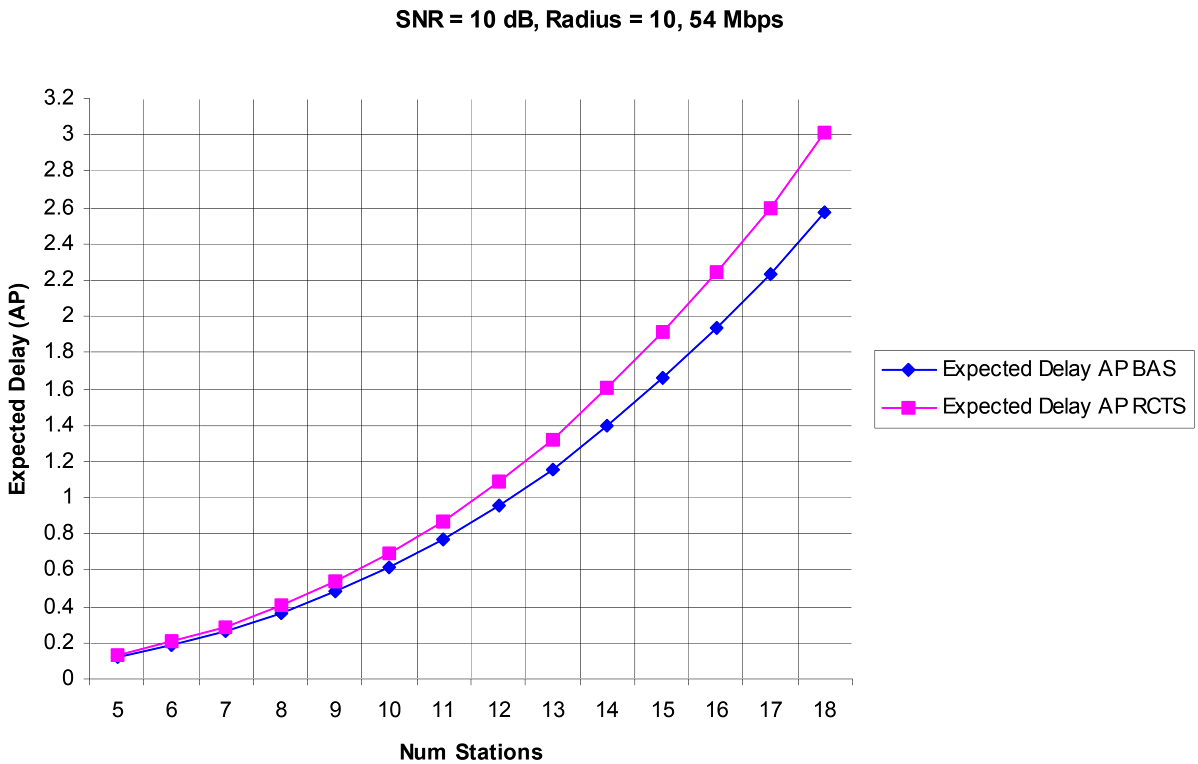

Figure 7.97. AP Expected Delay for SNR = 10 dB, Radius = 10 m, Bit Rate = 54 Mbps

In Figure 7.97 can be seen that the maximum number of stations that can be handled by the AP and have an average delay below the 200 ms threshold is 6. With 6 stations, the average delay of the AP is 188 ms and in Figure 7.99 can be seen that the standard deviations is of 15 ms. For the stations, their average delay is of 37 ms and the standard deviations is of 3 ms. As a preliminary conclusion, for this scenario it is possible to transmit VoWLAN.

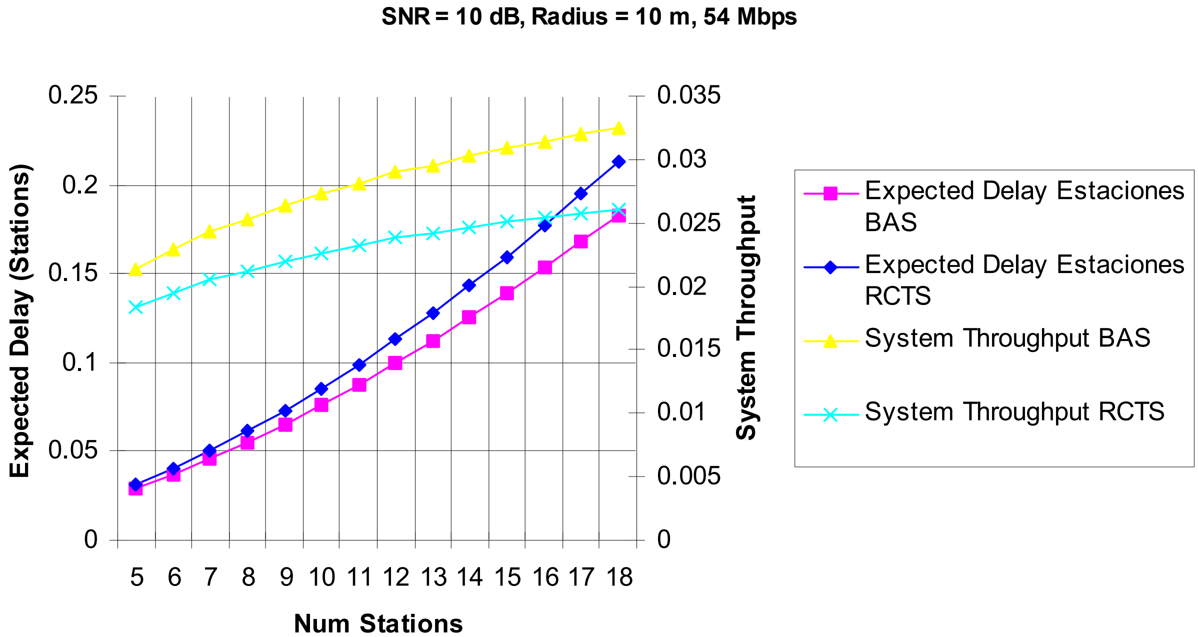

Figure 7.98. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 10 m, Bit Rate = 54 Mbps

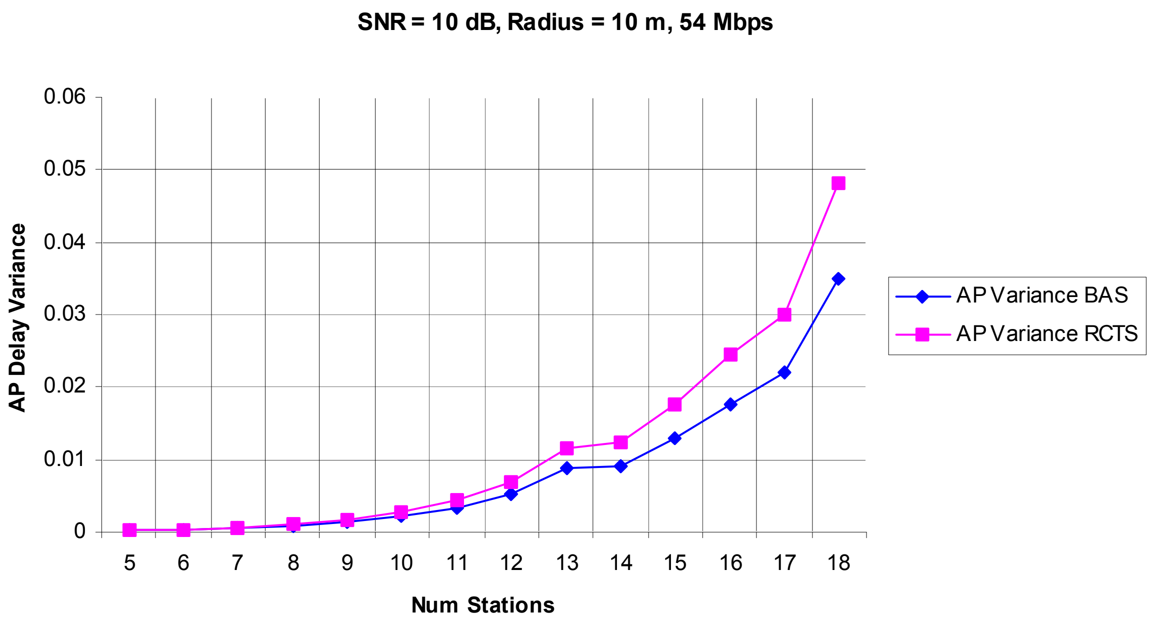

Figure 7.99. AP Delay Variance for SNR = 10 dB, Radius = 10 m, Bit Rate = 54 Mbps

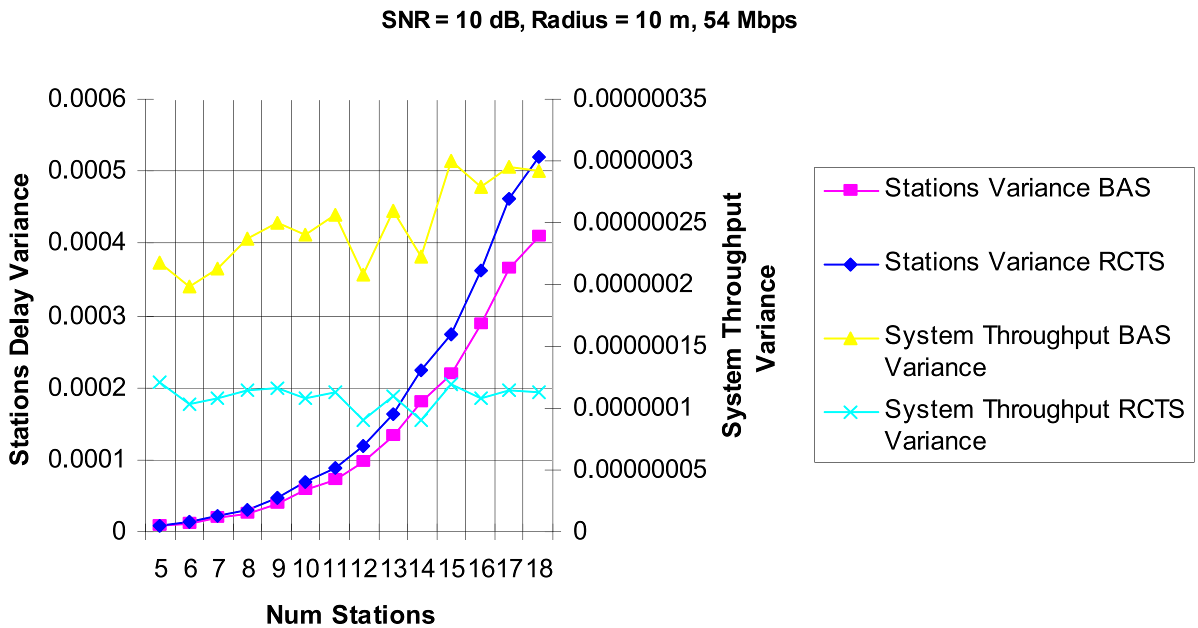

Figure 7.100. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 10 m, Bit Rate = 54 Mbps

For the case when the radius of coverage is changed to 20 meters, figures 7.101 to 7.104 show the numerical simulation results.

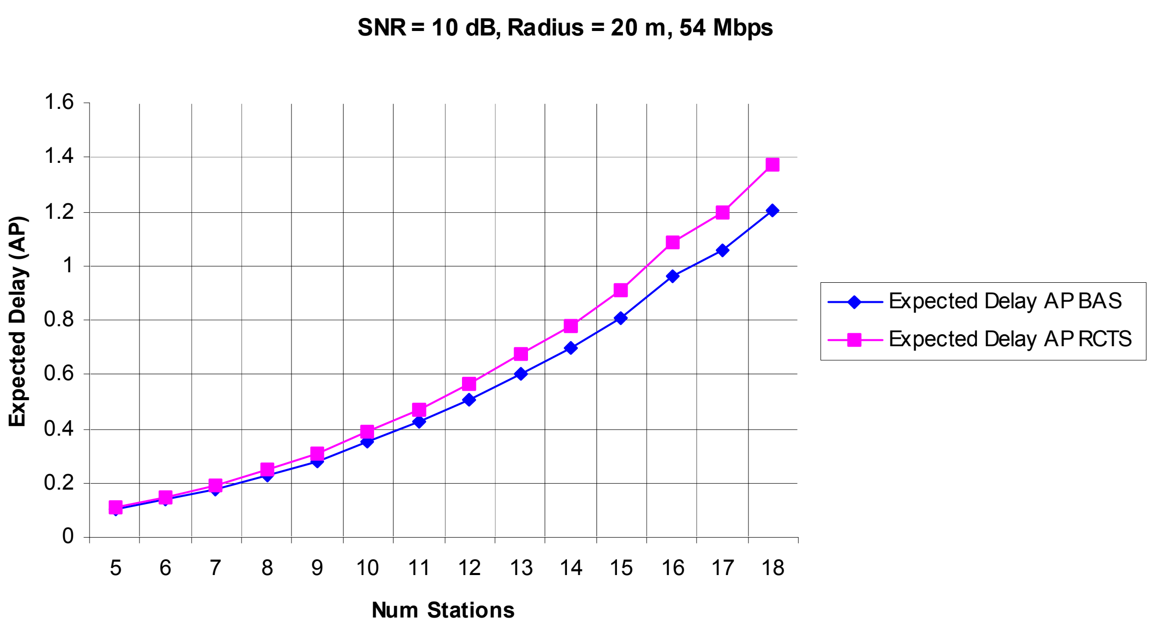

Figure 7.101. AP Expected Delay for SNR = 10 dB, Radius = 20 m, Bit Rate = 54 Mbps

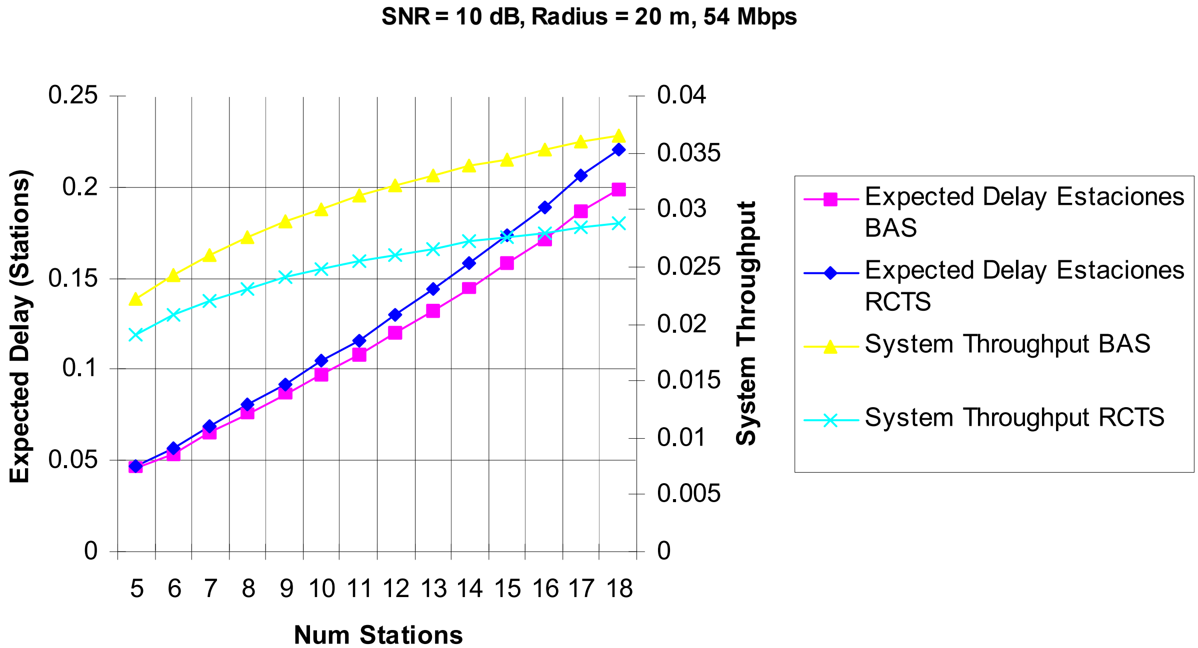

Figure 7.102. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 20 m, Bit Rate = 54 Mbps

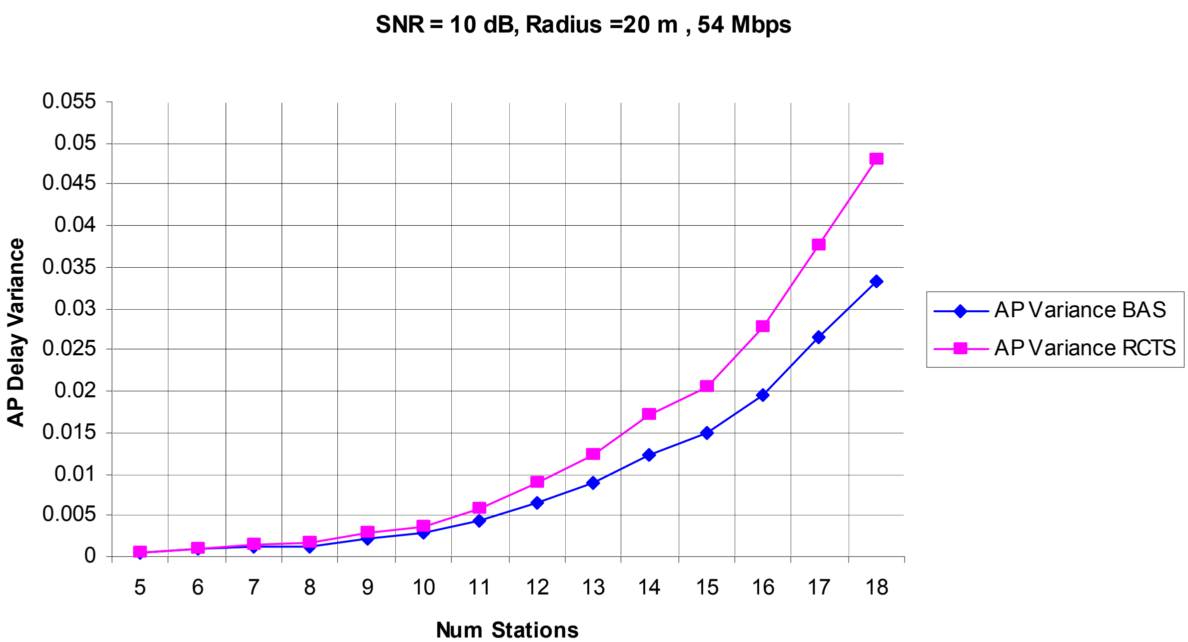

Figure 7.103. AP Delay Variance for SNR = 10 dB, Radius = 20 m, Bit Rate = 54 Mbps

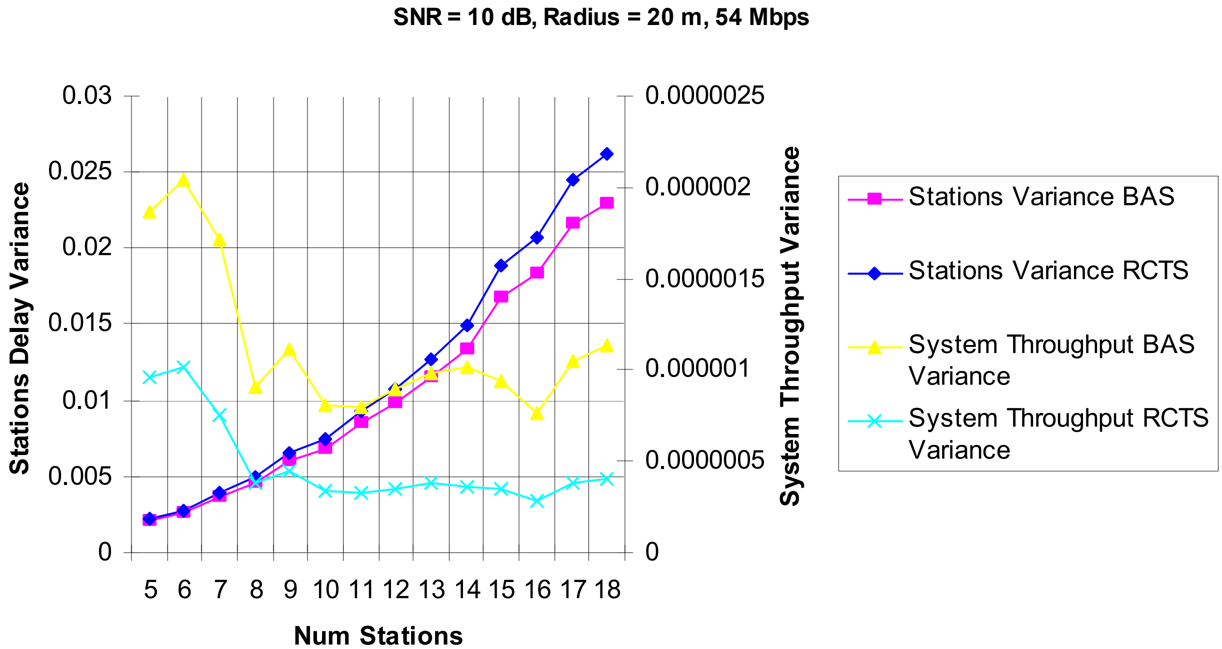

Figure 7.104. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 20 m, Bit Rate = 54 Mbps

As expected, the 20 meters radius at 54 Mbps is the best-case scenario for the transmission of VoWLAN. In Figure 7.101 can be seen that the maximum number of stations the AP can handle below the 200 ms threshold is 7 stations. For this 7 stations, the AP will have an average delay of 180 ms and a standard deviation of 35 ms, giving a maximum delay of215 ms, which is below the maximum allowable delay threshold of 250 ms. For the case of the stations, Figure 7.103 show that the average delay of a station is of 65 ms with a standard deviation of 60 ms (See Figure 7.104). For this scenario, the transmission of VoWLAN is possible.

In figures 7.105 to 7.108 the numerical simulation results for the case of changing the radius to 30 meters is shown. As can be seen in Figure 7.106, the average delay of the stations is highly above the 250 ms threshold. As an immediate conclusion, it is not possible to transmit VoWLAN for this scenario.

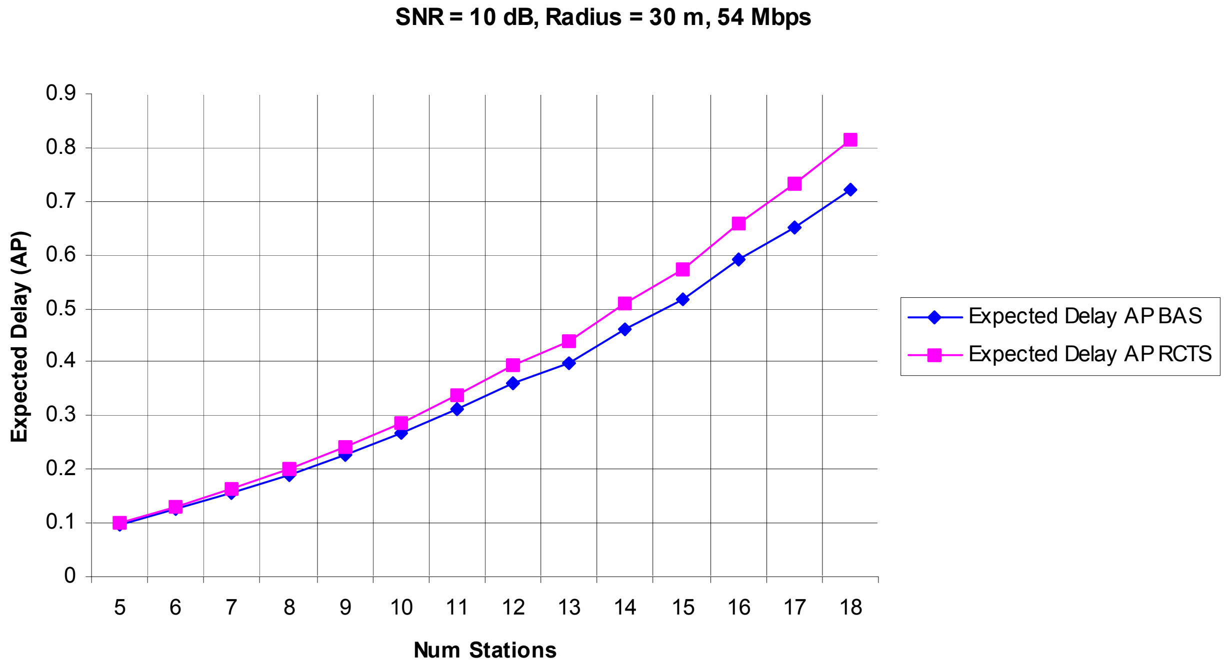

Figure 7.105. AP Expected Delay for SNR = 10 dB, Radius = 30 m, Bit Rate = 54 Mbps

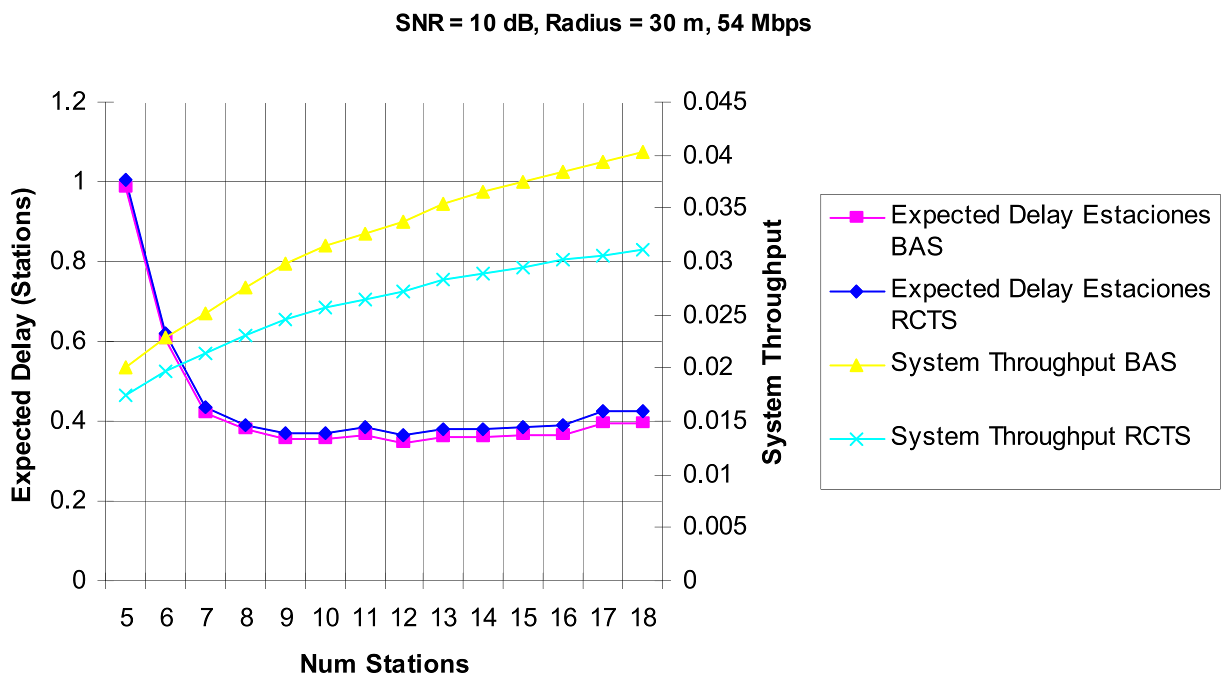

Figure 7.106. Stations Expected Delay and System Throughput for SNR = 10 dB, Radius = 30 m, Bit Rate = 54 Mbps

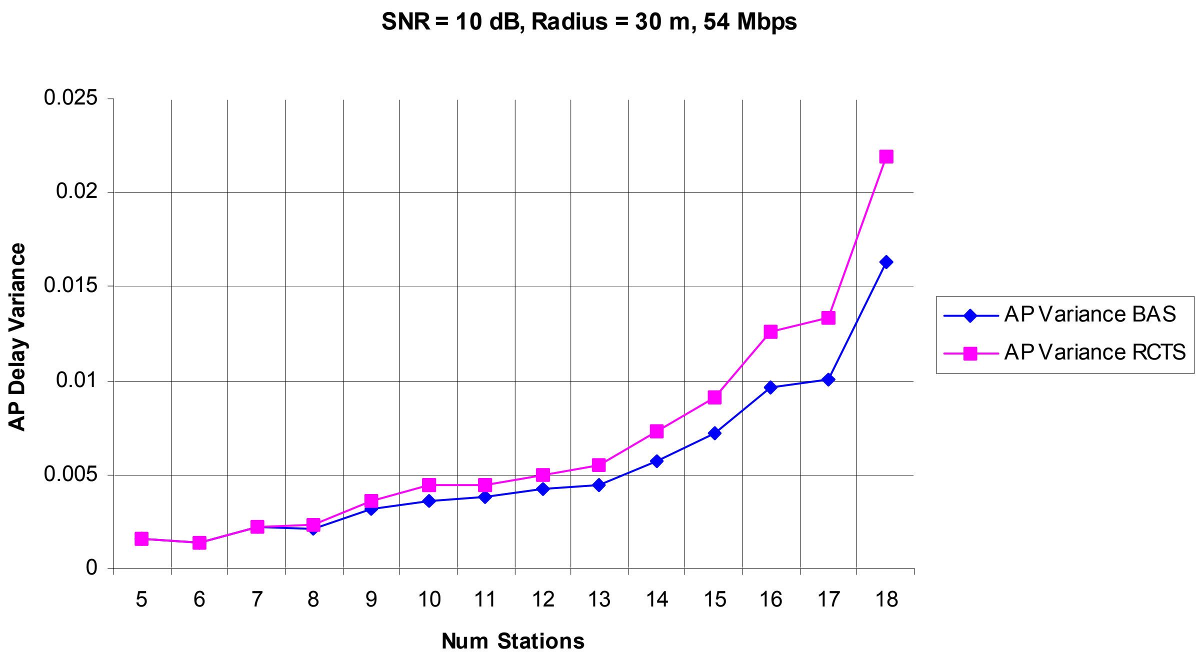

Figure 7.107. AP Delay Variance for SNR = 10 dB, Radius = 30 m, Bit Rate = 54 Mbps

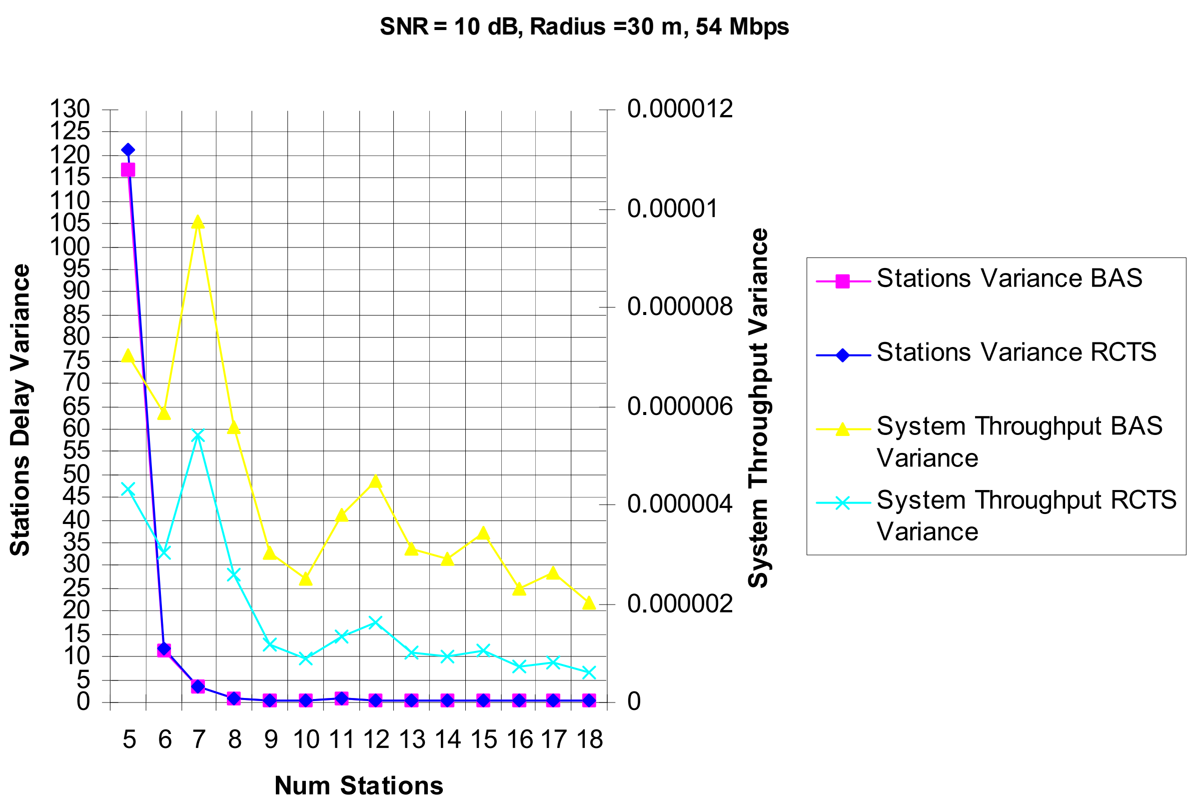

Figure 7.108. Stations Delay Variance and System Throughput Variance for SNR = 10 dB, Radius = 30 m, Bit Rate = 54 Mbps

As can be seen in Figure 7.106, the average delay of the stations is high above the 250 ms threshold. As an immediate conclusion, the transmission of VoWLAN is not possible in this kind of scenarios.

7.1.10 Optimal scenarios for the transmission of VoWLAN (when there are no other interfering WLANs)

Tables 7.2 to 7.10 show optimal scenarios in which the transmission of VoWLAN is possible and in which cases it is not. The last column of each table tells if it is possible to transmit VoWLAN in that specific scenario. The transmission of VoWLAN is possible if the maximum delay of the Uplink and the Downlink is less than 250 ms. The first column represent the bit rate of the system; the second column represents the average delay when the AP and the stations are below the 200 ms threshold; the third column represents the maximum number of stations required for the correct transmission of VoWLAN (delay less than 200 ms in the uplink and the downlink), as has been seen, the required maximum number of stations is defined by the AP average delay. The forth, fifth, sixth and seventh columns represent the average delay, the variance delay, the standard deviation delay and the maximum delay for the required number of stations in column orange.

Table 7.2 Optimal transmission of VoWLAN. SNR = 6 dB, Radius = 10 m, BAS Mechanism

SNR = 6 dB, Radius = 10 m, BAS Mechanism							
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
5.5 Mbps	5	5 Stations	0.198851192	0.00013311	0.011537311	0.210388504	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	13		0.044160977	1.0141E-05	0.003184496	0.047345473	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
11 Mbps	5	5 Stations	0.158952692	7.68266E-05	0.00876508	0.167717772	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	15		0.034873004	7.07908E-06	0.002660653	0.037533658	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
54 Mbps	6	6 Stations	0.193161052	0.000116771	0.010806048	0.2039671	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	18		0.036307853	9.71657E-06	0.003117142	0.039424995	

As can be seen in Figure 7.106, the average delay of the stations is high above the 250 ms threshold. As an immediate conclusion, the transmission of VoWLAN is not possible in this kind of scenarios.

7.1.10 Optimal scenarios for the transmission of VoWLAN (when there are no other interfering WLANs)

Tables 7.2 to 7.10 show optimal scenarios in which the transmission of VoWLAN is possible and in which cases it is not. The last column of each table tells if it is possible to transmit VoWLAN in that specific scenario. The transmission of VoWLAN is possible if the maximum delay of the Uplink and the Downlink is less than 250 ms. The first column represent the bit rate of the system; the second column represents the average delay when the AP and the stations are below the 200 ms threshold; the third column represents the maximum number of stations required for the correct transmission of VoWLAN (delay less than 200 ms in the uplink and the downlink), as has been seen, the required maximum number of stations is defined by the AP average delay. The forth, fifth, sixth and seventh columns represent the average delay, the variance delay, the standard deviation delay and the maximum delay for the required number of stations in column orange.

Table 7.2 Optimal transmission of VoWLAN. SNR = 6 dB, Radius = 10 m, BAS Mechanism

SNR = 6 dB, Radius = 10 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.198851192	0.00013311	0.011537311	0.210388504	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	13		0.044160977	1.0141E-05	0.003184496	0.047345473	
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.158952692	7.68266E-05	0.00876508	0.167717772	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	15		0.034873004	7.07908E-06	0.002660653	0.037533658	
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.193161052	0.000116771	0.010806048	0.2039671	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	18		0.036307853	9.71657E-06	0.003117142	0.039424995	

Table 7.3 Optimal transmission of VoWLAN. SNR = 6 dB, Radius = 20 m, BAS Mechanism

SNR = 6 dB, Radius = 20 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.161917219	0.000960779	0.030996438	0.192913657	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	14		0.04514993	0.00020495	0.014316075	0.059466005	
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.175871	0.001120624	0.033475719	0.209346719	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	17		0.04507861	0.000174328	0.013203335	0.058281945	
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	7	7 Stations	0.18912775	0.000994952	0.031542859	0.220670609	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	19		0.045176318	0.00020175	0.014203883	0.059380202	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.141499398	0.000598734	0.024469041	0.165968439	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	19		0.03753202	0.000148364	0.012180479	0.049712499	

Table 7.4 Optimal transmission of VoWLAN. SNR = 6 dB, Radius = 30 m, BAS Mechanism

SNR = 6 dB, Radius = 30 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.184411964	0.001560608	0.039504528	0.223916492	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	9		0.141533852	0.073167164	0.270494295	0.412028147	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.136703944	0.00076343	0.027630237	0.164334181	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	9		0.131292221	0.061416656	0.24782384	0.379116061	
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	7	7 Stations	0.197566043	0.001926212	0.043888631	0.241454674	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	12		0.129129323	0.050501969	0.224726431	0.353855754	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.151314032	0.000676099	0.0260019	0.177315931	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	12		0.122850737	0.065999952	0.256904557	0.379755295	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.110682533	0.000854614	0.02923379	0.139916323	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	12		0.126039618	0.074946649	0.273763856	0.399803474	

SNR = 6 dB, Radius = 30 m, BAS Mechanism							
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	8	8 Stations	0.195991613	0.002228669	0.047208785	0.243200397	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	16		0.125306876	0.048853618	0.221028546	0.346335423	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	7	7 Stations	0.152129603	0.000670888	0.025901502	0.178031106	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	16		0.120098538	0.043382069	0.208283626	0.328382164	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.12094692	0.000487406	0.02207728	0.1430242	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	16		0.109720052	0.045795917	0.213999806	0.323719858	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.093746466	0.00073673	0.027142778	0.120889244	FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	16		0.098546789	0.043187011	0.207814848	0.306361637	

Table 7.5 Optimal transmission of VoWLAN. SNR = 8 dB, Radius = 10 m, BAS Mechanism

SNR = 8 dB, Radius = 10 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.198969019	0.000216407	0.014710778	0.213679797	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	12		0.044623138	1.11908E-05	0.003345265	0.047968403	
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.155333379	0.000122456	0.011066004	0.166399383	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	15		0.035204899	6.97824E-06	0.002641636	0.037846535	
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.190743134	0.000179747	0.013406982	0.204150115	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	18		0.03676694	9.61436E-06	0.003100703	0.039867643	

Table 7.6 Optimal transmission of VoWLAN. SNR = 8 dB, Radius = 20 m, BAS Mechanism

SNR = 8 dB, Radius = 20 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.155198305	0.000956322	0.030924463	0.186122768	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	13		0.05090423	0.000788094	0.028073009	0.078977239	
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.166302487	0.000986973	0.031416128	0.197718615	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	16		0.050364732	0.000694131	0.026346359	0.076711091	
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	7	7 Stations	0.183103629	0.000852379	0.029195533	0.212299162	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	19		0.050288211	0.000726557	0.026954728	0.077242939	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.137502997	0.000682069	0.026116445	0.163619442	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	19		0.041938714	0.000490339	0.022143607	0.064082321	

Table 7.7 Optimal transmission of VoWLAN. SNR = 8 dB, Radius = 30 m, BAS Mechanism

SNR = 8 dB, Radius = 30 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	Not Possible	N O T P O S S I B L E				FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	0		N O T P O S S I B L E				
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	7	Not Possible	N O T P O S S I B L E				FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	0		N O T P O S S I B L E				
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	8	Not Possible	N O T P O S S I B L E				FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	0		N O T P O S S I B L E				

Table 7.8 Optimal transmission of VoWLAN. SNR = 10 dB, Radius = 10 m, BAS Mechanism

SNR = 10 dB, Radius = 10 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.194448106	0.000327639	0.01810079	0.212548896	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	12		0.044977138	1.48851E-05	0.003858121	0.048835259	
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.15448982	0.000155385	0.012465335	0.166955155	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	15		0.035553165	8.92552E-06	0.002987562	0.038540727	
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.188725507	0.000222726	0.014923996	0.203649502	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	18		0.037242352	1.12319E-05	0.003351406	0.040593758	

Table 7.9 Optimal transmission of VoWLAN. SNR = 10 dB, Radius = 20 m, BAS Mechanism

SNR = 10 dB, Radius = 20 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	5	5 Stations	0.147947272	0.000677492	0.026028673	0.173975945	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	12		0.060378561	0.002513379	0.050133608	0.110512168	
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.163136929	0.000680931	0.026094648	0.189231577	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	15		0.062202667	0.002849662	0.053382224	0.11558489	
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	7	7 Stations	0.179557854	0.000927079	0.035648097	0.210005821	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	18		0.06563917	0.00371585	0.060957774	0.126596944	
	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	6 Stations	0.138382166	0.000928501	0.030471311	0.168853477	TRUE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	18		0.053936509	0.002598229	0.050972825	0.104909335	

Table 7.10 Optimal transmission of VoWLAN. SNR = 10 dB, Radius = 30 m, BAS Mechanism

SNR = 10 dB, Radius = 30 m, BAS Mechanism							
5.5 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	6	Not Possible	NOT POSSIBLE				FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	0		NOT POSSIBLE				
11 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	7	Not Possible	NOT POSSIBLE				FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	0		NOT POSSIBLE				
54 Mbps	Max. Number of Stations with AP Expected Delay below 200 m sec (**Downlink**)	Required Number of Stations	AP Average Delay	AP Variance	AP Standard Deviation	AP Max. Delay	Transmission of VoWLAN
	8	Not Possible	NOT POSSIBLE				FALSE
	Max. Number of Stations with Stations Expected Delay below 200 m sec. (**Uplink**)		Sta. Average Delay	Sta. Variance	Sta. Standard Deviation	Sta. Max. Delay	
	0		NOT POSSIBLE				

Looking at all the tables, it is clear that the best way to achieve the highest capacity for the transmission of VoWLAN is using the 54 Mbps bit rate, a coverage radius of 20 meters, 5, 6 or 7 stations and the BAS mechanism.

Knowing the best possible way to achieve the highest capacity for VoWLAN in the system, we now limit our results to the 54 Mbps bit rate with a 20 meters radius of coverage. With this in mind, we now present the cumulative distribution functions for the delay given by the numerical simulations results for 5, 6 and 7 stations; and for the signal to noise ratios of 6, 8 and 10 dB. The numerical simulations result for the cumulative distribution function for this scenarios are shown in figures 7.109 through 7.126.

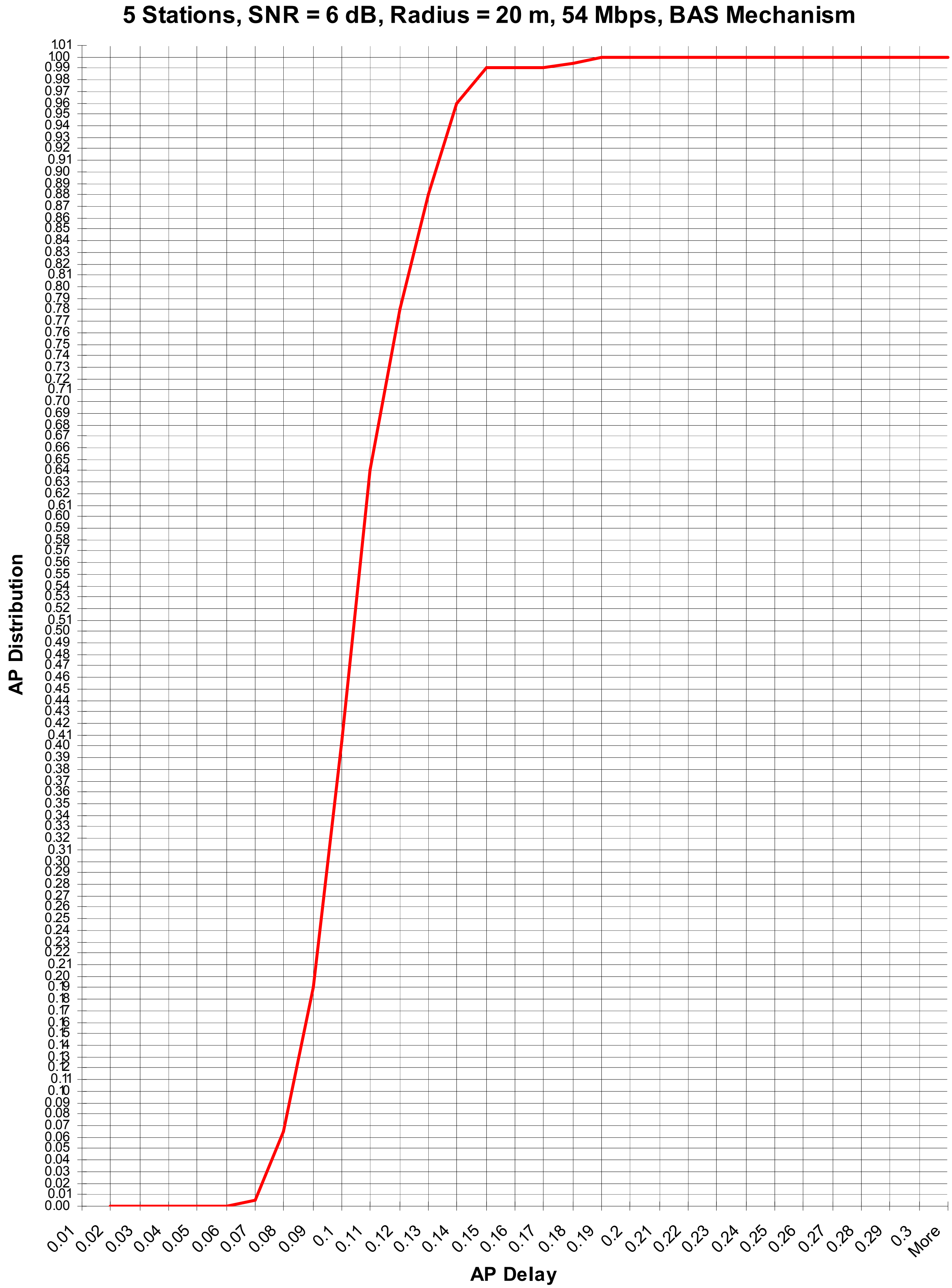

Figure 7.109. Access Point Delay Distribution for 5 Stations, SNR = 6 dB

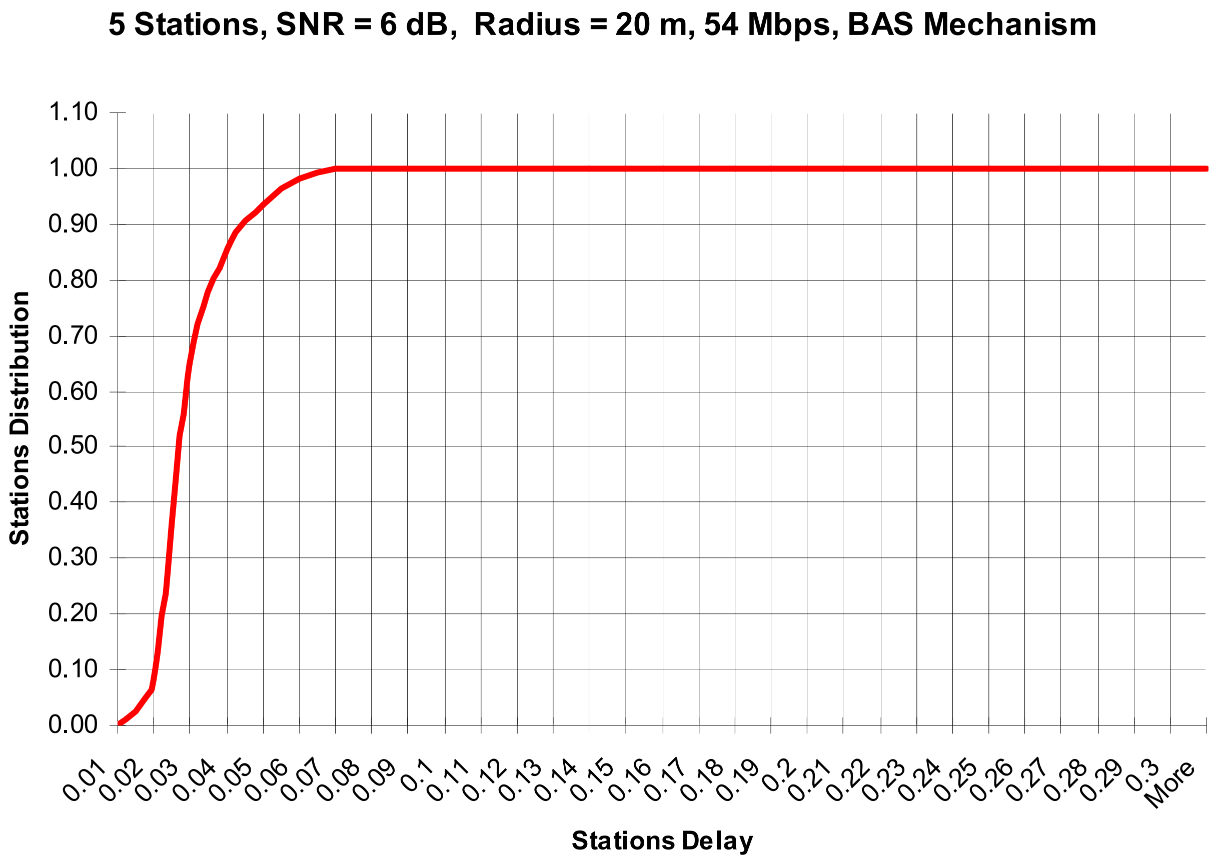

Figure 7.110. Stations Delay Distribution for 5 Stations, SNR = 6 dB

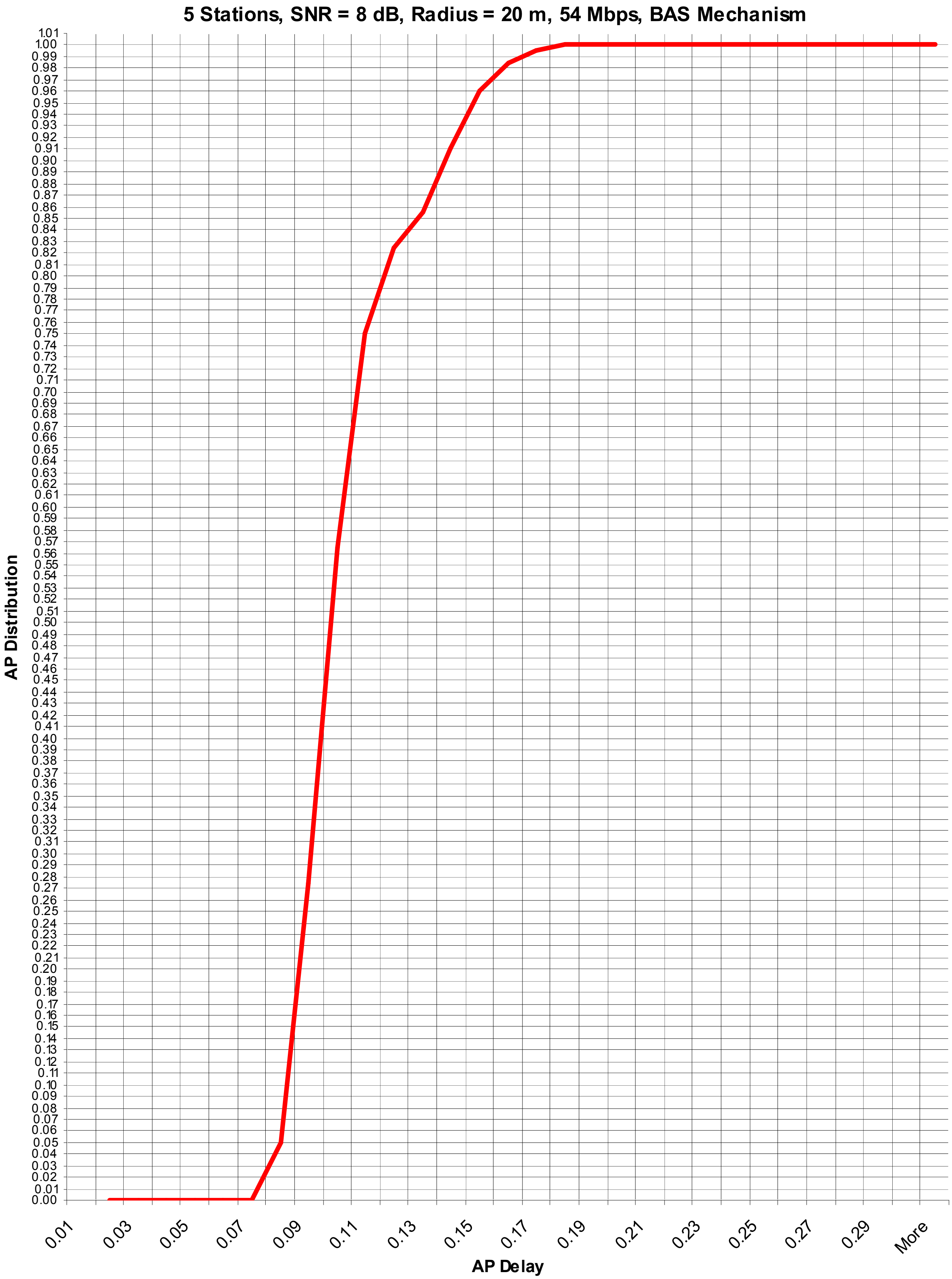

Figure 7.111. AP Delay Distribution for 5 Stations, SNR = 8 dB

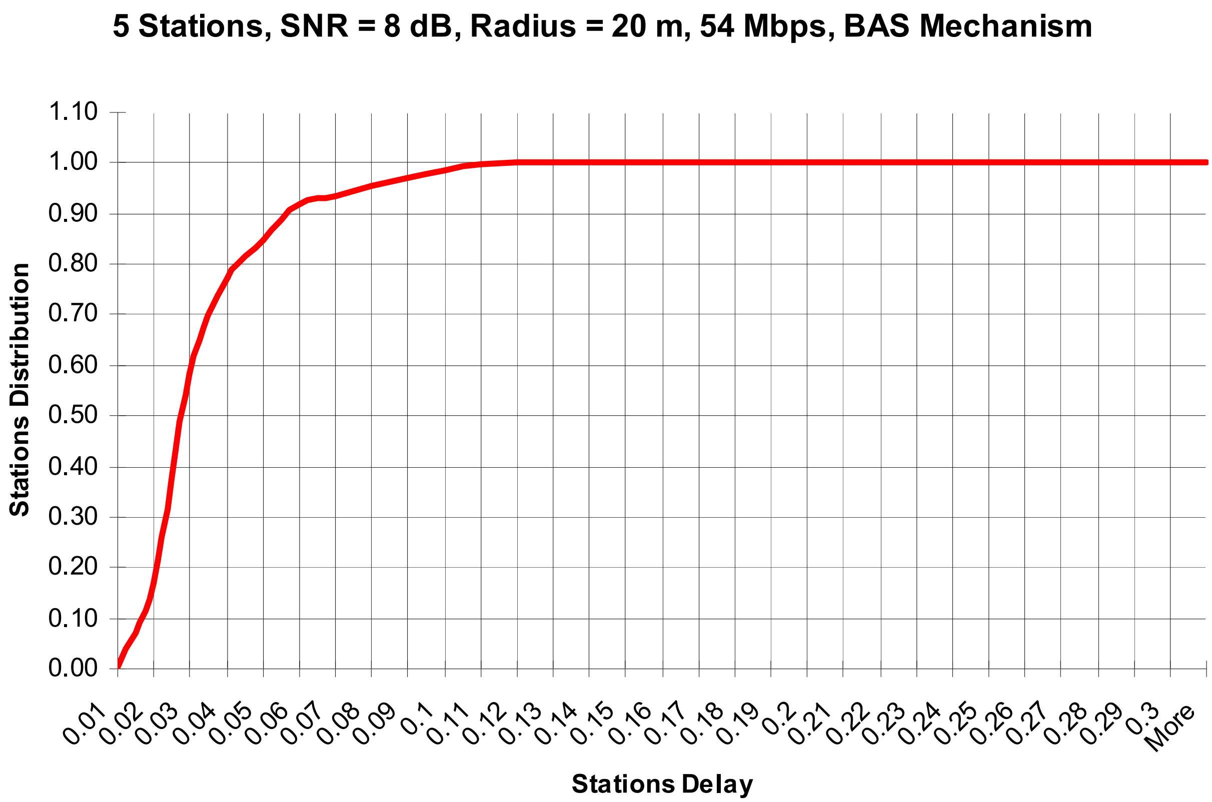

Figure 7.112. Stations Delay Distribution for 5 Stations, SNR = 8 dB

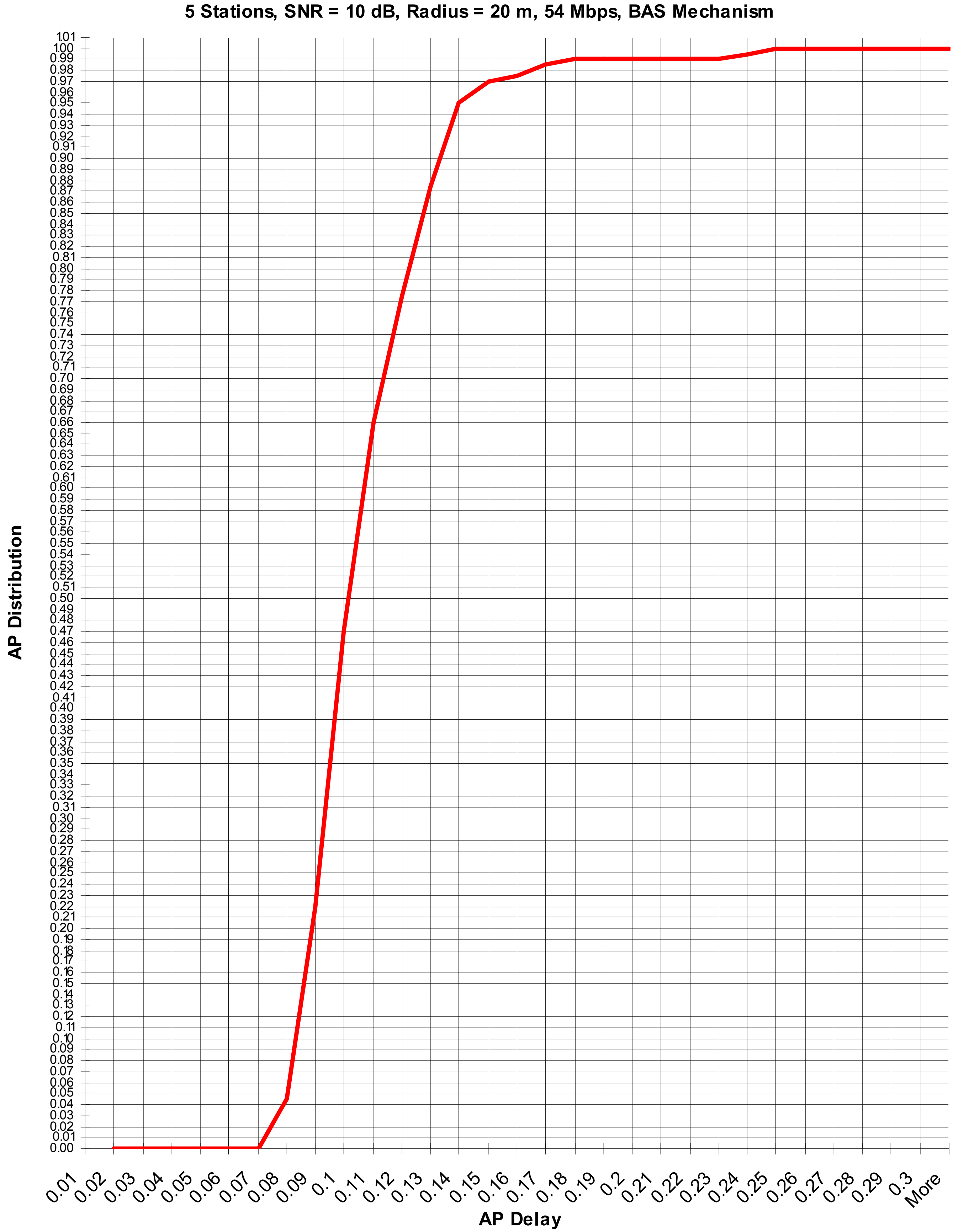

Figure 7.113. AP Delay Distribution for 5 Stations, SNR = 10 dB

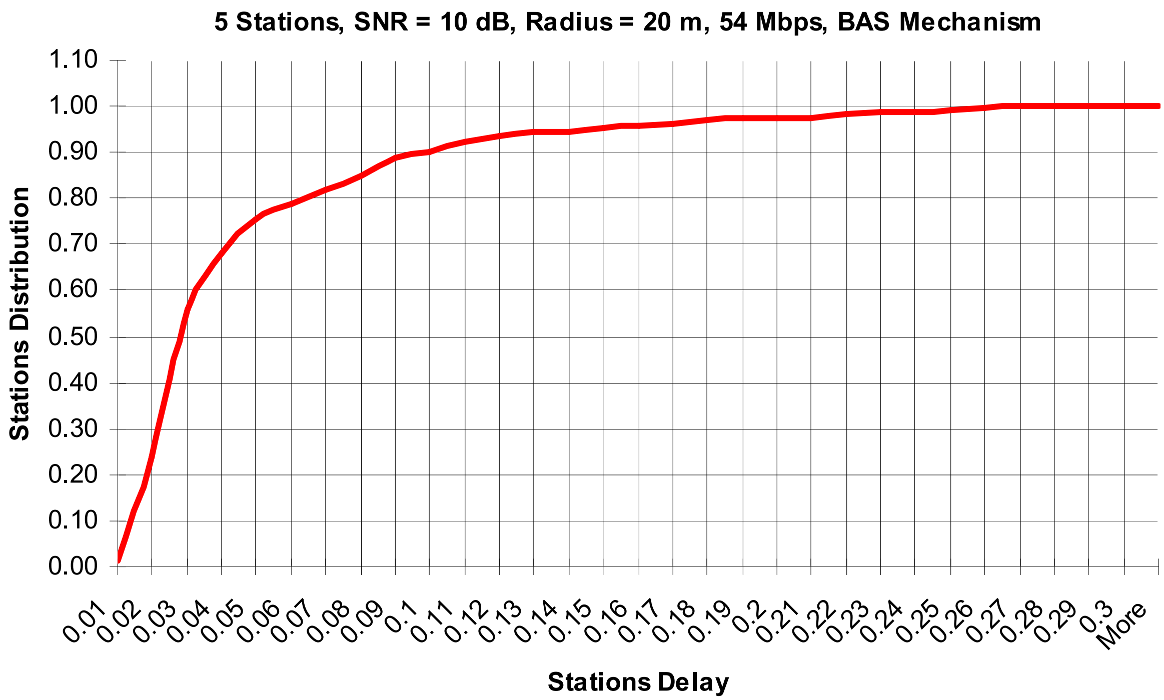

Figure 7.114. Stations Delay Distribution for 5 Stations, SNR = 10 dB

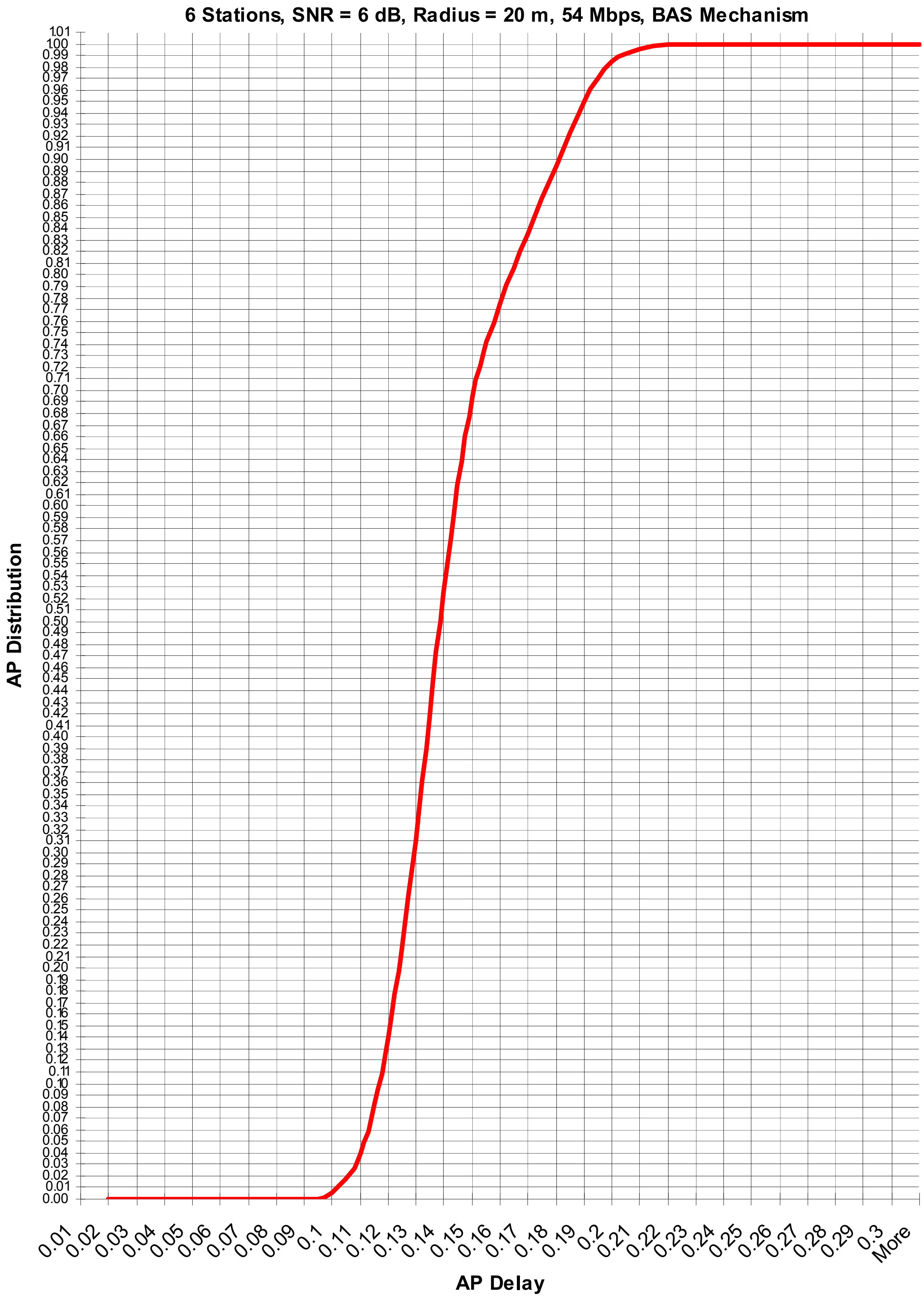

Figure 7.115. AP Delay Distribution for 6 Stations, SNR = 6 dB

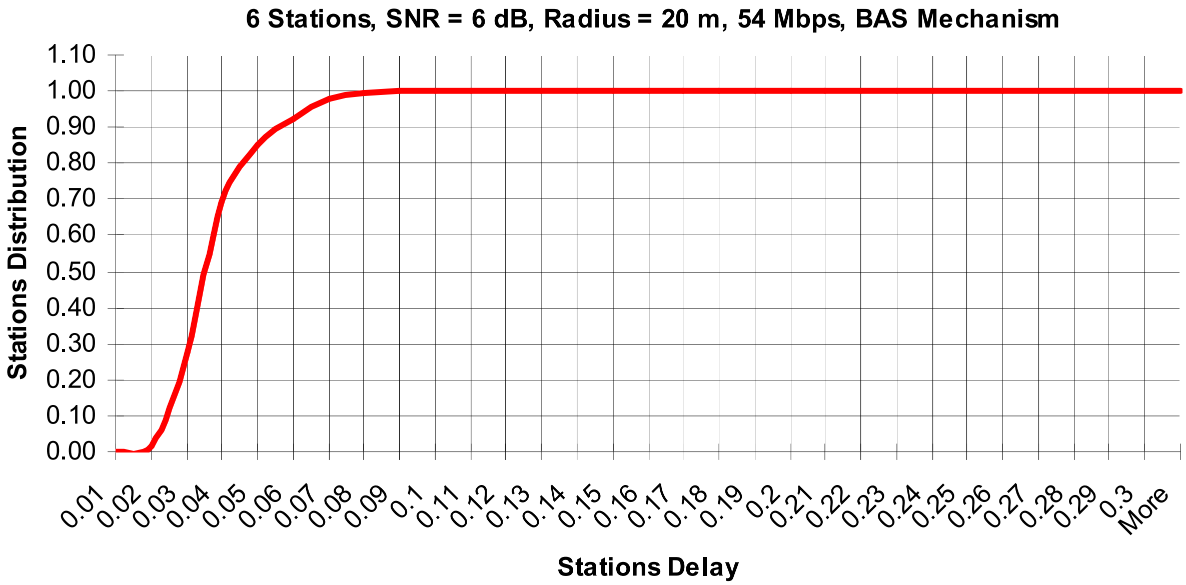

Figure 7.116. Stations Delay Distribution for 6 Stations, SNR = 6 dB.

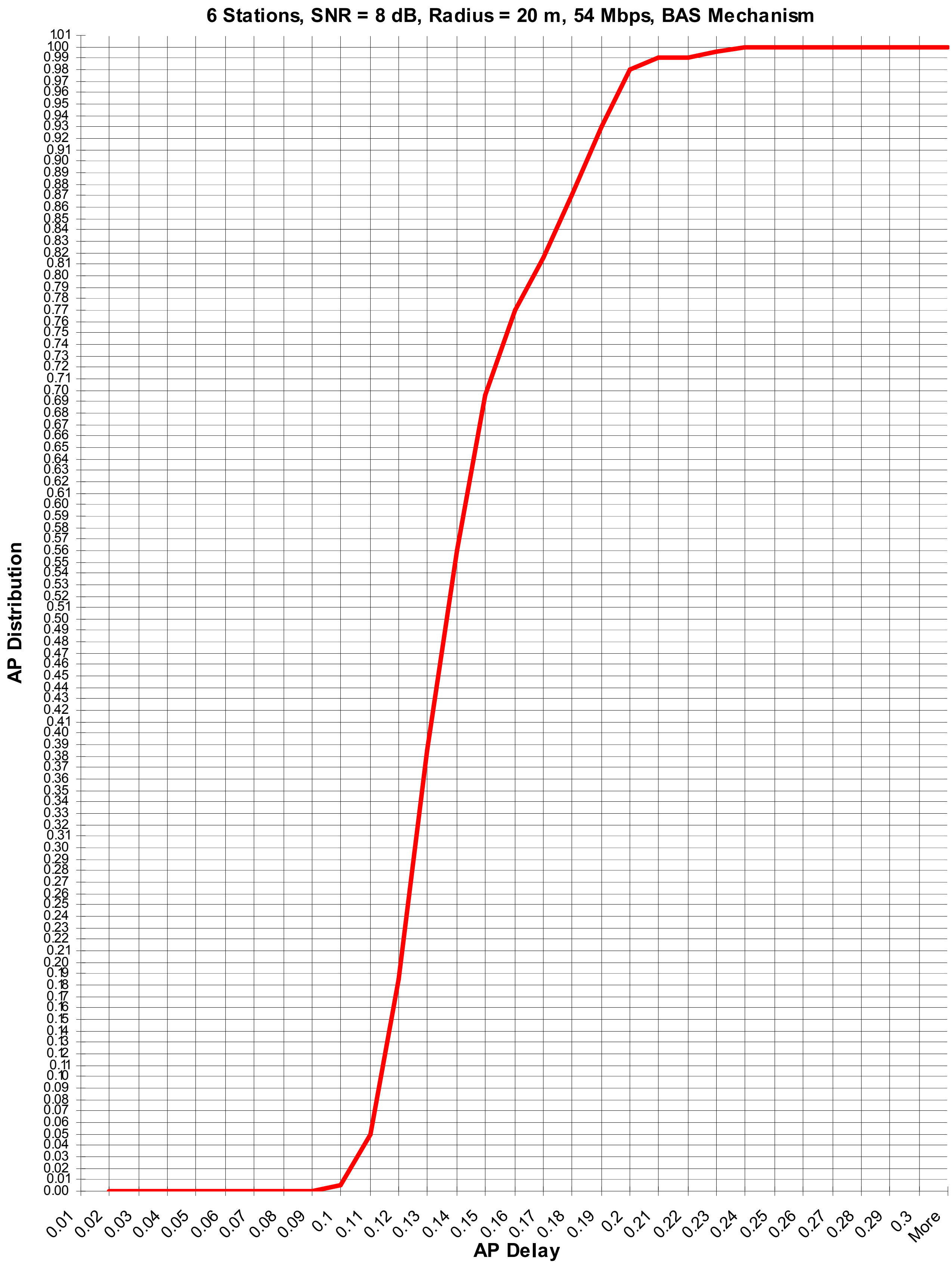

Figure 7.117. AP Delay Distribution for 6 Stations, SNR = 8 dB.

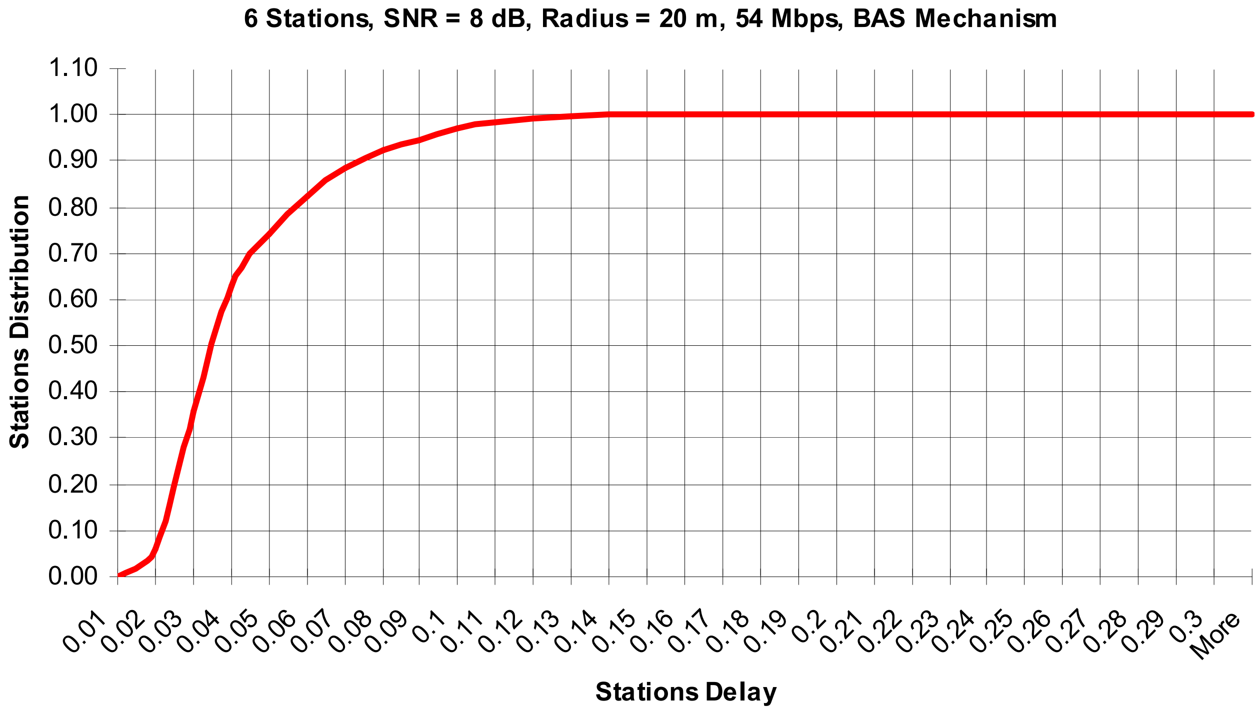

Figure 7.118. Stations Delay Distribution for 6 Stations, SNR = 8 dB.

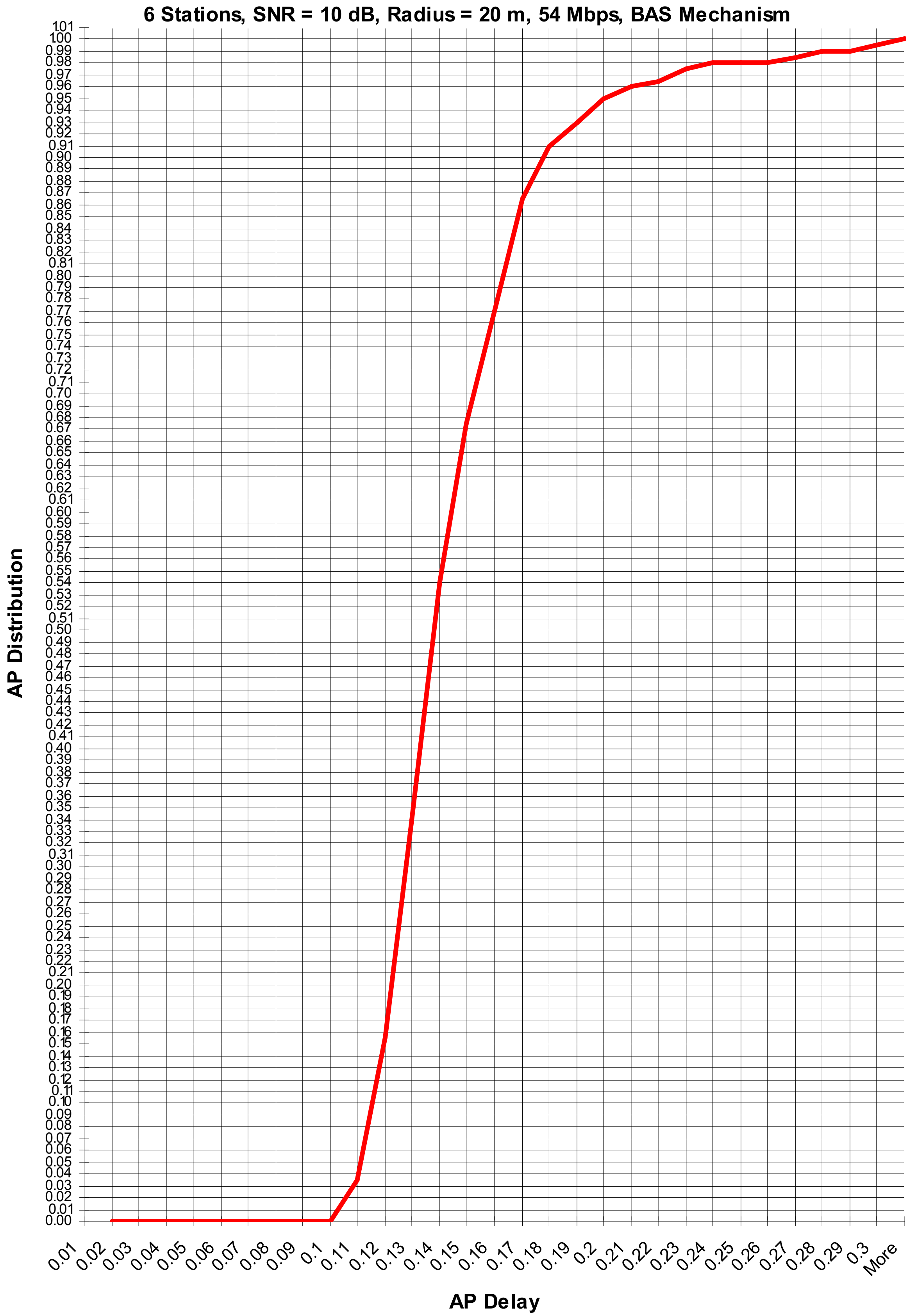

Figure 7.119. AP Delay Distribution for 6 Stations, SNR = 10 dB.

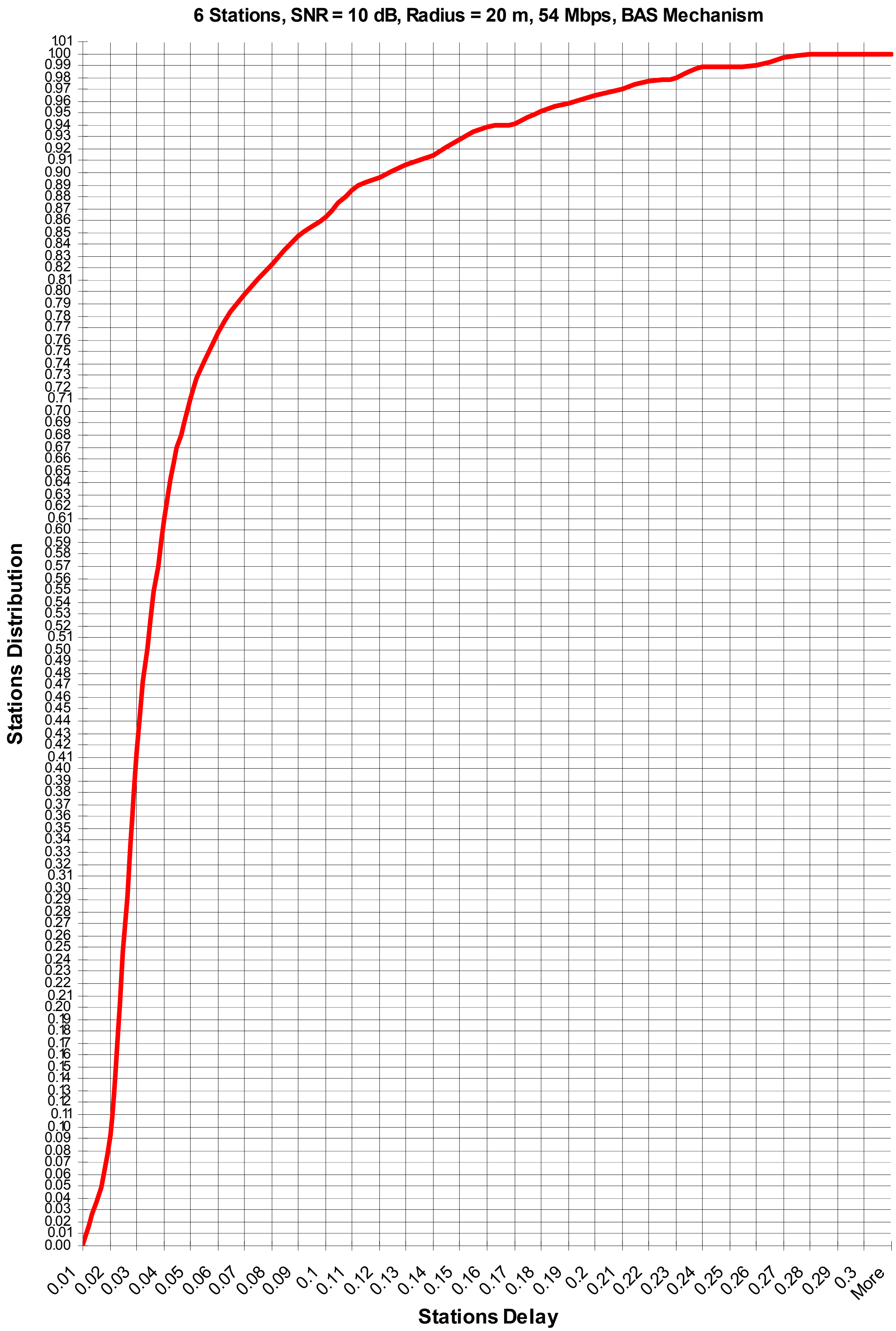

Figure 7.120. Stations Delay Distribution for 6 Stations, SNR = 10 dB.

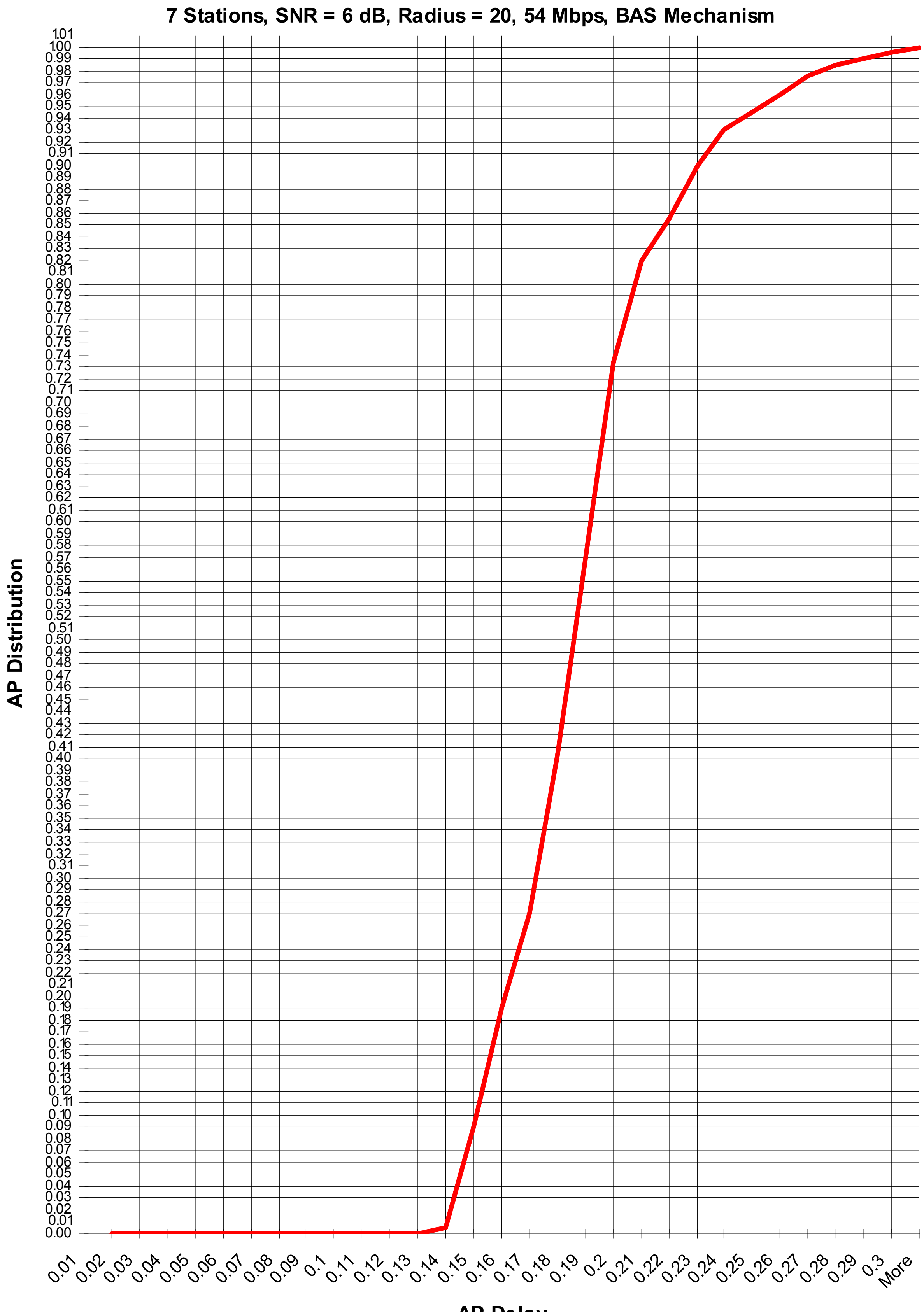

Figure 7.121. AP Delay Distribution for 7 Stations, SNR = 6 dB.

(

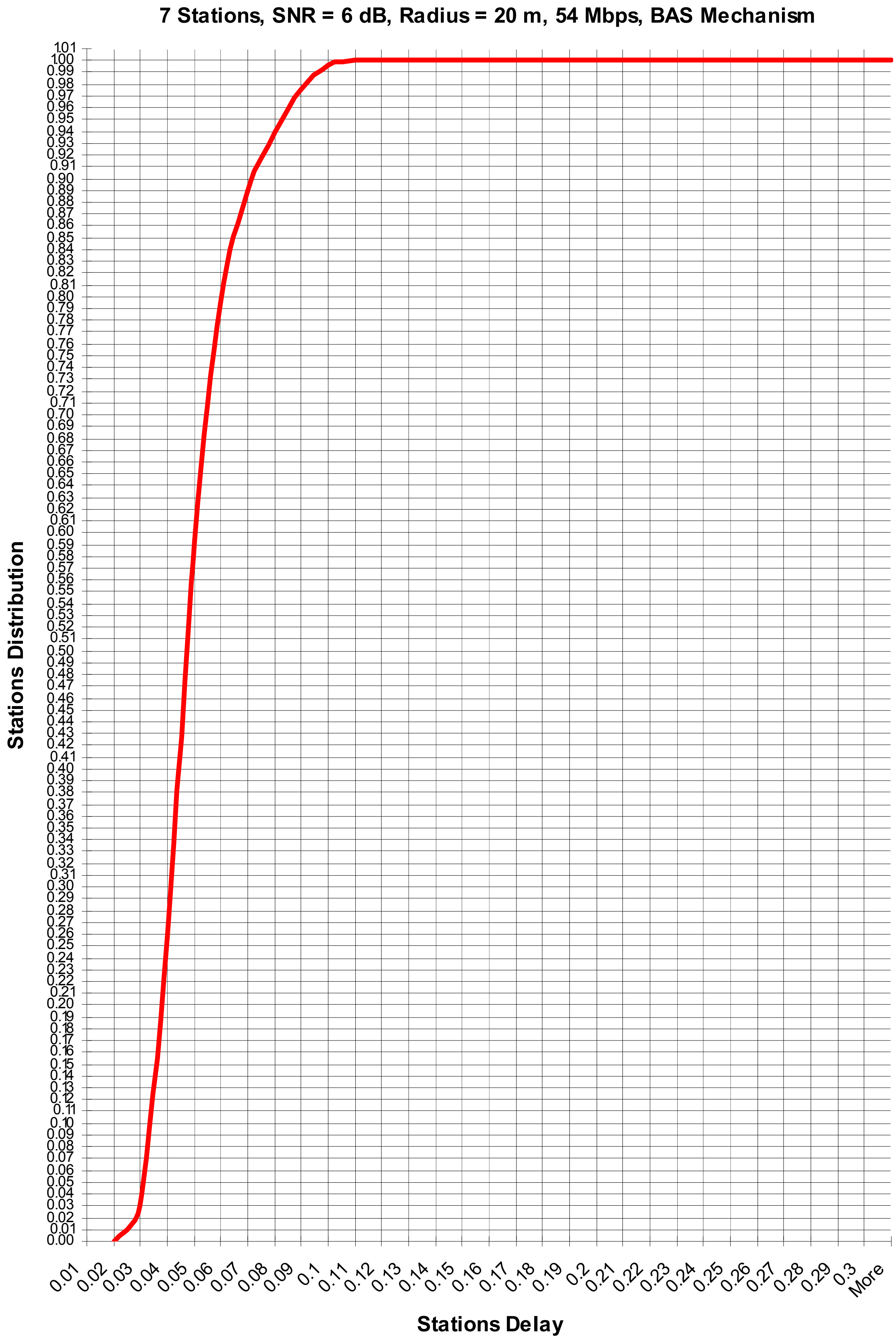

Figure 7.122. Stations Delay Distribution for 7 Stations, SNR = 6 dB.

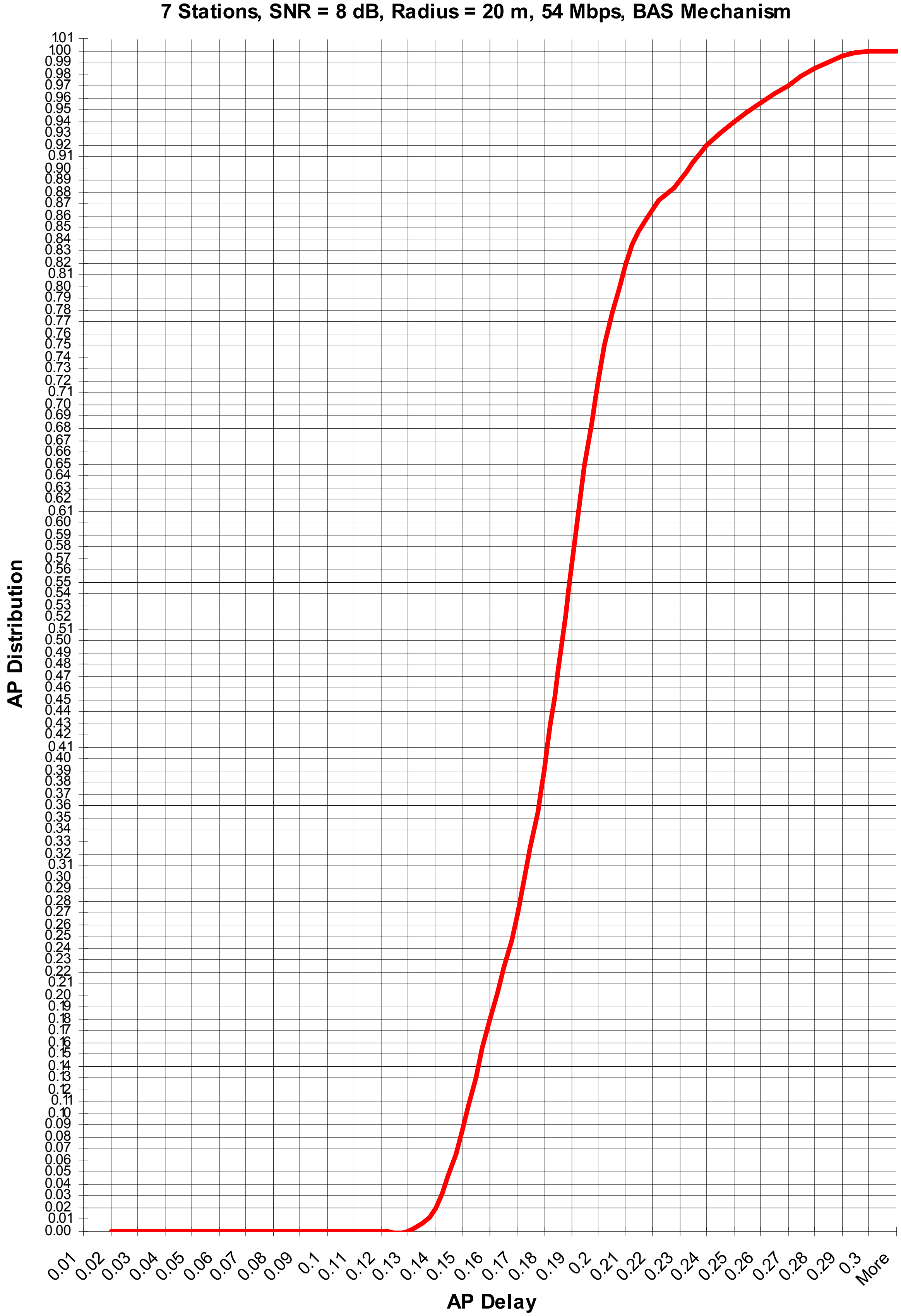

Figure 7.123. AP Delay Distribution for 7 Stations, SNR = 8 dB.

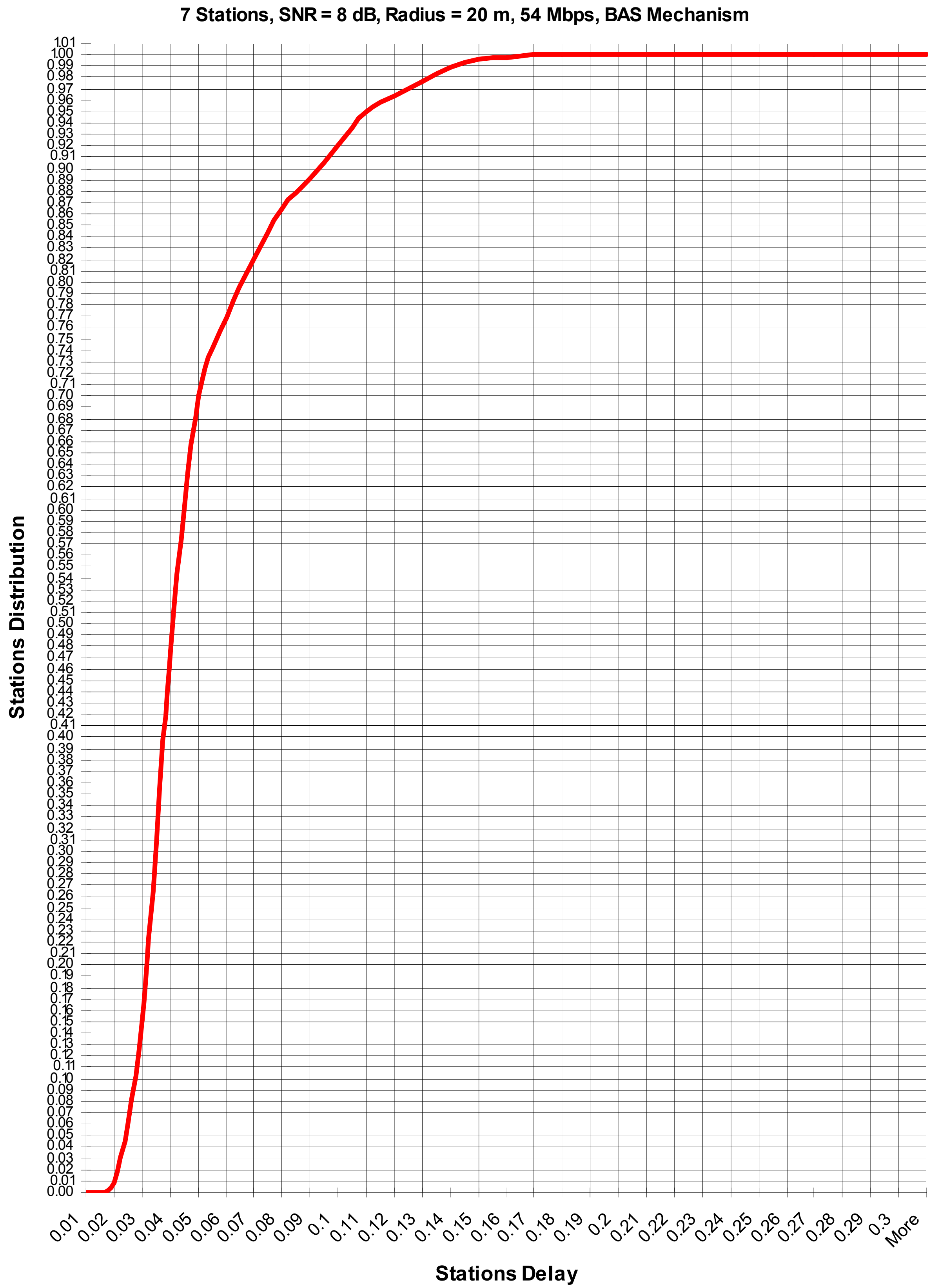

Figure 7.124. Stations Delay Distribution for 7 Stations, SNR = 8 dB.

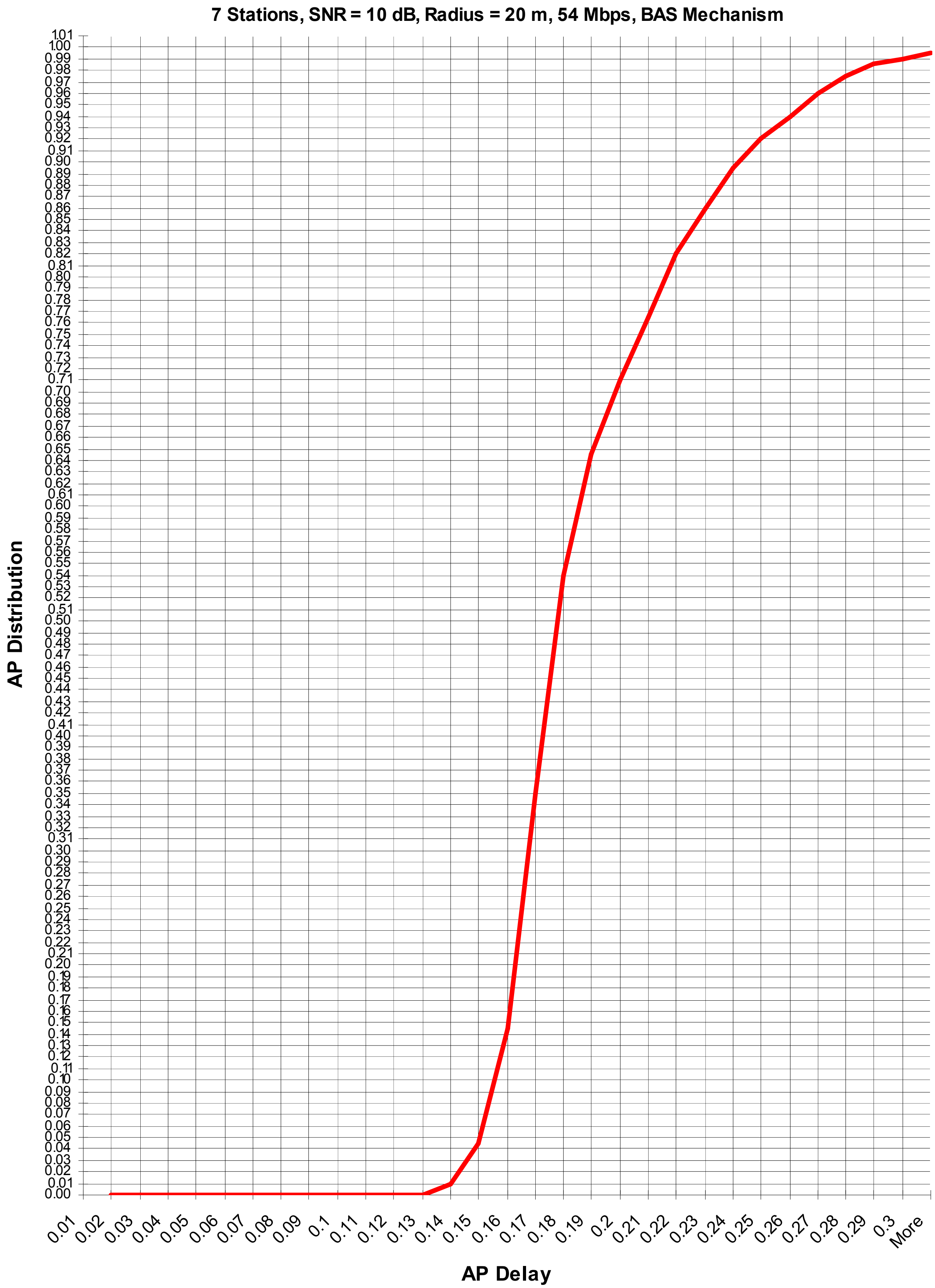

Figure 7.125. AP Delay Distribution for 7 Stations, SNR = 10 dB.

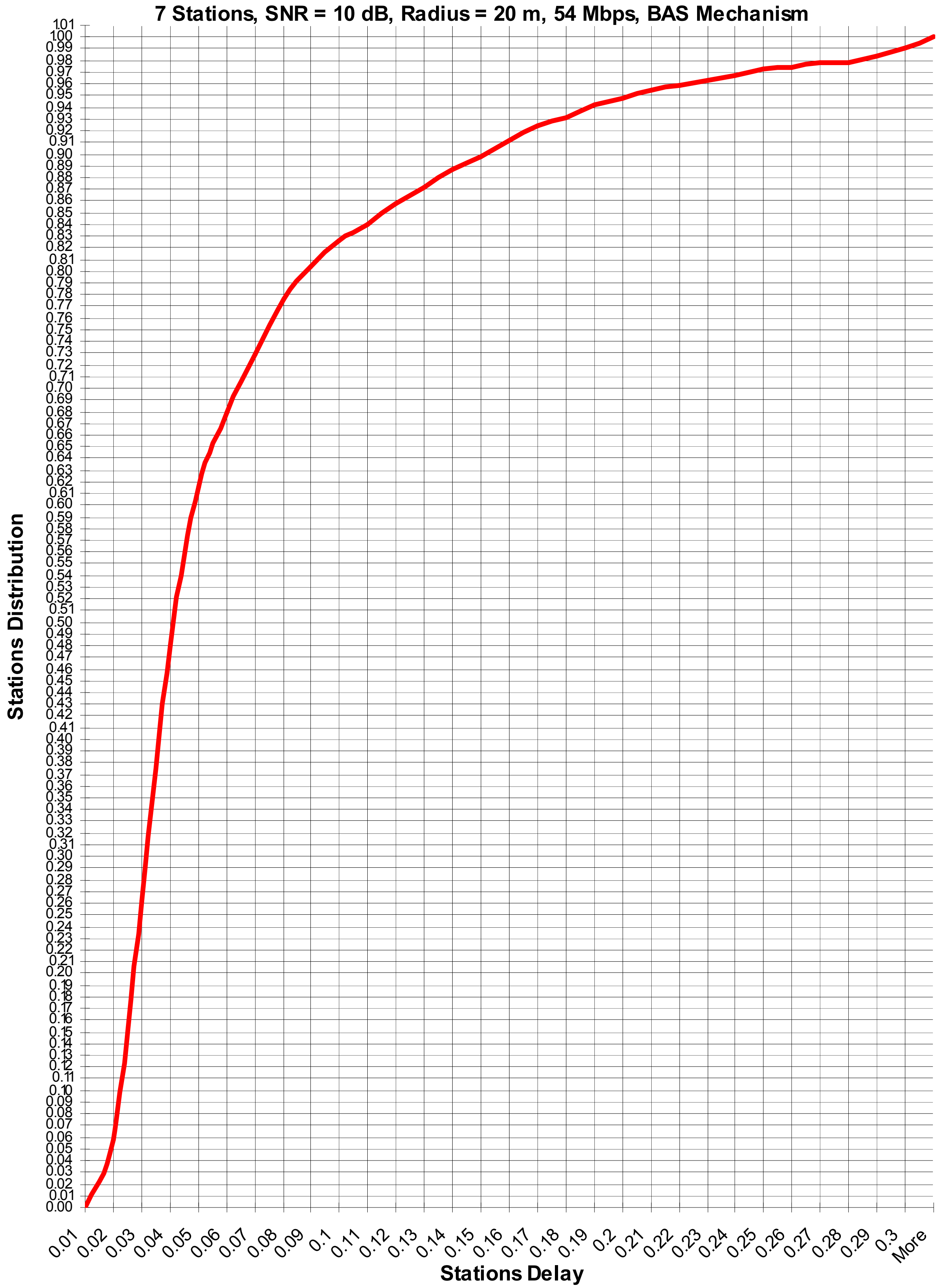

Figure 7.126. Stations Delay Distribution for 7 Stations, SNR = 10 dB.

In Figure 7.109 and 7.110 the cumulative distribution functions for the downlink and the uplink when there are 5 stations, the radius of coverage is of 20 meters and the SNR is 6 dB is presented.

Table 7.11 summarizes the most important results for figures 7.109 and 7.110

Table 7.11. Delay Distribution for 5 Stations, SNR = 6 dB, Radius = 20 m, 54 Mbps, BAS.

	AP (Downlink)	Stations (Uplink)
P[Delay < 150 ms]	0.990	1
P[Delay < 200 ms]	1	1
P[Delay < 250 ms]	1	1

Figure 7.111 and 7.112 show the cumulative distribution functions for the downlink and the uplink when there are 5 stations, the radius of coverage is of 20 meters and the SNR is of 8 dB. Table 7.12 summarizes the most important results for figures 7.111 and 7.112.

Table 7.12. Delay Distribution for 5 Stations, SNR = 8 dB, Radius = 20 m, 54 Mbps, BAS.

	AP (Downlink)	Stations (Uplink)
P[Delay < 150 ms]	.970	1
P[Delay < 200 ms]	1	1
P[Delay < 250 ms]	1	1

Figure 7.113 and 7.114 show the cumulative distribution functions for the downlink and the uplink when there are 5 stations, the radius of coverage is of 20 meters and the SNR is of 10 dB. Table 7.13 summarizes the most important results for figures 7.113 and 7.114.

Table 7.13. Delay Distribution for 5 Stations, SNR = 10 dB, Radius = 20 m, 54 Mbps, BAS.

	AP (Downlink)	Stations (Uplink)
P[Delay < 150 ms]	.966	0.96
P[Delay < 200 ms]	0.99	0.98
P[Delay < 250 ms]	0.999	0.99

Figure 7.115 and 7.116 show the cumulative distribution functions for the downlink and the uplink when there are 6 stations, the radius of coverage is of 20 meters and the SNR is of 6 dB. Table 7.14 summarizes the most important results for figures 7.115 and 7.116.

Table 7.14. Delay Distribution for 6 Stations, SNR = 6 dB, Radius = 20 m, 54 Mbps, BAS.

	AP (Downlink)	Stations (Uplink)
P[Delay < 150 ms]	0.69	1
P[Delay < 200 ms]	0.986	1
P[Delay < 250 ms]	1	1

Figure 7.117 and 7.118 show the cumulative distribution functions for the downlink and the uplink when there are 6 stations, the radius of coverage is of 20 meters

and the SNR is of 8 dB. Table 7.15 summarizes the most important results for figures 7.117 and 7.118.

Table 7.15. Delay Distribution for 6 Stations, SNR = 8 dB, Radius = 20 m, 54 Mbps, BAS.

	AP (Downlink)	Stations (Uplink)
P[Delay < 150 ms]	0.683	1
P[Delay < 200 ms]	0.98	1
P[Delay < 250 ms]	1	1

Figure 7.119 and 7.120 show the cumulative distribution functions for the downlink and the uplink when there are 6 stations, the radius of coverage is of 20 meters and the SNR is of 10 dB. Table 7.16 summarizes the most important results for figures 7.119 and 7.120.

Table 7.16. Delay Distribution for 6 Stations, SNR = 10 dB, Radius = 20 m, 54 Mbps, BAS.

	AP (Downlink)	Stations (Uplink)
P[Delay < 150 ms]	0.673	0.928
P[Delay < 200 ms]	0.952	0.965
P[Delay < 250 ms]	0.98	0.99

Figure 7.121 and 7.122 show the cumulative distribution functions for the downlink and the uplink when there are 7 stations, the radius of coverage is of 20 meters and the SNR is of 6 dB. Table 7.17 summarizes the most important results for figures 7.121 and 7.122.

Table 7.17. Delay Distribution for 7 Stations, SNR = 6 dB, Radius = 20 m, 54 Mbps, BAS.

	AP (Downlink)	Stations (Uplink)
P[Delay < 150 ms]	0.09	1
P[Delay < 200 ms]	0.73	1
P[Delay < 250 ms]	0.946	1

Figure 7.123 and 7.124 show the cumulative distribution functions for the downlink and the uplink when there are 7 stations, the radius of coverage is of 20 meters and the SNR is of 8 dB. Table 7.18 summarizes the most important results for figures 7.12 and 7.124.

Table 7.18. Delay Distribution for 7 Stations, SNR = 8 dB, Radius = 20 m, 54 Mbps, BAS.

	AP (Downlink)	Stations (Uplink)
P[Delay < 150 ms]	0.08	0.996
P[Delay < 200 ms]	0.72	1
P[Delay < 250 ms]	0.94	1

Figure 7.125 and 7.126 show the cumulative distribution functions for the downlink and the uplink when there are 7 stations, the radius of coverage is of 20 meters and the SNR is of 10 dB. Table 7.19 summarizes the most important results for figures 7.125 and 7.126.

7.2 WLAN scenario 2: One WLAN with a finite number of stations surrounded by other interfering WLAN's

We now know that the best possible way to transmit VoWLAN is with no more than 7 stations, with a maximum radius of coverage of 20 meters, with a 54 Mbps bit rate and using the basic access mechanism. From the theoretical analysis point of view, the engineering planning discussed above must be followed for the worst-case scenario in the transmission of VoWLAN. Although, the Wi-Fi technology is a license free wireless technology and it will be susceptible to interference generated by neighbor WLAN transmissions (co-channel interference).

The primary objective of this section is to show the numerical simulation results of the delay impact to our desired WLAN caused by other interfering WLAN's.
Figure 7.127 shows the general scenario to be exposed in this section.

R_1= Radius of coverage of WLAN of interest

R_2= Radius at where other interfering WLAN's are located (AP referenced)

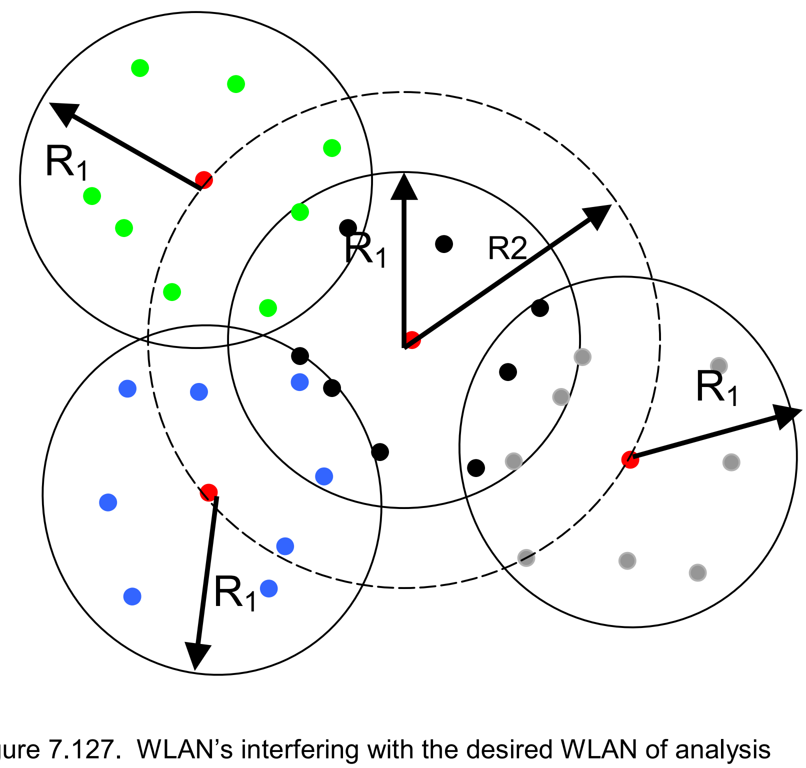

Figure 7.127. WLAN's interfering with the desired WLAN of analysis

Even though all the WLAN's are interfering with each other, our main objective it to know what is happening to the delay in the WLAN located at the center. In Figure 7.127, R_1 refers to the maximum radius of coverage where their respective stations can be located. (Note: R_1 doesn't refer to the maximum radius of reception coverage). R_1 is assumed to be equal for all the WLAN's and is assumed to be of 20 meters (assuming that all the WLAN's have the best individual WLAN engineering planning of the transmission of VoWLAN)

R_2 refers to the distance of our desired AP to other interfering AP's (Note: the AP's are the red points). Distance R_2 is assumed to have fixed values, and all the interfering AP are uniformly distributed in some place at exactly this distance. The three fixed values R_2 has are 10, 20 and 30 meters.

For the number of stations of each WLAN, it is assumed that all the WLAN's have the same number of stations. In the numerical simulations results we use the optimal number of stations obtained in the above section, which are 5, 6 and 7 stations. In general, the scenarios analyzed will first consider that all the WLAN's have 5 stations (including the desired WLAN), then the results will be shown for 6 stations and the last one will be for 7 stations.

There is one more variable that plays an important roll when analyzing the WLAN's interference scenarios. This variable is the minimum signal to noise radio for correct signal reception. As it was analyzed the above section, the results when varying the SNR for correct signal detection will be shown and it will be shown the advantages of having a high SNR for correct signal reception when interference is a factor.

7.2.1. Interference Scenario 1: 5 Stations for each WLAN, SNR = 6 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

In Table 7.20 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters.

Table 7.20. 5 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.210808677	0.00359643	0.075010801	0.000818703	0.017566576	5.33141E-06
2	0.357383317	0.012435095	0.13783192	0.002323259	0.013852109	3.39321E-06
3						

As it can be seen, if an interfering AP with 5 stations uniformly distributed around it is placed at 10 meters of our desired WLAN, the AP expected delay is of 210 ms with a standard deviation of 60 ms. Thus, for this scenario, the transmission of VoWLAN is not possible if there are other WLANs at 10 meters near the AP. Also, as expected, the system throughput diminishes as the number of interfering WLANs increases.

In Table 7.21 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters.

Table 7.21. 5 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.142015407	0.001463552	0.043101681	0.000339189	0.024450254	6.70486E-06
2	0.222202302	0.006229792	0.066784978	0.001104451	0.020305625	7.35806E-06
3						

The numerical results shown in Table 7.21 show that if only one interfering AP is at 20 meters from our AP, the transmission of VoWLAN is still possible. For one interfering station the average delay is of 142 ms and the standard deviation is of 38 ms. For two interfering stations uniformly placed at 20 meters, the transmission of VoWLAN is not possible.

In Table 7.22 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters.

Table 7.22. 5 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.10615783	0.000636562	0.028251572	0.000149643	0.029748677	3.58547E-06
2	0.117781942	0.001171906	0.029079138	0.000184894	0.028669606	4.55649E-06
3	0.13025467	0.001891925	0.030515382	0.000225132	0.02661938	7.44553E-06
4	0.149751252	0.001942567	0.033641402	0.000292281	0.024740186	6.14909E-06
5	0.162557817	0.002161239	0.034070566	0.000297882	0.023729715	5.43835E-06
6	0.183511084	0.002678592	0.035125874	0.000301581	.022568418	5.628412E-06

For this scenario, it can be seen that when R_2 is of 30 meters, up to 6 WLAN's can be surrounding our WLAN and still the transmission of VoWLAN is possible. (see Table 7.22)

7.2.2. Interference Scenario 2: 5 Stations for each WLAN, SNR = 8 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

For this scenario, the signal to noise ratio for correct signal reception has been raised to 8 dB. It will be shown that with this increase, our WLAN suffers less from the co-channel interference of other stations.

In Table 7.23 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters.

Table 7.23. 5 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.184866161	0.002309328	0.075588349	0.001644801	0.018248461	5.95467E-06
2	0.340697144	0.014592029	0.14888995	0.00618796	0.013581012	5.46578E-06
3						

Table 7.23 shows an improvement in the interference tolerance. For this case of SNR of 8 dB and with all WLAN's having 5 stations on them, it is possible to have an interfering WLAN at a distance of 10 meters (AP to AP referenced) and still transmit VoWLAN. In this case, the AP expected delay is of 184 ms and has a standard deviation of 48 ms.

In Table 7.24 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters.

Table 7.24. 5 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.129189471	0.001318026	0.042159991	0.000619446	0.025014765	6.5042E-06
2	0.179755023	0.003203783	0.05634846	0.001331924	0.022041681	5.17714E-05
3						

As shown in Table 7.24, it is now possible to have 2 interfering WLANs at 20 meters from our AP and still be able to transmit VoWLAN. With 2 interfering WLANs at 20, the average delay is of 180 ms and the standard deviation is of 56 ms.

In Table 7.25 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters.

Table 7.25. 5 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.095416473	0.00061662	0.025970552	0.000197947	0.029814325	3.94175E-06
2	0.098024079	0.000584706	0.025740246	0.000180319	0.029605681	3.70525E-06
3	0.101796737	0.00066944	0.025655232	0.000157462	0.028707332	4.98013E-06

As it can be seen in Table 7.25 and as somewhat expected. At a SNR of 8 dB, the average delay of the AP, stations and the system throughput, goes on asymptotically. As a general conclusion, for a receiver's sensitivity of 8 dB, the interfering WLANs located beyond 30 meters does not affect in a great manner the delay of our WLAN.

7.2.3. Interference Scenario 3: 5 Stations for each WLAN, SNR = 10 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

The signal to noise ratio for correct signal detection is now risen to 10 dB.

In Table 7.26 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters.

Table 7.26. 5 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.178852098	0.002233991	0.096688649	0.007320882	0.017266683	7.23073E-06
2	0.303810878	0.008538309	0.183364899	0.022958263	0.013205434	7.07892E-06
3						

As shown in Table 7.26, there can be only one interfering WLAN at a distance of 10 meters for the transmission of VoWLAN to be possible. In this case, the average delay is of 178 ms with a standard deviation of 47 ms. If two interfering WLAN are located at a distance of 10 meters (AP to AP referenced), the transmission of VoWLAN is not possible.

In Table 7.27 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters.

Table 7.27. 5 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.115585244	0.00071503	0.046566246	0.001754639	0.0255874	1.18781E-05
2	0.150407046	0.002333001	0.059502386	0.003001051	0.022066114	1.34972E-05
3	0.187611035	0.004386975	0.063529191	0.003113051	0.020973075	1.27646E-05

Table 7.27 shows the maximum number of interfering WLANs that can be surrounding our WLAN of analysis is three. With three interfering WLANs the average delay of the AP is of 187 ms with a standard deviation of 66 ms, giving a maximum delay of 253 ms, which is a little slightly above the 250 ms threshold.

In Table 7.28 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters.

Table 7.28. 5 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.083539242	0.000269618	0.025442147	0.000431114	0.029739253	5.25322E-06
2	0.088476975	0.000454678	0.02545946	0.00029731	0.02956865	6.32811E-06
3	0.089020925	0.000411948	0.025466681	0.000266957	0.028881217	4.57801E-06

As shown in Table 7.28, the interference caused by the WLANs surrounding our WLAN at a distance of 30 meters does not affects in a great manner the delay of our WLAN. As it can be seen, the average expected delay of our AP follows an asymptotical value as the number of surrounding interfering WLANs increases. For this scenario, it is possible to transmit VoWLAN.

7.2.4. Interference Scenario 4: 6 Stations for each WLAN, SNR = 6 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

We now consider the case when the number of stations is increased to 6 (all the WLANs have an AP serving 6 stations).

In Table 7.29 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters and the number of stations is six.

Table 7.29. 6 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.298256433	0.005957457	0.091990294	0.00107271	0.018863206	3.96159E-06
2						

As it can be seen in Table 7.29, with only one interfering WLAN at a distance of 10 (AP to AP referenced), it is not possible to transmit VoWLAN. The average delay of our WLAN will be of 298 ms, which makes it impossible to meet the VoWLAN requirements of delay.

In Table 7.30 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters and the number of stations is six. VoWLAN is not possible for this scenario.

Table 7.30. 6 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.210403197	0.00278226	0.0550037	0.000592811	0.025457248	5.89986E-06
2						

In Table 7.31 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters and the number of stations is six.

Table 7.31. 6 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.154636198	0.001208649	0.034749593	0.000190072	0.031410453	2.98477E-06
2	0.169820037	0.001338524	0.035430862	0.000245694	0.030214931	4.16971E-06
3	0.193938481	0.002711152	0.040108962	0.000342727	0.028273749	5.71281E-06
4	0.21484143	0.003046843	0.042529715	0.000395824	0.026917457	5.42815E-06

Table 7.31 show that for the SNR of 6 dB, there can be at most four interfering WLANs at a distance of 30 meters form our WLAN of interest (AP to AP referenced) for the correct transmission of VoWLAN.

7.2.5. Interference Scenario 5: 6 Stations for each WLAN, SNR = 8 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

We continue showing the numerical simulations results for the case when we raise the SNR to 8 dB and the number of stations is six.

In Table 7.32 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters and the number of stations is six.

Table 7.32. 6 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.265043809	0.004141332	0.098304578	0.002747488	0.018746941	7.19271E-06
2						

Table 7.32 shows that for six stations there can not be any surrounding interfering WLAN at a distance of 10 if we want to transmit VoWLAN.

In Table 7.33 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters and the number of stations is six.

Table 7.33. 6 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.187334695	0.00210103	0.052313108	0.000897551	0.026184525	6.05017E-06
2						

Table 7.33 show it is possible to have only one interfering WLAN at a distance of 20 meters for the transmission of VoWLAN. In this scenario, the expected delay is of 187 ms and the standard deviation is of 46 ms, thus, the maximum delay is still under the 250 ms threshold.

In Table 7.34 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters and the number of stations is six.

Table 7.34. 6 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.135761064	0.000952781	0.03393807	0.000279508	0.031546583	4.19279E-06
2	0.143380623	0.001099409	0.03394391	0.000279198	0.030697593	4.35521E-06
3	0.153043413	0.001581406	0.034070819	0.000299962	0.029017749	5.23092E-06
4	0.165460044	0.001852916	0.034965996	0.000309977	0.027268235	5.99061E-06
5	0.189142201	0.002423206	0.040590481	0.000344463	0.024946634	6.30E-06
6						

Table 7.34 shows there can be a maximum of 5 interfering WLANs at a distance of 30 meters. For the case of 5 interfering WLANs, the average delay of the AP in our WLAN is of 189 ms with a standard deviation of 49 ms, which is still below the 250 ms threshold.

7.2.6. Interference Scenario 6: 6 Stations for each WLAN, SNR = 10 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

The SNR is now raised to 10 dB and the number of stations is still six.

In Table 7.35 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters, the number of stations is six and the SNR is 10 dB.

Table 7.35. 6 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.246355766	0.003210863	0.119950944	0.010880667	0.018142425	6.06709E-06
2						

Table 7.35 shows it is not possible to transmit VoWLAN under this conditions.

In Table 7.36 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters, the number of stations is six and the SNR is 10 dB.

Table 7.36. 6 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.169382625	0.002199824	0.05906451	0.002972913	0.026488946	1.68151E-05
2	0.214249179	0.003927312	0.063733848	0.002574167	0.024065992	1.5747E-05
3						

In Table 7.36 the maximum number of interfering WLANs that can be surrounding our WLAN for the correct transmission of VoWLAN is one. For this case, the average delay is of the AP is of 169 ms with a standard deviation of 47 ms.

In Table 7.37 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters, the number of stations is six and the SNR is 10 dB.

Table 7.37. 6 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.121034514	0.000919123	0.034644937	0.000480189	0.031837773	5.24238E-06
2	0.1221937	0.000937629	0.034870284	0.000386464	0.030937218	5.29169E-06
3	0.124730976	0.00090571	0.034907741	0.000305098	0.029905083	4.15334E-06

For the scenario shown in Table 7.37, it is possible to transmit VoWLAN if other surrounding interfering WLANs are at 30 meters or beyond. It is also seen that the AP expected delay has an asymptotic tendency around the 120's ms.

7.2.7. Interference Scenario 7: 7 Stations for each WLAN, SNR = 6 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

We now show the numerical simulation results for the case when the number of stations increases to seven.

In Table 7.38 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters, the number of stations is seven and the SNR is 6 dB.

Table 7.38. 7 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.408988836	0.008848491	0.110316005	0.001483925	0.019885732	4.06989E-06
2						

Table 7.38 shows it is not possible to transmit VoWLAN when we have seven stations in our WLAN and in all the interfering ones; and this interfering stations are located at a distance of 10 meters from our WLAN of analysis (AP to AP referenced). For only one interfering WLAN the average delay for the AP of analysis is of 408 ms.

In Table 7.39 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters, the number of stations is seven and the SNR is 6 dB.

Table 7.39. 7 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.281379045	0.005180471	0.067040518	0.000934236	0.026548017	5.60478E-06
2						

When the distance of our WLAN to the interfering ones is of 20 m, it is not possible to transmit VoWLAN if one interfering WLAN is located anywhere in that distance (AP to AP referenced).

In Table 7.40 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters, the number of stations is seven and the SNR is 6 dB.

Table 7.40. 7 Stations in all WLAN's, SNR = 6 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.207873046	0.002248206	0.042179097	0.000289457	0.032802609	1.96941E-06
2						

In Table 7.40 it is shown that for the WLANs, each one having seven stations, it is only possible to have 1 interfering WLAN at a distance of 30 meters form our WLAN (AP to AP referenced). For this case, the expected delay is of 207 ms with a standard deviation of 47 ms. The maximum delay will be of 254 ms.

7.2.8. Interference Scenario 8: 7 Stations for each WLAN, SNR = 8 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

The numerical simulation results for raising the signal to noise radio for correct signal detection to 8 dB are shown in this subsection.

In Table 7.41 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters, the number of stations is seven and the SNR is 8 dB.

Table 7.41. 7 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.355509656	0.005204967	0.116962386	0.003697279	0.01966863	5.57008E-06
2						

Table 7.41 shows it is not possible to transmit VoWLAN when other WLANs are located at 10 meters from the WLAN of interested (AP to AP referenced)

In Table 7.42 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters, the number of stations is seven and the SNR is 8 dB.

Table 7.42. 7 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.238461752	0.002934088	0.062666517	0.001381722	0.027525699	7.64672E-06
2						

Table 7.42 shows it is not possible to transmit VoWLAN if there is any interfering WLAN located at a distance of 20 meters from our WLAN of analysis. The average delay of our AP is of 238 ms but with a standard deviation of 54 ms.

In Table 7.43 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters, the number of stations is seven and the SNR is 8 dB.

Table 7.43. 7 Stations in all WLAN's, SNR = 8 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.192851657	0.002262335	0.041161504	0.000406476	0.032967883	3.09099E-06
2	0.197168324	0.002067629	0.043734496	0.000395124	0.031861632	4.20158E-06
3	0.204558168	0.00203584	0.045958215	0.000398285	0.029846281	4.214505-06
4						

Table 7.43 shows the maximum number of interfering WLANS that can be surrounding our WLAN of analysis is three. With three interfering WLANs at a distance of 30 m from our WLAN, the average delay is of 204 ms with a standard deviation of 44 ms.

7.2.9. Interference Scenario 9: 7 Stations for each WLAN, SNR = 10 dB for all the WLAN's, all WLAN's at 54 Mbps, all WLAN's with BAS mechanism, R_1 = 20 meters and R_2 variable.

The SNR for correct signal reception is now raised to 10 dB and the numerical simulation results are shown in this subsection.

In Table 7.44 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 10 meters, the number of stations is seven and the SNR is 10 dB.

Table 7.44. 7 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 10 m

Number of Interfering WLANs, R_2 = 10 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.321918085	0.006158013	0.13339754	0.012772555	0.019896534	9.90921E-06
2						

For the scenario in Table 7.44 it is not possible to transmit VoWLAN. If there is any WLAN at a distance of 10 meters from our WLAN of analysis, the transmission of VoWLAN will not be possible due to the high delay of the AP.

In Table 7.45 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 20 meters, the number of stations is seven and the SNR is 10 dB.

Table 7.45. 7 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 20 m

Number of Interfering WLANs, R_2 = 20 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.215258528	0.002982365	0.064584852	0.002696639	0.027989133	8.39032E-06
2						

Table 7.45 shows it is not possible the transmission of VoWLAN if there is any surrounding interfering stations at a distance of 20 meters. The average delay is of 215 ms with a standard deviation of 55 ms.

In Table 7.46 the expected values and the variances for the AP and stations delay is shown; as well as the system throughput for the case when R_2 is 30 meters, the number of stations is seven and the SNR is 10 dB.

Table 7.46. 7 Stations in all WLAN's, SNR = 10 dB, 54 Mbps, BAS Mechanism, R_2 = 30 m

Number of Interfering WLANs, R_2 = 30 m	AP Expected Delay	AP Delay Variance	Stations Expected Delay	Stations Delay Variance	System Throughput	System Throughput Variance
1	0.164337113	0.001232067	0.0361339	0.000726483	0.033170215	4.88466E-06
2	0.16693524	0.001336381	0.036766623	0.000565463	0.03240859	5.42864E-06
3	0.182122205	0.001964571	0.036603	0.000493397	0.030706334	5.24162E-06
4	0.204	0.002245862	0.0369518	0.004935871	0.028286587	5.23E-06
5						

Table 7.45 shows it is possible to transmit VoWLAN when there are at most 4 surrounding interfering WLANs at a distance of 30 meters (AP to AP referenced). In the case of 4 interfering WLAN s, the expected delay of our AP of analysis is of 204 ms with a standard deviation of 47 ms, giving a maximum delay of 251 ms.

As it can be seen, the transmission of VoWLAN is possible with the correct engineering planning.

Chapter 8

Conclusions and Further Research

In this thesis, we analyzed the performance of the IEEE 802.11 standard for its capability to transmit VoWLAN, and we identified the required scenarios and conditions for its transmission.

In this chapter, we present the general conclusions of the research and the recommended future research is presented in the last section of the chapter.

8.1 Conclusions

In Chapter 7, we assumed the worst case conditions for the transmission fo VoWLAN. Under this cirsunstances and with obtained numerical results, we can conclude specifically the following:

1. If there is a guarantee that there will be no interfering WLANs, the best way to do the engineering planning is with the 802.11a technology, which has the 54 Mbps bit rate, using the BAS mechanism, with a radius of coverage of 20, serving 7 stations and use in all the receivers the smallest SNR for correct signal detection. If any IEEE 802.11 technology increases its bit rate it will result in a better option to transmit VoWLAN.

2. If there is an interference issue or if the planning of the system will be in a place were interference is a concern, the best way to implement it is to use again the IEEE 802.11a with a higher SNR for correct signal detection in all the receivers; and depending on the scenario it will required to put only six or five stations for the correct transmission of VoWLAN. From the numerical results in Chapter 7, it will be a guarantee that interfering WLANs at a distance of 30 m will not cause significant interference to degrade the transmission of VoWLAN.

3. The system throughput for the transmission of VoWLAN is very small due to the small packet size and the large MAC and PHY headers.

Although, the numerical results of Chapter 7 can be considered as very pessimistic scenarios; the results still shows us that the transmission of VoWLAN can only get better from this further; this is true if we have flexibility with some of the parameters. For example, one of the fundamental assumptions of the theoretical analysis is that the stations are in a state of saturation, which means that the buffer of a stations is always non-empty and all the time has something to transmit. This is a worst case condition; in the transmission of voice, it is considered that only 40% of the time a user will be speaking, so a voice factor of 0.4 is considered in doing analysis. Having this kind of flexibility allows the system to be less busy and the number of stations for the transmission of VoWLAN can be slightly increased.

There is also flexibility in the path loss exponent. When there is not so much obstacles between the AP and the stations, the coverage radius can also be increased for the case when there is no other interfering WLANs.

A path loss factor of 4 was used in Chapter 7. For the case when there are other interfering WLANs in the system and there are a lot of obstacle between all the stations and access points, the path loss can be increased up to 7. This will cause that the number of surrounding interfering WLANs can be grater for the transmission of VoWLAN or also, the interfering WLANs can be located nearer our WLAN of interest.

As can be seen, we can get a more optimistic number of transmitting VoWLAN stations operating in a high interference scenario just by varying some of these factors, and the base reference (worst case conditions) can be obtained with the results of Chapter 7.

8.2 Future Research

According to the investigation fo this work, the following suggestions are to be considered for further research:

- Future research on the system throughput and average delay must be made on the future variants of the IEEE 802.11 standard.
- The backbone performance for Wi Fi must be analyzed to have a total delay analysis (interconetcion with WiMax)
- Resarch on 3G wireless technologies for the interconnection with Wi FI and determine the factors-issues for compatibility
- Is real time video over Wi-Fi possible?

BIBLIOGRAPHY

[1] Bianchi, Guiseppe, “Performance Analysis of the IEEE 802.11 Distributed Coordination Function,” *IEEE Journal on Selected Areas in Communications*, Vol. 18, No. 3, pp. 535-47, March 2000

[2] Ziouva, E., Antonakopoulos, T., “CSMA/CA Performance under High Traffic Conditions,” *Computer Communications*, Vol 25, No. 1, pp. 313-321, May 2002

[3] M. Zorzi and R.R. Rao, “Capture and Retransmission Control in Mobile Radio,” *IEEE Journal on Selected Areas in Commjunications*, Vol. 12, No. 8, pp. 1289-1298, Oct 1994.

[4] Stuber L. Gordon, *Principles of Mobile Communication*, Kluwer Academic Publishers, 1996.

[5] C. T. Lau and C. Leung, “Capture Models for Mobile Packet Radio Networks ,” *IEEE Trans. on Commun.*, Vol. COM-40, pp. 917-925, May 1992.

[6] Bing Benny, *Wireless Local Area Networks*, The New Wireless Revolution. Wiley Interscience, 2002

[7] K. Huang, K. Chen, “Interference Analysis of the Nonpersistent CSMA with Hiddel Terminals in Multicell Wireless Data Networks,” *Proc. PIMRC*, Toronto 1995, pp. 907-911, Sept. 1995

[8] G. Bianchi, L. Fratta. M. Olvieti, “Performance evaluation and enhancement of the CSMA/CA MAC protocol for 802.11 Wireless LANs, Personal Indoor and Mobile Radio Communications,” *PIMRC*, Taipei, Taiwan 1996 pp. 392-396

[9] T.S. Ho, K.C. Chen, “Performance analysis of IEEE 802.11 CSMA/CA medium access control protocol,” *Personal Indoor and Mobile Radio Communications*,. PIMRC, Taipei, Taiwan 1996 pp. 407-411

[10] H.S. Chhaya, S. Gupta, “Performance modeling of asynchronous data transfers of IEEE 802.11 MAC protocol,” *Wireless Networks* 3 (1997) 217-234

[11] F. Cali, M. Conti. E. Gregori, “Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit,” *IEEE/ACM Trans. On Networking,* Vol. 8, No. 6, Dec. 2000.

[12] Prasad Neeli, Prasad Anand, *WLAN Systems and Wireless IP for Next Generation Communications,* Artech House, 2002

[13] Sánchez Jonam, *Performance Analysis of the WLAN's IEEE 802.11b road to 3G*, Master Thesis, Monterrey, N.L. June 2003.

[14] Sikora Axel, *Wireless Personal and Local Area Networks*, Wiley, 2001.

[15] Rappaport, Theodore, *Wireless Communications: Principles and Practice*, Prentice Hall Inc., 1996.

[16] Yacoub Michel Daoud, *Foundations of Mobile Radio Engineering*, CRC Press, 1993

[17] P802.11, "Draft Standard for wireless LAN medium access control (MAC) and physical layer (PHY) specification," *IEEE* (1997)

[18] Frank Ohrtman, *Voice over 802.11,* Artech House, 2004.