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**Interference and Traffic Simulation Studies
of
Digital In-Building Wireless Systems**

by

Derek F. K. YU, B. A. Sc.

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of**

Master of Engineering

**Ottawa-Carleton Institute for Electrical Engineering
Department of Systems and Computer Engineering
Carleton University**

Ottawa, Ontario

March 31, 1993

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of Digital In-Building Wireless Systems"
submitted by Derek F. K. YU, B. A. Sc.
in partial fulfillment of the requirements for
the degree of Master of Engineering**

Thesis Supervisor

Thesis Supervisor

Chair, Department of System and Computer Engineering

Carleton University

May 6, 1993

Abstract

Computer simulations have been used to study the effects of a number of factors on the traffic capacity and interference characteristics of TDMA In-Building Wireless Systems. These factors include wall attenuation, transmitter power control, and the acceptable level of Signal to Interference Ratio (SIR) to establish a call and to maintain the call. High wall attenuation, characteristic of high frequency operation (above 20 GHz), is included in the studies. Simulation results indicate that well-designed systems with portable power control and low call setup SIR threshold in buildings with high wall attenuation can reach the theoretical traffic capacity level. In general, simulation results show a high probability of a dominant interferer. Hence, the main cause of a blocked or dropped call is due to a strong dominant interferer. Therefore, improvements in system performance with increased capacity and improved communications quality are expected by incorporating interference cancellation techniques.

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Chapter 1

Introduction

1.1 Background

In our highly mobile society, portable communications has reached a point where it is regarded as an essential business tool. This is observed in the rapidly growing market for existing cellular radio communications systems. Market research also indicates that if networks and products can provide a portable communications service at a quality and cost similar to that of today's wired telephone systems, a high percentage of the population will subscribe to a portable communications service. People do have a strong desire to be free of the constraints imposed by the wired communications network.

Current mobile cellular systems are designed to work with vehicular radio equipment. These designs have inherent characteristics that limit their suitability for portable handheld usage. Vehicles are normally used outdoors. Portables are mostly used indoors where people spend most of their time. The signal received by the portable in an in-building, business environment suffers an additional building penetration loss. In practice, many of the call attempts from in-building units fail. In addition, vehicular systems were not designed to handle the traffic intensity required within an office building, and the portable needs frequent battery recharging which is not convenient.

A second generation of portable communications equipment with greater functionality will be made possible through the application of digital techniques and technologies. There has been significant interest and demand for a high capacity digital in-building wireless systems. These systems will provide toll quality service and they will be

integrated into business telephone systems. The portable telephone will be a lightweight unit with low power consumption. It would not only offer users true mobility, but it would also provide the flexibility of changing or creating various communications services in existing buildings without the need for expensive, time-consuming rewiring, and it would also drastically reduce wiring in a new building.

The challenge is to offer such services to the majority of the people in a building, not just a selected few. This will most certainly involve a sophisticated local radio communications system whose engineering requires knowledge of the spatial and temporal statistics of the signal attenuation, the multipath delay spread, and the statistical characteristics of the interference. These properties of indoor radio channel can have strong impact on the performance of the portable communications systems.

Unfortunately, these properties are not invariant, they change from one situation to another. All of them vary depending on the operating frequency, the building structure, and its contents. Therefore, the architecture of a general in-building wireless communications system must be flexible and easily adaptable to different building configurations.

It is very important to understand what are the critical design parameters before planning an architecture for an in-building communications system. This understanding also helps to determine where improvements are needed and to stimulate research activities.

Several approaches can be used toward the design of an appropriate architecture. The first approach is to construct prototype systems, but this approach is extremely expensive and time consuming since a large number of system parameters have to be varied and examined. There are also architectures that can not be realized with current technology. The prototype system would have to be installed in a wide variety of locations to enable a full scale system study. As a result, it would require the involvement of hundreds of people and a large number of portables and base stations. It would also be a lengthy process as statistics could only be collected when the system is fully loaded.

The second approach is to perform pure analysis on the communications systems. This is not practical due to the complexity of the problem and the large number of variables.

A more practical alternative is to construct computer based simulation models which can accurately represent different system architectures. The simulation models can then be used to investigate the various interactions between system parameters and obtain the corresponding system performance. The simulation method is a low cost but efficient approach for the determination of practical system design parameters.

1.2 Objectives

The main objective of this thesis is to investigate the interference characteristics of in-building wireless communications systems; particularly, the statistical distributions of signal to interference ratio at the portable and the base station. Is the interference mainly coming from a single dominant interferer or a number of strong equal power interferers? For situations with a strong dominant interferer, what is the probability that it is a co-channel interferer? The answer to these questions are important because they affect the design of the radio transceivers in optimizing the performance of frequency reuse radio systems. Interference is often assumed to be like Gaussian noise since it is the sum of many independent signals. This assumption is not true if one signal dominates the total interference power. In the case of two or three equal power interferers, the combined interfering signal is cyclostationary. Active research is being performed to suppress interference that exhibits this property [23] [24]. In general, interference cancellation techniques work best for one dominant interferer. The computer simulation approach is used to perform this task as different system scenarios can be modeled easily for investigation.

The available frequency spectrum in the UHF band (300 MHz to 3 GHz) is extremely limited due to the existence of many applications which operate within this band. It is unlikely that adequate bandwidth in the UHF band will be made available to wireless

in-building systems by the regulators in the near future. In higher frequency bands (above 20 GHz), a greater amount of spectrum may become available, but signal propagation in these bands is different due to the different absorption and reflection characteristics of building materials as a function of frequency. Signals at these frequency bands experience higher attenuation through office partitions, building floors and walls.

In in-building wireless systems, it is not mainly the absolute received signal power that determines the quality of a communications channel, but the ratio of the strength of the desired signal to the interfering signal. Frequency channels can be reused if this signal to interference ratio (SIR) is high enough. The acceptable levels of SIR to establish a new call and to maintain the call vary depending on the techniques employed to overcome multipath fading and to suppress the effects of interference. Antenna, frequency, or time diversity can be used to minimize the probability of the desired signal being in deep fade. Equalization techniques can be applied to suppress interference.

The second objective of this thesis is to study the effects on system capacity as a function of the acceptable SIR levels, wall attenuation, power control algorithms, and dynamic channel allocation schemes. A Grade of Service (GOS) of 1% is used in the comparison of system performance. The definition of Grade of Service of a system is the sum of the blocking probability for a new call and ten times the probability of dropping an established call. This research also serves as a stepping stone to understanding the relationship between system parameters and system performance. A number of simulated system scenarios are selected for the investigation of the interference characteristics of in-building communications systems.

1.3 Thesis Highlights

A single floor PBX environment with 16 cells is used in all the simulation scenarios. All simulation results in the traffic capacity studies are compared with a reference capacity derived from the Erlang B blocking probability formula based on the

following two assumptions. Each cell is assumed to be isolated from other cells, and all allocated radio equipment resources in each cell can be used simultaneously.

High wall attenuation between cells helps to attenuate interference from the surrounding cells before it reaches the receiver. A receiver which requires a lower call setup SIR threshold can tolerate more interference or is capable of overcoming signal fading. Power control regulates transmitter emitted power and keeps it at a lower level. In general, all three facts are shown to improve system traffic capacity. Simulation results from scenarios without radio resource limitation indicate that certain systems with high wall attenuation, portable power control, and low call setup SIR threshold can minimize the effects of both co-channel and adjacent channel interference and reach the Erlang B traffic capacity limit.

The behavior of a system in its operating environment directly affects the interference characteristics. If the operating environment consists of good cell isolation due to high wall attenuation, interfering signals from surrounding cells are greatly attenuated. Under this condition, the system can experience strong adjacent channel interference if the radio performance allows adjacent channels to be used within the same cell. Simulation results from scenarios with 60 dB wall attenuation indicate a probability of at least 66% of a dominant adjacent channel interferer. However, in systems with low wall attenuation, the probability of a dominant co-channel interferer is much higher. In general, simulation results show a high probability of a dominant interferer.

1.4 Thesis Organization

The remaining chapters of this thesis are organized as follows. Chapter two provides an overview of the environment and operation of in-building wireless systems. It includes discussions on radio interface, call processing algorithms, models of signal propagation and interference, and traffic models. After the overview, the system models used in the simulated systems are described in detail in chapter three. In chapter four,

simulation results on system capacity are presented. The impact on system capacity due to changes in acceptable SIR levels, wall attenuation, power control algorithm, and system resources limitations are discussed. The benefits of employing dynamic channel allocation are also illustrated. In chapter five, an investigation of the statistical characteristics of interference are presented. The probability that there is a dominant interferer, a dominant co-channel interferer or a dominant adjacent channel interferer in all simulated systems is summarized. Finally in chapter six, the thesis concludes with a discussion and recommendations for further research.

Chapter 2

Simulation of Wireless Systems

A simulator is a computer program which mimics the operation of a system as closely as is feasible. Therefore, it is essential to understand the important aspects of the environment and operation of wireless systems, and then apply appropriate mathematical and probabilistic behavior models in the simulation. This chapter describes the major components in the simulation of wireless systems.

2.1 Overview of the In-Building Wireless System Simulator

The simulator is designed specifically to emulate the operation and behavior of in-building wireless telephone systems. It is a macroscopic system simulator that can be used to study the overall system performance under a wide variety of conditions. It produces statistical information as output at the end of the simulation. The output information includes the total number of simulated calls setup, the number of blocked and dropped calls, and the total number of call handover attempts and successful handovers. The total number of normally terminated calls is a simulator input parameter and it affects the duration of the simulation.

The environment and activity of the wireless system are simulated using mathematical and queuing models. The parameters that can be modeled include: the physical arrangement of system component, and building attributes; different models of radio propagation; various algorithms used to establish calls, reassign calls, and perform power control; and different population models and traffic densities. The simulator does

not emulate the signaling activity within the wireless telephone network from the setup to the termination of a call. As a result, it cannot be used to study the message congestion characteristics of a system. It also cannot be used directly to study the received signal characteristic at the waveform level. However, information about the mean power level of the desired and interfering signals can be obtained from an information trace file. This file can optionally be generated by the simulator. This information can be used to characterize the received signal by a waveform analysis program.

Several options exist that specify the output of the simulator. The statistics that determine the grade of service of a system are always saved. Optionally, it can also generate three different trace files; they are files of call event activities, history of signal to interference ratio, and interference signal strength. The call event activities include call setup, call handover, call blocked, call dropped and call ended. These files can be analyzed to discover secondary system statistics. The simulator can analyze these files to display statistics on channel and radio usage, call distribution profiles, locations of calls that were blocked or dropped, and an activity plot of the signal to interference ratio of calls that were eventually dropped. The statistical characteristics of interference and the probability of a dominant interferer can be obtained by analyzing records in the trace file of interference signal strength.

The original design and programming of the simulator [1] was done by G. L. Plett during the summer before his final year of undergraduate studies at Carleton University. The research work was initiated in conjunction with Bell-Northern Research (BNR). He further developed the simulator for his senior undergraduate project. The simulator was further enhanced by Plett after he joined BNR following his graduation. It is used intensively at BNR in the study of the capacity of in-building wireless systems. As part of this thesis, I have added to the simulator, a number of power control algorithms and the capability of generating the trace file of interference signal strength. The trace file is used for the statistical study of interference characteristics.

2.2 Wireless System Topology

There are three common configurations for low-power wireless applications. These are: business use, telepoint use, and residential use. The business environment is characterized by very high traffic capacity requirements. This necessitates a high density of base stations to handle the load. The telepoint environment provides a public access service (wireless phone booth) and is installed in public areas such as shopping and transportation centres. The telepoint service requires a lower density of base stations, but typically a much larger area is to be served. The residential service includes environments from low density single home developments to apartment buildings. As a result, it must operate over a wide range of user densities, and there are generally fewer users per base station than in the other environments.

Figure 1: System Topology

A wireless system is typically made up of a number of base stations and a number of portable wireless telephones. The base stations are connected to a wireless system controller. The controller is connected to either the public or private communication networks as shown in Figure 1. The service region or floor area served by each base station defines a cell. In normal in-building applications, these cells overlap such that continuous coverage is provided within the service area.

2.3 Wireless Call Processing Operation

Call processing operation involves a number of coordinated procedures performed by the portable, base station, and wireless radio system controller. These procedures are invoked during call setup, call handover, and call termination. The call setup and handover procedures are particularly important because they affect the system performance directly. For example, it is desirable to setup or handover a call to a base station and use a channel that will not cause any ongoing calls to be prematurely terminated. At call setup, it is acceptable to block a call which will potentially cause a number of dropped calls after it is setup. The next paragraph describes simplified examples of call processing operations.

When a portable enters the wireless service area, it registers with the base station it can most clearly detect. This is generally the closest base station. Should the portable ever detect a base station with a stronger received signal than the one to which it is registered, it will attempt to register with that new base station. This ensures that each portable can move anywhere within the range of the system, and still originate and receive calls.

An outgoing call attempt originating at a portable is routed through the base station to which the portable is registered. If an outgoing call attempt finds the base station busy, an attempt will be made to setup the call to another base station in the area. If a base station is available, the channel with the least amount of interference received by the portable will be used to setup the call. If no acceptable channel or base station is found, the call is blocked. Incoming telephone calls to portables are routed through the base stations in the

other direction. If at any time the signal to interference ratio of the call becomes unacceptable at either the portable or the base station, a call handover attempt is made. If a call handover cannot be achieved within a fixed number of seconds, the call will be dropped.

2.4 Frequency Allocation

Each base station is equipped with resources to service a certain number of traffic channels. The channels that a base station is allowed to use may either be pre-set in the base station when it is installed, or be allowed to dynamically change so that the base station can operate on any free channel in the available band.

Figure 2: Fixed Frequency Allocation Plan in Cellular Application

The first scheme is called fixed channel allocation and is commonly used in cellular applications. Figure 2 shows an example of a fixed frequency allocation plan [2]. The same idea can be applied to the in-building application. The coverage area is partitioned into smaller areas, with each area containing a certain number of base stations deployed in a channel reuse pattern. Typically the available band of channels is divided evenly among the

base stations within a channel reuse pattern. In a pattern size of seven, each of the seven base stations would be able to use one seventh of the total number of channels. The method of assigning channels within the channel reuse pattern is chosen such that co-channel and adjacent channel interference is minimized.

The second scheme is called dynamic channel allocation (DCA). Each base station in the system is allowed to operate on any free channel in the available band. The channel allocation algorithm is usually based on transmission quality measurements performed by the base station, or by the portable, or both. Two common criteria used in the measurements are minimum interference and maximum signal to interference ratio. DCA has advantages over the fixed frequency scheme. Dynamic channel allocation offers improved capacity and spectrum utilization in in-building wireless systems [3]. However, systems which use dynamic channel allocation require the use of programmable radio synthesizers at the portables and base stations. In fixed channel allocation schemes, the portable also needs programmable radio synthesizer to establish communications connection with different cells as the portable user roam from one cell to another cell.

2.5 Multiple-Access Techniques

Wireless systems multiplex a number of traffic channels into the assigned radio band. Two of the common techniques are frequency division multiple access (FDMA), and time division multiple access (TDMA). In FDMA, the available radio band is divided into a number of frequency bands, where each band is a traffic channel. In TDMA, the whole radio band is used to transmit a very high bit rate signal. This signal is divided into time slots, each time slot being a traffic channel. There are also hybrid systems which are combinations of TDMA and FDMA. In hybrid systems the radio band is broken up into a number of sub-bands. A TDMA signal is transmitted on each of these sub-bands. These different access techniques are illustrated in Figure 3.

In addition to this primary multiplexing, a secondary multiplexing is required since the telephone channel is bi-directional. Two methods can be used and they are called time division duplex (TDD) and frequency division duplex (FDD). In TDD, both directions of the conversation (base to portable and portable to base) occur on the same frequency, but at different times; i.e., first the base station sends its information, then the portable(s) send their information, and the cycle repeats. In FDD, two separate frequency bands are used. Base stations transmit to portables on one frequency and portables transmit to base stations on the other.

Figure 3: Multiplexing Techniques

There is another class of multiple-access techniques known as Code Division Multiple Access (CDMA). Direct-Sequence Spread-Spectrum Multiple-Access is a common form of CDMA in which every user is assigned a code sequence and it is modulated onto a carrier signal together with the user's digital information. In a typical code, there are many code chips per user data bit and this spreads the bandwidth of the transmitted signal.

The entire channel bandwidth is used by all users of the system at one time. In order to achieve a low level of mutual interference among the users, the code sequences applied by each user in spreading the information signal must have low cross-correlation properties. CDMA will not be considered in this thesis.

2.6 Propagation Models

The propagation model describes how the radio signal travels from a transmitter (Tx) to a receiver (Rx), and is used to predict the radio signal strength as a function of position and Tx to Rx separation. The radio propagation, particularly within a building, is quite complex and statistical propagation models have been developed based on measurements. There are a number of similar models that can be used to describe the indoor radio environment. Propagation parameters are observed to vary significantly depending on building design and construction. Most models consider the path attenuation, shadowing, and signal fading effects.

2.6.1 Path Attenuation

Attenuation is the average loss of signal power due to distance and obstructions. If distance 'd' alone is considered in free space, the average strength of the received signal varies as $1/d^2$. The exponent value 2 is the rate of decay in free space. The rate of decay in an indoor environment is a strong function of building type, the layout of rooms and corridors, the number of floors and walls, the location of furniture, etc. Narrowband measurements at 900 MHz and 1700 MHz in [4] show that the rate of decay varies between 1.2 and 6.5 in office buildings with different partitioning materials, and density of rooms and floors. This model is described by the following formula and is known as the Power Law Attenuation model.

$$\text{Average Attenuation (dB)} = L_{1 \text{ meter}} + 10\gamma \log(d)$$

where $L_{1 \text{ meter}}$ = free space propagation loss at 1 meter distance (dB)
 d = distance between transmitter and receiver (m)
 γ = signal decay rate (in free space, $\gamma = 2$)

Signal propagation measurements also show that site-specific information can be used to obtain a better path loss prediction within buildings. The model specifically includes floor and wall factors. The average attenuation is calculated by taking the sum of free space ($\gamma = 2$) propagation loss and losses through floors and walls, the model [5][6] is described by the following formula:

$$\text{Average Attenuation (dB)} = L_{1 \text{ meter}} + 20 \log(d) + mF + nW$$

where $L_{1 \text{ meter}}$ = free space propagation loss at 1 meter distance (dB)
 d = distance between transmitter and receiver (m)
 m = number of floors between transmitter and receiver
 F = attenuation per floor (dB)
 n = number of walls between transmitter and receiver
 W = attenuation per wall (dB)

2.6.2 Shadow Fading (Long-Term Fading)

The variation in the mean signal strength is the shadowing effect. It is mainly caused by the building configuration and man-made environment between the base station and the portable unit, and it varies slowly with position and time. The shadowing effect for indoor wireless communications environments is usually considered to be log-normally distributed (a normal distribution on a dB scale) with a standard deviation σ in dB [7]. The value of σ is determined as a function of general surroundings.

2.6.3 Rayleigh Fading (Short-Term Fading)

When radio signals from the transmitter follow different paths, diffracting and reflecting off obstructions, and then eventually recombining at the receiving antenna, they interfere with each other both constructively and destructively. The properties of this multi-path interference have been empirically studied, with the conclusion that instantaneous received power statistics can be well described as a Rayleigh distributed random variable [2]. As a result, the probability density function (pdf) of the received signal $r(t)$ is

$$p(r) = \frac{r}{\alpha^2} \exp\left(-\frac{r^2}{2\alpha^2}\right)$$

and the cumulative probability distribution (CPD) of $r(t)$, the probability that r is less than level A , is

$$P(r \leq A) = \int_0^A \frac{r}{\alpha^2} \exp\left(-\frac{r^2}{2\alpha^2}\right) dr = 1 - \exp\left(-\frac{A^2}{2\alpha^2}\right)$$

where the mean square of r is $E[r^2] = 2\alpha^2$.

The cumulative probability distribution of $r(t)$ is shown in Figure 4a.

Figure 4a: Statistical Properties of a Rayleigh-Fading Signal

The x axis is the signal level in dB with respect to the root mean square (rms) level of $r(t)$. The figure shows that there is a 63% probability of fading below the average signal strength, and a 37% chance of the recombining waveforms increasing the signal strength. The maximum signal increase due to constructive interference is approximately 10 dB. Destructive interference causes fading or signal decrease. The probability of a fade deeper than 10 dB is 10%. There is a 1% probability of having a fade deeper than 20 dB. Thus, for example, if the demodulation system requires a signal to interference ratio (SIR)

threshold of 11 dB for satisfactory speech quality, then, for a 1% speech outage probability, the actual average SIR must be 31 dB (20 dB higher).

2.7 Diversity

The Rayleigh fading channel poses a demanding design problem to wireless system designers. Diversity is a commonly used technique to overcome this short term fading.

A diversity scheme is a method that is used to recover information from several signals transmitted over independently fading paths. The objective is to combine the multiple signals and reduce the effect of excessively deep fades. Since the chance of having two deep fades from two uncorrelated signals at any instant is rare, the effect of the fades can be reduced by combining them. Common methods of diversity combining are selective combining, maximum-ratio combining, and equal-gain combining. These methods involve relatively simple weighted sums of multiple received signals. Details on these combining methods [30] are not described in this thesis.

There are basically six methods of achieving diversity reception. They are space diversity, field-component diversity, polarization diversity, angle diversity, frequency diversity, and time diversity. Two of the most commonly used diversity techniques are space and frequency diversity.

A system employing space diversity uses multiple antennae that are spatially separated to the extent that the received signals from the antennae are uncorrelated. For multipath radio environments with angle of arrival uniformly distributed over 0 to 2π , the correlation is small for antenna separations of $\lambda/4$ or greater [7], where λ is the wavelength of the carrier signal being transmitted. Assuming the signals received in each diversity branch are uncorrelated, the probability of the received signals r in one branch is less than level A is

$$P(r \leq A) = 1 - \exp\left(-\frac{A^2}{2\alpha^2}\right)$$

Then, the probability of the received signals in all M branches are simultaneously less than level A is

$$P(r_1, \dots, r_M \leq A) = \left(1 - \exp\left(-\frac{A^2}{2\alpha^2}\right) \right)^M$$

This is the distribution of the best signal selected from M branches and it is plotted in Figure 4b for diversity systems with 1,2,3,4, and 6 branches [8]. If a portable or base station with a single antenna has the probability 'p' of being in a deep fade, the same system using two-branch space diversity will have probability 'p²' of being in a deep fade. A system with p² diversity will experience a 10 dB benefit in the average required SIR at an outage rate of 1%. Therefore, for the example in the previous section, an average SIR of 21 dB instead of 31 dB is needed to give an outage probability of 1% with dual antenna diversity.

The principle behind frequency diversity is the same. Experimental measurements at 915 MHz have indicated that any two frequencies separated by at least 10 MHz will experience uncorrelated fading [9]. Thus, there is a similar p² improvement by transmitting the signal on two frequencies, and using the stronger received signal. By employing both spatial and frequency diversity, a p⁴ improvement can be realized. This will provide a 16 dB benefit in the average SIR requirement for 1% outage probability.

Figure 4b: Probability Distribution of M-branch Selection Diversity System

2.8 Interference

It is not only the absolute received signal power that determines the quality of a communications channel, but the ratio of the strength of the desired signal to the interfering signal. Frequency channels can be reused if this signal to interference ratio (SIR) is high

enough. The following sub-sections describe four different types of interference. They are co-channel interference, adjacent and alternate channel interference, intermodulation interference, and interference due to unsynchronized timing.

2.8.1 Co-Channel Interference

A design objective for both mobile-radio systems and in-building wireless systems is to conserve the available spectrum. This is accomplished by reusing allocated traffic channels in areas located as close to each other as possible. As a result, each active call on a traffic channel will cause co-channel interference to all other calls on that traffic channel. The limitation in distance for reusing traffic channels can be determined by the amount of co-channel interference.

2.8.2 Adjacent and Alternate Channel Interference

Given a modulation technique and channel plan for a system, a small but significant portion of the transmitted signal may spill into adjacent frequency channels. This interference is called adjacent channel interference. Gaussian Minimum Shift Keying [10] (GMSK) is the modulation technique used for a number of current generation wireless standards such as CT2 and DECT. The transmitted spectrum of a GMSK signal with BT product of 0.5 and the adjacent channel interference is shown in Figure 5.

As shown in the figure, the power in each adjacent channel is about 35 dB lower than the power in the centre channel. Once this is filtered by the receiver's channel filter, there is still a sizable contribution to the adjacent channel. Some of the signal also spills into the second, third, fourth (etc.) adjacent frequency channels. The level of this interference is generally quite low, but it may still have an effect on the use of these adjacent channels. This interference is termed alternate channel interference.

Figure 5: GSM Spectrum (BT=0.5)

2.8.3 Interference due to Unsynchronized Timing

Synchronization is a time-domain issue referring to the frame level or slot level timing of a system. Two systems are synchronized if they start and stop sending the radio bursts at the same time. In typical wireless systems, portables extract their timing information from the base station to which they are communicating (all transceivers in a base station will be synchronized). So, a portable is always synchronized with its base station. However, if all of the base stations in the environment are not synchronized to each other, some additional interference arises as the transmissions of one radio system overlap others. There are two effects due to unsynchronized operation. One affects TDMA systems, and the other affects TDD systems. Note that TDMA-TDD systems will experience both effects.

In TDMA, if two systems are synchronized, one traffic channel in one system will be a co-channel interferer to one traffic channel in the other system, and an adjacent channel

interferer to two traffic channels. In unsynchronized TDMA systems, there will be a relative time slip between one system and another. Because of this time slip, a traffic channel in one system will be a co-channel interferer to two traffic channels in the other system, and an adjacent channel interferer to four. Thus, the effective number of interferers in an unsynchronized system is doubled, and the number of usable traffic channels may be reduced by a factor of two. This is illustrated in Figure 6.

Figure 6: Unsynchronized Interference in TDMA Systems

In TDD systems, there is an additional effect caused by unsynchronized operation. In a synchronized system, all base stations transmit at the same time, followed by all portables which are also transmitting at the same time. Thus a portable receives signals only from the base stations. Likewise, the base stations receive signals only from portables. However, when the base stations are unsynchronized, one base station may be transmitting while the other base station's portables are transmitting (and vice versa). This results in portables being interfered with by portables and base stations; and base stations being interfered with by other base stations and portables. This is illustrated in Figure 7.

Figure 7: Unsyncronized Interference in TDD Systems

In both cases, the interference can be eliminated by synchronizing the base stations and systems. However, this is not always feasible. For example, it may not be practical to synchronize different PBX systems operating on different floors of a multi-tenant office building.

2.8.4 Intermodulation Distortion

Intermodulation products are generated when there is a non-linearity in the signal path [8]. This typically occurs in transmit power amplifiers, receive front-end amplifiers, and mixers. If, for example, an amplifier has the following response function:

$$V_{out} = a V_{in} + b V_{in}^3$$

the output signal will have additional components due to the presence of the cubed term. If the input signal to this amplifier consists of three tones

$$V_{in} = A \cos \alpha t + B \cos \beta t + C \cos \gamma t$$

where α , β and γ represent three different carrier frequencies within the system operation band, then the output of the amplifier is described by the following equation:

$$\begin{aligned}
V_{out} = & [a A + 0.75 b A (A^2 + 2 B^2 + 2 C^2)] \cos \alpha t \\
& + [a B + 0.75 b B (2 A^2 + B^2 + 2 C^2)] \cos \beta t \\
& + [a C + 0.75 b C (2 A^2 + 2 B^2 + C^2)] \cos \gamma t \\
& + 0.75 b A^2 B \cos [(2 \alpha - \beta) t] + 0.75 b A^2 C \cos [(2 \alpha - \gamma) t] \\
& + 0.75 b B^2 A \cos [(2 \beta - \alpha) t] + 0.75 b B^2 C \cos [(2 \beta - \gamma) t] \\
& + 0.75 b C^2 A \cos [(2 \gamma - \alpha) t] + 0.75 b C^2 B \cos [(2 \gamma - \beta) t] \\
& + 1.5 b A B C \cos [(\alpha + \beta - \gamma) t] + 1.5 b A B C \cos [(\alpha + \gamma - \beta) t] \\
& + 1.5 b A B C \cos [(\gamma + \beta - \alpha) t] \\
& + \{ \text{terms at frequencies outside the band} \}
\end{aligned}$$

the terms that fall within band are the frequencies at α , β , γ , $2\alpha-\beta$, $-\alpha-\gamma$, $2\beta-\alpha$, $2\beta-\gamma$, $2\gamma-\alpha$, $2\gamma-\beta$, $\alpha+\beta-\gamma$, $\alpha+\gamma-\beta$, and $\gamma+\beta-\alpha$. The α , β , and γ terms are the desired ones, and the rest are the undesirable intermodulation products.

The level of the intermodulation products is determined by the factor 'b' in the response function. This factor is related to the "third order intercept" (TOI) parameter of the amplifier or mixer. In general, the larger the TOI, the smaller is the intermodulation distortion. As a receiver moves closer to a transmitter, the desired signal gets stronger and so do the intermodulation products. In fact, the intermod products can increase in strength by 3 dB for each 1 dB increase in the level of the desired signal. This is observed from the coefficients of all the intermodulation product terms. As a result, the closer the distance between a portable and a base station, the stronger the effect of intermodulation distortion.

In contrast with synchronization which is a time domain problem, intermodulation distortion is an issue in the frequency domain. Therefore, all FDMA, Multi-Carrier TDMA, and FDD systems are affected. However, Multi-Carrier TDMA systems are less affected than FDMA systems because of a smaller number of frequency carriers. Intermodulation distortion has greater effect on systems which have a large number of

frequency carriers operating simultaneously close together. Intermodulation products can be reduced by proper design of the radio circuitry.

2.9 Power Control

Power control in a wireless communications system can prevent a portable from transmitting at full power to a nearby base station. The reason is to avoid a high power signal from driving the base station receiver into saturation and therefore reducing the base station sensitivity or making the base station inoperable. In principle, the portable and the base station could transmit at the minimum power level that resulted in an acceptable SIR at the receiver.

By using power control, the capacity of the system can also increase, this is due to the fact that individual interference can be reduced. With less interference, the frequency reuse distance is shorter and the system capacity increases.

Power control is also an effective technique to reduce the effect of intermodulation products. By reducing the transmitted power by a factor ξ , the resulting decrease in the power of the intermodulation products can be up to ξ^3 . Therefore, whenever the transmitted power can be reduced and still maintain an adequate SIR, the effect of intermodulation distortion is reduced.

2.10 Traffic Model

Calls processed by a telephone system come from a pool of users. From the viewpoint of a central office in a large city, the number of users is very large and can be considered infinite with very little error. This is the assumption of most telephony queuing theory. These systems are described in Section 2.10.1. However, in the case of in-building wireless systems, the population tends to vary between tens of subscribers to several thousands, and thus must be treated differently when the number of subscribers is small. Finite population models are described in Section 2.10.2.

2.10.1 Infinite Population, m-Server Loss Systems

In this model, there are m available servers, an infinite population, and blocked calls are cleared [11]. Each newly arriving call is given its private server. However, if a call arrives when all servers are occupied, that call is 'lost' and returns immediately to the arriving state as if it had just completed service. The Markov chain in Figure 8 describes the state-transition-rate of such a system. There is a constant arrival rate λ , and a constant departure rate μ for every call in the system. The circles represent states. In this case, being in state n means n out of the total m servers are in use. The arcs connecting the states show the relative probability of going from one state to another.

Figure 8: State-transition-rate diagram for infinite population m-server loss system $M/M/m/m/\infty$

The system is characterized by analyzing the equilibrium state. By using the simple conservation of flow relationship, which is equivalent to drawing a vertical line separating adjacent states and equating flows across this boundary, the following recurrence relationship is obtained. The equation that computes the probability of having n customers in the system can be derived from this recurrence relationship.

$$p_n = \left(\frac{\lambda}{n\mu} \right) p_{n-1} ;$$

$$p_n = \begin{cases} p_0 \left(\frac{\lambda}{\mu} \right)^n \frac{1}{n!} & n \leq m \\ 0 & n > m \end{cases}$$

The probability p_0 can be solved based on the fact that the summation of the entire probability distribution is equal to one. The expression for p_0 is

$$p_0 = \left[\sum_{j=0}^m \left(\frac{\lambda}{\mu} \right)^j \frac{1}{j!} \right]^{-1}$$

The value p_m is of great interest in telephony. It is the blocking probability of the system. The blocking probability is equal to the probability of an arrival with all m servers are busy.

$$p_{block} = \frac{\lambda p_m}{\sum_{n=0}^m \lambda p_n} = \frac{p_m}{\sum_{n=0}^m p_n}$$

The arrival rate λ is a constant and it is canceled out of the equation. The remaining summation in the denominator is equal to one, so the blocking probability is equal to the probability that all m servers are busy.

$$p_{block} = p_m = \frac{\left(\frac{\lambda}{\mu} \right)^m \frac{1}{m!}}{\sum_{j=0}^m \left(\frac{\lambda}{\mu} \right)^j \frac{1}{j!}}$$

This probability expression is referred to as Erlang's B formula and is commonly denoted by $B(m, \lambda/\mu)$. It was first derived by Erlang in 1917. The ratio λ/μ is referred to as the traffic intensity of the system and is usually expressed in Erlangs [11].

The blocking probability is a performance measure of communications systems. In a wired system, the blocking probability can be accurately predicted when the number of servers m and the traffic intensity λ/μ are given. Thus, the blocking probability can be used as a guideline in system resources provisioning. In wireless communications systems, the blocking probability is a function of two additional factors. They are the effects of interference and resource sharing among adjacent cells. In general, the effects of interference degrade the system performance while resource sharing improves it. The blocking probability is also used by researchers as a comparative metric to study the performance of wireless communications systems [13].

An important measure of a queueing system is the average number of customers in the system $\bar{N}$.

$$\begin{aligned}\bar{N} &= \sum_{n=0}^{\infty} np_n \\ &= \frac{\sum_{n=0}^m n \left(\frac{\lambda}{\mu}\right)^n \frac{1}{n!}}{\sum_{j=0}^m \left(\frac{\lambda}{\mu}\right)^j \frac{1}{j!}} \\ &= \left(\frac{\lambda}{\mu}\right) \frac{\sum_{n=0}^{m-1} \left(\frac{\lambda}{\mu}\right)^n \frac{1}{n!}}{\sum_{j=0}^m \left(\frac{\lambda}{\mu}\right)^j \frac{1}{j!}} \\ &= \left(\frac{\lambda}{\mu}\right) (p_0 + p_1 + \dots + p_{m-1})\end{aligned}$$

Since $p_0 + p_1 + \dots + p_m = 1$, $p_0 + p_1 + \dots + p_{m-1} \approx 1$ if $p_{block} = p_m \approx 0$. As a result, λ/μ is a good approximation of $\bar{N}$ when the blocking probability is small. In the case of an infinite number of servers and the blocking probability is zero, the value λ/μ becomes $\bar{N}$.

If the traffic intensity and the average service time of the system are given, the average inter-call arrival time can be computed as followed:

$$\frac{\lambda}{\mu} = \text{Traffic Intensity}$$

$$\lambda^{-1} = \frac{1}{\text{Traffic Intensity}} \mu^{-1}$$

2.10.2 Finite Population, m-Server Loss Systems

One of the primary assumption of the Erlang B model is that there is a constant arrival rate to the system, no matter how many users are active. This does not accurately model the situation where there are a small number of users. In a finite population, the number of actual phones must be taken into account. The Markov chain in Figure 9 describes the state-transition-rate of the system. In this model, a constant arrival rate per user λ_f is used, m is the number of servers, and N is the number of users in the system [11]. The number of users is assumed to be greater than the number of servers.

Figure 9: State-transition-rate diagram for finite population m-server loss system M/M/m/m/N ($N \geq m$)

The equations that describe the characteristics of the above system can be obtained by using the same equilibrium analysis.

$$p_n = \left(\frac{\lambda_f}{\mu} \right) \left(\frac{N-n+1}{n} \right) p_{n-1}$$

$$p_n = p_0 \left(\frac{\lambda_f}{\mu} \right)^n \binom{N}{n} \quad n \leq m$$

where

$$p_0 = \left[\sum_{j=0}^m \left(\frac{\lambda_f}{\mu} \right)^j \binom{N}{j} \right]^{-1}$$

thus

$$p_n = \frac{\left(\frac{\lambda_f}{\mu} \right)^n \binom{N}{n}}{\sum_{j=0}^m \left(\frac{\lambda_f}{\mu} \right)^j \binom{N}{j}}$$

This is known as the Engset distribution. The blocking probability of the system can be computed using the same method as described in the infinite population case. It is equal to the probability of an arrival when all m servers are busy.

$$\begin{aligned} p_{block} &= \frac{(N-m)\lambda_f p_m}{\sum_{j=0}^m (N-j)\lambda_f p_j} \\ &= \frac{(N-m)p_m}{N - \sum_{j=0}^m j p_j} \\ &= \frac{(N-m)p_m}{(N - \bar{N})} \end{aligned}$$

As the population size N grows to infinity, this finite population model becomes identical to the Erlang B model. $\bar{N}$ is the average number of users in the system.

The expression λ_f/μ has a different meaning than λ/μ in the Erlang B model. It is a function of e where e is the generated traffic per user in Erlangs. The definition of e is equal to the ratio of the average service time to the sum of the average service time and the average inter-call time of a user.

$$e = \frac{\frac{1}{\mu}}{\frac{1}{\lambda_f} + \frac{1}{\mu}}$$

$$\frac{e}{1-e} = \frac{\frac{1}{\lambda_f} + \frac{1}{\mu}}{\frac{1}{\lambda_f}}$$

$$\frac{\lambda_f}{\mu} = \frac{e}{1-e}$$

then

$$\lambda_f^{-1} = \frac{1-e}{e} \mu^{-1}$$

Therefore, if the traffic per user and the average service time is given, the average inter-call time of a user can be computed.

2.10.3 Comparison of Infinite and Finite Population Models

It is important to understand the differences between infinite and finite population models and use them appropriately in the simulation of in-building wireless systems. Assuming the number of servers is large, there will always be resources to serve each arriving call. In other words, there is no blocking in either systems. Figure 10a shows a comparison of probability distributions for infinite and finite population models. The traffic intensity is 200 Erlangs for both models. For the finite population case, four different traffic per user are considered, they are 0.15, 0.3, 0.5 and 0.7 Erlangs per user which correspond to system populations of 1333, 667, 400 and 286 users.

Figure 10a: Comparison of Infinite and Finite Population models (200 Erlangs Traffic Intensity)

The figure shows that the probability distributions of both infinite and finite models are almost identical at 0.15 Erlangs of traffic per user, but it is significantly different for the other cases. It is important to know whether this is still true for a much smaller system. A comparison is done at 0.15 Erlangs of traffic per user for systems with a traffic intensity of 10 Erlangs (150 users). Figure 10b shows that both distributions are also very close even in a 10 Erlangs system. As a result, the infinite population model is still a good

approximation for in-building wireless systems as long as the traffic per user is close to 0.15 Erlangs.

Figure 10b: Comparison of Infinite and Finite Population models (10 Erlangs Traffic Intensity)

Chapter 3

Simulated System Description

A general discussion on the environment, modeling, and operation of in-building wireless systems was given in chapter 2. In this chapter, major components of the simulated system are described. These include multiplexing techniques, system floor plan and layout, traffic modeling, signal propagation and interference modeling, and call processing algorithms.

The objectives of this thesis are to investigate the changes in system capacity and interference characteristics due to variations in a number of selected system parameters. These parameters are the acceptable SIR levels for call setup and handover, wall attenuation, number of time slots per carrier, power control, frequency allocation schemes, and radio resources. The different simulation cases for each of these parameters are described in Section 3.5.

The metric used to measure the performance of the simulated systems is "Grade of Service" (GOS). Its value is based on objective measurable quantities such as the number of blocked and dropped calls. Normally, the GOS is fixed at an acceptable value in order to determine the maximum system capacity and utilization which meet the GOS objective. The definitions of GOS, system capacity, and average system utilization are described in this chapter. Finally, the chapter ends with a discussion on simulation length and accuracy. The simulated system parameters and models are also summarized in a table at the end of the chapter.

3.1 Multi-Carrier TDMA-TDD System

A hybrid FDMA/TDMA channel multiplexing system is used in all of the simulation cases. Time division duplex (TDD) is used as the secondary multiplexing to provide bi-directional communications. Most of the simulations assume an assigned radio spectrum of 8 MHz. The bandwidth per carrier is 1 MHz, and there are eight channels (time slots) per carrier. The traffic channel arrangement of this multi-carrier TDMA-TDD system is shown in Figure 11. This arrangement provides a total of 64 traffic channels in the 8 MHz spectrum allocation. In the frequency axis, frequency f_1 to f_8 are the eight different carrier frequencies. The time axis indicates that both directions of the conversation occur in the same traffic channel but at different time intervals. The base station sends its information, then the portable(s) send their information, and the cycle repeats.

Figure 11: 8 MHz Multi-Carrier TDMA-TDD System

In three of the simulation groups, a 4 MHz spectrum assignment is assumed. The number of carriers is kept the same but the bandwidth per carrier becomes 500 KHz. As a result, there are only four channels (time slots) per carrier and a total of 32 traffic channels

within the 4 MHz spectrum allocation. It is assumed that the bandwidth of the channels in all simulated systems is such that it is a flat fading environment.

In the simulation, each base station is equipped with a fixed number of radios to service the traffic within its cell or adjacent cells. In a fixed frequency plan, the operating frequency of each radio is fixed. Therefore, all time slots served by a radio have to operate on the same carrier frequency. However, in a dynamic channel allocation scheme, each radio can operate on any free channel in the available band for each time slot. It is also assumed that the radio is capable of switching to any one of the eight carrier frequencies between adjacent slots. The portable is also capable of operating on any one of the carrier frequency and time slot combinations. Figure 12 shows an example of the channel usage of a base station which operates in a system with 4 MHz spectrum allocation. The base station is equipped with eight radios. The figure indicates that Radio 1 is serving two calls at f_3 and f_5 on slot 2 and slot 4 respectively. Radio 2 is currently fully utilized and Radio 8 is operating on f_8 , f_2 and f_8 on slot 1, slot 3 and slot 4 respectively. There is no restriction on carrier usage on different time slots within the same radio, but different carriers must be used by different radios on the same time slot.

Figure 12: Example of Channel Usage of a Base Station with Dynamic Channel Allocation

3.2 System Floor Plan and Traffic Model

A single floor PBX environment is used in all the simulation scenarios. There is only one service provider for the entire floor. The system floor plan is given in Figure 13.

The dimension of the floor is 64 meters by 64 meters. There are sixteen base stations in the system, they are mounted on the ceiling and uniformly placed in a 4 X 4 pattern. The portable user is either sitting or standing in his office and the minimum separation between the portable and the base station is 2 meters. The transmission timing of the base stations are all synchronized with each other.

Figure 13: Simulated System Floor Plan

Each base station is equipped with a fixed number of radio transceivers, the exact number of radios depends on the simulated system scenario. There are walls which isolate the base stations from each other. The wall attenuation parameter can vary within a range of values; the purpose is to simulate different building material and/or different system operating frequency.

Signal propagation of millimeter waves is very different from the propagation characteristics of the 900 MHz radio signal. Ongoing researches are being performed to characterize and model its behaviors. At 60 GHz, signal propagation inside a building is ray-like with a high wall penetration loss. Signal coverage within an enclosed area depends on the reflections from the surfaces of the building [17]. Consequently, reflections from walls play a major role in maintaining a high signal level throughout a closed environment. Figure 14 describes the transmissivity and reflectivity of three different building materials.

Material	Transmissivity %	Reflectivity %
Plasterboard 1 cm thickness	42.0	2.0
Chipboard 1.9 cm thickness	4.5	20.0
Autoclaved aerated concrete blocks 10 cm thickness	0.0001	16.0

Figure 14: Transmissivity and reflectivity of some common materials at 60 GHz

All simulated systems assume the offered traffic per user is less than 0.15 Erlangs, and the Markov Birth-Death process with an infinite population is used as the traffic model in the simulated systems. It has been shown in Section 2.10.3 that the probability distributions of both infinite and finite population models are almost identical at 0.15 Erlangs of traffic per user. The average call duration (μ^{-1}) is 3 minutes and the call

durations are exponentially distributed. The traffic intensity is an input parameter to the traffic simulator and the average inter-call arrival time (λ^{-1}) can be computed by the following equations. The inter-call arrival time is also exponentially distributed.

$$\lambda^{-1} = \frac{1}{\text{Traffic Intensity}} \mu^{-1}$$

The portable location is generated randomly and is uniformly distributed over the floor. No calls originate from outside the building. There is no portable mobility, the portable is assumed to be at the same location throughout the duration of the call. However, the SIR of the call can change during the call due to the surrounding activities. New calls can be initiated and some calls may end.

3.3 Signal Propagation and Interference

It is not mainly the absolute received signal power that determines the quality of a communications channel, but the ratio of the strength of the desired signal to the interfering signals. All simulated scenarios include the effects of co-channel and adjacent channel interference. There is no additional interference caused by unsynchronized operation because the transmission timing of all base stations are synchronized with each other. Intermodulation is also not considered in the scope of this thesis because it is a secondary effect caused by the imperfection of the radio circuitry. Intermodulation can be reduced or eliminated through careful engineering. If intermodulation is included in the simulation, the time required to complete a simulation can increase on the order of ten times to a hundred times just to account for the calculation of the strength and location of intermodulation products.

The strength of the co-channel interference is calculated based on the signal propagation model. The power that spills into the adjacent channel is assumed to be 30 dB lower than the power in the centre channel. An investigation on the comparative effect of

different levels of Adjacent Channel Rejection (ACR) on the capacity of the Digital European Cordless Telecommunications (DECT) system was performed by McCann and Croft [18]. Their results indicate a change in the ACR from the specified 28 dB to 31 dB only increases the system capacity by about 4%. A further improvement to the ACR has no significant effect on the system capacity. In the scope of this research, an adjacent channel rejection of 30 dB is used.

The signal model assumes free space propagation (rate of decay = 2), and it specifically includes the wall factor and shadowing effects [5][6]. The floor factor is not shown in the model because all simulated scenarios are single floor systems. The signal level (in dBm) at the receiver is:

$$S = S_{1 \text{ meter}} - 20 \log(d) - nW + X_{\sigma}$$

where	$S_{1 \text{ meter}}$	=	signal level at one meter (dBm)
	d	=	distance between transmitter and receiver (m)
	n	=	number of walls between transmitter and receiver
	W	=	attenuation per wall (dB)
	X_{σ}	=	random shadow fading ($\sigma = 8$ dB, included when Tx and Rx separation is greater than 2.8 meters)

As indicated in a review on radio propagation into and within buildings by D. Moltdar [4], the shadow fading within office buildings in urban areas is log-normally distributed with a standard deviation range from 4 dB to 10 dB. In this thesis, the shadow fading is modeled by a log-normally distributed random variable X_{σ} with a standard deviation of 8 dB. The shadow fading is included in the signal model when the transmitter and receiver separation is greater than 2.8 meters. For separation of less than 2.8 meters, there is a very high probability of Line of Sight (LOS) communications between the transmitter and the receiver, and the signal propagation follows free space propagation without shadowing.

The received signal strength is calculated at call setup or handover. It is fixed for the duration of the call or until a handover takes place. For systems that use the same carrier frequency for both uplink and downlink communications between the portable and the base station, the average propagation path losses of the desired signals in both directions are identical. However, the interferences received at either end can be very different.

The effect of multipath fading is not included in the above signal propagation model. However, it is accounted for by setting a higher SIR requirement for call setup and handover. The required SIR margin is based on the statistical properties of a fading signal and the amount of diversity reception. These have been discussed previously in sections 2.6.3 and 2.7.

The useability of a communications channel depends on the amount of interference on that channel. The channel can be used if the signal to interference ratio is high enough. In the absence of interference, the radio coverage depends on a number of factors. These factors include transmitter power level, propagation path loss, thermal noise level, and the required signal to interference ratio at the receiver to obtain satisfactory speech quality. The following paragraph describes an example which illustrates the relationship between these factors and radio coverage.

In the case of a TDMA system that operates at 850 MHz, the channel bandwidth is 1 MHz with an emitted power of 10 dBm at the antenna. The system requires 21 dB signal to interference ratio at the receiver to operate properly. The 21 dB threshold corresponds to 11 dB carrier to interference plus noise ratio required by the receiver and a 10 dB Rayleigh fade margin for a system with diversity. The thermal noise power is approximately -174 dBm/Hz at room temperature [29]. Therefore, the thermal noise level is -114 dBm for a 1 MHz channel. The signal level at one meter distance can be calculated by substituting the value of λ and setting d to one meter in the following equation:

$$S_{1\text{ meter}} = \text{Tx Power} - \text{Free Space Loss at 1 meter}$$

$$\begin{aligned} S_{1\text{ meter}} &= 10 \text{ dBm} - 20 \log \left(\frac{4\pi d}{\lambda} \right) \\ &= 10 \text{ dBm} - 20 \log \left(\frac{4\pi}{0.353} \right) = -21 \text{ dBm} \end{aligned}$$

With 21 dB SIR requirement at the receiver, the base station has an operational range of 72 dB from the one meter reference distance. This means that the receiver can still provide satisfactory operation for signal attenuation of up to 72 dB due to propagation loss beyond the first meter of separation.

As indicated by the previous equation, the free space propagation loss at 1 meter is a function of signal wavelength λ . The shorter is the signal wavelength, the higher is the signal loss. Therefore, for systems with higher operating frequency, it is necessary to increase the transmitter power level to provide the same level of operational range. The scope of this thesis is to study the effects on system operation as a function of call setup SIR threshold and power control. As a result, all simulated systems assume the same radio operational range as long as the call setup SIR threshold and the amount of power control are the same. It is assumed that the radio operational range at different operating frequency is maintained at the same level by means of transmitter power adjustment or different signal transmission technology. With these assumptions, the operational range changes when a different SIR threshold and/or amount of power control are used. The following model describes their relationship:

$$\begin{array}{ccccc} \text{Range from} & & \text{Amount of} & & \text{Required SIR} \\ \text{1 meter reference} & (\text{dB}) = & \text{Power Control} & - & \text{at Receiver} \\ & 93 \text{ dB} & & & \end{array}$$

For the case where there is no power control and the required SIR threshold is 21 dB, the operational range of the radio is 72 dB. If the SIR requirement changes from 21 dB to 12

dB, the range increases from 72 dB to 81 dB. If power control is enabled and the transmitted power level becomes 20 dB lower, the range decreases by 20 dB.

3.4 Call Processing Algorithm

The call processing algorithm for an in-building wireless system is particularly important because it directly affects the system performance. If the algorithm allows a call to be setup on a channel that will cause a chain of handovers to occur, the system can become very unstable and may result in a large number of dropped calls.

Interference at the receiver is the result of surrounding call activities. The call processing algorithm has a direct effect on the interference characteristics because it dictates how each call is setup and handed over. An algorithm with measurement based channel assignment provides better received signal quality than an algorithm with random channel assignment [15].

The following sections describe the call processing procedures of the simulated in-building wireless system.

3.4.1 Call Setup or Blocking

The call setup procedure is invoked when a portable initiates a call attempt or there is an incoming call to a portable. The occurrence of these events follows a Poisson arrival process. Before the execution of the call setup procedure, the position of the portable is generated such that portables are uniformly distributed over the floor area. The call setup process attempts to setup the call with the best base station on the best traffic channel [15] [16] according to the frequency allocation plan.

At the beginning of the call setup process, the propagation loss between the portable and all base stations is calculated. The base station with the least propagation loss is selected first, this is normally the closest base station. If this base station is fully occupied

(no radio resources available to support an additional call), then the next best base station is selected.

After a base station is selected, the interference level on all available channels of the base station is calculated based on the same propagation model. The availability of channels for each base station is governed by the frequency allocation plan. The system attempts to setup the call on the traffic channel with the least amount of interference as seen by the portable. The setup attempt is successful when the signal to interference ratios for both uplink and downlink communications are at least equal to the required call setup SIR threshold. If the SIR requirements are not satisfied, the next best channel is selected. If none of these channels satisfies the call setup requirements, the next best base station will be selected.

These steps are repeated until the call is setup with a base station on a traffic channel which satisfies the call setup SIR requirements and the frequency allocation plan. If the call cannot be setup after the exhaustive search, the call is blocked.

3.4.2 Call Handover or Dropping

The call handover process is exactly the same as the call setup process except call handover attempts are scheduled every three seconds if the previous attempt fail. Each call is able to perform four handover attempts (within ten seconds) before it is dropped.

If at any time the signal to interference ratio of a call becomes unacceptable at either the portable or the base station, a call handover attempt is initiated. During the handover period, some other calls may end or have a handover to a different base station and/or traffic channel. The result of these activities can improve the SIR on the current traffic channel so it is no longer necessary to handover the call. However, if there is no satisfactory improvement on the current traffic channel and the call handover cannot be achieved within ten seconds, the call is dropped.

3.4.3 Normal Call Termination

The call is ended normally when the call termination is requested by the user(s).

At the end of a successful call setup, an end event is scheduled for the call. The duration of the call is determined by the Markov process and is exponentially distributed. If the call is not terminated prematurely due to strong interference, the call will end normally at the scheduled time.

3.5 Performance Evaluation of System Parameters

A number of system parameters are selected for an investigation of their effects on system capacity and interference characteristics. These parameters are acceptable SIR levels for call setup and handover, wall attenuation, number of time slots per carrier, power control, radio resources, and frequency allocation schemes. The different simulation cases for each of these parameters are described in this section.

A Grade of Service of 1% is used as the objective for all simulated systems. The definition of Grade of Service is described in section 3.6. The study of interference characteristics is also carried out at 1% Grade of Service.

3.5.1 Signal to Interference Thresholds

The SIR thresholds for call setup, handover, and drop are configured to be the same in all simulations. The initial setting is 21 dB which corresponds to 11 dB carrier to interference plus noise ratio required by the receiver and a 10 dB Rayleigh fade margin. The 10 dB fade margin is obtained based on a 2-branch diversity system at 1% outage probability. The required thresholds can be further reduced by incorporating more diversity and/or interference suppression techniques. Three additional settings are included in the simulations, they are 18 dB, 15 dB and 12 dB. The objective is to observe the impact on

system capacity and interference characteristics when the required SIR thresholds are lowered.

3.5.2 Wall Attenuation

One of the main factors that governs the propagation of radio signal inside buildings is the attenuation by walls, space dividers, screens, doors, windows, floors, and furniture. Based on published attenuation measurements, curves of attenuation versus frequency for common building materials were derived and reported in reference [19]. The curves are reproduced in Figure 15. All materials are one inch thick. The curves show a large range of attenuation levels from one material to another. They also indicate a substantial increase in attenuation for some materials as the operating frequency changes from 5 GHz to 40 GHz.

Each base station in the simulated floor plan is isolated by walls. Different wall attenuations in the range of 10 dB to 60 dB are used, the purpose is to simulate systems with different building material or operating frequency.

3.5.3 Number of Time Slots per Carrier

A hybrid FDMA/TDMA channel multiplexing system is used in all of the simulation cases. The system has eight frequency carriers, the number of time slots per carrier depends on the assumption of the amount of assigned spectrum. In the case of 4 MHz spectrum assignment, there are 4 time slots per carrier. When the amount of spectrum is doubled (8 MHz), the number of time slots per carrier is also doubled (8 slots/carrier).

In two of the simulation groups, the capacity of a system with 4 MHz spectrum assignment is compared with a system with 8 MHz assigned spectrum. The purpose is to study the gain in system capacity when the allocated spectrum is doubled.

**Figure 15: Attenuation of Common Buildings Materials
(Reproduced from Reference [19])**

3.5.4 Power Control

Transmitter power control is included as an objective in the simulation studies. The radio is capable of switching its output power level between two settings: normal and low power. At low power setting, the transmitted power is 20 dB lower than the normal

setting. The low power setting is used in the transmitter as long as the signal to interference ratio at the receiver exceeds the required SIR thresholds for call setup, handover, and drop. Three different system scenarios are simulated; systems with no power control, systems with power control at the portable only, and systems with power control at both base station and portable.

3.5.5 Radio Resource Limitation

It is not always feasible to incorporate a large number of radio transceivers in a base station, this is especially true when the operating frequency is beyond 20 GHz. With new technologies as reported in reference [20], it will still be unlikely to have a large number of 20 GHz radios in a base station in the near future.

The simulation studies begin with scenarios that do not have any radio resource limitation. Each base station is equipped with eight radios and is allowed to operate on any free channel in the available bandwidth. Then, scenarios with two radios per base station are simulated. The results with no radio resource limitation serve as the capacity references for the later cases.

3.5.6 Frequency Allocation Schemes

Most of the simulated systems use dynamic channel allocation. Only one simulation group use a fixed frequency plan. The objective is to compare their system performance. Figure 16 describes the frequency plan of the system. The cluster size is four and each base station is allowed to operate on two preset frequencies. The typical method to design a fixed frequency allocation plan is based on channel reuse distance. Since the floor plan has to be the same for all scenarios, it is necessary to determine the required SIR threshold for this cluster size.

Figure 16: Fixed Frequency Plan

For each cell, as indicated in Figure 16, there are three other co-channel cells in the system. Two of the co-channel cells are located two cells away and the other co-channel cell is separated by four interior walls. Therefore, in general, the closest co-channel interferer is separated by two interior walls. If a portable is located at its cell boundary between its base station and one of its closest co-channel base stations, the distance between the portable and its base station is 8 meters and the distance between the portable and the co-channel base station is 24 meters. The difference between the two signal propagation losses without shadowing for a 10 dB attenuation per interior wall (the smallest wall attenuation used in the thesis) is 29.5 dF. The SIR at the portable is 29.5 dB

if the transmitter power of both base stations are identical. If the portable has two equal power co-channel interferers from the two closest co-channel cells, the SIR will be at 26.5 dB. This justifies the use of the four SIR settings (21 dB, 18 dB, 15 dB and 12 dB) in the simulations.

3.6 Grade of Service, System Capacity and Average System Utilization

In a telephone network, two of the factors that measure system performance are the percentage of call attempts that are blocked, and the percentage of calls that are dropped. Dropped calls are considered much less desirable than blocked calls, and they are weighted more heavily when assessing performance. The metric used to measure the performance of the simulated systems is called Grade of Service (GOS). The adopted definition of the GOS of a system is the sum of blocking probability and ten times the dropping probability [21]. As noted, dropped calls are considered to be more critical to avoid and are explicitly included in the GOS metric.

$$\text{GOS (\%)} = \% \text{ calls blocked} + 10 \times \% \text{ calls dropped}$$

where

$$\% \text{ calls blocked} = \frac{\# \text{ of Blocked Calls}}{\# \text{ of Call Setup Attempts}} \times 100\%$$

$$\% \text{ calls dropped} = \frac{\# \text{ of Dropped Calls}}{\# \text{ of Dropped Calls} + \# \text{ of Normally Ended Calls}} \times 100\%$$

A low value of the GOS indicates good performance, and an objective GOS of 1% is used in the comparison of system performance.

The capacity of a system is defined as the time average of the number of active calls (in Erlangs) at 1% GOS level.

System Capacity (Erlangs) = Average number of active calls at 1% GOS

The average system utilization is the ratio of the average number of active communications connections to the maximum number of communications connections available in the system.

$$\text{Average System Utilization} = \frac{\text{Average Number of Active Communications Connections at 1\% GOS}}{\text{Maximum Number of System Communications Connections}}$$

Where

$$\begin{aligned} \text{Maximum Number of System Communications Connections} &= \text{Number of Base Stations} \times \text{Number of Radios per Base Station} \times \text{Number of Channels per Radio} \end{aligned}$$

For any traffic driven systems with limited resources (radio or spectrum), it is impossible to reach an average system utilization of 100% without having a high probability of blocking. This observation is based on the general concept of queueing theory.

To achieve a 100% average system utilization without blocking, the total number of users must be the same as the maximum number of system communications connections, and all connections must be active simultaneously at all time without any call interruption.

System capacity in in-building wireless systems describes the maximum traffic that a system can handle and still satisfy the 1% GOS objective. For systems without any physical resource limitations, the system capacity becomes the absolute maximum traffic that the system can handle for a specific amount of spectrum allocation. However, for systems with limited resources, system capacity may not be a good performance indicator in some situations because it does not provide any information about the usage of system resources. In these situations, average system utilization is a better performance indicator.

3.7 Simulation Length and Accuracy

There is a tradeoff between speed and precision in the context of computer simulations. In general, simulations require a long period of time to execute. However, longer simulations yield more precise results. Therefore it is necessary to develop criteria to determine the required period of simulation.

The statistical accuracy must be achieved for the objective GOS of 1%. The criteria that determine the GOS are the percentages of blocked calls and dropped calls. The probability distribution of these factors can be approximated by a binomial distribution. The simulation consists of 'n' identical trials, each trial can result in a success (call setup) or failure (call blocked), the probability of success is approximately constant from trial to trial, and the trials are essentially independent. It can be shown that the standard deviation of GOS (σ_{GOS}) is:

$$GOS = (b + 10 d) \times 100\%$$

$$\sigma = \sqrt{nb(1-b) + 100(n-nb)d(1-d)}$$

$$\sigma_{GOS} = \frac{\sigma}{n} \times 100\%$$

$$\sigma_{GOS} = \sqrt{\frac{b(1-b) + 100d(1-b)(1-d)}{n}} \times 100\%$$

where 'b' is the probability of blocking a call, 'd' is the probability of dropping a call, and 'n' is the number of simulated call attempts.

Dropped calls are heavily weighted in the GOS calculation, so the worst case precision occurs when 'b' is approximately zero. With this assumption, the GOS has a standard deviation $\sigma_{GOS} = 10\sqrt{d(1-d)/n} \times 100\%$. At 1% Grade of Service, 'd' is equal

to 0.001. For a confidence level [22] of 90% that the GOS is in the range $[0.5\%, 1.5\%]$ ($\pm 1.645 \sigma_{\text{GOS}}$ confidence interval), 'n' must be in the order of 10,000 (10,810 to be exact).

Twelve thousand calls are simulated for each case in this thesis. The statistics for the first two thousand calls are discarded to allow the simulations to reach steady state conditions. Statistics are gathered for the remaining ten thousand calls. Thus, the worst case uncertainty at the 90% confidence level is $\pm 0.52\%$. The uncertainty would be $\pm 0.16\%$ if there are no dropped calls. The parameters of the simulated systems are described in Table 1.

No. of Calls per Simulation	12000 completed calls
"Warm-up" Calls	2000 completed calls
Access Technique	Hybrid FDMA/TDMA-TDD
Call Setup and Handover Algorithms	Best Base Station and Best Channel
Setup, Handover and Drop SIR Thresholds	Four Cases: 21, 18, 15, 12 [dB]
Time between Handover Attempts	3 [s]
Time before drop	10 [s]
Channel Allocation	Two Cases: 1) Dynamic Channel Allocation, and 2) Fixed Frequency Plan (cluster size = 4)
Attenuation Algorithm	$\text{Attenuation} = L_1 \text{ meter} + 20 \log_{10} d + nW \text{ [dB]}$
Wall Attenuation (W)	Six Cases: 10, 20, 30, 40, 50, 60 [dB]
Shadowing Standard Deviation	8 [dB]
Adjacent Channel Rejection	30 [dB]
Tx Timing Synchronization	Yes
Power Control	Three Cases: None, Portable Only (-20 dB), Both Portable and Base Station (-20 dB)
Operation Range / Radio Coverage	For 21, 18, 15, 12 dB SIR Thresholds: Normal Transmitter Power: 72, 75, 78, 81 dB propagation loss from first meter separation respectively Power Control (low power): 52, 55, 58, 61 dB propagation loss from first meter separation respectively
Number of Freq. Carriers	8
Number of Time Slots/Carrier	4 (4 MHz spectrum allocation) 8 (8 MHz spectrum allocation)
Number of Transceivers per Base Station	Two Cases: 2 or 8 Radio Transceivers per Base Station
Base Station Height	2 [m]
Population Model	Infinite
Call Holding Time (mean)	180 [s]

Table 1: Summary of System Parameters and Models

Chapter 4

Results and Analysis on System Capacity and Utilization

4.1 Introduction

The traffic capacity of a system, as defined in previous chapter, is the time average of the number of active calls (in Erlangs) at 1% GOS level. The definition of GOS is the sum of blocking probability and ten times the dropping probability. As a result, system capacity is a function of all the factors that affect the probability of a call being blocked or dropped.

In wireless communications systems, two conditions have to be satisfied before a call can be setup or handed off. These two conditions are the availability of an operable communications channel and radio equipment resources. If both conditions cannot be satisfied during call setup or handover, the call is blocked or dropped respectively. Therefore, system capacity of in-building wireless systems is affected by interference and radio resource sharing among adjacent cells. In general, the effects of interference degrade system performance while resource sharing improves it.

The performance of the radio transceiver can have a strong impact on system performance because it affects the systems response to the effects of interference. The possibility of resource sharing among adjacent cells can also be affected indirectly because an available radio in the adjacent cells without an operable frequency channel is not usable.

The performance of the radio transceiver is included in the model by the parameter for the SIR thresholds for call setup and handover.

Signal propagation within buildings directly affects the SIR level at the radio receiver. If the propagation loss for the desired signal is small and the propagation loss for the interfering signals is large, the received SIR level is good. However, the reverse conditions can result in an unacceptable SIR level. One of the main factors that governs the propagation of radio signal inside buildings is the attenuation by walls, space dividers, screens, doors and floors. The amount of attenuation also depends on the system operating frequency.

The use of transmitter power control may also improve system capacity since transmitter emitted power is kept at a lower level. Consequently, traffic channels may be reused in a shorter distance.

4.2 Objectives and Outlines

The main objective of this part of the research is to understand the relationship between some of the system parameters and system capacity. The results also provide important information to properly set up simulations for the investigation of interference characteristics. The system traffic intensity at 1% GOS for each scenario is computed and used as the simulation setting for the study of interference characteristics.

The remaining sections of this chapter are organized in the following sequence. In section 4.3 and 4.4, simulation results of systems without and with radio resource limitation are presented. For systems without radio resource limitation, each base station is capable of simultaneous operation on all frequency carriers for each time slot. For system with a limited number of radios per base station, the number of frequency carriers that can be used simultaneously for each time slot is limited by the number of radios. System sensitivity to call setup SIR thresholds, wall attenuations and power control is described. The potential increase in system capacity due to an increase in spectrum allocations, the

benefit of using dynamic channel allocation, and radio resources provisioning are also demonstrated. The chapter ends with a summary of important observations.

4.3 Systems without Radio Resource Limitation

All simulation results presented in this section consider systems without radio resource limitations. Each base station is capable of simultaneous operation on all frequency carrier and time slot combinations. However, it is usually not possible to use all traffic channels simultaneously by a base station due to the effects of co-channel and adjacent channel interferences at the portable and/or the base station. The objective is to study the changes in system traffic capacity as a function of a number of system parameters without the limiting effects imposed by the amount of radio equipment at each base station.

Each simulated system scenario is setup according to the parameter values described in Table 1. Multiple simulation runs are performed for each scenario, but each run involves a different level of traffic intensity and hence a different average number of active calls. The purpose is to vary the system traffic intensity until the system performance curve (GOS curve) reaches beyond the 1% level.

The GOS curves shown in Figure 17 describe the increase in system capacity as the required SIR thresholds decrease from 21 dB to 12 dB. These systems assume a 4 MHz spectrum allocation (8 frequency carriers with 4 time slots per carrier) with the following parameters: no power control, dynamic channel allocation algorithm used at call setup and handover, and 10 dB wall attenuation. The GOS intervals at 90% confidence level are also plotted with each simulated result and they appear as error bars with each point. The independent axis is the average number of active calls in Erlangs. The system capacity together with the confidence interval are computed by linear interpolation between the two closest points (one from above and one from below) to the 1% GOS level.

Figure 17: Example GOS Plots of Simulation Results

The above process has been performed on each simulated scenario and the results for systems without radio resource limitation are tabulated in Table 2. The values in the first column describe the amount of signal penetration loss through each wall. The assumed spectrum allocation for each system is shown in the second column. The third column indicates whether power control is incorporated into the simulation. For scenarios with power control at both portable and base station, power control can be enabled at either the portable or the base station or both depending on the situation. Dynamic channel allocation is used in all cases. Four different call setup and handover SIR thresholds are simulated, they are at 21 dB, 18 dB, 15 dB and 12 dB. The system capacity for each case

is obtained and the corresponding GOS confidence interval is computed. They are all tabulated in Table 2.

In some situations, it is important to express system performance in terms of average system utilization. The average system utilization at 1% GOS for each simulated case is calculated and tabulated in Table 3.

In the following subsections, system sensitivity to call setup SIR thresholds, wall attenuations and power control is described. The possible increase in system capacity due to an increase in spectrum allocations is also presented. Graphs are generated from the tabulated results and illustrations are included in the discussions.

Wall Atten (dB)	Spectrum (MHz)	Power Control	System Capacity (Erlangs) / 90% Confidence Interval (1% GOS $\pm$ x% GOS)							
			SIR = 21 dB		SIR = 18 dB		SIR = 15 dB		SIR = 12 dB	
			Capacity	x%	Capacity	x%	Capacity	x%	Capacity	x%
10	8	None	148	0.42	167	0.43	193	0.44	224	0.46
20	8	None	263	0.40	303	0.39	352	0.42	397	0.42
30	8	None	382	0.40	397	0.43	448	0.41	489	0.41
40	8	None	418	0.44	462	0.43	509	0.46	579	0.45
50	8	None	443	0.45	483	0.45	537	0.47	657	0.45
60	8	None	440	0.45	505	0.43	550	0.45	661	0.45
10	4	None	62	0.40	68	0.44	79	0.45	91	0.48
20	4	None	105	0.39	117	0.45	130	0.46	157	0.44
30	4	None	137	0.41	153	0.44	181	0.43	201	0.46
40	4	None	163	0.44	180	0.45	206	0.44	248	0.44
50	4	None	168	0.46	183	0.47	212	0.47	251	0.45
60	4	None	170	0.46	188	0.45	213	0.47	256	0.45
10	4	Portable	62	0.43	72	0.44	83	0.44	98	0.41
20	4	Portable	118	0.44	127	0.43	152	0.43	165	0.43
30	4	Portable	160	0.45	183	0.42	206	0.46	220	0.47
40	4	Portable	194	0.47	238	0.43	304	0.42	324	0.43
50	4	Portable	225	0.47	285	0.46	335	0.34	353	0.18
60	4	Portable	229	0.43	280	0.45	338	0.35	352	0.18
10	4	Both P/BS	85	0.42	95	0.44	113	0.47	134	0.46
20	4	Both P/BS	141	0.47	157	0.46	188	0.42	209	0.45
30	4	Both P/BS	181	0.44	212	0.45	234	0.47	263	0.48
40	4	Both P/BS	212	0.47	252	0.46	299	0.46	334	0.35
50	4	Both P/BS	221	0.47	293	0.42	335	0.39	353	0.20
60	4	Both P/BS	225	0.43	292	0.46	338	0.38	353	0.23

Table 2: System Capacity for Systems without Radio Resource Limitation

Wall Atten (dB)	Spectrum (MHz)	Power Control	Average System Utilization (%) : 90% Confidence Interval (1% GOS + x% GOS)							
			SIR = 21 dB		SIR = 18 dB		SIR = 15 dB		SIR = 12 dB	
			Avg Util	x%	Avg Util	x%	Avg Util	x%	Avg Util	x%
10	8	None	14%	0.42	16%	0.43	19%	0.44	22%	0.46
20	8	None	26%	0.40	30%	0.39	34%	0.42	38%	0.42
30	8	None	37%	0.40	39%	0.43	44%	0.41	48%	0.41
40	8	None	41%	0.44	45%	0.43	50%	0.46	57%	0.45
50	8	None	43%	0.45	47%	0.45	52%	0.47	64%	0.45
60	8	None	43%	0.45	49%	0.43	54%	0.45	66%	0.45
10	4	None	12%	0.40	13%	0.44	16%	0.45	18%	0.48
20	4	None	20%	0.39	23%	0.45	29%	0.46	31%	0.44
30	4	None	27%	0.41	30%	0.44	35%	0.43	39%	0.46
40	4	None	32%	0.44	35%	0.45	40%	0.44	48%	0.44
50	4	None	33%	0.46	36%	0.47	41%	0.47	49%	0.45
60	4	None	33%	0.46	37%	0.45	41%	0.47	50%	0.45
10	4	Portable	12%	0.43	14%	0.44	16%	0.44	19%	0.41
20	4	Portable	23%	0.44	25%	0.43	30%	0.43	32%	0.43
30	4	Portable	31%	0.45	36%	0.42	40%	0.46	43%	0.47
40	4	Portable	38%	0.47	47%	0.43	59%	0.42	63%	0.43
50	4	Portable	44%	0.47	56%	0.46	65%	0.34	69%	0.18
60	4	Portable	45%	0.43	55%	0.45	66%	0.35	69%	0.18
10	4	Both P/BS	17%	0.42	18%	0.44	22%	0.47	26%	0.46
20	4	Both P/BS	28%	0.47	31%	0.46	37%	0.42	41%	0.45
30	4	Both P/BS	35%	0.44	41%	0.45	46%	0.47	51%	0.48
40	4	Both P/BS	41%	0.47	49%	0.46	58%	0.46	65%	0.35
50	4	Both P/BS	43%	0.47	57%	0.42	65%	0.39	69%	0.20
60	4	Both P/BS	44%	0.43	57%	0.46	66%	0.38	69%	0.23

Table 3: Average System Utilization for Systems without Radio Resource Limitation

4.3.1 Absolute Maximum Capacity of Systems without Radio Resource Limitation (Erlang B Limit)

As discussed in section 4.1, system capacity can be affected by two factors; effects of interference and resources sharing among adjacent cells. In general, the effects of interference degrade system performance while resources sharing improves it.

All results presented in section 4.3 are for simulated systems without radio resource limitation. In other words, if there is a call and there is an operable communications channel within the cell, there are always radio resources available to set up the connection. There is no need for radio resource sharing among adjacent cells.

Under these assumptions, if co-channel and adjacent channel interference effects can be minimized so that all channels are operable within the same cell, then the maximum limit of system capacity within a cell can be computed by the Erlang B blocking probability formula and the relationship between the average number of active calls and traffic intensity. At low wall attenuation, the channel reuse distance extends beyond one cell and it is impossible to use the same channel within two adjacent cells. At high wall attenuation of 50 dB and 60 dB, each cell is isolated from each other. If the performance of radio transmitters and receivers is good and the emitted radio power are properly controlled, adjacent channels can be used within the same isolated cell without any difficulty. In this situation the simulated system can reach the Erlang B traffic capacity limit. Once this limit is reached, further increases in system capacity require an increase in the frequency spectrum allocation.

The simulated frequency plan of a TDMA system with 4 MHz spectrum allocation consists of 8 frequency carriers and 4 time slots per carrier. This provides a total of 32 traffic channels for each isolated cell. According to an Erlang B calculation, each cell can support 22 Erlangs of traffic at 1% blocking probability (1% GOS). For a system with 16 isolated cells, the system traffic capacity is 352 Erlangs. This is equivalent to an average

system utilization of 69%. For simulated systems with 8 MHz spectrum allocation, there are 64 traffic channels and each isolated cell can support 50 Erlangs of traffic. Therefore, the system traffic capacity is 800 Erlangs which is equivalent to an average system utilization of 78%. These two Erlang B limits are included in system capacity plots for comparisons and discussions.

4.3.2 Sensitivity to Wall Attenuations

The available frequency spectrum in the UHF bands (300 MHz to 3 GHz) is extremely limited due to the existence of many applications which operate within this band. In higher frequency bands (above 20 GHz), a greater amount of spectrum may become available. Signals at these frequency bands experience higher attenuation through office partitions, building floors and walls. The purpose of varying the wall attenuation from 10 dB to 60 dB is to simulate different operating frequencies or building materials. The objective is to investigate the change in system capacity as a function of wall attenuation.

Plots of system capacity as a function of wall attenuation are generated for four different scenarios as shown in Figure 18 to Figure 21. The first scenario considers an 8 MHz system without power control. The last three scenarios are 4 MHz systems. They are systems without power control, with power control at portable, and with power control at both portable and base station. Each graph consists of five curves, four of the curves are results of four different SIR threshold setting. The last curve indicates the Erlang B Limit.

Simulation results show a steady increase in system capacity as the wall attenuation increases from 10 dB to 40 dB. This is due to the decrease in channel reuse distance as the attenuation per wall increases. At 10 dB attenuation per wall, the channel reuse distance can extend beyond three to four cells. As the attenuation increases, the co-channel interference effect from a distant cell decreases rapidly because the interfering signal has to penetrate a larger number of walls.

As the wall attenuation is increased from 50 dB and 60 dB, there is no increase in system capacity for all cases. At these levels of wall attenuation, each cell is reasonably isolated. The limiting factor is adjacent channel interference effects within the same cell. This applies to all cases except scenarios with power control and 12 dB to 15 dB call setup SIR threshold. In these situations, the system capacity is mainly spectrum limited. The Erlang B Limit is reached for cases with power control and 12 dB SIR threshold. The combined effect of power control and low call setup SIR threshold produces this result. Detailed explanations are provided in the discussions on the effects of using power control in section 4.3.5.

Figure 18: System Capacity vs Wall Attenuation (8 MHz Systems, No Power Control, No Radio Resource Limitation)

Figure 19: System Capacity vs Wall Attenuation (4 MHz Systems, No Power Control, No Radio Resource Limitation)

Figure 20: System Capacity vs Wall Attenuation (4 MHz Systems, Power Control at Portable, No Radio Resource Limitation)

Figure 21: System Capacity vs Wall Attenuation (4 MHz Systems, Power Control at Both Sides, No Radio Resource Limitation)

4.3.3 Sensitivity to Call Setup SIR Thresholds

The required call setup SIR threshold is initially set at 21 dB. This setting corresponds to 11 dB carrier to interference plus noise ratio required by the receiver and a 10 dB Rayleigh fade margin. The required thresholds can be further reduced by incorporating more diversity and/or interference suppression techniques. Three additional settings are included in the simulations, they are 18 dB, 15 dB and 12 dB. The objective is to observe the impact on system capacity when the required SIR threshold is lowered.

Graphs of system capacity as a function of required SIR threshold are generated for four different scenarios as shown in Figure 24 to Figure 27. The first scenario considers an 8 MHz system without power control. The last three scenarios are 4 MHz systems. These are systems without power control, with power control at portable, and with power control at both portable and base station. Each graph consists of seven curves, six of the

curves are results of six different wall attenuation setting. The last curve indicates the Erlang B Limit.

Simulation results show continuous increase in system capacity as the required call setup SIR threshold is lowered. This is also true even at very high wall attenuation. At high wall attenuation, a decrease in the required SIR threshold can increase the probability of using adjacent channels within the same cell. This will be explained later in the discussion.

At 50 dB or 60 dB wall attenuation, the results indicate a diminishing return in system capacity as the SIR threshold is lowered from 18 dB to 12 dB for systems with power control. This is due to the fact that the system capacity is approaching the Erlang B Limit.

A system which can tolerate more interference or is capable of overcoming signal fading can operate at a lower call setup SIR threshold. Being able to tolerate more interference seems to have the same effect : having a higher wall attenuation between cells. In one case, the interference is suppressed by means of an equalizer or optimum combining antenna [25] [26] [27] in the receiver. In the other case, the interference is attenuated before it reaches the receiver. It is only true if the desired signal S is from within the same cell and all interfering signals I are from the surrounding cells as shown in Figure 22a. If both desired signal and interfering signals are from within the same cell, having a higher wall attenuation will not affect the interfering signals received by the base station. This is described in Figure 22c. In the situation where a portable is served by a base station in an adjacent cell, the desired signal suffers a penetration loss through the surrounding walls. Some of the interfering signals may also be attenuated, but the interfering signals from within the same cell are not affected. At high wall attenuation, it becomes impossible for portables to be served by base station in adjacent cells. This concept is described in Figure 22b. The ability to share resources among adjacent cells is

very important for systems with limited radio resources in each cell. Its impact on systems with two radios per base station will be discussed in section 4.4.

Figure 22: Different Wall Attenuation Effects on Desired and Interfering Signals

It is expected that a 10 dB reduction in call setup SIR threshold should give a higher gain in system capacity than a 10 dB increase in wall attenuation. This is based on the fact that the receiver can tolerate a 10 dB higher interfering power from within the same cell or surrounding cells. The receiver is also capable of handling a signal that is 10 dB weaker with the same level of interfering power. For the 10 dB increase in wall attenuation, only interference from the surrounding cells are attenuated. Table 4 shows the percentage increase in system capacity as a result of a 10 dB increase in wall attenuation or a 9 dB (from 21 dB to 12 dB) decrease in the required SIR threshold. The first two columns describe the reference setting of the comparison. System capacity at the reference setting is used as the reference to compute the percentage increase in system capacity due to the change in attenuation per wall or required SIR threshold.

		% Increase in System Capacity (10 dB Increase in Wall Attenuation / 9 dB Decrease in SIR Threshold)							
Reference		8 MHz System No Power Control		4 MHz System No Power Control		4 MHz System Power Control at Portable		4 MHz System Power Control at Base Station and Portable	
Wall Attenuation	SIR Threshold	Wall Atten	SIR Threshold	Wall Atten	SIR Threshold	Wall Atten	SIR Threshold	Wall Atten	SIR Threshold
10	21 dB	78%	52%	68%	47%	89%	57%	67%	58%
20	21 dB	45%	51%	31%	50%	36%	40%	28%	48%
30	21 dB	9%	28%	20%	47%	21%	37%	17%	46%
40	21 dB	6%	39%	3%	52%	16%	67%	4%	58%
50	21 dB	-1%	48%	1%	49%	2%	57%	2%	60%

Table 4: Percentage Gain in System Capacity for 10 dB increase in Wall Attenuation or 9 dB decrease in SIR Threshold

For cases with reference setting of 20 dB wall attenuation and beyond, simulation results consistently show a higher increase in system capacity due to the change in required SIR threshold than wall attenuation. However, the opposite is true for cases with reference setting at 10 dB wall attenuation. This can be explained by the effect of wall attenuation on channel reuse distance as shown in Figure 23. The figure shows the simulated system floor plan with each cell named in alphabetical order and where cell F is considered as the

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PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

reference cell. The table on the right shows the number of walls that a signal from a specific cell has to penetrate before it reaches cell F. As the attenuation per wall changes from 10 dB to 20 dB, the signal penetration loss for one, two, three and four walls increases from 10 dB, 20 dB, 30 dB and 40 dB to 20 dB, 40 dB, 60 dB and 80 dB respectively. As a result, co-channel interference effects are substantially decreased (more than 10 dB) due to the 10 dB change in wall attenuation and the channel reuse distance becomes much smaller. This explains why the overall increase in system capacity due to the change in wall attenuation from 10 dB to 20 dB is higher than SIR threshold.

A	B	C	D	No. of Walls Penetration	Cell List
E	• F	G	H		
I	J	K	L		
M	N	O	P		
				1	B, E, G, J
				2	A, C, H, I, K, N
				3	D, L, M, O
				4	P

F - Reference Cell

Figure 23: Effects of Wall Attenuation on Channel Reuse Distance

As the attenuation per wall is set higher and higher, simulation results show diminishing returns in system capacity. The change from 50 dB to 60 dB wall attenuation does not result in any increase in system capacity. At 50 dB wall attenuation, the interference effect from adjacent cells is negligible, a further increase in wall attenuation will not affect the traffic capacity of the system because it cannot reduce interference effect from within the same cell. However, a 9 dB decrease in the required SIR threshold produces an average of 50% increase in system capacity. The lowering of the required SIR

threshold reduces adjacent channel interference effect by 9 dB and results in a higher probability of using adjacent channel within the same cell.

Figure 24: System Capacity vs SIR Threshold (8 MHz Systems, No Power Control, No Radio Resource Limitation)

Figure 25: System Capacity vs SIR Threshold (4 MHz Systems, No Power Control, No Radio Resource Limitation)

Figure 26: System Capacity vs SIR Threshold (4 MHz Systems, Power Control at Portable, No Radio Resource Limitation)

Figure 27: System Capacity vs SIR Threshold (4 MHz Systems, Power Control at Both Sides, No Radio Resource Limitation)

4.3.4 4 MHz vs 8 MHz System Spectrum Allocations

It has been observed in a number of simulated cases that system capacity reaches the Erlang B Limit. A further increase in system capacity would require an additional frequency spectrum allocation. It is important to obtain the percentage increase in system capacity due to an increase in allocated spectrum. A 100% increase in spectrum allocation (4 MHz to 8 MHz) is used in the study. The channel plans of both systems consist of 8 frequency carriers, the 4 MHz system has 4 time slots per carrier and the 8 MHz system has 8, and the total number of traffic channels is 32 and 64 respectively. Neither system has transmitter power control.

Ten graphs have been generated from the simulation results and they are shown in Figures 30 to 39. The first four figures consist of graphs of system capacity versus wall attenuation at four different call setup SIR thresholds. The last six figures are plots of system capacity versus SIR threshold at six different wall attenuation settings. Each graph consists of four curves; two curves are the results of the two different spectrum allocations, and the other two curves indicate the two different Erlang B Limits.

The percentage increase in system capacity is computed for each case and tabulated in Table 5. The computed results show an average of 155% increase in system capacity as a result of doubling the number of traffic channels. A number of simulated cases produce close to 170% increase in system capacity.

Wall Attenuation	Percentage Increase in System Capacity (4 MHz to 8 MHz Allocation)			
	SIR = 21 dB	SIR = 18 dB	SIR = 15 dB	SIR = 12 dB
10	137%	145%	143%	146%
20	151%	160%	171%	153%
30	179%	159%	148%	143%
40	156%	157%	147%	134%
50	163%	164%	153%	162%
60	158%	169%	159%	159%

Table 5: Percentage Increase in System Capacity due to Doubling of Spectrum Allocation

The Erlang B blocking probability formula can be used to compute the potential increase in system capacity due to a 100% increase in the number of traffic channels. The Erlang B calculations at 1% blocking probability produce a system capacity of 21.9 Erlangs for systems with 32 channels and 50.1 Erlangs for systems with 64 channels. This is equivalent to a 129% increase in system capacity and is less than the simulated results. The probability distributions of the number of active channels at 1% blocking probability are shown in Figure 28. The probability distributions are obtained from the equation that computes the probability of having n active channels. First, the traffic intensity (λ/μ) of a m channels system at 1% blocking probability is obtained by solving the following equation:

$$p_{block} = p_m = \frac{\left(\frac{\lambda}{\mu}\right)^m \frac{1}{m!}}{\sum_{j=0}^m \left(\frac{\lambda}{\mu}\right)^j \frac{1}{j!}} = 0.01$$

The equation is obtained by setting the Erlang B blocking probability formula to 0.01. Then, the probability distribution is obtained by evaluating the following probability formula for each n values from 0 to m .

$$p_n = \frac{\left(\frac{\lambda}{\mu}\right)^n \frac{1}{n!}}{\sum_{j=0}^m \left(\frac{\lambda}{\mu}\right)^j \frac{1}{j!}}$$

The distribution for systems with 64 channels has a wider spread than the system with 32 channels. The potential increase in system capacity as a result of doubling the number of channels becomes smaller when the number of channels considered is large. Table 6 shows the traffic capacity of systems with different number of channels. The number of channels ranges from 8 to 512. The percentage increase in system capacity is also calculated for each case. The results obtained from queueing analysis provide a general understanding on the effects of doubling the spectrum allocation of a system.

Figure 28: PDF of Channel Usage for 32 and 64 Channels at 1% Blocking Probability (Erlang B Model)

Number of Channels	System Capacity (Erlangs)	# of Channel Increase		% Increase in System Capacity
		From	To	
8	3.1	8	16	184%
16	8.8	16	32	149%
32	21.9	32	64	129%
64	50.1	64	128	119%
128	109.5	128	256	112%
256	231.9	256	512	107%
512	481.1			

Table 6: Traffic Capacity of Systems with Different Number of Channels

In reality, the probability of a blocked call at call setup depends on two factors, the availability of an idle channel and its operability. A channel is operable if the signal to interference ratio is higher than the call setup SIR threshold at both portable and base station. It is not possible to accurately analyze the situation solely with queueing theory. The effects of interference affect the availability of an idle channel and therefore must be included in the analytical process. The probability of an available channel at a given channel loading has to be obtained and combined with queueing theory to achieve a more accurate prediction.

Unfortunately, the probability of an available channel at a given channel loading is very complex and it varies from system to system. It is a function of signal propagation environment, the positions of the communicating portable and base station and their interferers, and call setup and reassignment channel allocation algorithms. Figure 29 describes the effects of channel allocation algorithms on channel availability. An 'X' in a frequency slot means the channel is active. The results of two different allocation schemes are shown in Figure 29, both cases have three active calls. All five idle channels can be

inoperable in the first case if the portables of the three existing calls are very close to the base station and the call setup request is coming from a distant portable. In the second case, a new call can be setup on either frequency f_7 or f_8 because these two channels are free from adjacent channel interference.

Both simulated scenarios consist of systems without power control and the probability of using adjacent channels within the same cell is small. As a result, the effective channel availability is approximately half of the actual number of channels. The results in Table 6 indicate a 149% increase in system capacity as the number of effective channels increases from 16 to 32. This is much closer to the average increase of 155% in system capacity from the actual simulation results.

a) All Idle Channels Subject to Adjacent Channel Interference

b) Two Idle Channels are free from Adjacent Channel Interference

Figure 29: Effects of Different Channel Assignment Algorithms on Channel Availability

Figure 30: System Capacity of 4MHz vs 8MHz Spectrum Allocations (21 dB SIR Threshold, No Radio Resource Limitation)

Figure 31: System Capacity of 4MHz vs 8MHz Spectrum Allocations (18 dB SIR Threshold, No Radio Resource Limitation)

Figure 32: System Capacity of 4MHz vs 8MHz Spectrum Allocations (15 dB SIR Threshold, No Radio Resource Limitation)

Figure 33: System Capacity of 4MHz vs 8MHz Spectrum Allocations (12 dB SIR Threshold, No Radio Resource Limitation)

Figure 34: System Capacity of 4MHz vs 8MHz Spectrum Allocations (10 dB Wall Attenuation, No Radio Resource Limitation)

Figure 35: System Capacity of 4MHz vs 8MHz Spectrum Allocations (20 dB Wall Attenuation, No Radio Resource Limitation)

Figure 36: System Capacity of 4MHz vs 8MHz Spectrum Allocations (30 dB Wall Attenuation, No Radio Resource Limitation)

Figure 37: System Capacity of 4MHz vs 8MHz Spectrum Allocations (40 dB Wall Attenuation, No Radio Resource Limitation)

Figure 38: System Capacity of 4MHz vs 8MHz Spectrum Allocations (50 dB Wall Attenuation, No Radio Resource Limitation)

Figure 39: System Capacity of 4MHz vs 8MHz Spectrum Allocations (60 dB Wall Attenuation, No Radio Resource Limitation)

4.3.5 Power Control

One of the objectives of the simulation studies was to consider transmitter power control. In the simulation performed, the radio is capable of switching its output power level between two settings: normal and low power. At the low power setting, the transmitted power is 20 dB lower than the normal setting. The low power setting is used in the transmitter as long as the signal to interference ratio at the receiver exceeds the required SIR thresholds for call setup, handover, and drop. Three different system scenarios are simulated. They are systems with no power control, systems with power control at the portable only, and systems with power control at both base station and portable. For systems with power control at both portable and base station, transmitter power control can be enabled at the portable or the base station or both depending on the situation. The base station is also capable of transmitting at different power levels for different time slots.

The benefits of using transmitter power control are described in Figures 40 and 41. The benefits of power control at the portable is more easily understood in the case of an isolated cell as interference effects from the portables and the base stations of the surrounding cells have been minimized by the high wall attenuation. As a result, the SIR at portables is not a concern. If the SIR at the base station is above the SIR threshold, the call can be setup. The problem arises when a connection has been setup with a portable which is next to the base station as shown in Figure 40. If portable A is transmitting at full power on channel f_5 , it is very unlikely that channel f_4 and f_6 can be used to serve portables that are far away. This is because the base station experiences a high level of adjacent channel interference on these two channels and the signals from the distant portables are considerably weaker. If the transmitter power at portable A is 20 dB lower, portable B and C will have a much higher probability of operating on channel f_6 and f_4 .

For systems with low wall attenuation, power control at the portables also reduces the co-channel interference effect to surrounding base stations.

Figure 40: Benefit of using Power Control at Portable

The benefits of power control at base station is most easily understood in the situation when wall attenuation is low as shown in Figure 41. If the base station is transmitting at full power, co-channel interference effects can cover a distance beyond two to three cells. If the base station is communicating with a nearby portable, the base station can operate at the low power setting as long as the SIR at portable A is acceptable. As a result, co-channel interference received at portables B, C and D is 20 dB lower. This effect has to be combined with power control at portables B, C and D to obtain maximum gain in shortening the channel reuse distance. In addition, the adjacent channel interference effect to a portable which is communicating with an adjacent base station is also reduced. This results in a higher probability of radio resource sharing among adjacent cells. This effect is described by portable E in Figure 41.

Figure 41: Benefit of using Power Control at Base Station

There are some drawbacks in using power control at the base station if the receiver at the portable produces strong intermodulation products. The level of the intermodulation products is determined by the "third order intercept" (TOI) of the amplifier or mixer. In general, the larger the TOI, the smaller is the intermodulation distortion. The effects of intermodulation distortion greatly affect portables that are next to a base station. The effect is further enhanced if the desired signal received from the base station is 20 dB lower. This situation is illustrated in Figure 42. Portable A is located next to the base station and it is operating on channel f_6 . Three other communications connections are also established within the same cell and they are operating at full power on channels f_3 , f_4 and f_7 . The base station is also transmitting at full power on f_3 , f_4 and f_7 at portable A. One of the three tone intermodulation products ($f_3 + f_7 - f_4 = f_6$) occurs on channel f_6 . The SIR at portable A can be unacceptable depending on its distance from the base station. The closer the portable is to the base station the stronger the intermodulation products. The strength of the intermodulation products increase exponentially as the portable moves toward the base

station. If the received signal from the base station is further reduced by 20 dB, portable A has to either request a power increase from the base station or initiate a handover. In this example, portable A may not be able to handover to any other channels because channels f_3 , f_4 and f_7 also produce intermodulation products on f_1 , f_2 , f_5 and f_8 . Eventually, the connection with portable A is dropped.

All simulations performed in this thesis do not include the effects of receiver intermodulation distortion. Scenarios with power control at both portable and base station are simulated to investigate its potential gain in system capacity. If there is a large capacity gain to have power control at both portable and base station, it will be necessary to assure the receiver performance limits the effects of intermodulation distortion.

Figure 42: Difficulty of using Power Control at Base Station (Near-Far Problem)

Ten graphs have been generated from the simulation results and they are shown in Figure 44 to Figure 53. The first four figures consist of graphs of system capacity versus wall attenuation at four different call setup SIR thresholds. The last six figures are plots of system capacity versus SIR threshold at six different wall attenuation settings. Each graph consists of four curves; three of the curves are results of the three different system scenarios, the last curve indicates the Erlang B Limit.

All ten graphs show that systems with power control at both portable and base station are consistently better than systems without power control. The first four graphs indicate a larger percentage increase in system capacity when the wall attenuation is beyond 40 dB and the required SIR threshold is lower than 21 dB. For scenarios with power control and 12 dB required SIR threshold, the system capacity increases and reaches the Erlang B Limit as the wall attenuation increases from 10 dB to 60 dB. Simulation results also indicate that system capacity of scenarios with portable power control are similar to scenarios without power control at low wall attenuation. However, at high wall attenuation, the system capacity is similar to scenarios with power control at both portable and base station.

The larger percentage increase in system capacity for systems with high wall attenuation and low call setup SIR threshold is due to an increased probability of using adjacent channels within the same cell. Figure 43 is an example of a system with 60 dB of wall attenuation and 12 dB call setup SIR threshold. At high wall attenuation, the cell is reasonably isolated from the interference effects of the surrounding cells. A further decrease in the required call setup SIR threshold increases the probability of using adjacent channel within the same cell.

The locations of the two portables described in the figure are at the two extreme distances from the base station. Portable A is at the minimum distance (2 meters) and portable B is at the corner of the cell which is 11.3 meters from the base station. Portable A and Portable B are operating on channel f_5 and f_6 respectively. When adjacent channels

are used with the same base station, the base station transmitter power of these channels must be at the same level to maintain satisfactory SIR at the portables. Without any strong external interference, the SIR at both portables is always above the required SIR threshold. The worst SIR at the portable is 27 dB which is the sum of two equal power adjacent channel interferers from the same base station.

Figure 43: Adjacent Channel Interference Effects in the Extreme Situation

The SIR at the base station depends on the difference in received power from the two portables. The receiver requires 12 dB SIR to operate satisfactorily and the adjacent channel attenuation is 30 dB. Therefore, the signal received from portable A can be 18 dB stronger than from portable B. Since portable A is capable of decreasing its transmitter power by 20 dB as directed by the base station, the difference between the two propagation path losses cannot be greater than 38 dB. The difference between the two free space path losses without shadowing is 15 dB. Therefore, portable B can setup the connection on a channel adjacent to the operating channel of portable A as long as the difference in their

shadowing is less than 23 dB. The shadowing effect is modeled by a log-normal distribution with a standard deviation of 8 dB. If two random variables are independent and normally distributed, then their sum is also normally distributed. As a result, the sum (or difference) of the two independent shadowing effects is log-normally distributed with a standard deviation of 11.3 dB. The probability of their difference being greater than 23 dB is 2.1%. This indicates a 98% probability that adjacent channels can be used to serve the two portables in the extreme situation.

With power control at the portable, adjacent channel interference effects are minimized within the same cell. As a result, there is a very high probability that all channels can be used at the same time, and system capacity reaches the Erlang B Limit.

As described in the beginning of the section, there are two benefits with power control enabled at the portable. At high wall attenuation, it increases the probability of using adjacent channels within the same cell. When adjacent channels are used with the same base station, the base station transmitter power of these channels must be at the same level to maintain satisfactory SIR at the portables. The lowering of the transmitter power at base stations does not have any impact on system capacity because interference effects from surrounding base stations have already been minimized by high wall attenuation. For high wall attenuation scenarios, systems with portable power control have the same traffic capacity as the systems with portable and base station power controls.

At low wall attenuation, it is not possible to use adjacent channels within the same cell because they are most likely used in the adjacent cells. Therefore, power control at portables can only reduce co-channel interference effect to surrounding base stations. This effect has to be combined with power control at base stations to obtain maximum gain in shortening the channel reuse distance. With low wall attenuation, systems with portable power control have similar traffic capacity as systems without power control.

The percentage increase in system capacity for the two power control scenarios is tabulated in Table 7. From 10 to 30 dB wall attenuation, the average increase in system

capacity due to portable and base station power controls is 37%. For scenarios with 40 to 60 dB wall attenuation, the increase in system capacity due to portable power control can be as much as 60%.

Wall Atten.(dB)	Power Control	Percentage Increase in System Capacity with Power Control			
		SIR = 21 dB	SIR = 18 dB	SIR = 15 dB	SIR = 12 dB
10	Portable	0%	6%	5%	7%
20	Portable	13%	9%	17%	5%
30	Portable	17%	19%	14%	10%
40	Portable	19%	33%	47%	31%
50	Portable	34%	56%	58%	40%
60	Portable	34%	49%	59%	38%
10	Both P/BS	36%	39%	42%	47%
20	Both P/BS	35%	35%	44%	34%
30	Both P/BS	32%	38%	29%	31%
40	Both P/BS	30%	40%	45%	35%
50	Both P/BS	31%	60%	58%	41%
60	Both P/BS	32%	56%	59%	38%

Table 7: Percentage Increase in System Capacity with Power Control (No Radio Limitation)

Figure 44: System Capacity of Systems with and without Power Control (21 dB SIR Threshold, No Radio Resource Limitation)

Figure 45: System Capacity of Systems with and without Power Control (18 dB SIR Threshold, No Radio Resource Limitation)

Figure 46: System Capacity of Systems with and without Power Control (15 dB SIR Threshold, No Radio Resource Limitation)

Figure 47: System Capacity of Systems with and without Power Control (12 dB SIR Threshold, No Radio Resource Limitation)

Figure 48: System Capacity of Systems with and without Power Control (10 dB Wall Attenuation, No Radio Resource Limitation)

Figure 49: System Capacity of Systems with and without Power Control (20 dB Wall Attenuation, No Radio Resource Limitation)

Figure 50: System Capacity of Systems with and without Power Control (30 dB Wall Attenuation, No Radio Resource Limitation)

Figure 51: System Capacity of Systems with and without Power Control (40 dB Wall Attenuation, No Radio Resource Limitation)

Figure 52: System Capacity of Systems with and without Power Control (50 dB Wall Attenuation, No Radio Resource Limitation)

Figure 53: System Capacity of Systems with and without Power Control (60 dB Wall Attenuation, No Radio Resource Limitation)

4.3.6 Discussions on Radio Resource Provisioning

It is not desirable to equip each base station with radio resources to operate on all channels simultaneously unless it is absolutely necessary. If the capacity requirement of the system only demands 50% of the available resources, the other 50% will be wasted and the system is highly underutilized. In addition, it is not always feasible to incorporate a large number of radio transceivers in a base station, this is especially true when the operating frequency is beyond 20 GHz. At these frequencies, the manufacturing costs for transceivers are expected to be high. There is a need for radio resource provisioning during system installation.

Accurate computer simulations can provide information regarding radio resource provisioning. To accomplish this task, the simulation program has to be able to produce a statistical report on channel and radio usage of a base station.

With the help of system simulations, it is possible to predict the radio requirement of each base station for a specific system topology and capacity requirement. It is very easy to perform radio resource provisioning for FDMA-TDD systems, because each base station radio can only operate on one channel at a time. As a result, the channel and radio usage of a base station are identical. To obtain the radio requirement of a FDMA-TDD system at maximum capacity level, the system is simulated at 1% GOS level. The radio requirement per base station is the maximum number of radios used within a base station during the simulation. If it is not necessary to operate at maximum system capacity, simulations with a specific capacity requirement can be performed with the number of radios per base station varied until the system performance reaches the 1% GOS level.

To perform radio resource provisioning for TDMA-TDD systems is more difficult than FDMA-TDD systems because each base station radio can operate on a number of traffic channels at the same time.

The usage of radios within a base station depends on interference between portables and base stations, and on the channel allocation algorithm of the system. The probability distributions of channel and radio usage for a 4 MHz system are shown in Figures 54 and 55. This 4 MHz system has power control at both portable and base station, the wall attenuation is 60 dB and the required call setup SIR threshold is 12 dB. According to the discussion on power control in section 4.3.5, this system consists of 16 isolated cells with all channels within each cell having a high probability of simultaneous usage. As a result, this system reaches the Erlang B Limit.

The main objective of radio resource provisioning is to allocate the minimum number of radios in each base station and still meet the system capacity requirement. If the channel allocation algorithm maximizes the use of a radio before it allocates channels that require the use of an additional radio, the statistical report on radio usage of base station truly reflects the radio requirement of a base station. If this principle applies to the sample system which has a high probability of simultaneous usage of all channels within each cell, the probability of one active radio is the sum of the probabilities of one active channel to four active channels. The probability of two active radios is the sum of the probabilities of five active channels to eight active channels and similarly for the higher number of active radios. The results of the prediction based on channel usage of base station are shown in Figure 56. The simulation results on radio usage of the same system are also included in the figure for comparison.

The channel allocation algorithm used in the simulated system tends to use a higher number of radios than the predicted case. This indicates the algorithm does not maximize the use of a radio before another radio is used. If the algorithm did maximize the use of a radio before another one is used, then the predicted and the simulated results should be similar. This is because each cell in the described 4 MHz system is isolated from each other by the 60 dB wall attenuation and all channels within each cell have a high probability of simultaneous usage.

Figure 54: Channel Usage of Base Station

Figure 55: Radio Usage of Base Station

In this example, it is quite easy to determine the radio requirements of each base station based on the capacity requirement for each cell because the interference between portables and base stations has minimal effect on the availability of operable communications channels. For scenarios where interference effects are involved in the determination of system capacity, an intelligent guess based on channel usage is needed. The process has to be reiterated with simulations to obtain the optimum number of radios per base station.

The maximum number of channels and radios used within a base station for most of the simulated scenarios are tabulated in Table 8. All scenarios are simulated at 1% GOS.

Figure 56: Radio Usage Comparison between Simulated Result and Prediction based on Channel Usage

Wall Atten (dB)	Spectrum (MHz)	Power Control	Maximum Number of Channels Used / Maximum Number of Radios Used							
			SIR = 21 dB		SIR = 18 dB		SIR = 15 dB		SIR = 12 dB	
			channels	radios	channels	radios	channels	radios	channels	radios
10	8	None	23	5	27	5	28	5	30	6
20	8	None	30	6	33	6	38	6	42	7
30	8	None	39	7	42	7	46	8	49	8
40	8	None	43	7	47	8	52	8	58	8
50	8	None	45	7	48	7	56	8	62	8
60	8	None	45	7	49	8	55	8	62	8
10	4	None	14	5	14	6	15	6	18	6
20	4	None	18	6	19	6	21	6	24	7
30	4	None	22	6	23	7	25	8	27	8
40	4	None	24	7	25	8	27	8	30	8
50	4	None	24	8	25	7	27	8	31	8
60	4	None	24	8	25	8	27	8	30	8
10	4	Both P/BS	17	6	18	6	19	7	21	7
20	4	Both P/BS	21	7	24	7	25	8	27	8
30	4	Both P/BS	25	7	27	8	29	8	32	8
40	4	Both P/BS	27	8	30	8	32	8	32	8
50	4	Both P/BS	28	8	32	8	32	8	32	8
60	4	Both P/BS	29	8	32	8	32	8	32	8

Table 8: Maximum Number of Channels and Radios used by a Base Station without Radio Resource Limitation

4.4 Systems with Two Radios per Cell

Simulation results and discussions in section 4.3 provide insight on the behaviors of systems without radio resource limitation. Similar scenarios are also simulated for systems with limited radio resources per base station. The objective is to observe the differences in their system responses.

All simulated scenarios consist of systems with 8 MHz spectrum allocation. There are eight frequency carriers and eight time slots per carrier. Each base station is equipped with two radios which can serve a maximum of sixteen portables.

According to the results from Table 8, all systems simulated in this section are highly radio resource limited. Systems can increase capacity by more than 100% by increasing the number of radios to four. This reasoning is purely based on queueing theory.

As previously stated in section 4.3.6, it may not be feasible to incorporate a large number of radio transceivers in a base station especially when the operating frequency is beyond 20 GHz. It is valuable to discover what factors are more important in a highly radio resource limited situation.

Results for systems with two radios per base station are tabulated in Table 9 and 10. Performance in terms of system capacity are given in Table 9. The corresponding average system utilization is shown in Table 10. The format of the tables is identical to Tables 2 and 3 in section 4.3. The only difference is in the second column. Instead of giving the size of spectrum allocation, the method of channel allocation is shown. The short forms DCA and FFP stands for Dynamic Channel Allocation and Fixed Frequency Plan, respectively.

In the following subsections, system sensitivity to call setup SIR thresholds, wall attenuations and power control is described. Performance comparison between systems which use Fixed Frequency Plan and Dynamic Channel Allocation are presented. Graphs are generated from the tabulated results and illustrations are included in the discussions. A system capacity reference is also defined based on Erlang B model. It helps to highlight important observations and serves as the basis in discussions.

Wall Atten (dB)	Frequency Plan	Power Control	System Capacity (Erlangs) / 90% Confidence Interval (1% GOS $\pm$ x% GOS)							
			SIR = 21 dB		SIR = 18 dB		SIR = 15 dB		SIR = 12 dB	
			Capacity	x%	Capacity	x%	Capacity	x%	Capacity	x%
10	FFP	None	102	0.42	113	0.37	126	0.39	143	0.38
20	FFP	None	138	0.25	148	0.16	150	0.22	154	0.16
30	FFP	None	140	0.22	145	0.18	141	0.23	148	0.17
40	FFP	None	140	0.19	143	0.16	140	0.22	144	0.18
50	FFP	None	140	0.16	139	0.19	138	0.25	144	0.16
60	FFP	None	137	0.15	138	0.19	139	0.19	138	0.22
10	DCA	None	129	0.35	152	0.33	165	0.36	174	0.32
20	DCA	None	161	0.23	169	0.29	175	0.29	183	0.29
30	DCA	None	164	0.18	172	0.16	178	0.22	178	0.29
40	DCA	None	160	0.29	166	0.26	171	0.25	174	0.31
50	DCA	None	153	0.23	155	0.31	163	0.23	174	0.24
60	DCA	None	140	0.16	144	0.16	150	0.16	156	0.16
10	DCA	Portable	139	0.32	155	0.31	172	0.34	186	0.26
20	DCA	Portable	169	0.24	178	0.27	181	0.35	187	0.26
30	DCA	Portable	169	0.25	170	0.26	180	0.34	185	0.24
40	DCA	Portable	162	0.29	171	0.27	170	0.34	183	0.24
50	DCA	Portable	156	0.16	160	0.26	167	0.25	175	0.30
60	DCA	Portable	140	0.16	144	0.16	151	0.16	154	0.27
10	DCA	Both P/BS	160	0.34	183	0.24	192	0.29	201	0.33
20	DCA	Both P/BS	187	0.17	192	0.24	199	0.15	206	0.16
30	DCA	Both P/BS	184	0.28	189	0.22	194	0.15	198	0.18
40	DCA	Both P/BS	184	0.18	188	0.18	191	0.19	194	0.20
50	DCA	Both P/BS	160	0.16	172	0.20	184	0.17	186	0.23
60	DCA	Both P/BS	140	0.16	145	0.16	151	0.16	160	0.16

Table 9: System Capacity for Systems with Two Radios per Cell

Wall Atten (dB)	Frequency Plan	Power Control	Average System Utilization (%) / 90% Confidence Interval (1% GOS $\pm$ x% GOS)							
			SIR = 21 dB		SIR = 18 dB		SIR = 15 dB		SIR = 12 dB	
			Avg Util	x%	Avg Util	x%	Avg Util	x%	Avg Util	x%
10	FFP	None	40%	0.42	44%	0.37	49%	0.39	56%	0.38
20	FFP	None	54%	0.25	58%	0.16	58%	0.22	60%	0.16
30	FFP	None	55%	0.22	57%	0.18	55%	0.23	58%	0.17
40	FFP	None	55%	0.19	56%	0.16	55%	0.22	56%	0.18
50	FFP	None	55%	0.16	54%	0.19	54%	0.25	56%	0.16
60	FFP	None	54%	0.15	54%	0.19	54%	0.19	54%	0.22
10	DCA	None	50%	0.35	50%	0.33	64%	0.36	68%	0.32
20	DCA	None	63%	0.23	66%	0.29	66%	0.29	72%	0.29
30	DCA	None	64%	0.18	67%	0.16	70%	0.22	69%	0.29
40	DCA	None	63%	0.29	65%	0.26	67%	0.25	68%	0.31
50	DCA	None	60%	0.23	60%	0.31	64%	0.23	68%	0.24
60	DCA	None	55%	0.16	56%	0.16	59%	0.16	61%	0.16
10	DCA	Portable	54%	0.32	61%	0.31	67%	0.34	73%	0.26
20	DCA	Portable	66%	0.24	69%	0.27	71%	0.35	73%	0.26
30	DCA	Portable	66%	0.25	67%	0.26	70%	0.34	72%	0.24
40	DCA	Portable	63%	0.29	67%	0.27	67%	0.34	71%	0.24
50	DCA	Portable	61%	0.16	62%	0.26	65%	0.25	68%	0.30
60	DCA	Portable	55%	0.16	56%	0.16	59%	0.16	60%	0.27
10	DCA	Both P/BS	62%	0.34	71%	0.24	75%	0.29	79%	0.33
20	DCA	Both P/BS	73%	0.17	75%	0.24	78%	0.15	81%	0.16
30	DCA	Both P/BS	72%	0.28	74%	0.22	76%	0.15	77%	0.18
40	DCA	Both P/BS	72%	0.18	73%	0.18	74%	0.19	76%	0.20
50	DCA	Both P/BS	62%	0.16	67%	0.20	72%	0.17	73%	0.23
60	DCA	Both P/BS	55%	0.16	57%	0.16	59%	0.16	62%	0.16

Table 10: Average System Utilization for Systems with Two Radios per Cell

4.4.1 Capacity Reference of Simulated Systems with Two Radios per Cell (Erlang B Reference)

The Erlang B Reference Capacity used in all subsequent discussions is derived from the same assumptions as the Erlang B Limit. Each cell is assumed to be isolated from other cells, and all resources can be used simultaneously within the same cell. In other words, interference effects have been minimized such that resources can be fully utilized to serve portables that are within the same cell without any difficulty. Even though both Erlang B Limit and Erlang B Reference Capacity are derived from the same assumptions, they have different interpretations. The Erlang B Limit is the absolute maximum capacity of systems without radio resource limitation. For systems with radio resource limitation, Erlang B Reference Capacity is the maximum capacity that can be reached by a system without any radio resources sharing among surrounding cells. In situations when radio resource sharing is possible, the system capacity can exceed the Erlang B Reference Capacity.

All simulated systems for this section assume an 8 MHz spectrum allocation, there are 8 frequency carriers and 8 time slots per carrier. Each cell is equipped with two radios to support a maximum of 16 communications connections. Based on Erlang B calculation and the relationship between the average number of active calls and traffic intensity, each cell can support 8.8 Erlangs of traffic at 1% blocking probability. For systems with 16 isolated cells, the system traffic capacity is 141 Erlangs. This is equivalent to 55% of average system utilization. This Erlang B Reference Capacity is included in system capacity plots for comparison purposes.

4.4.2 Sensitivity to Wall Attenuations

Graphs of system capacity versus wall attenuation are generated for four different simulated scenarios. They are shown in Figure 57 to Figure 60. The first three scenarios

are systems with Dynamic Channel Allocation. They are systems without power control, with power control at the portable, and with power control at both portable and base station. The last scenario considers systems with Fixed Frequency Plan and no power control. Each graph has five curves, four curves are results of four different SIR threshold setting. The last curve indicates the Erlang B Reference Capacity.

As the wall attenuation increases from 10 dB to 60 dB, simulation results from scenarios with Dynamic Channel Allocation show an initial increase in system capacity and then a gradual decrease to the neighborhood of the Erlang B Reference Capacity. The system capacity peaks at either 20 dB or 30 dB of wall attenuation. Although these results indicate a system capacity greater than the Erlang B Reference Capacity, this is the result of radio resource sharing between adjacent cells. As described in the previous section, the Erlang B Reference Capacity in a system with two radios per cell is defined as the maximum capacity of the system without any radio resources sharing between adjacent cells.

The gradual decrease in system capacity as the wall attenuation increases toward 60 dB is due to the decrease in the probability of radio resource sharing between adjacent cells. As shown in Figure 22b, the desired signal from a portable which is located in an adjacent cell suffers a penetration loss through the surrounding wall. At higher wall attenuation, the desired signal strength is weaker and the probability that a portable from an adjacent cell can be served is smaller.

There are two opposing effects as the wall attenuation increases. Co-channel interference effects from surrounding cells become weaker, the channel reuse distance is shortened and system capacity increases. However, radio resource sharing becomes more difficult and system capacity decreases. The system capacity peaks at the wall attenuation level where the changes of the two opposing effects are equal. At 20 dB or 30 dB attenuation per wall, the interference received from cells that are separated by two or more walls is greatly attenuated, but the probability that portables can be served by adjacent base

stations (separated by a single wall) is still very high. As the wall attenuation increases further, system capacity decreases toward the Erlang B Reference Capacity.

For systems with Fixed Frequency Plan, system capacity is limited to Erlang B Reference Capacity even at 20 dB or 30 dB wall attenuation. Further explanations are given in the next section.

Figure 57: System Capacity vs Wall Attenuation (Dynamic Channel Allocation, No Power Control, Two Radios per Cell)

Figure 58: System Capacity vs Wall Attenuation (Dynamic Channel Allocation, Power Control at Portable, Two Radios per Cell)

Figure 59: System Capacity vs Wall Attenuation (Dynamic Channel Allocation, Power Control at Portable & Base Station, Two Radios per Cell)

Figure 60: System Capacity vs Wall Attenuation (Fixed Frequency Plan, No Power Control, Two Radios per Cell)

4.4.3 Dynamic vs Fixed Frequency Allocation Schemes

Most of the simulated systems use dynamic channel allocation. Only one simulation group uses a fixed frequency plan. Graphs of simulation results between systems with dynamic channel allocation and fixed frequency plan are shown in Figures 63 to 72. The first four figures are graphs of system capacity versus wall attenuation at four different required SIR thresholds. The last six figures are graphs of system capacity versus SIR threshold at six different wall attenuation levels. Each graph has three curves, two curves are results of the two different channel allocation schemes. The last curve indicates the Erlang B Reference Capacity.

Simulation results show that systems with dynamic channel allocation are consistently better than systems with fixed frequency plan except at 60 dB wall attenuation. At such a high wall attenuation, radio resource sharing between adjacent cells is impossible and each isolated cell can only serve a maximum of sixteen portables simultaneously. The difference in performance between the two systems is small.

The traffic capacity of systems with the fixed frequency plan is limited to the neighborhood of the Erlang B Reference Capacity. Figure 61 describes the fixed frequency plan. The sixteen cells in the figure are named from A to P. The limitation in system capacity can be explained by the strong co-channel and adjacent channel interference effects imposed by the frequency plan. The operating frequencies of cell J are f_2 and f_6 and the operating frequencies of all its immediate adjacent cells (separated by a single wall) are the adjacent channels of f_2 and f_6 . The operating frequencies of cells F and N are f_3 and f_7 , and the operating frequencies of cells I and K are f_1 and f_5 .

There are two undesirable interference effects in this frequency plan. At low wall attenuation, cell J is subjected to strong co-channel interference from both cells B and L. If the desired signal path between a portable and the base station in cell J has high shadowing attenuation, strong co-channel interference can prevent that portable from setting up a call or cause an established communications connection to terminate prematurely. This explains why most of the system capacity is well below Erlang B Reference Capacity at 10 dB attenuation per wall. At higher wall attenuation, strong adjacent channel interference effects prevent radio resource sharing between adjacent cells. When all radio resources within cell J are fully utilized, an additional call initiation within cell J has to be served by adjacent cells or it will be blocked. It is impossible to get any radio resource sharing beyond 30 dB wall attenuation because received signal at the portable from the adjacent base station is very weak and adjacent channel interference from the local base station is strong. The SIR at the portable is most likely below the call setup SIR threshold and the call is blocked.

This situation does not happen in systems with dynamic channel allocation because base station and portable have the freedom to agree on a channel that is free of adjacent channel interference effects from the local base station. This is why traffic capacity of systems with dynamic channel allocation are consistently better. The percentage difference in system capacity between the two cases are shown in Table 11 with dynamic channel allocation consistently better. However, the gain in system capacity is achieved at the cost of increased system complexity.

A ● f_1 f_5	B ● f_2 f_6	C ● f_1 f_5	D ● f_2 f_6
E ● f_4 f_8	F ● f_3 f_7	G ● f_4 f_8	H ● f_3 f_7
I ● f_1 f_5	J ● f_2 f_6	K ● f_1 f_5	L ● f_2 f_6
M ● f_4 f_8	N ● f_3 f_7	O ● f_4 f_8	P ● f_3 f_7

Figure 61: Fixed Frequency Plan

Wall Attenuation	SIH Threshold	FFP	DCA	% Difference
10	21	102	129	26.5%
10	18	113	152	34.5%
10	15	126	165	31.0%
10	12	143	174	21.7%
20	21	138	161	16.7%
20	18	148	169	14.2%
20	15	150	175	16.7%
20	12	154	183	18.8%
30	21	140	164	17.1%
30	18	145	172	18.6%
30	15	141	178	26.2%
30	12	148	178	20.3%
40	21	140	160	14.3%
40	18	143	166	16.1%
40	15	140	171	22.1%
40	12	144	174	20.8%
50	21	140	153	9.3%
50	18	139	155	11.5%
50	15	138	163	18.1%
50	12	144	174	20.8%
60	21	137	140	2.2%
60	18	138	144	4.3%
60	15	139	150	7.9%
60	12	138	155	12.3%

Table 11: Percentage Gain in System Capacity with Dynamic Channel Allocation over Fixed Frequency Plan

For systems with fixed frequency plan, the strong effect of adjacent channel interference can be alleviated by careful planning. One of the alternatives is to increase the cluster size from four cells to eight cells with one operating frequency per cell. Figure 62 describes one of the possible arrangements. The suggested configuration is fine as long as the system capacity requirement can be met by a single radio in each cell. In business applications, the required system capacity is normally very high. This necessitates a high density of radio resources to handle the load and fixed frequency planning becomes a real challenge. As indicated by the simulation results, dynamic channel allocation instead of fixed frequency plan is highly recommended for business applications.

Figure 62: Modified Frequency Plan

For systems with the fixed frequency plan and 20 dB wall attenuation, simulation results in Figure 68 indicate an increase in system capacity beyond the Erlang B Reference Capacity as the required SIR threshold decreases from 21 dB to 12 dB. This implies that there is still some probability for a portable to communicate with an adjacent base station on a channel adjacent to the operating channels of the local base station.

For systems with dynamic channel allocation and 60 dB wall attenuation, Figure 72 shows an increase in system capacity beyond the Erlang B Reference Capacity as the call setup SIR threshold is lower. This indicates that radio resource sharing between adjacent cells is still possible for systems with dynamic channel allocation at high wall attenuation. As the required SIR threshold is lower, the operation range between portable and base station increase. Since each cell is equipped with two radios, it is always possible to find a traffic channel that is free of adjacent channel interference effects from the local base station. Under these conditions, an increase in the operation range increases the probability that a portable can be served by an adjacent base station.

Figure 63: Dynamic vs Fixed Frequency Allocations (21 dB SIR Threshold, Two Radios per Cell)

Figure 64: Dynamic vs Fixed Frequency Allocations (18 dB SIR Threshold, Two Radios per Cell)

Figure 65: Dynamic vs Fixed Frequency Allocations (15 dB SIR Threshold, Two Radios per Cell)

Figure 66: Dynamic vs Fixed Frequency Allocations (12 dB SIR Threshold, Two Radios per Cell)

Figure 67: Dynamic vs Fixed Frequency Allocations (10 dB Wall Attenuation, Two Radios per Cell)

Figure 68: Dynamic vs Fixed Frequency Allocations (20 dB Wall Attenuation, Two Radios per Cell)

Figure 69: Dynamic vs Fixed Frequency Allocations (30 dB Wall Attenuation, Two Radios per Cell)

Figure 70: Dynamic vs Fixed Frequency Allocations (40 dB Wall Attenuation, Two Radios per Cell)

Figure 71: Dynamic vs Fixed Frequency Allocations (50 dB Wall Attenuation, Two Radios per Cell)

Figure 72: Dynamic vs Fixed Frequency Allocations (60 dB Wall Attenuation, Two Radios per Cell)

4.4.4 Sensitivity to Call Setup SIR Thresholds

Graphs of system capacity as a function of required SIR threshold are generated for four different simulated scenarios as shown in Figure 73 to Figure 76. The first three scenarios consider systems with dynamic channel allocation. Shown are systems with no power control, systems with power control at the portable, and systems with power control at both portable and base station. The last scenario is systems with a fixed frequency plan. Each graph consists of seven curves, the first six curves are results of six different wall attenuation settings. The last curve indicates the Erlang B Reference Capacity.

Performance discussions of systems with fixed frequency plan can be found in the previous section (Section 4.4.3). This section concentrates mainly on systems with dynamic channel allocation.

For systems with dynamic channel allocation, simulation results show an increase in system capacity as the required SIR threshold is decreased from 21 dB to 12 dB. This applies to all simulated cases. Results also indicate a larger increase in system capacity at 10 dB wall attenuation as the SIR threshold is lowered from 21 dB to 15 dB.

For systems with lower wall attenuation, the desired signal received from an adjacent cell suffers less wall penetration loss. These systems have a greater potential increase in system capacity than systems with higher wall attenuation. This is due to a higher probability of radio resource sharing between adjacent cells when interference effects are properly controlled and minimized.

Based on the discussion in the previous section, the potential increase in radio resource sharing at high wall attenuation depends on the degree of improvement in the operation range between portable and base station. As the required SIR threshold is lowered, the operation range improves by the same magnitude and the probability of radio resource sharing increases. This explains the increase in system capacity as a result of a decrease in SIR threshold at high wall attenuation.

At low wall attenuation, co-channel interference effects limit the number of operable communications channels used within a cell or shared between adjacent cells. This is confirmed by the results shown in Figure 73. The traffic capacity of systems with 10 dB wall attenuation and 21 dB call setup SIR threshold is below the Erlang B Reference Capacity. This implies that radio resources within each cell cannot be fully utilized due to external interference. In systems with two radios per cell, radio resource sharing between adjacent cells only happens when radio resources are fully utilized within a cell. If external interference can limit a channel from being used within a cell, its effect is even stronger on a signal which suffers an additional wall attenuation. As the SIR threshold is lowered, co-channel interference effects decrease and the probability of radio resource sharing between adjacent cells increases. Since systems with low wall attenuation have a greater potential increase in system capacity than systems with high wall attenuation, system capacity is expected to have a larger increase as SIR threshold is lowered. This explains the larger increase in system capacity at 10 dB wall attenuation as a result of a decrease in the required call setup SIR threshold.

Figure 73: System Capacity vs SIR Threshold (Dynamic Channel Allocation, No Power Control, Two Radios per Cell)

Figure 74: System Capacity vs SIR Threshold (Dynamic Channel Allocation, Power Control at Portable, Two Radios per Cell)

Figure 75: System Capacity vs SIR Threshold (Dynamic Channel Allocation, Power Control at Portable & Base Station, Two Radios per Cell)

Figure 76: System Capacity vs SIR Threshold (Fixed Frequency Plan, No Power Control, Two Radio per Cell)

4.4.5 Power Control

Simulation results of different power control scenarios are shown in Figures 77 to 86. The first four figures consist of graphs of system capacity versus wall attenuation at four different call setup SIR thresholds. The last six figures are plots of system capacity versus SIR threshold at six different wall attenuation settings. Each graph consists of four curves, three of the curves are the results of the three different system scenarios. They are systems without power control, systems with power control at the portable, and systems with power control at both portable and base station. The last curve indicates the Erlang B Reference Capacity.

All ten graphs indicate that systems with portable power control are slightly better than systems with no power control, and systems with power control at both portable and base station are consistently better than the other two scenarios except at 60 dB wall

attenuation. This result is different from what was observed in systems without radio resource limitation. In systems without radio resource limitation, performance of systems with power control at the portable is comparable with systems with power control at both the portable and the base station at high wall attenuation. For systems with two radios per cell, the benefits of portable power control at high wall attenuation, as described in Figure 40, can never be achieved. There is no need to use adjacent channels within the same cell when the base station is capable of using only two different frequencies for each time slot.

At low wall attenuation, co-channel interference has a strong effect in limiting the system capacity. However, power control at both portable and base station can reduce co-channel interference effects and the channel reuse distance becomes shorter. Power control at the base stations, as described in Figure 41, has the additional benefit of reducing adjacent channel interference to a portable which is communicating with an adjacent base station, hence increasing the probability of radio resource sharing between adjacent cells. If interference effects have been reduced to a level at which system resources can be shared between adjacent cells without any difficulty, the system can be analyzed as if these adjacent cells have been combined into a bigger cell. When four adjacent cells are considered as one bigger cell, there are a total of eight radios within the combined cell boundary and they can support a traffic capacity of 50 Erlangs. Therefore, in this simplified system model, the total system capacity is 200 Erlangs. At 10 dB to 20 dB wall attenuation and 12 dB SIR threshold, system capacity of 200 Erlangs has been reached by systems with power control at both portable and base station.

Even at 40 dB to 50 dB wall attenuation, the benefit of using base station power control to reduce adjacent channel interference effects at the portable produces an average increase of 11% in system capacity. The percentage increases in system capacity due to the use of power control is tabulated in Table 12. The reason for the small negative percentages in the table for systems with portable power control is due to statistical variations of the simulation results.

At 60 dB wall attenuation, system performances of all three different scenarios are identical. At this wall attenuation, operation range has a stronger effect on system performance. When the transmitted signal from the portable to an adjacent base station is highly attenuated, the received Signal to Noise Ratio (SNR) at the base station is unacceptable and the call is blocked. Having power control at the base station does not produce a higher system capacity because the limiting factor is the SNR at the adjacent base station.

Wall Atten.(dB)	Power Control	Percentage Increase in System Capacity with Power Control			
		SIR = 21 dB	SIR = 18 dB	SIR = 15 dB	SIR = 12 dB
10	Portable	7%	2%	5%	7%
20	Portable	5%	5%	3%	2%
30	Portable	3%	-1%	1%	4%
40	Portable	1%	3%	-1%	5%
50	Portable	2%	3%	2%	0%
60	Portable	0%	0%	0%	-1%
10	Both P/BS	24%	21%	17%	15%
20	Both P/BS	16%	14%	14%	13%
30	Both P/BS	12%	10%	9%	11%
40	Both P/BS	15%	13%	11%	12%
50	Both P/BS	5%	11%	12%	7%
60	Both P/BS	0%	1%	1%	3%

Table 12: Percentage Increase in System Capacity with Power Control (Two Radios per Cell)

Figure 77: System Capacity of Systems with and without Power Control (21 dB SIR Threshold, Two Radios per Cell)

Figure 78: System Capacity of Systems with and without Power Control (18 dB SIR Threshold, Two Radios per Cell)

Figure 79: System Capacity of Systems with and without Power Control (15 dB SIR Threshold, Two Radios per Cell)

Figure 80: System Capacity of Systems with and without Power Control (12 dB SIR Threshold, Two Radios per Cell)

Figure 81: System Capacity of Systems with and without Power Control (10 dB Wall Attenuation, Two Radios per Cell)

Figure 82: System Capacity of Systems with and without Power Control (20 dB Wall Attenuation, Two Radios per Cell)

Figure 83: System Capacity of Systems with and without Power Control (30 dB Wall Attenuation, Two Radios per Cell)

Figure 84: System Capacity of Systems with and without Power Control (40 dB Wall Attenuation, Two Radios per Cell)

Figure 85: System Capacity of Systems with and without Power Control (50 dB Wall Attenuation, Two Radios per Cell)

Figure 86: System Capacity of Systems with and without Power Control (60 dB Wall Attenuation, Two Radios per Cell)

4.5 Summary

4.5.1 Scenarios without Radio Resource Limitation

All simulation results regarding scenarios without radio resource limitation show an increase in system capacity as the wall attenuation is increased from 10 dB to 40 dB. This increase in capacity is due to the decrease in channel reuse distance as the attenuation per wall increases. At 10 dB wall attenuation, the channel reuse distance can extend beyond three or four cells. As the attenuation increases, co-channel interference from a distant cell decreases rapidly because the interfering signal has to penetrate a large number of walls.

As the wall attenuation increases from 50 dB to 60 dB, there is no increase in system capacity. The limiting factor for system capacity with no power control is adjacent channel interference effects within the same cell. At 50 dB wall attenuation, each cell is reasonably isolated. A further increase in wall attenuation does not reduce the adjacent channel interference from within the same cell and the system capacity is maintained at the same level. For scenarios with power control, the system capacity is mainly spectrum limited. The Erlang B Capacity Limit is reached. The combined effect of portable power control, low call setup SIR threshold and good cell isolation produces this result.

Simulation results also indicate that the system capacity of scenarios with portable power control is similar to scenarios without power control at low wall attenuation. However, at high wall attenuation, the system capacity with portable power control is similar to scenarios with power control at both portable and base station. At low wall attenuation, portable power control has to be combined with base station power control to minimize the channel reuse distance. At high wall attenuation, portable power control increases the probability of simultaneous use of adjacent channels within the same cell by reducing adjacent channel interference at the base station from portables that are close to the

base station to portables that are further away. When adjacent channels are used within the same base station, the base station transmitter power of these channels must be at the same level to maintain satisfactory SIR at the portables. The lowering of the transmitter power at base stations does not have any impact on system capacity because interference effects from surrounding base stations have already been minimized by high wall attenuation.

Simulation results also indicate an increase in system capacity as the required call setup SIR threshold is lowered. This is also true even at very high wall attenuation. At high wall attenuation, the interference effect from adjacent cells is minimized. The lowering of the required SIR threshold reduces adjacent channel interference effects from within the same cell by the same magnitude and results in a higher probability of using adjacent channels within the cell.

At 50 dB and 60 dB wall attenuation, the results indicate a diminishing return in system capacity as the SIR threshold is lowered from 18 dB to 12 dB for systems with power control. This is due to the fact that the system capacity is approaching the Erlang B limit and the system becomes spectrum limited.

Simulation results also show an average of 155% increase in system capacity as a result of a 100% increase in spectrum allocation. A number of simulated cases produce close to 170% increase in system capacity. In general, systems with less than 100 traffic channels can obtain more than 100% increase in system capacity as the number of traffic channels doubles due to an increase in spectrum allocation.

4.5.2 Scenarios with Two Radios per Cell

As the wall attenuation increases from 10 dB to 60 dB, simulation results of scenarios with two radios per cell show an initial increase in system capacity and then a gradual decrease to the neighborhood of the Erlang B Reference Capacity. The system capacity peaks at either 20 dB or 30 dB of wall attenuation.

There are two opposing effects as the wall attenuation increases. Co-channel interference effects from surrounding cells become weaker, the channel reuse distance is shortened and system capacity increases. However, radio resource sharing becomes more difficult and system capacity decreases. The desired signal from a portable which is located in an adjacent cell suffers a penetration loss through the surrounding wall. At higher wall attenuation, the desired signal strength is weaker and the probability that a portable from an adjacent cell can be served is smaller. The system capacity peaks at the wall attenuation level where the changes due to the two opposing effects are equal. At 20 dB or 30 dB attenuation per wall, the interference received from cells that are separated by two or more walls is greatly attenuated, but the probability that portables can be served by adjacent base stations (separated by a single wall) is still very high. As the wall attenuation increases further, system capacity decreases towards the Erlang B Reference Capacity.

Simulation results indicate that systems with power control at both portable and base station are consistently better than systems with no power control or portable power control except at 60 dB wall attenuation. This result differs from what was observed in systems without radio resource limitation. In systems without radio resource limitation, performance of systems with power control at portables is comparable with systems with power control at both portable and base station at high wall attenuation. For systems with two radios per cell, the benefits of portable power control at high wall attenuation can never be achieved. There is no need to use adjacent channels within the same cell when the base station is capable of using only two different frequencies for each time slot.

At low wall attenuation, co-channel interference has strong effects in limiting the system capacity. However, power control at both portable and base station can reduce co-channel interference effects and the channel reuse distance becomes shorter. Base station power control has an additional benefit of reducing adjacent channel interference effect to a portable which is communicating with an adjacent base station, hence increasing the probability of radio resource sharing between adjacent cells.

At 60 dB wall attenuation, the performance of systems with or without power control is identical. At this wall attenuation, operation range has a stronger effect on system performance. When the transmitted signal from the portable to an adjacent base station is highly attenuated, the received Signal to Noise Ratio (SNR) at the base station is unacceptable and the call is blocked. Having power control at the base station does not produce a higher system capacity because the limiting factor is the SNR at the adjacent base station.

Simulation results also show an increase in system capacity as the required SIR threshold is decreased from 21 dB to 12 dB. This is also true even at high wall attenuation. The reason for the increase in system capacity at high wall attenuation is different from scenarios without resource limitation. In a highly radio resource limited scenario of two radios per cell, the potential increase in radio resource sharing at high wall attenuation depends on the degree of improvement in the operation range between portable and base station. As the required SIR threshold is lowered, the operation range improves by the same magnitude and the probability of radio resource sharing increases.

The performance of systems with dynamic channel allocation is consistently better than systems with fixed frequency plans. In the in-building wireless application, where systems have to offer high traffic capacity, fixed frequency planning is a real challenge for systems with a small number of frequency carriers. The frequency plan has to maximize the availability of traffic channels within a cell by minimizing the interference interactions between co-channel cells, adjacent cells and within a cell. For situations that require the maximum traffic capacity from a system which has a limited number of carriers, dynamic channel allocation is highly recommended over fixed frequency planning.

Chapter 5

Results and Analysis of Interference Characteristics

5.1 Introduction

The statistical characteristics of interference at both portable and base station depend on the level of system traffic intensity. If the average number of calls in progress (active calls) is small compared to the amount of available frequency channels in the system, each call is most likely to be assigned to a channel which does not interfere with others. The system should perform very well without any blocked or dropped calls, but the system is underutilized.

On the other hand, it is not meaningful to study the interference characteristics when the probability of call blocking and dropping is very high because the system will never be operated under that condition. As a result, the investigation of interference characteristics is performed at the system performance level of 1% GOS. The system traffic intensity at 1% GOS can be obtained from the simulation results described in previous chapter.

In general, the behavior of a system in its operating environment directly affects the interference characteristics. If the operating environment has good cell isolation due to high wall attenuation, interfering signals from surrounding cells are greatly attenuated. Under this condition, the system can experience strong adjacent channel interference if radio performance together with proper use of portable power control allows adjacent channels to be used within the same cell. This system behavior has already been discussed in chapter four.

The amount of radio resources allocated within each cell can also affect the interference characteristics. If radio resources are very limited and only a small percentage of frequency channels can be used within the whole system, the SIR of each communications connection will be excellent and the traffic capacity is mainly radio resource limited.

A number of simulated system scenarios from chapter four are selected for the investigation of the interference characteristics of the in-building wireless communications systems. These scenarios include systems with different wall attenuation characteristics and call setup SIR thresholds. The effects of power control and radio resource limitation are also included in the investigation.

Each simulation is setup to give a system performance level of approximately 1% GOS. The duration of each simulation is arranged to produce at least 2500 call samples. Call samples are obtained periodically at a fixed interval, and the interval is long enough such that almost all calls in one sampling state would have terminated before the next sampling state.

5.2 Objectives and Outlines

The main objective of this part of the research is to investigate the interference characteristics of in-building wireless communications systems. Is the interference mainly from a single dominant interferer or a number of strong equal power interferers? In general, interference cancellation techniques work best to suppress a single dominant interferer. For situations with a strong dominant interferer, what is the probability that it is a co-channel interferer? These investigations have been conducted on a number of system scenarios from chapter four and they are presented in subsequent sections.

The remaining sections of this chapter are organized in the following sequence. The definition of a dominant interferer is given in section 5.3, and it helps to focus the studies to a specific group of statistical data. The scope of the investigations then becomes

more manageable. The significance of 27 dB and 30 dB SIR values at the portable are explained in section 5.4. Simulation results of systems without and with radio resource limitation are presented in section 5.5 and 5.6 respectively. For scenarios with radio resource limitation, two radios per cell is assumed. Interference behaviors due to different wall attenuation characteristics, call setup SIR thresholds, and the use of power control are presented for these two major groups of scenarios. All studies regarding different wall attenuations are performed at 21 dB call setup SIR threshold. For scenarios without radio resource limitation, studies with different call setup SIR thresholds are carried out at both 10 dB and 60 dB attenuation per wall. For scenarios with two radios per cell, only 10 dB attenuation per wall is considered in the studies with different call setup SIR thresholds. The chapter ends with a summary of important observations.

5.3 Definition of a Dominant Interferer

For most of the common digital modulation schemes, the probability of a bit error is much better than 10^{-6} at a SIR greater than 40 dB. Therefore, it is not necessary to include high SIR data in the statistical studies of the probability of a dominant interferer. At high SIR, it does not matter whether there is one interferer which is significantly stronger than the others, the radio receiver can still demodulate the signal without any difficulty. The error probability curves of the most common modulation techniques [28] also indicate that an improvement of 6 dB in Signal to Noise Ratio (SNR) can improve the error probability from 10^{-2} to 10^{-6} .

An interferer is considered dominant if its interfering power is at least 6 dB stronger than the sum of all other interferences given the overall SIR at the receiver is within 20 dB of the call setup SIR threshold. In other words, all data with SIR more than 20 dB above the call setup SIR threshold are excluded from the calculation of the probability of a dominant interferer.

5.4 Significance of 27 dB and 30 dB SIR Values at the Portable

At high wall attenuation (40 dB to 60 dB), the SIR values of 27 dB and 30 dB at the portable can be used as indicators to observe the usage of adjacent channels within the same cell. The portable is receiving interference from one of its adjacent channels when the SIR at the portable is 30 dB. At the SIR value of 27 dB, the portable is receiving interference from both of its adjacent channels. These situations occur when the received adjacent channel interference at the portable originates from its own base station.

In the simulated floor plan, the use of adjacent channels within the same cell is likely only at high wall attenuation. At lower wall attenuations, the adjacent channels are most likely used in the surrounding cells and reusing the same channel between adjacent cells is impossible.

Figure 87: Adjacent Channel Interference at the Portable from its own Base Station

Figure 87 describes the scenario with 60 dB wall attenuation. The three portables shown in the figure are operating on the same time slot but at three consecutive frequency channels. The operating frequencies of portable 1, 2 and 3 are f_3 , f_4 and f_5 respectively. The high wall attenuation eliminates interference from the surrounding cells. If adjacent channels are used within the cell, their interference powers are significantly stronger than those coming from the surrounding cells. Since the propagation path loss from the base station to a portable is identical for all frequency channels, the transmitter power at the base station has to be the same for f_3 , f_4 and f_5 to ensure the SIR at all three portables are acceptable. For an adjacent channel attenuation factor of 30 dB, the SIR at the portable is 30 dB when one of its adjacent channels is used within the cell. The SIR is 27 dB when both adjacent channels are in use.

If the base station is transmitting at full power on one channel and at low power (20 dB weaker) on an adjacent channel, the SIR at the two portables are 50 dB and 10 dB respectively. The SIR value of 10 dB at one of the portables is unacceptable, the transmitter power at the base station has to be increased to full power to give a SIR of 30 dB at both portables. This is the reason why the transmitter power at the base station has to be the same for f_3 , f_4 and f_5 .

The SIR value at the base station does not have similar behavior because portables can be anywhere within the cell and the propagation loss for each connection is independent.

5.5 Systems without Radio Resource Limitation

All systems presented in this section assume a frequency allocation of 4 MHz. There are eight frequency carriers and four time slots per carrier. This gives a total of 32 traffic channels. Each base station is equipped with sufficient radio resources to support all 32 simultaneous communications connections if required and each portable is capable of operating on any one of the 32 traffic channels.

As described in the introduction of this chapter, all simulation results are obtained at the system performance level of 1% GOS. The cumulative probability distribution curves of the SIR at both portable and base station are generated and included in the discussions. Table 13 describes the probability of the SIR being within 20 dB of the call setup SIR threshold. The probabilities at both portable and base station are calculated based on the statistics of 3000 to 4500 call samples. Call samples are obtained periodically at a fixed interval, and a call sample is collected only if the call is subjected to at least one interferer. In other words, a call will be included as a sample when the same channel and/or its adjacent channels are used elsewhere within the system. The SIR for all call samples are obtained at the sampling time.

The probabilities of a dominant interferer at either portable and base station for each scenario are tabulated in Table 14. The probability of a dominant interferer is the conditional probability that an interferer is at least 6 dB above the sum of the others, given that the overall SIR is within 20 dB of call setup SIR threshold. There are two kinds of dominant interferers, it is either a co-channel interferer or an adjacent channel interferer. The conditional probabilities of these two kinds of dominant interferers are shown in the table. The values under the 'Combined' columns are the probability of a dominant interferer which is equal to the sum of the probability of a dominant co-channel interferer and a dominant adjacent channel interferer.

In the following subsections, interference characteristics of systems without power control are presented first. Their sensitivity to different wall attenuations and call setup SIR thresholds are described. Then, simulation results on systems with power control at both portable and base station are discussed.

Power Control	Wait Attenuation	SIR Threshold	Probability [SIR $\leq$ (SIR threshold + 20 dB)]	
			Base Station	Portable
None	10 dB	21 dB	31%	30%
None	10 dB	18 dB	30%	30%
None	10 dB	15 dB	31%	31%
None	10 dB	12 dB	30%	33%
None	20 dB	21 dB	17%	18%
None	30 dB	21 dB	10%	10%
None	40 dB	21 dB	8.2%	8.2%
None	50 dB	21 dB	6.7%	6.6%
None	60 dB	21 dB	5.6%	5.8%
None	60 dB	18 dB	6.8%	7.5%
None	60 dB	15 dB	9.0%	12%
None	60 dB	12 dB	18%	29%
Both P/BS	10 dB	21 dB	68%	63%
Both P/BS	10 dB	18 dB	67%	62%
Both P/BS	10 dB	15 dB	71%	65%
Both P/BS	10 dB	12 dB	74%	72%
Both P/BS	20 dB	21 dB	54%	48%
Both P/BS	30 dB	21 dB	37%	33%
Both P/BS	40 dB	21 dB	34%	30%
Both P/BS	50 dB	21 dB	28%	26%
Both P/BS	60 dB	21 dB	22%	21%
Both P/BS	60 dB	18 dB	47%	50%
Both P/BS	60 dB	15 dB	56%	66%
Both P/BS	60 dB	12 dB	49%	70%

Table 13: Probability of SIR within 20 dB of Call Setup SIR Threshold of Scenarios without Radio Resource Limitation

Power Control	Wall Atten (dB)	SIR Thres (dB)	Probability at Base Station			Probability at Portable		
			Co-Chan	Adj Chan	Combined	Co-Chan	Adj Chan	Combined
None	10	21	48%	22%	70%	46%	21%	67%
None	10	18	53%	18%	71%	52%	17%	69%
None	10	15	55%	14%	69%	55%	12%	67%
None	10	12	56%	11%	67%	54%	12%	66%
None	20	21	40%	29%	69%	41%	26%	67%
None	30	21	48%	35%	83%	50%	33%	83%
None	40	21	41%	52%	90%	42%	50%	92%
None	50	21	14%	78%	92%	13%	76%	89%
None	60	21	10%	93%	94%	4.4%	85%	89%
None	60	18	11%	95%	96%	17%	89%	91%
None	60	15	0.3%	92%	92%	0.5%	88%	89%
None	60	12	0.3%	92%	92%	0.1%	81%	81%
Both P/BS	10	21	47%	15%	62%	41%	16%	57%
Both P/BS	10	18	44%	14%	58%	40%	15%	55%
Both P/BS	10	15	48%	10%	58%	41%	9.8%	51%
Both P/BS	10	12	44%	9.1%	53%	38%	8.6%	47%
Both P/BS	20	21	40%	26%	66%	39%	24%	63%
Both P/BS	30	21	38%	39%	77%	37%	38%	75%
Both P/BS	40	21	39%	48%	87%	35%	46%	81%
Both P/BS	50	21	25%	63%	88%	19%	64%	83%
Both P/BS	60	21	7.8%	82%	90%	5.8%	77%	83%
Both P/BS	60	18	2.2%	85%	87%	2.8%	74%	77%
Both P/BS	60	15	0.7%	83%	84%	0.8%	68%	69%
Both P/BS	60	12	0.2%	83%	83%	0.3%	66%	66%

Table 14: Probability of a Dominant Interferer of Scenarios without Radio Resource Limitation

For each of the subsections, simulation results are presented by four different set of charts. First, the cumulative probability distributions (CPD) curves of SIR without noise at the portable and the base station are given. These curves provide information on the probability of SIR within 20 dB of call setup SIR threshold. Then, the conditional CPD curves of the power ratio of strongest interferer to all remaining interferers ($I_{\text{strongest}}/I_{\text{remain}}$) given the overall SIR is within 20 dB of the call setup SIR threshold are presented. These curves provide information on the probability of a dominant interferer. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are presented by a stacked column chart. Lastly, the conditional CPD curves of SIR at the portable and the base station are generated for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels. Portions of the results from Tables 13 and 14 will be duplicated and shown within each subsection for discussion purposes.

5.5.1 Systems without Power Control

Simulation results presented in this subsection are from systems without power control. The radios in both portable and base station are only capable of transmitting at the normal power level. Discussions regarding scenarios with different wall attenuations are presented first, then results from scenarios with different call setup SIR thresholds are described.

5.5.1.1 Sensitivity to Wall Attenuations

The cumulative probability distributions (CPD) of SIR at the portable and the base station are shown in Figures 88 and 89 respectively. Both figures indicate a substantial change in the probability of SIR beyond 60 dB as the wall attenuation is increased from 10

dB to 60 dB. The probability of SIR beyond 60 dB is approximately 10% and 90% respectively. The curves also appear to be shifting toward higher SIR values. This behavior can be explained by the fact that co-channel interference from the surrounding cells is greatly attenuated as the wall attenuation increases. In addition, the probability of using adjacent channels within the same cell is quite low. These are indicated by the CPD curve at the portable when the attenuation per wall is at 60 dB. The cumulative probabilities at 27 dB and 30 dB are 0.7% and 4.9% respectively. Between 30 dB to 55 dB, the probability maintains at the same level. The curve starts increasing at 60 dB and reaches 90% at approximately 110 dB. The SIR values beyond 55 dB are due to co-channel interference from the surrounding cells, whereas adjacent channel interference within the same cell is responsible for the initial 4.9% of the statistic. This indicates the probability of using adjacent channel within the same cell is very low when there is no power control and the call setup SIR threshold is at 21 dB. Since the majority of the strong interferers are coming from the surrounding cells, an increase in the wall attenuation produces a better SIR at the radio receiver.

The probabilities of the SIR being less than 41 dB (SIR threshold plus 20 dB) are tabulated in Table 15. For SIR less than 41 dB, the CPD of the power ratio of the strongest Interferer to all the remaining interferers at the portable and the base station are shown in Figures 90 and 91 respectively. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are obtained and shown in Table 16. The values in Table 16 are also shown as a stacked column chart in Figure 92.

Wall Attenuation	Probability [SIR $\leq$ 41 dB]	
	Base Station	Portable
10 dB	31%	30%
20 dB	17%	18%
30 dB	10%	10%
40 dB	8.2%	8.2%
50 dB	6.7%	6.6%
60 dB	5.6%	5.8%

Table 15: Probability of SIR less than 41 dB (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

Wall Atten (dB)	Probability at Base Station			Probability at Portable		
	Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
10	48%	22%	70%	46%	21%	67%
20	40%	29%	69%	41%	26%	67%
30	48%	35%	83%	50%	33%	83%
40	41%	52%	93%	42%	50%	92%
50	14%	78%	92%	13%	76%	89%
60	10%	93%	94%	4.4%	85%	89%

Table 16: Probability of a Dominant Interferer (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

In Figures 90 and 91, the CPD curves for systems with 10 dB and 20 dB wall attenuation are almost identical. At higher wall attenuations, the statistical behaviors are different. In general, the power ratio $I_{\text{strongest}}/I_{\text{remain}}$ is much greater at higher wall attenuations. At low wall attenuation, all interfering signals including the dominant interfering signal are coming from surrounding cells. A slight increase in wall attenuation will attenuate all interfering signals including the dominant interferer, and the statistical behaviors of $I_{\text{strongest}}/I_{\text{remain}}$ do not change. However, at higher wall attenuation (40 dB to

60 dB), there is a very high probability of a dominant adjacent channel interferer from within the same cell. An increase in wall attenuation affects all interference from surrounding cells but the dominant adjacent channel interferer. This explains why the power ratio $I_{\text{strongest}}/I_{\text{remain}}$ is much greater at higher wall attenuations.

For systems with 50 dB and 60 dB wall attenuations, there is approximately a 10% probability (8.3% for 50 dB and 11.2% for 60 dB) that the power ratio $I_{\text{strongest}}/I_{\text{remain}}$ is 0 dB at the portable as shown in Figure 90. This is due to the existence of two equal power adjacent channel interferers within the same cell.

As shown in Table 16 and Figure 92, the probability of a dominant interferer increases from the minimum level of 67% to the maximum level of 94% as the wall attenuation increases from 10 dB to 60 dB. At low wall attenuations (10 dB and 20 dB), the dominant interferer is from surrounding cells and the probability of a dominant co-channel interferer is higher than that of a dominant adjacent channel interferer. However, at high wall attenuation (50 dB and 60 dB), the probability of a dominant adjacent channel interferer accounts for the majority of the probability. The interfering signals from the surrounding cells are greatly attenuated and the corresponding SIR values at the receiver are normally higher than 41 dB. Therefore, almost all calls that are solely subject to interference from the surrounding cells are excluded in the determination of the probability of a dominant interferer. This explains the high probability of a dominant adjacent channel interferer because adjacent channel interference is the only possible interference within the same cell.

Figures 93 and 94 describe the probability distribution of SIR for calls without a dominant interferer ($I_{\text{strongest}}/I_{\text{remain}}$ is less than 6 dB given SIR is less than 41 dB). The distribution for the portable indicate a high probability that the SIR is at 27 dB for systems with high wall attenuation. The probability is 100% for systems with 60 dB wall attenuation. This indicates that a call with SIR less than 41 dB either has a dominant

interferer or is receiving strong interference from both adjacent channels in systems with high wall attenuation.

For wall attenuations of 10 dB, 20 dB and 30 dB, the probabilities of SIR being less than 31 dB (10 dB above the call setup SIR threshold) are 23%, 22% and 30% at the portable and 23%, 18% and 24% at the base station. These give an average of 23%. From Figures 90) and 91, the probabilities of a call without a dominant interferer ($I_{\text{strongest}}/I_{\text{remain}}$ is less than 6 dB) are approximately 37%, 37% and 20% at the portable and 34%, 35% and 18% at the base station. These give an average of 30% of all calls with SIR less than 41 dB. As a result, the average probability of calls with SIR less than 31 dB is 7% of all calls with SIR less than 41 dB. According to the discussion in section 5.3, calls with SIR at 10 dB above the SIR threshold will have very good error performance. The average probability of 7% indicates a low probability of calls with SIR within 10 dB of the call setup SIR threshold.

Figure 88: CPD of SIR at Portable (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

Figure 89: CPD of SIR at Base Station (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

Figure 90: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR less than 41 dB (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

Figure 91: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR less than 41 dB (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

Figure 92: Probability of a Dominant Interferer (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

Figure 93: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

Figure 94: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (21 dB SIR Threshold, No Power Control, No Radio Resource Limitation)

5.5.1.2 Sensitivity to Call Setup SIR Thresholds

Studies with different call setup SIR thresholds are carried out at two different wall attenuation (10 dB and 60 dB). Simulation results of systems with 10 dB wall attenuation are presented first and they are shown in Figures 95 to 101.

The probabilities of SIR being within 20 dB of SIR threshold are tabulated in Table 17. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are shown in Table 18.

SIR Threshold	Probability [SIR $\leq$ (SIR threshold + 20 dB)]	
	Base Station	Portable
21 dB	31%	30%
18 dB	30%	30%
15 dB	31%	31%
12 dB	30%	33%

Table 17: Probability of SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

SIR Thres (dB)	Probability at Base Station			Probability at Portable		
	Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
21	48%	22%	70%	46%	21%	67%
18	53%	18%	71%	52%	17%	69%
15	55%	14%	69%	55%	12%	67%
12	56%	11%	67%	54%	12%	66%

Table 18: Probability of a Dominant Interferer (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

The CPD curves shown in Figures 95 and 96 indicate a shift to the lower SIR values by approximately 3 dB as the call setup threshold decreases by 3 dB. This

observation is also confirmed by the results in Table 17, the probability of SIR being within 20 dB of the SIR threshold is approximately 30% for all four cases.

The distributions of the power ratio $I_{\text{strongest}}/I_{\text{remain}}$ shown in Figures 97 and 98 are almost identical for all four different SIR threshold settings. The probability of a dominant interferer as shown in Table 18 and Figure 99 is approximately 68% and there is a much higher probability of a dominant co-channel interferer. At 10 dB wall attenuation, simulation results from chapter four indicate the presence of channel reuse within these systems, and co-channel interfering power is normally stronger than the interfering power from the adjacent channels. This is why there is a higher probability of a dominant co-channel interferer.

It is also observed that the probability of a dominant adjacent channel interferer decreases as the SIR threshold decreases. As described in section 4.3.3, simulation results show a continuous increase in system capacity as the required call setup SIR threshold is lowered. This indicates a higher probability that a channel is reused; hence, a higher probability of a call receiving interference from both co-channel and adjacent channel interferers and co-channel interfering power is normally stronger. This is the reason for an increase probability of a dominant co-channel interferer and a decrease probability of a dominant adjacent channel interferer as the SIR threshold is lowered.

Figure 100 and Figure 101 show the conditional CPD curves of SIR at the portable and the base station for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels.

Figure 95: CPD of SIR at Portable (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 96: CPD of SIR at Base Station (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 97: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 98: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 99: Probability of a Dominant Interferer (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 100: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{dB}$ (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 101: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (10 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Simulation results regarding systems with 60 dB wall attenuation are shown in Figures 103 to 109. The probabilities of SIR being within 20 dB of SIR threshold are tabulated in Table 19. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are shown in Table 20.

SIR Threshold	Probability [$\text{SIR} \leq (\text{SIR threshold} + 20 \text{ dB})$]	
	Base Station	Portable
21 dB	5.6%	5.8%
18 dB	6.8%	7.5%
15 dB	9.0%	12%
12 dB	18%	29%

Table 19: Probability of SIR within 20 dB of SIR Threshold (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

SIR Thres (dB)	Probability at Base Station			Probability at Portable		
	Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
21	1.0%	93%	94%	4.4%	85%	89%
18	1.1%	95%	96%	1.7%	89%	91%
15	0.3%	92%	92%	0.5%	88%	89%
12	0.3%	92%	92%	0.1%	81%	81%

Table 20: Probability of a Dominant Interferer (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

At 60 dB wall attenuation, calls that are solely subject to interference from surrounding cells have very good SIR values and the values are normally higher than 41 dB. The probability of SIR being within 20 dB of the SIR threshold are mainly due to interference from within the same cell. From Table 19 and Figure 103, the increase in the probability of the SIR being within 20 dB of the SIR threshold as the SIR threshold is lowered is due to an increase in the probability of using adjacent channels within the cell.

In Figures 105 and 106, the distributions of the power ratio $I_{\text{strongest}}/I_{\text{remain}}$ for 12 dB SIR threshold are different from others. The curve appears to be shifted upward at the portable side as shown in Figure 105. The difference is due to increased probability of using both adjacent channels within the same cell when the SIR threshold is at 12 dB.

The probability of a dominant interferer as shown in Table 20 and Figure 107 is approximately 91%. The probability is consistently higher than 68% in cases with 10 dB wall attenuation. It is also observed that the probability of a dominant co-channel interferer is very insignificant.

At 60 dB wall attenuation, co-channel interfering signals from surrounding cells are greatly attenuated and calls that are solely subject to these interfering signals have very high SIR values. It is expected that these call samples are totally excluded from the determination of the probability of a dominant interferer. However, simulation results in

Table 20 still indicate a very small probability of a dominant co-channel interferer. The probability gets even smaller at a lower SIR threshold.

For calls with an adjacent channel interferer from within the same cell, there is a very high probability that its SIR value is within 20 dB of the SIR threshold and included in the determination of probability of a dominant interferer. For calls without an adjacent channel interferer from within the same cell, their interfering sources are solely from surrounding cells. It is still possible to have small occurrences with overall SIR values being within 20 dB of the SIR threshold and they are included in the statistic of a dominant interferer. Figure 102 demonstrates these situations.

Figure 102: Situations for a Dominant Co Channel Interferer at 60 dB Wall Attenuation

Two adjacent cells are shown in the figure and the two communications connections are operating on the same channel. Portable 2 is the only interferer of Base Station 1 and vice versa. The distance between Portable 2 and the two base stations is 11.3 meters. The distance between Portable 1 and Base Station 1 is also 11.3 meters. The solid arrow ,

indicate the direction of the desired signals and interfering signals are represented by the dashed arrows. The path losses (excluding wall losses and shadowing) are identical for all indicated signal paths. However, the desired signals from Portable 1 to Base Station 1 and Base Station 2 to Portable 2 experience very high shadowing loss, whereas the interfering signal path has very little shadowing besides the 60 dB wall attenuation. For a 21 dB SIR threshold, the interfering signal has to be within 41 dB of the desired signal to be considered as a dominant co-channel interferer. The condition can be satisfied if the joint shadowing effect of desired and interfering signal paths is greater than 19 dB. As discussed in section 4.3.5, the joint shadowing effect is log-normal distributed with a standard deviation of 11.3 dB. The probability of the joint shadowing effect being greater than 19 dB is 4.6%. As a result, it is still possible to have a small probability of a dominant co-channel interferer. For 12 dB SIR threshold, the joint shadowing effect has to be greater than 28 dB ($60 \text{ dB} - 32 \text{ dB} = 28 \text{ dB}$) before the interferer is considered as a dominant co-channel interferer. The probability of the joint shadowing effect being greater than 28 dB is 0.67%. This explains why the probability of a dominant co-channel interferer becomes negligible at 12 dB SIR threshold.

For calls without a dominant interferer and overall SIR values are within 20 dB of SIR threshold, there is almost 100% probability that the portable SIR is at 27 dB. This leads to an important observation. For calls with SIR being within 20 dB of the SIR threshold, the calls have a dominant adjacent channel interferer or receive strong interference from both adjacent channels.

Figure 108 and Figure 109 show the conditional CPD curves of SIR at the portable and the base station for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels.

Figure 103: CPD of SIR at Portable (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 104: CPD of SIR at Base Station (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 105: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR within 20 dB of SIR Threshold (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 106: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR within 20 dB of SIR Threshold (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 107: Probability of a Dominant Interferer (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 108: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

Figure 109: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{dB}$ (60 dB Wall Attenuation, No Power Control, No Radio Resource Limitation)

5.5.2 Systems with Power Control at Both Portable and Base Station

Radios at both portable and base station are capable of transmitting at a power level which is 20 dB lower than the normal setting. Transmitter power control can be enabled at the portable or the base station or both depending on the situation. The base station is also capable of transmitting at different power levels for different time slots.

Discussions regarding scenarios with different wall attenuations are presented first, then results from scenarios with different call setup SIR thresholds are described. Comparisons with scenarios with no power control are also given.

5.5.2.1 Sensitivity to Wall Attenuations

Simulation results of scenarios with different wall attenuations are shown in Figures 110 to 116. The call setup SIR threshold for all these scenarios is at 21 dB. The probabilities of SIR being less than 41 dB are tabulated in Table 21. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are obtained and shown in Table 22. The results from scenarios with no power control are also included in these tables.

Power Control	Wall Attenuation	Probability [SIR < 41 dB]	
		Base Station	Portable
None	10 dB	31%	30%
None	20 dB	17%	18%
None	30 dB	10%	10%
None	40 dB	8.2%	8.2%
None	50 dB	6.7%	6.6%
None	60 dB	5.6%	5.8%
Both P/BS	10 dB	68%	63%
Both P/BS	20 dB	54%	48%
Both P/BS	30 dB	37%	33%
Both P/BS	40 dB	34%	30%
Both P/BS	50 dB	28%	26%
Both P/BS	60 dB	22%	21%

Table 21: Probability Comparisons of SIR less than 41 dB for Systems with and without Power Control (21 dB SIR Threshold, No Radio Resource Limitation)

Power Control	Wall Attenuation (dB)	Probability at Base Station			Probability at Portable		
		Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
None	10	48%	22%	70%	46%	21%	67%
None	20	40%	29%	69%	41%	26%	67%
None	30	48%	35%	83%	50%	33%	83%
None	40	41%	52%	93%	42%	50%	92%
None	50	14%	78%	92%	13%	76%	89%
None	60	10%	93%	94%	4.4%	85%	89%
Both P/BS	10	47%	15%	62%	41%	16%	57%
Both P/BS	20	40%	26%	66%	39%	24%	63%
Both P/BS	30	38%	39%	77%	37%	36%	75%
Both P/BS	40	39%	48%	87%	35%	46%	81%
Both P/BS	50	25%	63%	88%	19%	64%	83%
Both P/BS	60	7.8%	82%	90%	5.8%	77%	83%

Table 22: Probability Comparisons of a Dominant Interferer for Systems with and without Power Control (21 dB SIR Threshold, No Radio Resource Limitation)

As shown in Table 21, Figure 88 to Figure 89 and Figure 110 to Figure 111, the SIR levels at both portable and base station are consistently lower for systems with power control. Although, as shown in the previous chapter, the capacity of systems with power control is higher. For systems without power control, the probabilities of the SIR being less than 41 dB range from 5.6% at 60 dB wall attenuation to 31% at 10 dB wall attenuation. The corresponding probabilities for systems with power control are 21% at 60 dB wall attenuation and 68% at 10 dB wall attenuation. The probability the SIR is less than 41 dB for systems with power control are at least 2.2 times the probability for systems without power control.

For calls with transmitter power control enabled, the desired signal at the receiver becomes 20 dB weaker. The SIR level is still high enough to provide satisfactory performance but there is a higher probability that the SIR level is at a lower value. If all

calls are operating at the lower transmitter power level and system coverage is still sufficient, the statistic of SIR levels should be similar to those without power control. This reasoning is based on the fact that both the desired signal and interfering signals are 20 dB weaker, the overall SIR level will not change. However, additional calls will take advantage of the decreased level of interference and operate at full power to obtain satisfactory SIR level which they cannot obtain at the lower transmitter power setting. As a result, the capacity of the system increases. Owing to the difference in transmitter power level, calls with power control enabled will be affected and their receiver SIR levels are lower. This is the main reason for the higher probability of lower receiver SIR in systems with power control.

For systems with high wall attenuation (30 dB to 60 dB), there is another reason for the increased probability of lower SIR level. As described in section 4.3.5, there is an increased probability of using adjacent channels within the same cell with portable power control and higher cell isolation. When adjacent channels are used within the same cell, the portable SIR level is either at 27 dB or 30 dB and the base station SIR level is most likely lower than 41 dB.

As indicated in Table 22, Figure 92 and Figure 114, the probability of a dominant interferer at both portable and base station are consistently lower for systems with power control. For systems without power control, the probabilities of a dominant interferer range from 67% at 10 dB wall attenuation to 94% at 60 dB wall attenuation. The corresponding probabilities for systems with power control are 57% at 10 dB wall attenuation and 90% at 60 dB wall attenuation.

For calls with a single interferer whose power level is within 41 dB of the desired signal, the interferer is considered as a dominant interferer. System capacity results from Table 2 of section 4.3 indicate an increase in traffic capacity of approximately 30% for systems with power control at both portable and base station. An increase in traffic intensity results in a lower probability of calls with a single interferer. If the power from

the second interferer is comparable with the first interferer, the call will no longer have a dominant interferer. This is the main reason for the decrease in the probability of a dominant interferer at low wall attenuation (10 dB to 30 dB).

At high wall attenuation (40 dB to 60 dB), the main reason for the decrease in the probability of a dominant interferer is due to an increase probability of using both adjacent channels within the same cell. This behavior can be observed by comparing the portable CPD curves in Figure 90 and Figure 112 for systems with 60 dB wall attenuation. For system without power control, the probability of two equal power adjacent channel interferers is 11% from Figure 90. From Figure 112, the probability for the system with power control is 16%. The increased probability ($16\% - 11\% = 5\%$ increase) of two equal power adjacent channel interferers accounts for the majority of the 6% ($89\% - 83\% = 6\%$ from Table 22) difference in the probability of a dominant interferer between systems with and without power control.

Figure 114 also indicates that most dominant interferers are co-channel interferers at low wall attenuation and adjacent channel interferers at high wall attenuation. These behaviors have been explained in section 5.5.1.1.

Figure 115 and Figure 116 show the conditional CPD curves of SIR at the portable and the base station for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels.

Figure 110: CPD of SIR at Portable (21 dB SIR Threshold, With Power Control, No Radio Resource Limitation)

Figure 111: CPD of SIR at Base Station (21 dB SIR Threshold, With Power Control, No Radio Resource Limitation)

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PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

Figure 112: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR less than 41 dB (21 dB SIR Threshold, With Power Control, No Radio Resource Limitation)

Figure 113: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR less than 41 dB (21 dB SIR Threshold, With Power Control, No Radio Resource Limitation)

Figure 114: Probability of a Dominant Interferer (21 dB SIR Threshold, With Power Control, No Radio Resource Limitation)

Figure 115: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (21 dB SIR Threshold, With Power Control, No Radio Resource Limitation)

Figure 116: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{dB}$ (21 dB SIR Threshold, With Power Control, No Radio Resource Limitation)

5.5.2.2 Sensitivity to Call Setup SIR Thresholds

Studies with different call setup SIR thresholds are carried out at 10 dB and 60 dB wall attenuations. Simulation results of systems with 10 dB wall attenuation are presented first and they are shown in Figures 117 to 123.

The probabilities of SIR being within 20 dB of SIR threshold are tabulated in Table 23. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are shown in Table 24. The results from scenarios with no power control are also included in these tables.

Power Control	SIR Threshold	Probability [SIR ≤ (SIR threshold + 20 dB)]	
		Base Station	Portable
None	21 dB	31%	30%
None	18 dB	30%	30%
None	15 dB	31%	31%
None	12 dB	30%	33%
Both P/BS	21 dB	68%	63%
Both P/BS	18 dB	67%	62%
Both P/BS	15 dB	71%	65%
Both P/BS	12 dB	74%	72%

Table 23: Probability Comparisons of SIR within 20 dB of SIR Threshold for Systems with and without Power Control (10 dB Wall Attenuation, No Radio Resource Limitation)

Power Control	SIR Thres (dB)	Probability at Base Station			Probability at Portable		
		Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
None	21	48%	22%	70%	46%	21%	67%
None	18	53%	18%	71%	52%	17%	69%
None	15	55%	14%	69%	55%	12%	67%
None	12	56%	11%	67%	54%	12%	66%
Both P/BS	21	47%	15%	62%	41%	16%	57%
Both P/BS	18	44%	14%	58%	40%	15%	55%
Both P/BS	15	48%	10%	58%	41%	98%	51%
Both P/BS	12	44%	9 1%	53%	38%	86%	47%

Table 24: Probability Comparisons of a Dominant Interferer for Systems with and without Power Control (10 dB Wall Attenuation, No Radio Resource Limitation)

As shown in Table 23, Figures 95 to 96 and Figures 117 to 118, the SIR levels at both portable and base station are consistently lower for systems with power control. For

systems without power control, the average probability of SIR being within 20 dB of SIR threshold is 31%. The average probability for systems with power control is 68%. The probabilities for systems with power control are approximately 2.2 times the probabilities for systems without power control. This characteristic at low wall attenuation has been explained in section 5.5.2.1.

As indicated in Table 24, Figure 99 and Figure 121, the probability of a dominant interferer at both portable and base station are consistently lower for systems with power control. For systems without power control, the average probability of a dominant interferer is 67.2% at the portable and 69.3% at the base station. The average probability for systems with power control is 52.5% at the portable and 57.8% at the base station. This behavior at low wall attenuation is also explained in section 5.5.2.1.

Figure 121 also indicate a steady decrease in the probability of a dominant interferer when the SIR threshold is lowered. At lower SIR threshold, the probability of a dominant adjacent channel interferer is also smaller. The steady decrease in the probability of a dominant interferer is due to a higher traffic intensity for systems with lower SIR threshold. System capacity results from Table 2 of section 4.3 indicate an increase in traffic capacity of 58% when SIR threshold is lowered from 21 dB to 12 dB. The mechanism by which an increase in traffic intensity results in a lower probability of a dominant interferer has been described in section 5.5.2.1. The decrease in the probability of a dominant adjacent channel interferer at lower SIR thresholds is explained in section 5.5.1.2.

Figure 122 and Figure 123 show the conditional CPD curves of SIR at the portable and the base station for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels.

Figure 117: CPD of SIR at Portable (10 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 118: CPD of SIR at Base Station (10 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 119: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 120: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 121: Probability of a Dominant Interferer (10 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 122: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (10 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 123: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{dB}$ (10 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Simulation results of systems with 60 dB wall attenuation are shown in Figures 124 to 130. The probabilities of SIR being within 20 dB of SIR threshold are tabulated in Table 25. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are obtained and shown in Table 26. The results from scenarios with no power control are also included in these tables.

For systems with power control, the probability of SIR within 20 dB of the SIR threshold increases from 21% to 70% at the portable and 22% to 49% at the base station as the SIR threshold is lowered from 21 dB to 12 dB. The increases at both the portable and base station are mainly due to a large increase in the probability of using adjacent channels within the same cell. The smaller increase at the base station is due to the fact that the interfering portables can be anywhere within the cell and their signal propagation losses are different. Table 26 also indicates a decrease in the probability of a dominant interferer from

83% to 66% at the portable and 90% to 83% at the base station as the SIR threshold is lowered.

Power Control	SIR Threshold	Probability [SIR $\leq$ (SIR threshold + 20 dB)]	
		Base Station	Portable
None	21 dB	5.6%	5.8%
None	18 dB	6.8%	7.5%
None	15 dB	9.0%	12%
None	12 dB	18%	29%
Both P/BS	21 dB	22%	21%
Both P/BS	18 dB	47%	50%
Both P/BS	15 dB	56%	66%
Both P/BS	12 dB	49%	70%

Table 25: Probability Comparisons of SIR within 20 dB of SIR Threshold for Systems with and without Power Control (60 dB Wall Attenuation, No Radio Resource Limitation)

Power Control	SIR Thres. (dB)	Probability at Base Station			Probability at Portable		
		Co-Chan	Adj-Chan.	Combined	Co-Chan.	Adj-Chan.	Combined
None	21	1.0%	93%	94%	4.4%	85%	89%
None	18	1.1%	95%	96%	1.7%	89%	91%
None	15	0.3%	92%	92%	0.5%	88%	89%
None	12	0.3%	92%	92%	0.1%	81%	81%
Both P/BS	21	7.8%	82%	90%	5.8%	77%	83%
Both P/BS	18	2.2%	85%	87%	2.8%	74%	77%
Both P/BS	15	0.7%	83%	84%	0.8%	68%	69%
Both P/BS	12	0.2%	83%	83%	0.3%	66%	66%

Table 26: Probability Comparisons of a Dominant Interferer for Systems with and without Power Control (60 dB Wall Attenuation, No Radio Resource Limitation)

All common interference characteristics of systems with high wall attenuation have been described and explained in section 5.5.1. Typical differences between the interference characteristics of systems with and without power control have been discussed in section 5.5.2.1. Figure 124 indicates a large increase in the probability of using adjacent channels within the same cell. The probability increases from 20% to 70% as the SIR threshold decreases from 21 dB to 12 dB. This behavior is the result of the combined effect of portable power control, good cell isolation and low call setup SIR threshold. A detailed explanation can be obtained from section 4.3.5.

Figure 128 and Table 26 indicate a 17% ($83\% - 66\% = 17\%$) decrease in the probability of a dominant interferer at the portable as the SIR threshold is lowered from 21 dB to 12 dB. This is mainly due to a higher probability of using both adjacent channels within the same cell as shown in Figure 126.

Figure 129 and Figure 130 show the conditional CPD curves of SIR at the portable and the base station for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels.

Figure 124: CPD of SIR at Portable (60 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 125: CPD of SIR at Base Station (60 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 126: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR within 20 dB of SIR Threshold (60 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 127: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR within 20 dB of SIR Threshold (60 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 128: Probability of a Dominant Interferer (60 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 129: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{dB}$ (60 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

Figure 130: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{dB}$ (60 dB Wall Attenuation, With Power Control, No Radio Resource Limitation)

5.6 Systems with Two Radios per Cell

All systems presented in this section assume a frequency allocation of 8 MHz. There are eight frequency carriers and eight time slots per carrier, resulting in a total of 64 traffic channels. A dynamic channel allocation scheme is used during call setup and handover. Each base station (cell) is equipped with two radios to support at most 16 simultaneous calls, and each radio is allowed to operate on any channel in the available band for each time slot. It is assumed that the radio is capable of switching to any one of the eight carrier frequencies between adjacent slots. The portable is also assumed to be able to operate on any one of the 64 traffic channels.

As described in the introduction of this chapter, all simulation results are obtained at the system performance level of 1% GOS. The cumulative probability distribution curves of the SIR at both portable and base station are generated and included in the discussions.

Table 27 describes the probability of the SIR being within 20 dB of the call setup SIR threshold. The probabilities at both portable and base station are calculated based on the statistics of 2600 to 4000 calls. Call samples are obtained periodically at a fixed interval, and a call sample is collected only if the call is subjected to at least one interferer. In other words, a call is included as a sample when the same channel and/or its adjacent channels are used elsewhere within the system. The SIR for all call samples are obtained at the sampling time.

Power Control	Wall Attenuation	SIR Threshold	Probability [SIR $\leq$ (SIR threshold + 20 dB)]	
			Base Station	Portable
None	10 dB	21 dB	28%	29%
None	10 dB	18 dB	31%	32%
None	10 dB	15 dB	29%	29%
None	10 dB	12 dB	25%	25%
None	20 dB	21 dB	7.8%	7.9%
None	30 dB	21 dB	1.3%	1.7%
None	40 dB	21 dB	0.5%	0.7%
None	50 dB	21 dB	0.1%	0.2%
None	60 dB	21 dB	0.0%	0.0%
Both P/BS	10 dB	21 dB	62%	54%
Both P/BS	10 dB	18 dB	64%	57%
Both P/BS	10 dB	15 dB	60%	54%
Both P/BS	10 dB	12 dB	55%	49%
Both P/BS	20 dB	21 dB	22%	19%
Both P/BS	30 dB	21 dB	4.8%	5.1%
Both P/BS	40 dB	21 dB	2.1%	2.2%
Both P/BS	50 dB	21 dB	0.2%	0.3%
Both P/BS	60 dB	21 dB	0.0%	0.0%

Table 27: Probability of SIR within 20 dB of Call Setup SIR Threshold for Scenarios with Two Radios per Cell

The probability of a dominant interferer at both portable and base station for each scenario are tabulated in Table 28. The table includes three columns of probability values. They are the probability of a dominant co-channel interferer, a dominant adjacent channel interferer, and the probability sum of these two kinds of dominant interferers is shown under the 'Combined' column. The values in the 'Combined' column describe the overall probability of a dominant interferer at the portable and the base station. For scenarios with less than 3% probability of SIR within 20 dB of the call setup SIR threshold, the computed probability of a dominant interferer is not accurate due to an insufficient number of call samples with SIR within 20 dB of SIR threshold. As a result, statistical information on these scenarios is not presented in subsequent sections. These scenarios include systems with wall attenuation from 40 dB to 60 dB as shown in Table 27. For the system with 30 dB wall attenuation and without power control, the probability of SIR being within 20 dB of the SIR threshold is less than 2% and it is also excluded from the discussions.

In systems with two radios per base station, most of the interferers are from the surrounding cells and some may be two or three cells away. Under this situation, the received power from the strongest interferer can be below the noise floor. If the received power level of the strongest interferer is below the noise floor, it is more suitable to consider the call as having no interferer because the radio receiver cannot distinguish it from noise. For calls with overall SIR within 20 dB of the SIR threshold and the strongest interferer is below the noise floor, the desired signal has to be very weak. This situation has a higher probability of happening at high wall attenuation when portables are served by adjacent cells. If the interfering signal from the dominant interferer is below the noise floor, the call should not be considered as part of the probability of a call with a dominant interferer. All results presented in section 5.5 regarding systems without radio resource limitation are not affected by this special situation. The effect on the results tabulated in Table 28 is small and only the case with power control, 30 dB wall attenuation and 21 dB call setup SIR threshold is affected. These differences will be discussed in section 5.6.2.1.

In general, simulation results indicate calls in systems with wall attenuation beyond 20 dB have a very good signal to interference ratio. These systems are highly radio resource limited. A significant increase in system traffic capacity can be expected by incorporating more radios in each base station.

Power Control	Wall Atten (dB)	SIR Thres (dB)	Probability at Base Station			Probability at Portable		
			Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
None	10	21	48%	20%	68%	49%	20%	69%
None	10	18	53%	13%	66%	52%	12%	64%
None	10	15	55%	12%	67%	55%	13%	68%
None	10	12	58%	9 0%	67%	59%	8 9%	68%
None	20	21	47%	30%	77%	44%	28%	72%
Both P/BS	10	21	46%	18%	64%	41%	18%	59%
Both P/BS	10	18	48%	16%	64%	43%	15%	58%
Both P/BS	10	15	50%	14%	64%	43%	14%	57%
Both P/BS	10	12	53%	13%	66%	47%	12%	59%
Both P/BS	20	21	45%	37%	82%	42%	37%	79%
Both P/BS	30	21	43%	41%	84%	34%	52%	86%

Table 28: Probability of a Dominant Interferer for Scenarios with Two Radios per Cell

In the following subsections, interference characteristics of systems without power control are presented first. Their sensitivity to different wall attenuations and call setup SIR thresholds are described. Then, simulation results on systems with power control at both portable and base station are discussed.

Simulation results are presented by four different set of charts. First, the cumulative probability distributions (CPD) curves of SIR without noise at the portable and the base station are presented. These curves provide information on the probability of SIR within 20 dB of call setup SIR threshold. Then, the conditional CPD curves of the power ratio of strongest interferer to all remaining interferers ($I_{\text{strongest}}/I_{\text{remain}}$) given the overall

SIR is within 20 dB of the call setup SIR threshold are obtained. These curves provide information on the probability of a dominant interferer. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are presented by a stacked column chart. Lastly, the conditional CPD curves of SIR at the portable and the base station are generated for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels. Portions of the results from Tables 27 and 28 will be duplicated and shown within each subsection for discussion purposes.

5.6.1 Systems without Power Control

Simulation results presented in this subsection are from systems without power control. The radios in both portable and base station are only capable of transmitting at the normal power level. Discussions regarding scenarios with different wall attenuations are presented first, then results from scenarios with different call setup SIR thresholds are described.

5.6.1.1 Sensitivity to Wall Attenuations

The cumulative probability distribution (CPD) of SIR at the portable and the base station are shown in Figures 131 and 132 respectively. Both figures indicate a substantial increase from 15% to 85% in the probability of calls with SIR beyond 60 dB as the wall attenuation is changed from 10 dB to 30 dB. For wall attenuation beyond 30 dB, the probability is almost 100%.

For eight frequency carriers systems with only two radios per cell, most of the interferers are in the surrounding cells and co-channel interferers are most likely a few cells away. The lack of radio resources can limit the ability to reuse frequency even though the interference environment allows greater frequency reuse. In Figures 131 and 132, the spacing between adjacent curves in the 40% to 60% probability region is between 20 dB to

30 dB. The corresponding curve spacing in Figures 88 and 89 for systems without radio resource limitation is approximately 10 dB. This indicates that interferers are generally further away in systems with two radios per cell and the impact on SIR as a result of an increased wall attenuation between cells is stronger. This also explains the substantial increase in the probability of calls with SIR beyond 60 dB as the wall attenuation is changed from 10 dB to 60 dB. With only two radios per base station (cell), it is unlikely that adjacent channels are used within the same base station as opposed to systems without radio resource limitations. This is confirmed by the results in Figure 131 that there is no probability concentrations at SIR values of 27 dB and 30 dB at the portable.

The probability of SIR being less than 41 dB is tabulated in Table 29. The conditional CPD curves of the power ratio of strongest interferer to all remaining interferers ($I_{\text{strongest}}/I_{\text{remain}}$) given the overall SIR is less than 41 dB are shown in Figure 133 for the portable and Figure 134 for the base station. Each figure consists of two CPD curves which correspond to scenarios with 10 dB and 20 dB wall attenuation. Statistics for systems with more than 20 dB wall attenuation are not included due to the lack of call samples with overall SIR less than 41 dB. Unlike the results given in Figures 90 and 91 for systems without radio resource limitation, the statistics of power ratio ($I_{\text{strongest}}/I_{\text{remain}}$) of strongest interferer to all other interferers as shown in Figures 133 and 134 are different between the system with 10 dB wall attenuation and the system with 20 dB wall attenuation. The CPD curves indicate that the system with 20 dB wall attenuation consistently has a higher probability of a higher power ratio between the strongest interferer and all other interferers than the system with 10 dB wall attenuation. This behavior is also the result of the lack of radio resource which limits the magnitude of frequency reuse. Consequently, there is a higher probability that the second strongest interferer is located much further away and subject to a much higher wall penetration loss than the strongest interferer. Since the second strongest interferer has to penetrate a larger number of walls, an increase in wall attenuation from 10 dB to 20 dB increases the power ratio between the

strongest and the second strongest interferer. This is the reason for the higher probability of higher power ratio between the strongest interferer and all other interferers.

Wall Attenuation	Probability [SIR $\leq$ 41 dB]	
	Base Station	Portable
10 dB	28%	29%
20 dB	7.8%	7.9%
30 dB	1.3%	1.7%
40 dB	0.5%	0.7%
50 dB	0.1%	0.2%
60 dB	0.0%	0.0%

Table 29: Probability of SIR less than 41 dB (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

Wall Atten (dB)	Probability at Base Station			Probability at Portable		
	Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
10	48%	20%	68%	49%	20%	69%
20	47%	30%	77%	44%	28%	72%

Table 30: Probability of a Dominant Interferer (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are shown in Table 30. The values in Table 30 are also presented in a stacked column chart in Figure 135. There is a slight increase in the overall probability of a dominant interferer at both the portable and the base station as the wall attenuation is increased from 10 dB to 20 dB. There is also a noticeable increase in the probability of a dominant adjacent channel interferer, the increase is mainly due to the decrease in co-channel interference effect as the wall attenuation increases.

For systems with two radios per base station and no power control, it is very unlikely to use adjacent channels within the same base station or when sharing radio resources from adjacent base stations. As a result, a possible reason for the increase in the probability of a dominant adjacent channel interferer is due to the decrease in co-channel interference. Since co-channel interferers are normally further away (especially true in systems with two radios per cell) and adjacent channel interferers from adjacent cells are much closer, an increase in wall attenuation can greatly decrease co-channel interference and have less effect on adjacent channel interferers from adjacent cells. From Table 9 of section 4.4, there is also a 25% increase in system capacity as the wall attenuation is changed from 10 dB to 20 dB. The increase in system traffic produces a higher probability of adjacent channels being used in adjacent cells, and the probability of a dominant adjacent channel interferer increases. Figure 136 and Figure 137 show the conditional CPD curves of SIR at the portable and the base station for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR level.

Figure 131: CPD of SIR at Portable (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

Figure 132: CPD of SIR at Base Station (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

Figure 133: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR less than 41 dB (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

Figure 134: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR less than 41 dB (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

Figure 135: Probability of a Dominant Interferer (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

Figure 136: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

Figure 137: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (21 dB SIR Threshold, No Power Control, Two Radios per Cell)

5.6.1.2 Sensitivity to Call Setup SIR Thresholds

Studies with different call setup SIR thresholds were carried out at 10 dB wall attenuation, and the simulation results are shown in Figures 138 to 144. The probabilities of the SIR being within 20 dB of the SIR threshold are tabulated in Table 31. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are shown in Table 32.

SIR Threshold	Probability [SIR $\leq$ (SIR threshold + 20 dB)]	
	Base Station	Portable
21 dB	28%	29%
18 dB	31%	32%
15 dB	29%	29%
12 dB	25%	25%

Table 31: Probability of SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

SIR Thres (dB)	Probability at Base Station			Probability at Portable		
	Co-Chan.	Adj-Chan.	Combined	Co-Chan.	Adj-Chan.	Combined
21	48%	20%	68%	49%	20%	69%
18	53%	13%	66%	52%	12%	64%
15	55%	12%	67%	55%	13%	68%
12	58%	9.0%	67%	59%	8.9%	68%

Table 32: Probability of a Dominant Interferer (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

All results presented in Figures 138 to 144 are very similar to results obtained from the same scenario but with no radio resource limitation. The system capacities of both systems are mainly limited by interference. As a result, the extra radios that are available in

systems without radio resource limitation do not have a substantial impact on the system capacity. This is the main reason why the results from both scenarios are very similar. Simulation results for the same scenario but with no radio resource limitation can be found in Tables 17 to 18 and Figures 95 to 101. Discussions on interference characteristics can be found in section 5.5.1.2.

Figure 138: CPD of SIR at Portable (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

Figure 139: CPD of SIR at Base Station (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

Figure 140: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

Figure 141: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

Figure 142: Probability of a Dominant Interferer (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

Figure 143: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{dB}$ (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

Figure 144: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{dB}$ (10 dB Wall Attenuation, No Power Control, Two Radios per Cell)

5.6.2 Systems with Power Control at Both Portable and Base Station

The scenarios presented in this section assume the radios at both portable and base station are capable of transmitting at a power level which is 20 dB lower than the normal setting. Transmitter power control can be enabled at the portable or the base station or both depending on the situation. The base station is also capable of transmitting at different power levels for different time slots. Discussions regarding scenarios with different wall attenuations are presented first, then results from scenarios with different call setup SIR thresholds are described.

5.6.2.1 Sensitivity to Wall Attenuations

Simulation results for scenarios with different wall attenuations are shown in Figures 146 to 153. The call setup threshold for all these scenarios is 21 dB. The probabilities of the SIR being less than 41 dB are tabulated in Table 33. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are shown in Table 34. Table 34 does not include any statistics for systems with more than 30 dB wall attenuation due to the lack of call samples with overall SIR less than 41 dB.

In the beginning of section 5.6, the case where the signal level of the dominant interferer is lower than the noise floor is discussed. If the interfering signal from the dominant interferer is below the noise floor, the call is not considered as a call with a dominant interferer. There is only one occurrence of this condition at the portable for the system with 20 dB wall attenuation. For the system with 30 dB wall attenuation, there are nine occurrences at the base station and eight occurrences at the portable. The statistics in Table 34 have been updated and shown in Table 35. The results in Tables 34 and 35 are also presented in the form of stacked column chart in Figures 150 and 151 respectively.

Power Control	Wall Attenuation	Probability (SIR $\leq$ 41 dB)	
		Base Station	Portable
Both P/BS	10 dB	62%	54%
Both P/BS	20 dB	22%	19%
Both P/BS	30 dB	4.8%	5.1%
Both P/BS	40 dB	2.1%	2.2%
Both P/BS	50 dB	0.2%	0.3%
Both P/BS	60 dB	0.0%	0.0%

Table 33: Probability of SIR less than 41 dB (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Power Control	Wall Atten (dB)	Probability at Base Station			Probability at Portable		
		Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
Both P/BS	10	46%	18%	64%	41%	18%	59%
Both P/BS	20	45%	37%	82%	42%	37%	79%
Both P/BS	30	43%	41%	84%	34%	52%	86%

Table 34: Probability of a Dominant Interferer Including Samples with Dominant Interference below Noise Floor (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Power Control	Wall Atten (dB)	Probability at Base Station			Probability at Portable		
		Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
Both P/BS	10	46%	18%	64%	41%	18%	59%
Both P/BS	20	45%	37%	82%	42%	37%	79%
Both P/BS	30	40%	39%	79%	34%	49%	83%

Table 35: Probability of a Dominant Interferer Excluding Samples with Dominant Interference below Noise Floor (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

The CPD curves of SIR at portable and base station are shown in Figures 146 and 147 respectively. These curves indicate that there is a higher probability that the SIR is lower at low wall attenuation when compared with scenarios without power control (described in section 5.6.1.1). As the wall attenuation increases, the statistical distribution approaches the results of systems without power control. At 50 dB wall attenuation, the CPD curves are very similar. At 60 dB wall attenuation, both statistical distributions become identical. This situation occurs because of the high wall attenuation and the limited radio resources in each cell. The high wall attenuation (60 dB) between cells minimizes the interference effects from adjacent cells and also makes resource sharing between adjacent cells impossible. All calls within the same cell operate on channels that do not interfere with each other due to the limited radio resources. All calls operate at low transmitter power level because there is no strong interference and the radio coverage within a cell is still sufficient even at the low transmitter power setting. As a result, the SIR distribution of systems with or without power control have to be identical at 60 dB wall attenuation because the only difference is the transmitter power level. The interfering signals are 20 dB lower and so is the desired signal, therefore the SIR does not change.

The conditional CPD curves of the power ratio of strongest interferer to all remaining interferers ($I_{\text{strongest}}/I_{\text{remain}}$) given the overall SIR is less than 41 dB are shown in Figure 148 for the portable and Figure 149 for the base station. Each figure consists of three CPD curves which correspond to scenarios with 10 dB, 20 dB and 30 dB wall attenuation. Statistics for systems with more than 30 dB wall attenuation are not included due to the lack of call samples with overall SIR less than 41 dB. The statistical behaviors of these curves are very similar to results from systems without power control (shown in Figures 133 and 134, and discussed in section 5.6.1.1).

The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are presented in Figures 150 and 151. Figure 150 includes all call samples with overall SIR less than 41 dB. The results presented in Figure

151 exclude all call samples where the dominant interferer is below the noise floor. There are some minor differences between the results in Figures 150 and 151. The results are identical except for scenario with 30 dB wall attenuation. At 30 dB wall attenuation (and excluding call samples where the dominant interference is below noise floor), the overall probability of a dominant interferer is lower than the probability from scenario with 20 dB wall attenuation. This behavior is expected because the situation where the dominant interference is below the noise floor is more likely to happen at higher wall attenuation as discussed at the beginning of section 5.6.

As the wall attenuation is increased from 10 dB to 20 dB, Figures 150 and 151 show a larger increase in the probability of a dominant adjacent channel interferer than for the scenario without power control in Figure 135. One reason for the probability increase is the decrease in co-channel interference as the wall attenuation increases. This discussion can be found in section 5.6.1.1. Another reason for the probability increase is the use of power control at the base station which increases the probability of resource sharing between adjacent cells on adjacent channels. This behavior is illustrated in Figure 145.

Figure 145: Radio Resource Sharing between Adjacent Cells using Adjacent Channels

The figure shows two portables A and B in the same cell. Portable A is currently communicating with Base Station 1 on channel f_5 and both sides are initially transmitting at the low power setting. In addition, there are no more radio resources in Base Station 1 to support another call. Therefore, Portable B attempts to establish its connection with Base Station 2 and the best usable channel is channel f_4 which is adjacent to channel f_5 . The call has been established and both Portable B and Base Station 2 are transmitting at full power to compensate for the additional wall attenuation. Portable B receives a lower adjacent channel interference (20 dB lower) from Base Station 1 due to base station power control, but Base Station 1 receives strong interference from Portable B. Depending on the distance between Portable A and Base Station 1, Portable A may need to transmit at full power to maintain a satisfactory SIR at Base Station 1. As a result, the probability of radio resource sharing between adjacent cells using an adjacent channel is higher with base station power control and the probability of a dominant adjacent channel interferer increases.

Figure 152 and Figure 153 show the conditional CPD curves of SIR at the portable and the base station for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels.

Figure 146: CPD of SIR at Portable (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Figure 147: CPD of SIR at Base Station (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Figure 148: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR less than 41 dB (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Figure 149: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR less than 41 dB (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Figure 150: Probability of a Dominant Interferer Including Samples with Dominant Interference below Noise Floor (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Figure 151: Probability of a Dominant Interferer Excluding Samples with Dominant Interference below Noise Floor (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Figure 152: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

Figure 153: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$ (21 dB SIR Threshold, With Power Control, Two Radios per Cell)

5.6.2.2 Sensitivity to Call Setup SIR Thresholds

Studies with different call setup SIR thresholds are carried out at 10 dB wall attenuation, and the simulation results are shown in Figures 154 to 160. The probabilities of SIR being within 20 dB of SIR threshold are tabulated in Table 36. The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are shown in Table 37.

SIR Threshold	Probability [SIR $\leq$ (SIR threshold + 20 dB)]	
	Base Station	Portable
21 dB	62%	54%
18 dB	64%	57%
15 dB	60%	54%
12 dB	55%	49%

Table 36: Probability of SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, With Power Control, Two Radios per Cell)

SIR Thres (dB)	Probability at Base Station			Probability at Portable		
	Co-Chan	Adj-Chan	Combined	Co-Chan	Adj-Chan	Combined
21	46%	18%	64%	41%	18%	59%
18	48%	16%	64%	43%	15%	58%
15	50%	14%	64%	43%	14%	57%
12	53%	13%	66%	47%	12%	59%

Table 37: Probability of a Dominant Interferer (10 dB Wall Attenuation, With Power Control, Two Radios per Cell)

As shown in Table 36, Figures 138 to 139 and Figures 154 to 155, the probabilities the SIR is within 20 dB of the call setup SIR threshold at both portable and base station are consistently higher for systems with power control. In other words, there is a higher

probability of calls with lower SIR in systems with power control; this fact is indicated by the steeper slope at the beginning of the CPD curves in Figures 154 and 155. This is due to the fact that calls that are operating at low transmitter power are subject to relatively stronger interference from calls that are transmitting at full power.

The CPD curves of the power ratio $I_{\text{strongest}}/I_{\text{remain}}$ as shown in Figures 156 and 157 are identical for all four different SIR threshold settings. The attenuation per wall for all four scenarios is 10 dB, and there is no difference in other parameters that can directly affect the signal propagation among different groups of interferer. As long as the decrease in the SIR threshold does not cause a major change in system behavior, the statistics should be identical. As indicated in Table 9 of section 4.4, a decrease in SIR threshold by 3 dB results in a slight increase in system capacity. The additional traffic can be regarded as extra samples from the same experiment.

The probabilities of a dominant interferer, a dominant co-channel interferer, and a dominant adjacent channel interferer are shown in Figure 158. The probability of a dominant interferer is approximately 58% at the portable and 64% at the base station. These two probabilities are slightly smaller than the results from scenarios without power control as shown in Figure 142. There is only a slight decrease in the probability of a dominant adjacent channel interferer as the SIR threshold decreases from 21 dB to 12 dB. The decrease in scenarios without power control is noticeably greater. In general, a decrease in SIR threshold results in an increase in system capacity and the average number of active calls increases. Higher traffic means more frequency reuse and the number of co-channel interferers increases, hence there is a higher probability of a dominant co-channel interferer and the probability of a dominant adjacent channel interferer decreases. However, in systems with power control (specifically base station power control) and two radios per cell, the decrease in SIR threshold also increases the magnitude of radio resource sharing between adjacent cells using adjacent channels. This increases the probability of a dominant adjacent channel interferer. The combined effect of the two opposing behaviors

cause a slight decrease in the probability of a dominant adjacent channel interferer as the SIR threshold decreases from 21 dB to 12 dB.

Figure 159 and Figure 160 show the conditional CPD curves of SIR at the portable and the base station for calls without a dominant interferer given their overall SIR are within 20 dB of SIR threshold. These curves provide statistical information on their SIR levels.

Figure 154: CPD of SIR at Portable (10 dB Wall Attenuation, With Power Control, Two Radios per Cell)

Figure 155: CPD of SIR at Base Station (10 dB Wall Attenuation, With Power Control, Two Radios per Cell)

Figure 156: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Portable for SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, With Power Control, Two Radios per Cell)

Figure 157: CPD of Power Ratio of Strongest Interferer to all Remaining Interferers at Base Station for SIR within 20 dB of SIR Threshold (10 dB Wall Attenuation, With Power Control, Two Radios per Cell)

Figure 158: Probability of a Dominant Interferer (10 dB Wall Attenuation, With Power Control, Two Radios per Cell)

**Figure 159: CPD of SIR at Portable for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$
(10 dB Wall Attenuation, With Power Control,
Two Radios per Cell)**

**Figure 160: CPD of SIR at Base Station for $I_{\text{strongest}}/I_{\text{remain}} < 6\text{ dB}$
(10 dB Wall Attenuation, With Power Control, Two Radios per Cell)**

5.7 Summary

5.7.1 Scenarios without Radio Resource Limitation

All simulation results of systems without radio resource limitation indicate a high probability of the existence of a dominant interferer. The probability of a dominant interferer for systems without power control is between 65% to 71% at 10 dB wall attenuation and 81% to 96% at 60 dB wall attenuation. The probability of a dominant interferer for systems with power control at both portable and base station is consistently lower. The corresponding probabilities are 46% to 62% at 10 dB wall attenuation and 66% to 90% at 60 dB wall attenuation.

At low wall attenuations (10 dB and 20 dB), the dominant interferer is from surrounding cells and the probability of a dominant co-channel interferer is higher than the probability of a dominant adjacent channel interferer.

At high wall attenuation (50 dB and 60 dB), the probability of a dominant adjacent channel interferer accounts for the majority of the probability. The interfering signals from the surrounding cells are greatly attenuated and the corresponding SIR values at the receiver are normally much higher than the call setup SIR threshold. Therefore, almost all calls that are solely subject to interference from the surrounding cells are excluded in the determination of the probability of a dominant interferer because their signal quality is excellent. This is the reason for the high probability of a dominant adjacent channel interferer because adjacent channel interference is the only possible interference within the same cell.

For calls with SIR within 20 dB of the SIR threshold in systems with 60 dB wall attenuation, the calls have a dominant adjacent channel interferer or receive strong interference from both adjacent channels.

Simulation results also indicate that the probability of a dominant interferer at both portable and base station are consistently lower for systems with portable and base station power control. For calls with a single interferer where the overall SIR within 20 dB of the SIR threshold, the interferer is considered as a dominant interferer. System capacity results show an increase in traffic capacity of approximately 30% for systems with portable and base station power control. An increase in traffic intensity results in a higher probability of calls with two or more comparable interferers. This is the reason for the lower probability of a dominant interferer at low wall attenuation. At high wall attenuation, the main reason for the lower probability of a dominant interferer is due to an increase in the probability of using both adjacent channels within the same cell.

5.7.2 Scenarios with Two Radios per Cell

In general, simulation results indicate calls in systems with wall attenuation beyond 20 dB have a very good signal to interference ratio. This is because most of the interferers are from the surrounding cells in systems with only two radios per cell. The lack of radio resources can limit the ability to reuse frequency even though the interference environment allows greater frequency reuse. Therefore, interferers are generally further away when compared with systems without radio resource limitation and the impact on SIR as a result of an increased wall attenuation between cells is stronger.

At high wall attenuation, the probability of a call with SIR being within 20 dB of the SIR threshold is negligible. There is insufficient data to obtain an accurate estimate of the probability of a dominant interferer, therefore statistical information of these cases are not presented. In fact, the SIR of each call is so good that the communications quality is excellent.

Simulation results of systems with two radios per cell also indicate a high probability of the existence of a dominant interferer. The probability of a dominant

interferer for systems without power control is between 64% to 77% and 58% to 87% for systems with power control at both portable and base station.

There is also a noticeable increase in the probability of a dominant adjacent channel interferer as the wall attenuation is increased from 10 dB to 20 dB. For systems without power control, the increase in the probability is mainly due to the decrease in co-channel interference as the wall attenuation increases. Since co-channel interferers are normally further away (especially true in systems with two radios per cell) and adjacent channel interferers from adjacent cells are much closer, an increase in wall attenuation can greatly decrease co-channel interference and has a smaller effect on adjacent channel interferers from adjacent cells. Traffic capacity shows a 25% increase in system capacity as the wall attenuation is changed from 10 dB to 20 dB. The increase in system traffic produces a higher probability of adjacent channels being used in adjacent cells, and the probability of a dominant adjacent channel interferer increases. For systems with portable and base station power control, there is another reason for the probability increase of a dominant adjacent channel interferer. Base station power control increases the probability of resource sharing between adjacent cells using adjacent channels. When this happens, both the local base station and the portable that is served by the adjacent base station are subject to adjacent channel interference from within the same cell boundary.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

High wall attenuation, characteristic of very high frequency operation (above 20 GHz), can provide very good cell isolation. This is especially true in a traditional office building with concrete interior walls where a base station has to be installed in each room and corridor. The system traffic capacity of such a system is mainly limited by adjacent channel interference from the portables within the same room. The interference can be reduced by having a wider frequency separation between adjacent channels since there is a greater amount of available spectrum above 20 GHz. It is also possible to reduce the interference effect by incorporating portable power control.

Simulation results from scenarios without radio resource limitation indicate that well-designed systems with high wall attenuation, portable power control, and low call setup SIR threshold can minimize the effects of both co-channel and adjacent channel interference and reach the Erlang B traffic capacity limit.

In general, power control at both portable and base station improves traffic capacity by reducing the amount of emitted interference.

In a highly radio resource limited system, radio resource sharing between adjacent cells accounts for a significant portion of the carried system capacity. Base station power control can enable a higher level of resource sharing by reducing adjacent channel interference to portables which are communicating with adjacent base stations.

The potential increase in system capacity due to a 100% increase in spectrum allocation can be substantially greater than 100% if the initial number of traffic channels is small. In the simulation, an increase from 32 to 64 traffic channels showed an average of 155% increase in system capacity.

For situations that require the best traffic capacity from a system with a limited number of frequency carriers, dynamic channel allocation is highly recommended over fixed frequency plans.

Simulation results show a high probability of a dominant interferer. In systems with low wall attenuation, the probability of a dominant co-channel interferer is higher. However, in systems with very good cell isolation, the probability of a dominant co-channel interferer is negligible, each call with overall SIR within 20 dB of SIR threshold either has a dominant adjacent channel interferer or receives strong interference from both adjacent channels. As a result, the main cause of a blocked or dropped call is due to a strong dominant interferer. Therefore, improvements in system performance with increased capacity and improved communications quality are expected by incorporating interference cancellation techniques.

The lack of radio resources in a system limits the ability to reuse frequency even though the interference environment allows greater frequency reuse. In a highly radio resource limited system with moderate cell isolation, the SIR of each call is excellent. As a result, if the system capacity requirement is low and the requirement can be satisfied by one radio per cell, a simple fixed frequency plan is sufficient.

For a more complete summary of all the observations, refer to Section 4.5 for the studies on traffic capacity and Section 5.7 for the studies on interference characteristics.

6.2 Recommendations for Future Research

High wall attenuation, one of the characteristics with operating frequency above 20 GHz, can provide very good cell isolation. This has been shown to be one of the major

factors that can greatly improve system traffic capacity. However, signal shadowing due to the human head may become a problem at these frequencies. As the user turns his head, the signal may experience a large fluctuations which is not desirable. A better understanding of the shadowing effects of the human body is necessary to ensure proper radio and system designs at these frequencies.

In a multi-tenant office building, it may not be practical to synchronize the transmission timing of each individual PBX system. As a result, some additional interference arises as the transmissions of one radio system overlap others. In TDD systems, portables of one system can interfere with portables of other systems and similarly base stations can interfere with base stations. It is valuable to assess the impact on traffic capacity and interference characteristics due to these additional interferences.

When a base station is communicating with a nearby portable, the base station can operate at a lower transmitter power setting. Simulation results have shown that base station power control can improve traffic capacity. However, if the same base station is currently serving a number of distant portables at full power, strong intermodulation products can be generated and affect the nearby portable. In fact, the closer the distance between the portable and the base station, the stronger the effect of intermodulation distortion. The base station has to operate at full power to maintain a satisfactory error performance at the nearby portable. The level of the intermodulation products is related to the "third order intercept" (TOI) parameter of the amplifier or mixer. It is important to understand the effects of intermodulation distortion on the system performance and ensure a proper design of the radio circuitry to minimize its impact on system traffic capacity.

Portable mobility is another area requiring study. In general, only a small number of portable users move from one place to the other. However, if the portable moves to a location that is directly under a base station, the portable can be affected by strong intermodulation distortion. If the intermodulation products are too strong and the call cannot be reassigned to another channel, the call is dropped. Similarly, a portable

transmitting a strong interfering signal at the base station affects the base station's ability to serve distant portables. Signal propagation measurements are also needed to obtain an accurate statistical model for signal shadowing as a portable is moving from one place to the other.

It is also important to study the combined effect of portable mobility and power control on system stability and traffic capacity. As a portable is moving away from its base station, the transmitter power has to be increased from the low power setting to the high power setting to compensate for the increased signal propagation loss. The sudden increase in the transmitter power affects all surrounding calls operating on the same channel or the adjacent channels. If a call cannot adjust to the increased interference, the call is dropped.

It is also useful to study the health effect of high frequency radio, and the data capacity of in-building wireless systems as opposed to voice capacity.

Appendix A Table of Simulation Results for Scenarios without Radio Resource Limitation

# of Slots per Carrier	Freq. Plan	Power Control	Wall Atten	SIR Thres	# of Active Calls when ended	Blocked Calls	Dropped Calls	Good Handovers	Avg # of Active Calls	GOS (%)
8	dynamic	none	10	21	111	4	1	164	109	0.14
8	dynamic	none	10	21	122	9	2	247	121	0.29
8	dynamic	none	10	21	143	23	4	344	136	0.63
8	dynamic	none	10	21	148	39	6	442	147	0.98
8	dynamic	none	10	21	166	71	22	558	158	2.80
8	dynamic	none	10	18	151	11	3	306	145	0.41
8	dynamic	none	10	18	165	24	4	419	158	0.64
8	dynamic	none	10	18	178	42	8	460	172	1.21
8	dynamic	none	10	18	186	67	26	610	184	3.25
8	dynamic	none	10	15	168	5	1	318	164	0.15
8	dynamic	none	10	15	177	9	2	397	176	0.29
8	dynamic	none	10	15	183	19	5	474	186	0.69
8	dynamic	none	10	15	196	34	8	510	197	1.13
8	dynamic	none	10	15	230	70	17	634	218	2.38
8	dynamic	none	10	12	201	8	3	389	200	0.38
8	dynamic	none	10	12	213	16	4	446	212	0.56
8	dynamic	none	10	12	216	24	8	497	225	1.03
8	dynamic	none	10	12	231	31	13	605	237	1.60
8	dynamic	none	10	12	254	49	18	651	249	2.27
8	dynamic	none	10	12	280	84	22	788	263	3.00
8	dynamic	none	20	21	223	9	1	137	218	0.19
8	dynamic	none	20	21	230	22	3	181	236	0.51
8	dynamic	none	20	21	257	41	5	235	256	0.90
8	dynamic	none	20	21	287	54	6	266	273	1.12
8	dynamic	none	20	18	280	20	2	206	276	0.39
8	dynamic	none	20	18	314	38	5	259	296	0.87
8	dynamic	none	20	18	325	68	6	268	315	1.25
8	dynamic	none	20	15	300	10	1	186	296	0.20
8	dynamic	none	20	15	325	17	2	198	316	0.36
8	dynamic	none	20	15	364	37	6	215	361	0.96
8	dynamic	none	20	15	383	52	10	276	368	1.50
8	dynamic	none	20	12	370	13	0	179	360	0.13
8	dynamic	none	20	12	393	19	3	201	380	0.48
8	dynamic	none	20	12	415	40	7	243	399	1.08
8	dynamic	none	20	12	452	75	16	287	421	2.31
8	dynamic	none	30	21	306	10	0	64	303	0.10
8	dynamic	none	30	21	333	14	0	69	321	0.14
8	dynamic	none	30	21	360	26	0	99	339	0.25
8	dynamic	none	30	21	379	33	3	111	363	0.62
8	dynamic	none	30	21	391	45	5	150	381	0.93
8	dynamic	none	30	21	429	85	13	194	397	2.11
8	dynamic	none	30	18	372	10	1	73	364	0.20
8	dynamic	none	30	18	401	25	2	72	382	0.44
8	dynamic	none	30	18	425	36	8	139	401	1.14
8	dynamic	none	30	18	446	64	7	172	416	1.31
8	dynamic	none	30	18	475	120	16	253	444	2.73
8	dynamic	none	30	15	397	12	1	69	388	0.22
8	dynamic	none	30	15	415	21	2	74	406	0.40
8	dynamic	none	30	15	460	32	4	148	425	0.70
8	dynamic	none	30	15	456	34	5	186	442	0.82
8	dynamic	none	30	15	478	61	8	221	461	1.38
8	dynamic	none	30	15	503	79	15	256	476	2.24

8	dynamic	none	30	12	453	19	2	148	449	0.38
8	dynamic	none	30	12	501	32	3	156	474	0.60
8	dynamic	none	30	12	518	46	6	202	490	1.03
8	dynamic	none	30	12	538	72	9	255	507	1.58
8	dynamic	none	30	12	553	68	14	294	525	2.04
8	dynamic	none	40	21	357	4	1	46	346	0.14
8	dynamic	none	40	21	376	6	2	69	364	0.26
8	dynamic	none	40	21	393	8	2	79	382	0.28
8	dynamic	none	40	21	413	25	3	133	400	0.54
8	dynamic	none	40	21	428	32	7	142	418	1.01
8	dynamic	none	40	21	460	47	14	229	436	1.84
8	dynamic	none	40	21	474	76	15	274	452	2.22
8	dynamic	none	40	18	440	25	3	165	436	0.54
8	dynamic	none	40	18	469	32	4	194	455	0.70
8	dynamic	none	40	18	495	38	10	255	472	1.36
8	dynamic	none	40	18	510	46	14	308	490	1.83
8	dynamic	none	40	15	502	17	4	211	486	0.56
8	dynamic	none	40	15	525	25	7	219	503	0.94
8	dynamic	none	40	15	546	27	9	288	522	1.15
8	dynamic	none	40	15	560	30	12	346	539	1.48
8	dynamic	none	40	12	547	15	1	201	518	0.24
8	dynamic	none	40	12	570	17	4	235	546	0.56
8	dynamic	none	40	12	598	26	6	320	570	0.84
8	dynamic	none	40	12	611	28	9	364	588	1.16
8	dynamic	none	40	12	636	27	14	392	606	1.65
8	dynamic	none	40	12	648	31	15	456	624	1.79
8	dynamic	none	40	12	665	37	24	479	641	2.74
8	dynamic	none	50	21	354	1	0	36	346	0.01
8	dynamic	none	50	21	379	1	0	49	365	0.01
8	dynamic	none	50	21	395	7	0	100	382	0.07
8	dynamic	none	50	21	406	13	3	104	400	0.42
8	dynamic	none	50	21	432	18	5	162	424	0.67
8	dynamic	none	50	21	456	28	7	229	442	0.97
8	dynamic	none	50	21	483	40	13	292	460	1.68
8	dynamic	none	50	18	463	8	2	224	459	0.28
8	dynamic	none	50	18	485	19	4	247	473	0.58
8	dynamic	none	50	18	510	25	11	312	491	1.34
8	dynamic	none	50	18	536	39	13	372	515	1.67
8	dynamic	none	50	15	483	7	0	211	486	0.07
8	dynamic	none	50	15	523	12	2	262	504	0.31
8	dynamic	none	50	15	539	17	3	278	522	0.46
8	dynamic	none	50	15	558	21	9	356	540	1.10
8	dynamic	none	50	15	586	31	17	420	569	1.99
8	dynamic	none	50	12	609	12	2	366	591	0.31
8	dynamic	none	50	12	631	21	4	374	609	0.60
8	dynamic	none	50	12	666	22	6	432	643	0.81
8	dynamic	none	50	12	723	40	12	566	686	1.57
8	dynamic	none	60	21	379	3	0	29	364	0.03
8	dynamic	none	60	21	396	7	1	80	382	0.17
8	dynamic	none	60	21	407	10	2	101	401	0.30
8	dynamic	none	60	21	433	22	4	173	424	0.61
8	dynamic	none	60	21	456	27	8	195	442	1.06
8	dynamic	none	60	21	481	38	14	290	460	1.76
8	dynamic	none	60	18	465	10	1	210	458	0.20
8	dynamic	none	60	18	508	24	3	191	475	0.53
8	dynamic	none	60	18	510	22	5	270	491	0.71
8	dynamic	none	60	18	534	43	8	346	514	1.21
8	dynamic	none	60	18	569	55	18	510	544	2.31
8	dynamic	none	60	15	491	7	2	192	486	0.27
8	dynamic	none	60	15	522	10	4	225	504	0.49
8	dynamic	none	60	15	561	23	5	322	540	0.72
8	dynamic	none	60	15	586	34	12	408	570	1.52
8	dynamic	none	60	12	618	16	3	300	590	0.45
8	dynamic	none	60	12	630	15	4	359	609	0.54

8	dynamic	none	60	12	655	21	5	420	626	0.70
8	dynamic	none	60	12	726	34	10	591	697	1.31
8	dynamic	none	60	12	757	68	16	569	724	2.22
4	dynamic	none	10	21	45	4	1	156	48	0.14
4	dynamic	none	10	21	58	29	3	303	60	0.59
4	dynamic	none	10	21	74	55	14	420	66	1.94
4	dynamic	none	10	21	68	98	25	460	72	3.55
4	dynamic	none	10	18	46	1	0	108	48	0.01
4	dynamic	none	10	18	62	9	3	215	61	0.39
4	dynamic	none	10	18	63	27	5	267	66	0.77
4	dynamic	none	10	18	74	34	13	332	72	1.63
4	dynamic	none	10	18	78	59	18	480	78	2.38
4	dynamic	none	10	15	54	0	0	89	55	0.00
4	dynamic	none	10	15	72	7	1	229	67	0.17
4	dynamic	none	10	15	68	10	3	233	72	0.40
4	dynamic	none	10	15	75	21	6	325	79	0.81
4	dynamic	none	10	15	98	31	19	392	84	2.20
4	dynamic	none	10	15	94	47	29	470	90	3.36
4	dynamic	none	10	15	105	118	43	637	101	5.43
4	dynamic	none	10	12	62	0	0	99	61	0.00
4	dynamic	none	10	12	80	3	1	184	73	0.13
4	dynamic	none	10	12	82	5	1	241	79	0.15
4	dynamic	none	10	12	85	15	1	277	86	0.25
4	dynamic	none	10	12	90	17	8	345	91	0.97
4	dynamic	none	10	12	107	33	16	526	103	1.92
4	dynamic	none	10	12	108	75	33	658	114	4.03
4	dynamic	none	20	21	83	7	1	96	85	0.17
4	dynamic	none	20	21	99	26	3	131	97	0.56
4	dynamic	none	20	21	109	42	3	158	103	0.71
4	dynamic	none	20	21	118	40	12	264	109	1.59
4	dynamic	none	20	2	120	55	22	257	115	2.73
4	dynamic	none	20	21	119	119	29	330	126	4.06
4	dynamic	none	20	21	144	169	34	405	137	5.02
4	dynamic	none	20	18	85	1	1	75	85	0.11
4	dynamic	none	20	18	97	14	1	87	97	0.24
4	dynamic	none	20	18	103	14	3	124	103	0.44
4	dynamic	none	20	18	117	17	6	159	109	0.77
4	dynamic	none	20	18	123	25	6	184	115	0.85
4	dynamic	none	20	18	118	27	12	236	121	1.46
4	dynamic	none	20	18	133	64	13	269	133	1.93
4	dynamic	none	20	18	135	93	21	309	144	3.00
4	dynamic	none	20	15	89	3	0	79	91	0.03
4	dynamic	none	20	15	102	4	0	115	103	0.04
4	dynamic	none	20	15	100	1	2	104	108	0.31
4	dynamic	none	20	15	120	14	2	151	115	0.34
4	dynamic	none	20	15	138	9	5	175	121	0.59
4	dynamic	none	20	15	140	18	7	181	127	0.88
4	dynamic	none	20	15	144	37	10	243	139	1.36
4	dynamic	none	20	15	151	45	18	284	151	2.24
4	dynamic	none	20	12	95	1	0	61	97	0.01
4	dynamic	none	20	12	111	1	0	112	109	0.01
4	dynamic	none	20	12	117	2	1	85	115	0.12
4	dynamic	none	20	12	122	4	4	107	121	0.44
4	dynamic	none	20	12	129	6	1	158	127	0.16
4	dynamic	none	20	12	145	6	4	144	133	0.46
4	dynamic	none	20	12	134	10	3	171	140	0.40
4	dynamic	none	20	12	152	16	5	176	146	0.66
4	dynamic	none	20	12	160	21	4	194	152	0.61
4	dynamic	none	20	12	171	35	12	234	163	1.54
4	dynamic	none	20	12	169	50	15	279	175	1.99
4	dynamic	none	30	21	134	21	2	104	121	0.41
4	dynamic	none	30	21	135	35	3	128	133	0.65
4	dynamic	none	30	21	145	42	8	143	139	1.21
4	dynamic	none	30	21	149	45	11	138	145	1.54

4	dynamic	none	30	21	151	72	19	180	156	2.60
4	dynamic	none	30	18	120	7	2	60	121	0.27
4	dynamic	none	30	18	142	16	1	72	133	0.26
4	dynamic	none	30	18	147	18	1	102	139	0.28
4	dynamic	none	30	18	150	20	5	121	145	0.70
4	dynamic	none	30	18	156	25	5	109	151	0.75
4	dynamic	none	30	18	162	30	12	153	157	1.49
4	dynamic	none	30	18	168	54	13	176	169	1.83
4	dynamic	none	30	18	183	73	32	189	180	3.90
4	dynamic	none	30	15	127	3	0	43	127	0.03
4	dynamic	none	30	15	147	10	1	75	139	0.20
4	dynamic	none	30	15	151	5	1	71	144	0.15
4	dynamic	none	30	15	155	11	1	80	152	0.21
4	dynamic	none	30	15	159	15	4	88	157	0.56
4	dynamic	none	30	15	169	15	1	93	164	0.25
4	dynamic	none	30	15	174	26	4	127	175	0.65
4	dynamic	none	30	15	188	41	10	141	187	1.40
4	dynamic	none	30	15	196	60	13	201	199	1.88
4	dynamic	none	30	15	224	80	19	269	211	2.67
4	dynamic	none	30	12	137	2	1	29	133	0.12
4	dynamic	none	30	12	158	1	0	47	146	0.01
4	dynamic	none	30	12	159	3	1	48	152	0.13
4	dynamic	none	30	12	165	3	1	53	158	0.13
4	dynamic	none	30	12	169	7	1	61	164	0.17
4	dynamic	none	30	12	178	10	0	60	176	0.10
4	dynamic	none	30	12	190	11	4	109	188	0.51
4	dynamic	none	30	12	205	23	7	141	200	0.92
4	dynamic	none	30	12	208	37	13	166	212	1.66
4	dynamic	none	30	12	217	49	13	208	224	1.78
4	dynamic	none	40	21	140	12	2	67	133	0.32
4	dynamic	none	40	21	156	18	3	77	145	0.48
4	dynamic	none	40	21	156	21	5	118	157	0.71
4	dynamic	none	40	21	176	39	9	159	169	1.28
4	dynamic	none	40	21	205	76	28	240	192	3.53
4	dynamic	none	40	18	151	8	2	48	146	0.28
4	dynamic	none	40	18	172	22	4	97	170	0.62
4	dynamic	none	40	18	185	27	8	101	181	1.06
4	dynamic	none	40	18	186	36	21	150	193	2.44
4	dynamic	none	40	18	200	49	17	204	206	2.17
4	dynamic	none	40	15	181	14	2	64	176	0.34
4	dynamic	none	40	15	189	15	3	103	188	0.45
4	dynamic	none	40	15	197	19	3	112	200	0.49
4	dynamic	none	40	15	210	26	12	163	212	1.45
4	dynamic	none	40	15	233	40	18	248	230	2.19
4	dynamic	none	40	12	209	7	1	101	206	0.17
4	dynamic	none	40	12	217	10	0	114	218	0.10
4	dynamic	none	40	12	252	15	4	177	231	0.55
4	dynamic	none	40	12	238	23	5	217	242	0.72
4	dynamic	none	40	12	256	38	13	266	260	1.67
4	dynamic	none	50	21	151	11	4	58	145	0.51
4	dynamic	none	50	21	159	16	5	96	157	0.66
4	dynamic	none	50	21	170	24	8	118	169	1.03
4	dynamic	none	50	21	183	32	14	174	181	1.71
4	dynamic	none	50	21	189	52	22	217	193	2.70
4	dynamic	none	50	18	166	9	2	55	158	0.29
4	dynamic	none	50	18	176	11	3	89	170	0.41
4	dynamic	none	50	18	177	17	7	100	182	0.87
4	dynamic	none	50	18	206	29	16	169	194	1.88
4	dynamic	none	50	18	214	47	17	224	206	2.15
4	dynamic	none	50	18	220	61	24	268	218	2.99
4	dynamic	none	50	18	257	92	36	407	240	4.37
4	dynamic	none	50	15	175	4	0	40	170	0.04
4	dynamic	none	50	15	185	9	2	79	182	0.13
4	dynamic	none	50	15	199	7	1	104	194	0.7

4	dynamic	none	50	15	212	15	7	145	206	0.85
4	dynamic	none	50	15	233	38	9	217	219	1.17
4	dynamic	none	50	15	236	41	13	313	242	1.70
4	dynamic	none	50	12	227	7	3	125	219	0.37
4	dynamic	none	50	12	250	15	5	162	231	0.66
4	dynamic	none	50	12	236	22	4	207	242	0.61
4	dynamic	none	50	12	250	26	9	252	254	1.15
4	dynamic	none	50	12	269	30	13	306	266	1.59
4	dynamic	none	50	12	290	37	18	387	290	2.15
4	dynamic	none	60	21	151	8	3	51	146	0.38
4	dynamic	none	60	21	158	16	6	83	157	0.76
4	dynamic	none	60	21	170	24	7	114	170	0.93
4	dynamic	none	60	21	182	33	14	139	181	1.72
4	dynamic	none	60	21	189	38	19	231	193	2.27
4	dynamic	none	60	18	163	9	2	66	158	0.29
4	dynamic	none	60	18	174	8	3	75	170	0.38
4	dynamic	none	60	18	181	17	3	106	182	0.47
4	dynamic	none	60	18	199	23	13	126	194	1.52
4	dynamic	none	60	18	200	35	18	210	205	2.14
4	dynamic	none	60	18	222	51	18	266	217	2.29
4	dynamic	none	60	18	247	81	29	375	241	3.67
4	dynamic	none	60	15	175	6	0	52	170	0.06
4	dynamic	none	60	15	187	10	0	75	182	0.10
4	dynamic	none	60	15	196	12	3	88	194	0.42
4	dynamic	none	60	15	203	14	5	130	206	0.64
4	dynamic	none	60	15	211	20	11	188	218	1.29
4	dynamic	none	60	15	239	48	16	280	242	2.06
4	dynamic	none	60	12	227	9	1	124	219	0.19
4	dynamic	none	60	12	246	12	5	160	231	0.62
4	dynamic	none	60	12	255	20	7	208	243	0.89
4	dynamic	none	60	12	261	27	7	228	255	0.96
4	dynamic	none	60	12	270	44	13	249	267	1.72
4	dynamic	none	60	12	299	58	17	392	291	2.26
4	dynamic	none	60	12	316	92	20	384	302	2.88
4	dynamic	portable	10	21	59	18	5	682	61	0.68
4	dynamic	portable	10	21	73	57	29	1132	72	3.45
4	dynamic	portable	10	21	91	129	57	1600	82	6.92
4	dynamic	portable	10	18	69	10	4	571	67	0.50
4	dynamic	portable	10	18	87	44	14	971	80	1.83
4	dynamic	portable	10	18	83	104	46	1490	92	5.60
4	dynamic	portable	10	15	79	7	4	565	78	0.47
4	dynamic	portable	10	15	93	42	19	1151	96	2.31
4	dynamic	portable	10	15	113	114	41	1564	109	5.19
4	dynamic	portable	10	12	93	8	2	578	90	0.21
4	dynamic	portable	10	12	107	37	19	1142	112	2.26
4	dynamic	portable	10	12	139	105	48	1628	130	5.80
4	dynamic	portable	20	21	104	9	3	313	103	0.39
4	dynamic	portable	20	21	120	34	8	563	121	1.13
4	dynamic	portable	20	21	128	74	21	829	138	2.82
4	dynamic	portable	20	18	119	5	1	256	115	0.15
4	dynamic	portable	20	18	139	24	13	480	136	1.53
4	dynamic	portable	20	18	148	62	19	642	154	2.50
4	dynamic	portable	20	15	142	10	4	232	128	0.50
4	dynamic	portable	20	15	158	40	7	424	156	1.09
4	dynamic	portable	20	15	192	103	23	683	183	3.29
4	dynamic	portable	20	12	160	13	4	286	154	0.53
4	dynamic	portable	20	12	175	49	12	423	180	1.68
4	dynamic	portable	20	12	213	103	29	701	204	3.89
4	dynamic	portable	30	21	147	7	3	239	137	0.37
4	dynamic	portable	30	21	157	22	6	396	157	0.82
4	dynamic	portable	30	21	175	37	16	586	178	1.96
4	dynamic	portable	30	18	145	3	2	146	151	0.23
4	dynamic	portable	30	18	180	27	5	253	180	0.76
4	dynamic	portable	30	18	207	62	23	542	209	2.90

4	dynamic	portable	30	15	181	8	2	125	178	0.28
4	dynamic	portable	30	15	200	18	7	232	204	0.88
4	dynamic	portable	30	15	230	55	17	440	229	2.24
4	dynamic	portable	30	12	199	9	4	93	198	0.49
4	dynamic	portable	30	12	224	21	10	209	229	1.20
4	dynamic	portable	30	12	265	47	20	346	258	2.45
4	dynamic	portable	40	21	166	7	1	206	161	0.17
4	dynamic	portable	40	21	189	8	6	395	185	0.68
4	dynamic	portable	40	21	205	29	13	720	208	1.58
4	dynamic	portable	40	15	184	3	1	97	178	0.13
4	dynamic	portable	40	18	213	10	1	219	213	0.20
4	dynamic	portable	40	18	245	30	10	498	247	1.29
4	dynamic	portable	40	15	209	2	0	76	204	0.02
4	dynamic	portable	40	15	249	7	2	183	250	0.27
4	dynamic	portable	40	15	308	20	4	415	294	0.59
4	dynamic	portable	40	15	344	68	15	555	331	2.15
4	dynamic	portable	40	12	244	2	1	69	245	0.12
4	dynamic	portable	40	12	297	9	4	127	288	0.49
4	dynamic	portable	40	12	338	39	7	181	329	1.08
4	dynamic	portable	50	21	171	2	0	196	166	0.02
4	dynamic	portable	50	21	198	1	1	353	192	0.11
4	dynamic	portable	50	21	222	13	6	689	218	0.73
4	dynamic	portable	50	21	235	25	14	1159	242	1.64
4	dynamic	portable	50	18	185	1	0	53	181	0.01
4	dynamic	portable	50	18	233	2	0	256	236	0.02
4	dynamic	portable	50	18	299	19	9	653	290	1.08
4	dynamic	portable	50	15	215	0	0	65	208	0.00
4	dynamic	portable	50	15	267	3	1	213	270	0.13
4	dynamic	portable	50	15	336	47	3	455	330	0.75
4	dynamic	portable	50	15	376	126	9	507	359	2.10
4	dynamic	portable	50	12	247	0	0	57	248	0.00
4	dynamic	portable	50	12	304	3	0	93	299	0.03
4	dynamic	portable	50	12	354	71	0	160	347	0.68
4	dynamic	portable	50	12	395	209	2	177	375	2.17
4	dynamic	portable	60	21	173	1	1	186	168	0.11
4	dynamic	portable	60	21	226	10	4	814	222	0.50
4	dynamic	portable	60	21	199	1	6	441	195	0.61
4	dynamic	portable	60	21	262	37	29	1485	260	3.25
4	dynamic	portable	60	18	192	1	0	57	185	0.01
4	dynamic	portable	60	18	234	2	0	278	237	0.02
4	dynamic	portable	60	18	302	19	10	648	288	1.18
4	dynamic	portable	60	15	215	0	0	68	210	0.00
4	dynamic	portable	60	15	269	2	1	228	273	0.12
4	dynamic	portable	60	15	339	47	4	445	333	0.85
4	dynamic	portable	60	15	376	130	4	520	359	1.64
4	dynamic	portable	60	12	249	0	0	62	253	0.00
4	dynamic	portable	60	12	307	3	0	90	300	0.03
4	dynamic	portable	60	12	353	69	0	136	346	0.66
4	dynamic	portable	60	12	394	210	2	193	375	2.18
4	dynamic	both	10	21	78	8	0	3858	73	0.08
4	dynamic	both	10	21	75	22	2	4619	79	0.42
4	dynamic	both	10	21	98	35	6	5209	85	0.94
4	dynamic	both	10	21	84	88	22	5756	90	3.06
4	dynamic	both	10	18	84	6	0	4050	85	0.06
4	dynamic	both	10	18	95	9	2	4723	91	0.29
4	dynamic	both	10	18	108	20	11	5247	97	1.37
4	dynamic	both	10	18	106	52	18	5706	102	2.31
4	dynamic	both	10	15	103	5	0	4640	103	0.05
4	dynamic	both	10	15	114	11	7	5051	109	0.81
4	dynamic	both	10	15	124	24	9	5673	115	1.14
4	dynamic	both	10	15	122	87	31	6404	126	3.94
4	dynamic	both	10	12	122	3	1	4940	121	0.13
4	dynamic	both	10	12	142	17	7	5852	133	0.87
4	dynamic	both	10	12	141	56	25	6489	145	3.04

4	dynamic	both	10	12	164	108	54	6969	156	6.42
4	dynamic	both	20	21	128	6	2	2448	127	0.26
4	dynamic	both	20	21	146	15	7	3156	139	0.85
4	dynamic	both	20	21	157	32	14	4019	151	1.71
4	dynamic	both	20	18	150	4	2	2497	39	0.24
4	dynamic	both	20	18	156	7	4	3214	152	0.47
4	dynamic	both	20	18	166	24	14	4293	163	1.63
4	dynamic	both	20	15	170	6	1	3116	164	0.16
4	dynamic	both	20	15	190	34	6	4450	188	0.93
4	dynamic	both	20	15	213	94	30	5220	204	3.90
4	dynamic	both	20	12	200	7	0	3963	194	0.07
4	dynamic	both	20	12	203	16	5	4522	206	0.66
4	dynamic	both	20	12	211	42	15	5020	218	1.91
4	dynamic	both	30	21	177	18	4	2598	176	0.58
4	dynamic	both	30	21	187	36	12	3634	187	1.54
4	dynamic	both	30	21	206	59	24	4034	199	2.97
4	dynamic	both	30	18	192	10	2	2493	188	0.30
4	dynamic	both	30	18	198	10	4	2887	200	0.50
4	dynamic	both	30	18	208	28	7	3627	212	0.97
4	dynamic	both	30	18	238	74	36	4371	228	4.20
4	dynamic	both	30	15	226	9	3	3417	224	0.39
4	dynamic	both	30	15	229	17	10	3746	236	1.16
4	dynamic	both	30	15	245	34	20	4107	248	2.33
4	dynamic	both	30	12	238	5	3	3189	243	0.36
4	dynamic	both	30	12	267	15	5	3414	256	0.66
4	dynamic	both	30	12	270	16	10	3672	266	1.15
4	dynamic	both	40	21	198	15	4	2215	200	0.56
4	dynamic	both	40	21	208	18	8	2619	212	0.98
4	dynamic	both	40	21	242	59	23	3818	236	2.87
4	dynamic	both	40	18	226	11	0	2143	222	0.11
4	dynamic	both	40	18	245	16	6	2860	248	0.76
4	dynamic	both	40	18	270	41	21	3616	272	2.49
4	dynamic	both	40	15	266	5	1	2774	267	0.15
4	dynamic	both	40	15	298	13	6	3043	291	0.73
4	dynamic	both	40	15	325	40	12	2981	315	1.58
4	dynamic	both	40	12	280	4	1	2542	279	0.14
4	dynamic	both	40	12	308	10	3	2602	303	0.40
4	dynamic	both	40	12	336	39	2	2492	327	0.58
4	dynamic	both	40	12	372	89	10	2241	349	1.85
4	dynamic	both	40	12	394	189	11	1999	370	2.88
4	dynamic	both	50	21	199	3	0	1184	194	0.03
4	dynamic	both	50	21	221	14	7	1994	218	0.84
4	dynamic	both	50	21	236	36	17	3004	242	2.06
4	dynamic	both	50	21	259	48	26	3222	253	3.06
4	dynamic	both	50	21	291	114	44	3677	276	5.47
4	dynamic	both	50	18	267	14	3	2387	267	0.44
4	dynamic	both	50	18	303	27	5	2845	291	0.76
4	dynamic	both	50	18	323	53	25	2869	313	3.00
4	dynamic	both	50	15	319	15	2	2512	309	0.36
4	dynamic	both	50	15	338	43	5	2384	332	0.91
4	dynamic	both	50	15	382	2	6	2220	364	1.67
4	dynamic	both	50	12	330	3	1	2256	321	0.32
4	dynamic	both	50	12	344	60	0	2136	344	0.58
4	dynamic	both	50	12	384	142	2	1778	366	1.56
4	dynamic	both	50	12	400	285	1	1512	386	2.77
4	dynamic	both	50	12	423	448	3	1369	401	4.42
4	dynamic	both	60	21	207	7	0	1466	206	0.07
4	dynamic	both	60	21	222	18	11	2087	230	1.27
4	dynamic	both	60	21	262	37	21	2887	254	2.45
4	dynamic	both	60	18	242	2	0	1726	243	0.02
4	dynamic	both	60	18	266	10	3	2137	267	0.40
4	dynamic	both	60	18	303	22	7	2564	291	0.91
4	dynamic	both	60	18	317	51	19	2618	314	2.39
4	dynamic	both	60	15	318	11	0	2226	303	0.11

4	dynamic	both	60	15	335	37	5	2227	327	0.86
4	dynamic	both	60	15	344	52	5	2247	338	1.00
4	dynamic	both	60	15	373	97	4	2117	349	1.33
4	dynamic	both	60	15	395	185	7	2006	370	2.45
4	dynamic	both	60	15	397	318	8	1843	398	3.76
4	dynamic	both	60	12	323	14	0	2042	315	0.14
4	dynamic	both	60	12	344	48	1	2017	339	0.56
4	dynamic	both	60	12	365	81	1	1934	349	0.88
4	dynamic	both	60	12	379	117	1	1820	360	1.21
4	dynamic	both	60	12	384	250	3	1584	380	2.65
4	dynamic	both	60	12	416	390	3	1335	397	3.91
4	dynamic	both	60	12	427	621	0	1121	413	5.62
4	dynamic	both	60	12	417	817	5	995	427	7.77

Appendix B Table of Simulation Results for Scenarios with Two Radios per Cell

# of Slots per Carrier	Freq Plan	Power Control	Wall Atten	SIR Thres	# of Active Calls when ended	Blocked Calls	Dropped Calls	Good Handovers	Avg # of Active Calls	GOS (%)
8	dynamic	none	10	21	62	0	0	10	61	0.00
8	dynamic	none	10	21	89	1	0	75	91	0.01
8	dynamic	none	10	21	106	6	0	169	106	0.06
8	dynamic	none	10	21	136	22	2	254	121	0.42
8	dynamic	none	10	21	158	122	13	482	150	2.48
8	dynamic	none	10	21	175	401	56	822	175	9.34
8	dynamic	none	10	18	62	0	0	9	61	0.00
8	dynamic	none	10	16	90	0	0	52	91	0.00
8	dynamic	none	10	18	123	10	1	183	121	0.20
8	dynamic	none	10	18	145	21	2	291	136	0.41
8	dynamic	none	10	18	155	59	3	370	151	0.68
8	dynamic	none	10	18	183	225	31	681	178	5.25
8	dynamic	none	10	15	62	0	0	4	61	0.00
8	dynamic	none	10	15	90	0	0	43	91	0.00
8	dynamic	none	10	15	120	2	0	136	121	0.02
8	dynamic	none	10	15	155	34	0	299	151	0.33
8	dynamic	none	10	15	167	57	5	304	166	1.06
8	dynamic	none	10	15	185	134	8	531	180	2.10
8	dynamic	none	10	12	62	0	0	4	61	0.00
8	dynamic	none	10	12	90	0	0	21	91	0.00
8	dynamic	none	10	12	120	3	0	84	121	0.03
8	dynamic	none	10	12	157	9	0	170	152	0.09
8	dynamic	none	10	12	177	77	5	383	181	1.25
8	dynamic	none	10	12	200	184	9	552	194	2.67
8	dynamic	none	10	12	212	340	13	652	206	4.52
8	dynamic	none	10	12	219	910	53	899	222	13.41
8	dynamic	none	20	21	62	0	0	0	61	0.00
8	dynamic	none	20	21	90	0	0	5	91	0.00
8	dynamic	none	20	21	123	5	0	22	121	0.05
8	dynamic	none	20	21	158	32	0	71	151	0.31
8	dynamic	none	20	21	187	164	7	151	179	2.28
8	dynamic	none	20	21	215	550	8	336	202	5.90
8	dynamic	none	20	18	62	0	0	0	61	0.00
8	dynamic	none	20	18	90	0	0	1	91	0.00
8	dynamic	none	20	18	123	5	0	13	121	0.05
8	dynamic	none	20	18	153	30	0	62	151	0.29
8	dynamic	none	20	18	166	62	2	107	166	0.81
8	dynamic	none	20	18	184	136	5	161	179	1.81
8	dynamic	none	20	18	210	435	10	324	204	5.08
8	dynamic	none	20	18	203	1112	25	490	218	12.30
8	dynamic	none	20	15	62	0	0	0	61	0.00
8	dynamic	none	20	15	90	0	0	4	91	0.00
8	dynamic	none	20	15	122	0	0	19	121	0.00
8	dynamic	none	20	15	155	13	2	51	152	0.33
8	dynamic	none	20	15	174	46	3	97	166	0.74
8	dynamic	none	20	15	186	96	2	159	180	1.13
8	dynamic	none	20	15	209	376	7	337	206	4.25
8	dynamic	none	20	15	210	978	23	508	222	11.02
8	dynamic	none	20	12	62	0	0	0	61	0.00
8	dynamic	none	20	12	90	0	0	2	91	0.00
8	dynamic	none	20	12	121	1	0	14	121	0.01
8	dynamic	none	20	12	156	9	0	62	152	0.09
8	dynamic	none	20	12	177	54	2	149	181	0.73
8	dynamic	none	20	12	214	294	10	273	206	3.79

8	dynamic	none	20	12	202	873	13	561	224	9.17
8	dynamic	none	20	12	230	1720	36	742	233	17.84
8	dynamic	none	30	21	123	4	1	7	121	0.14
8	dynamic	none	30	21	155	53	0	49	151	5.32
8	dynamic	none	30	21	185	169	1	132	179	1.73
8	dynamic	none	30	21	202	541	11	311	203	6.13
8	dynamic	none	30	21	213	1161	24	420	218	12.58
8	dynamic	none	30	18	122	1	0	10	121	0.01
8	dynamic	none	30	18	154	22	0	38	151	0.22
8	dynamic	none	30	18	182	131	0	142	180	1.27
8	dynamic	none	30	18	207	446	13	298	204	5.48
8	dynamic	none	30	18	211	1089	29	486	219	12.50
8	dynamic	none	30	15	120	3	0	15	121	0.03
8	dynamic	none	30	15	156	20	0	52	151	0.20
8	dynamic	none	30	15	187	98	1	149	180	1.06
8	dynamic	none	30	15	211	375	8	294	205	4.34
8	dynamic	none	30	15	210	991	27	479	221	11.52
8	dynamic	none	30	12	122	1	0	13	121	0.01
8	dynamic	none	30	12	156	13	0	44	152	0.13
8	dynamic	none	30	12	176	81	3	124	180	1.09
8	dynamic	none	30	12	216	315	7	319	206	3.69
8	dynamic	none	30	12	213	917	22	517	223	10.42
8	dynamic	none	40	21	123	5	0	8	121	0.05
8	dynamic	none	40	21	159	35	2	38	151	0.54
8	dynamic	none	40	21	185	162	4	116	179	1.96
8	dynamic	none	40	21	201	527	14	296	203	6.30
8	dynamic	none	40	21	205	1203	39	370	217	14.39
8	dynamic	none	40	18	121	4	0	10	121	0.04
8	dynamic	none	40	18	155	27	1	38	151	0.37
8	dynamic	none	40	18	186	135	3	142	180	1.61
8	dynamic	none	40	18	209	500	14	294	204	6.06
8	dynamic	none	40	18	208	1123	25	395	218	12.38
8	dynamic	none	40	15	122	1	0	9	121	0.01
8	dynamic	none	40	15	156	17	0	36	152	0.17
8	dynamic	none	40	15	190	109	3	143	180	1.36
8	dynamic	none	40	15	218	423	14	327	204	5.37
8	dynamic	none	40	15	200	1043	21	443	220	11.36
8	dynamic	none	40	12	121	2	0	9	121	0.02
8	dynamic	none	40	12	159	15	0	41	152	0.15
8	dynamic	none	40	12	178	79	5	122	180	1.27
8	dynamic	none	40	12	212	376	7	306	206	4.25
8	dynamic	none	40	12	205	960	17	504	222	10.28
8	dynamic	none	50	21	137	10	0	8	121	0.10
8	dynamic	none	50	21	145	74	1	30	151	0.82
8	dynamic	none	50	21	184	249	4	93	178	2.79
8	dynamic	none	50	21	182	687	10	174	199	7.31
8	dynamic	none	50	21	229	1425	15	232	214	13.71
8	dynamic	none	50	18	120	8	0	11	121	0.08
8	dynamic	none	50	18	158	53	3	37	151	0.82
8	dynamic	none	50	18	187	196	3	114	179	2.19
8	dynamic	none	50	18	208	568	17	206	202	6.96
8	dynamic	none	50	18	217	1285	17	313	216	12.85
8	dynamic	none	50	15	120	2	0	12	121	0.02
8	dynamic	none	50	15	153	29	0	44	151	0.28
8	dynamic	none	50	15	182	149	5	111	179	1.94
8	dynamic	none	50	15	203	467	8	221	204	5.17
8	dynamic	none	50	15	209	1127	15	335	218	11.43
8	dynamic	none	50	12	123	0	0	8	121	0.00
8	dynamic	none	50	12	155	19	0	39	152	0.19
8	dynamic	none	50	12	189	104	2	134	180	1.21
8	dynamic	none	50	12	204	391	9	276	205	4.59
8	dynamic	none	50	12	201	1012	21	382	221	11.10
8	dynamic	none	60	21	131	26	0	1	121	0.26
8	dynamic	none	60	21	154	142	0	1	150	1.38

8	dynamic	none	60	21	178	427	1	7	175	4.13
8	dynamic	none	60	21	189	933	0	43	196	8.39
8	dynamic	none	60	21	219	1674	4	59	209	14.47
8	dynamic	none	60	18	133	19	0	4	121	0.19
8	dynamic	none	60	18	151	124	0	9	150	1.21
8	dynamic	none	60	18	177	363	2	42	176	3.92
8	dynamic	none	60	18	181	869	2	64	196	8.06
8	dynamic	none	60	18	212	1588	7	96	210	14.15
8	dynamic	none	60	15	136	13	0	3	121	0.13
8	dynamic	none	60	15	143	102	0	18	150	1.00
8	dynamic	none	60	15	189	322	5	64	177	3.56
8	dynamic	none	60	15	184	758	5	108	198	7.42
8	dynamic	none	60	15	214	1469	6	158	213	13.17
8	dynamic	none	60	12	136	9	0	8	121	0.09
8	dynamic	none	60	12	147	73	0	25	151	0.71
8	dynamic	none	60	12	185	250	1	83	178	2.50
8	dynamic	none	60	12	213	609	5	149	201	6.52
8	dynamic	none	60	12	212	1320	8	222	215	12.24
8	dynamic	portable	10	21	62	0	0	11	61	0.00
8	dynamic	portable	10	21	90	0	0	136	91	0.00
8	dynamic	portable	10	21	108	3	0	268	106	0.03
8	dynamic	portable	10	21	120	9	0	467	121	0.09
8	dynamic	portable	10	21	143	75	9	1082	151	1.63
8	dynamic	portable	10	21	189	311	37	1806	176	6.64
8	dynamic	portable	10	18	62	0	0	11	61	0.00
8	dynamic	portable	10	18	90	0	0	69	91	0.00
8	dynamic	portable	10	18	123	3	1	278	121	0.13
8	dynamic	portable	10	18	144	11	1	488	136	0.21
8	dynamic	portable	10	18	153	46	2	723	151	0.65
8	dynamic	portable	10	18	189	177	15	1336	179	3.20
8	dynamic	portable	10	18	211	546	50	1867	201	10.03
8	dynamic	portable	10	15	62	0	0	2	61	0.00
8	dynamic	portable	10	15	90	0	0	56	91	0.00
8	dynamic	portable	10	15	121	2	0	192	121	0.02
8	dynamic	portable	10	15	157	15	2	438	152	0.36
8	dynamic	portable	10	15	174	42	3	681	166	0.71
8	dynamic	portable	10	15	191	90	5	902	180	1.37
8	dynamic	portable	10	15	197	206	11	1204	193	3.08
8	dynamic	portable	10	15	207	393	16	1490	206	5.30
8	dynamic	portable	10	12	62	0	0	0	61	0.00
8	dynamic	portable	10	12	90	0	0	38	91	0.00
8	dynamic	portable	10	12	123	0	0	101	121	0.00
8	dynamic	portable	10	12	158	4	1	318	152	0.14
8	dynamic	portable	10	12	178	52	1	616	181	0.61
8	dynamic	portable	10	12	200	140	4	903	196	1.75
8	dynamic	portable	10	12	219	278	9	1065	207	3.56
8	dynamic	portable	10	12	191	881	19	1482	224	9.84
8	dynamic	portable	20	21	106	0	0	10	106	0.00
8	dynamic	portable	20	21	123	5	0	22	121	0.06
8	dynamic	portable	20	21	147	7	0	50	136	0.07
8	dynamic	portable	20	21	156	25	2	100	151	0.45
8	dynamic	portable	20	21	183	126	1	242	180	1.32
8	dynamic	portable	20	21	210	432	9	444	204	4.96
8	dynamic	portable	20	18	120	3	0	17	121	0.03
8	dynamic	portable	20	18	156	18	0	72	151	0.18
8	dynamic	portable	20	18	167	34	1	113	166	0.43
8	dynamic	portable	20	18	173	51	2	128	169	0.70
8	dynamic	portable	20	18	190	92	2	179	180	1.09
8	dynamic	portable	20	18	214	369	7	366	206	4.18
8	dynamic	portable	20	18	198	1010	24	602	221	11.39
8	dynamic	portable	20	15	123	0	0	14	121	0.00
8	dynamic	portable	20	15	156	8	0	74	152	0.08
8	dynamic	portable	20	15	168	23	1	116	167	0.33
8	dynamic	portable	20	15	179	56	4	206	181	0.94

8	dynamic	portable	20	15	216	288	7	436	207	3.44
8	dynamic	portable	20	15	199	868	15	668	223	9.33
8	dynamic	portable	20	12	123	0	0	13	121	0.00
8	dynamic	portable	20	12	158	1	2	42	152	0.21
8	dynamic	portable	20	12	188	36	1	157	181	0.45
8	dynamic	portable	20	12	220	228	7	341	208	2.88
8	dynamic	portable	20	12	212	781	15	682	226	8.59
8	dynamic	portable	20	12	249	1631	46	906	236	18.25
8	dynamic	portable	30	21	122	1	0	5	121	0.01
8	dynamic	portable	30	21	154	23	1	40	151	0.33
8	dynamic	portable	30	21	184	127	2	153	180	1.43
8	dynamic	portable	30	21	211	454	8	293	204	5.06
8	dynamic	portable	30	21	208	1108	27	486	219	12.47
8	dynamic	portable	30	18	123	0	0	8	121	0.00
8	dynamic	portable	30	18	156	17	0	44	151	0.17
8	dynamic	portable	30	18	187	107	4	139	180	1.44
8	dynamic	portable	30	18	213	394	14	368	206	5.11
8	dynamic	portable	30	18	204	1019	27	481	221	11.75
8	dynamic	portable	30	15	123	0	0	7	121	0.00
8	dynamic	portable	30	15	157	7	0	51	152	0.07
8	dynamic	portable	30	15	175	64	4	155	180	1.02
8	dynamic	portable	30	15	216	309	10	376	206	3.93
8	dynamic	portable	30	15	213	940	20	565	223	10.41
8	dynamic	portable	30	12	123	0	0	8	121	0.00
8	dynamic	portable	30	12	158	6	1	46	152	0.16
8	dynamic	portable	30	12	177	54	1	152	181	0.63
8	dynamic	portable	30	12	214	253	4	386	208	2.82
8	dynamic	portable	30	12	213	834	20	566	225	9.53
8	dynamic	portable	40	21	122	5	1	4	121	0.15
8	dynamic	portable	40	21	156	31	1	40	151	0.40
8	dynamic	portable	40	21	181	140	6	128	180	1.96
8	dynamic	portable	40	21	207	481	11	280	204	5.59
8	dynamic	portable	40	21	213	1144	27	424	218	12.74
8	dynamic	portable	40	18	121	2	0	10	121	0.02
8	dynamic	portable	40	18	158	19	2	47	152	0.39
8	dynamic	portable	40	18	190	113	2	154	180	1.30
8	dynamic	portable	40	18	214	449	14	313	206	5.60
8	dynamic	portable	40	18	206	1066	33	442	220	12.72
8	dynamic	portable	40	15	122	1	0	8	121	0.01
8	dynamic	portable	40	15	156	9	2	44	152	0.29
8	dynamic	portable	40	15	185	90	5	133	180	1.38
8	dynamic	portable	40	15	212	376	19	330	206	5.44
8	dynamic	portable	40	15	207	981	26	543	222	11.34
8	dynamic	portable	40	12	123	0	0	5	121	0.00
8	dynamic	portable	40	12	156	10	0	52	152	0.10
8	dynamic	portable	40	12	175	66	1	149	181	0.73
8	dynamic	portable	40	12	213	311	10	327	206	3.96
8	dynamic	portable	40	12	217	915	21	527	223	10.30
8	dynamic	portable	50	21	90	0	0	1	91	0.00
8	dynamic	portable	50	21	137	8	0	5	121	0.08
8	dynamic	portable	50	21	128	11	0	4	123	0.11
8	dynamic	portable	50	21	143	27	0	20	136	0.27
8	dynamic	portable	50	21	150	67	0	28	151	0.66
8	dynamic	portable	50	21	186	250	1	98	178	2.50
8	dynamic	portable	50	21	186	656	7	158	200	6.75
8	dynamic	portable	50	21	216	1329	22	242	214	13.68
8	dynamic	portable	50	18	122	6	0	7	121	0.06
8	dynamic	portable	50	18	152	45	1	33	151	0.54
8	dynamic	portable	50	18	184	168	4	127	179	2.02
8	dynamic	portable	50	18	210	572	7	213	202	6.00
8	dynamic	portable	50	18	204	1196	30	318	216	13.45
8	dynamic	portable	50	15	120	1	0	13	121	0.01
8	dynamic	portable	50	15	153	28	1	40	151	0.38
8	dynamic	portable	50	15	179	134	2	120	180	1.50

8	dynamic	portable	50	15	211	440	13	271	204	5.42
8	dynamic	portable	50	15	206	1087	13	401	218	10.91
8	dynamic	portable	50	12	122	1	0	6	121	0.01
8	dynamic	portable	50	12	156	15	1	51	152	0.25
8	dynamic	portable	50	12	188	89	3	137	180	1.17
8	dynamic	portable	50	12	217	371	9	290	305	4.40
8	dynamic	portable	50	12	214	983	19	414	221	10.66
8	dynamic	portable	60	21	131	26	0	1	121	0.36
8	dynamic	portable	60	21	156	141	0	8	150	1.37
8	dynamic	portable	60	21	177	423	0	26	175	3.99
8	dynamic	portable	60	21	190	934	0	55	196	8.40
8	dynamic	portable	60	21	215	1701	2	63	209	14.47
8	dynamic	portable	60	18	133	19	0	3	121	0.19
8	dynamic	portable	60	18	155	125	0	15	150	1.22
8	dynamic	portable	60	18	189	378	0	33	176	3.58
8	dynamic	portable	60	18	175	652	1	75	196	7.83
8	dynamic	portable	60	18	210	1590	6	112	210	14.07
8	dynamic	portable	60	15	136	13	0	5	121	0.13
8	dynamic	portable	60	15	143	99	0	24	150	0.97
8	dynamic	portable	60	15	176	300	1	70	177	2.96
8	dynamic	portable	60	15	190	729	3	116	198	6.97
8	dynamic	portable	60	15	216	1466	7	189	213	13.24
8	dynamic	portable	60	12	136	9	0	8	121	0.09
8	dynamic	portable	60	12	153	86	2	32	151	0.86
8	dynamic	portable	60	12	183	230	1	81	178	2.31
8	dynamic	portable	60	12	211	611	2	147	201	5.84
8	dynamic	portable	60	12	210	1262	15	241	216	12.48
8	dynamic	both	10	21	62	0	0	126	61	0.00
8	dynamic	both	10	21	90	0	0	653	91	0.00
8	dynamic	both	10	21	106	0	0	1126	106	0.00
8	dynamic	both	10	21	123	0	0	1882	121	0.00
8	dynamic	both	10	21	157	17	2	3513	152	1.37
8	dynamic	both	10	21	186	149	11	5199	180	1.54
8	dynamic	both	10	18	62	0	0	74	61	0.10
8	dynamic	both	10	18	90	0	0	474	91	0.10
8	dynamic	both	10	18	123	0	0	1275	121	0.10
8	dynamic	both	10	18	139	0	0	1917	137	0.00
8	dynamic	both	10	18	159	3	0	2528	152	0.03
8	dynamic	both	10	18	177	58	1	4065	181	0.67
8	dynamic	both	10	18	216	351	16	5241	205	4.91
8	dynamic	both	10	15	62	0	0	46	61	0.00
8	dynamic	both	10	15	90	0	0	317	91	0.00
8	dynamic	both	10	15	123	0	0	851	121	0.00
8	dynamic	both	10	15	160	0	0	1805	152	0.00
8	dynamic	both	10	15	172	7	0	2609	167	0.07
8	dynamic	both	10	15	179	21	0	3352	182	0.21
8	dynamic	both	10	15	208	88	4	3771	196	1.25
8	dynamic	both	10	15	222	224	9	4512	208	3.04
8	dynamic	both	10	12	62	0	0	29	61	0.00
8	dynamic	both	10	12	90	0	0	175	91	0.00
8	dynamic	both	10	12	123	0	0	607	121	0.00
8	dynamic	both	10	12	160	0	0	1315	152	0.00
8	dynamic	both	10	12	185	10	0	2375	182	0.10
8	dynamic	both	10	12	193	33	3	3124	197	0.62
8	dynamic	both	10	12	222	137	4	3561	210	1.72
8	dynamic	both	10	12	205	691	10	4281	228	7.34
8	dynamic	both	20	21	106	0	0	49	106	0.00
8	dynamic	both	20	21	123	0	0	100	121	0.00
8	dynamic	both	20	21	144	2	0	171	136	0.02
8	dynamic	both	20	21	158	5	0	271	152	0.05
8	dynamic	both	20	21	181	43	0	679	181	0.42
8	dynamic	both	20	21	214	268	3	1307	207	2.86
8	dynamic	both	20	18	123	0	0	61	121	0.00
8	dynamic	both	20	18	158	0	0	215	152	0.00

8	dynamic	both	20	18	173	12	0	333	167	0.12
8	dynamic	both	20	18	174	11	0	431	170	0.11
8	dynamic	both	20	18	181	23	1	557	182	0.33
8	dynamic	both	20	18	210	192	2	1229	209	2.05
8	dynamic	both	20	18	211	800	7	1846	226	7.96
8	dynamic	both	20	15	123	0	0	41	121	0.00
8	dynamic	both	20	15	159	0	0	168	152	0.00
8	dynamic	both	20	15	173	4	0	317	167	0.04
8	dynamic	both	20	15	182	15	0	491	182	0.15
8	dynamic	both	20	15	226	156	0	1074	209	1.50
8	dynamic	both	20	15	216	727	11	1649	228	7.74
8	dynamic	both	20	12	123	0	0	38	121	0.00
8	dynamic	both	20	12	159	0	0	132	152	0.00
8	dynamic	both	20	12	186	7	0	431	182	0.07
8	dynamic	both	20	12	222	119	0	928	210	1.15
8	dynamic	both	20	12	212	625	13	1468	230	7.06
8	dynamic	both	20	12	228	1499	20	1748	238	14.76
8	dynamic	both	30	21	123	0	0	15	121	0.00
8	dynamic	both	30	21	157	5	1	64	152	0.15
8	dynamic	both	30	21	177	53	2	181	181	0.72
8	dynamic	both	30	21	217	254	5	487	207	2.92
8	dynamic	both	30	21	215	892	18	794	234	9.81
8	dynamic	both	30	18	123	0	0	15	121	0.00
8	dynamic	both	30	18	158	4	0	40	152	0.04
8	dynamic	both	30	18	190	34	1	159	181	0.43
8	dynamic	both	30	18	216	225	1	469	208	2.25
8	dynamic	both	30	18	210	802	14	608	226	8.67
8	dynamic	both	30	15	123	0	0	7	121	0.00
8	dynamic	both	30	15	158	2	0	43	152	0.02
8	dynamic	both	30	15	178	26	0	153	182	0.25
8	dynamic	both	30	15	215	190	0	419	209	1.83
8	dynamic	both	30	15	221	720	7	831	227	7.28
8	dynamic	both	30	12	123	0	0	6	121	0.00
8	dynamic	both	30	12	158	1	0	41	152	0.01
8	dynamic	both	30	12	182	17	0	162	182	0.17
8	dynamic	both	30	12	225	153	1	385	209	1.57
8	dynamic	both	30	12	209	672	10	773	229	7.17
8	dynamic	both	40	21	123	0	0	5	121	0.00
8	dynamic	both	40	21	157	9	0	22	152	0.09
8	dynamic	both	40	21	178	63	0	87	181	0.62
8	dynamic	both	40	21	216	313	8	245	207	3.77
8	dynamic	both	40	21	210	957	11	442	222	9.66
8	dynamic	both	40	18	123	0	0	4	121	0.00
8	dynamic	both	40	18	159	4	0	18	152	0.04
8	dynamic	both	40	18	184	47	0	84	181	0.46
8	dynamic	both	40	18	211	245	3	228	208	2.64
8	dynamic	both	40	18	205	903	15	484	225	9.62
8	dynamic	both	40	15	123	0	0	0	121	0.00
8	dynamic	both	40	15	159	4	0	24	152	0.04
8	dynamic	both	40	15	188	37	0	82	181	0.36
8	dynamic	both	40	15	213	200	3	212	208	2.22
8	dynamic	both	40	15	216	787	7	502	227	7.85
8	dynamic	both	40	12	123	0	0	0	121	0.00
8	dynamic	both	40	12	158	1	0	11	152	0.01
8	dynamic	both	40	12	180	23	0	86	182	0.23
8	dynamic	both	40	12	221	174	3	241	210	1.97
8	dynamic	both	40	12	222	737	13	567	228	8.02
8	dynamic	both	50	21	90	0	0	0	91	0.00
8	dynamic	both	50	21	120	5	0	3	121	0.05
8	dynamic	both	50	21	127	12	0	2	123	0.12
8	dynamic	both	50	21	145	16	0	6	136	0.16
8	dynamic	both	50	21	158	56	0	20	151	0.55
8	dynamic	both	50	21	182	202	0	56	179	1.95
8	dynamic	both	50	21	208	568	3	127	201	5.57

8	dynamic	both	50	21	210	1208	14	208	216	11.96
8	dynamic	both	50	18	123	3	0	3	121	0.03
8	dynamic	both	50	18	155	30	0	16	151	0.29
8	dynamic	both	50	18	189	122	1	57	180	1.28
8	dynamic	both	50	18	213	444	5	146	204	4.66
8	dynamic	both	50	18	206	1079	11	296	220	10.66
8	dynamic	both	50	15	121	1	0	8	121	0.01
8	dynamic	both	50	15	156	13	0	24	152	0.13
8	dynamic	both	50	15	175	73	0	80	181	0.71
8	dynamic	both	50	15	220	315	3	192	207	3.29
8	dynamic	both	50	15	218	906	12	362	223	9.33
8	dynamic	both	50	12	123	0	0	4	121	
8	dynamic	both	50	12	158	3	0	18	152	0.03
8	dynamic	both	50	12	177	53	1	72	181	0.62
8	dynamic	both	50	12	214	246	2	207	208	2.56
8	dynamic	both	50	12	216	822	10	412	226	8.44
8	dynamic	both	60	21	131	26	0	1	121	0.26
8	dynamic	both	60	21	156	140	0	2	150	1.36
8	dynamic	both	60	21	171	423	0	10	175	3.99
8	dynamic	both	60	21	166	909	0	23	196	8.21
8	dynamic	both	60	21	214	1684	3	48	209	14.45
8	dynamic	both	60	18	133	19	0	1	121	0.19
8	dynamic	both	60	18	150	119	0	5	150	1.16
8	dynamic	both	60	18	185	370	0	26	176	3.51
8	dynamic	both	60	18	180	823	0	53	197	7.48
8	dynamic	both	60	18	212	1554	3	82	212	13.50
8	dynamic	both	60	15	136	13	0	1	121	0.13
8	dynamic	both	60	15	144	96	0	9	150	0.94
8	dynamic	both	60	15	175	280	0	20	177	2.68
8	dynamic	both	60	15	177	713	0	60	199	6.56
8	dynamic	both	60	15	223	1363	7	130	214	12.38
8	dynamic	both	60	12	124	5	0	0	121	0.06
8	dynamic	both	60	12	152	60	0	11	151	0.69
8	dynamic	both	60	12	183	199	0	40	179	1.92
8	dynamic	both	60	12	199	547	1	88	202	5.19
8	dynamic	both	60	12	217	1175	4	179	217	10.71
8	fixed	none	10	21	62	0	0	40	61	0.00
8	fixed	none	10	21	95	11	1	258	91	0.21
8	fixed	none	10	21	106	36	9	478	106	1.25
8	fixed	none	10	21	130	113	33	693	120	4.39
8	fixed	none	10	21	140	447	122	1089	144	16.23
8	fixed	none	10	21	153	972	248	1224	162	32.75
8	fixed	none	10	18	62	0	0	21	61	0.00
8	fixed	none	10	18	89	1	0	152	91	0.01
8	fixed	none	10	18	119	48	9	512	121	1.37
8	fixed	none	10	18	142	116	36	687	135	4.71
8	fixed	none	10	18	159	211	70	817	148	8.97
8	fixed	none	10	18	163	631	152	939	169	20.74
8	fixed	none	10	15	62	0	0	22	61	0.00
8	fixed	none	10	15	90	0	0	115	91	0.00
8	fixed	none	10	15	136	19	3	328	121	0.49
8	fixed	none	10	15	159	99	28	576	150	3.75
8	fixed	none	10	15	165	229	35	627	162	5.68
8	fixed	none	10	15	180	377	75	747	175	10.99
8	fixed	none	10	12	62	0	0	13	61	0.00
8	fixed	none	10	12	89	0	0	53	71	0.00
8	fixed	none	10	12	120	8	1	191	21	0.18
8	fixed	none	10	12	152	60	7	364	151	1.29
8	fixed	none	10	12	180	236	38	506	178	6.04
8	fixed	none	10	12	183	454	44	579	189	8.63
8	fixed	none	10	12	186	689	52	583	199	11.48
8	fixed	none	10	12	213	1362	97	608	213	21.20
8	fixed	none	20	21	62	0	0	5	61	0.00
8	fixed	none	20	21	89	1	0	25	91	0.01

8	fixed	none	20	21	107	5	0	33	106	0.05
8	fixed	none	20	21	132	20	0	53	121	0.20
8	fixed	none	20	21	149	122	4	98	150	1.59
8	fixed	none	20	21	176	396	7	107	176	4.44
8	fixed	none	20	18	62	0	0	2	61	0.00
8	fixed	none	20	18	89	1	0	19	91	0.01
8	fixed	none	20	18	134	18	0	49	121	0.18
8	fixed	none	20	18	142	47	0	61	136	0.46
8	fixed	none	20	18	148	114	0	72	150	1.11
8	fixed	none	20	18	166	382	4	96	176	4.01
8	fixed	none	20	15	62	0	0	3	61	0.00
8	fixed	none	20	15	89	1	0	19	91	0.01
8	fixed	none	20	15	136	16	0	32	121	0.16
8	fixed	none	20	15	145	94	1	50	150	1.02
8	fixed	none	20	15	167	186	1	54	164	1.90
8	fixed	none	20	15	192	337	3	98	177	3.50
8	fixed	none	20	12	62	0	0	1	61	0.00
8	fixed	none	20	12	89	1	0	15	91	0.01
8	fixed	none	20	12	137	13	0	17	121	0.13
8	fixed	none	20	12	146	72	0	42	151	0.70
8	fixed	none	20	12	180	288	1	78	177	2.85
8	fixed	none	20	12	187	475	4	75	189	4.85
8	fixed	none	20	12	187	727	7	112	199	7.36
8	fixed	none	20	12	213	1433	15	134	213	13.79
8	fixed	none	30	21	133	20	0	5	121	0.20
8	fixed	none	30	21	149	123	2	8	150	1.40
8	fixed	none	30	21	176	411	0	21	175	3.88
8	fixed	none	30	21	198	950	3	32	196	8.83
8	fixed	none	30	21	211	1719	9	28	208	15.30
8	fixed	none	30	18	133	19	1	5	121	0.29
8	fixed	none	30	18	148	119	0	7	150	1.16
8	fixed	none	30	18	180	392	1	21	176	3.81
8	fixed	none	30	18	178	923	4	35	196	8.71
8	fixed	none	30	18	220	1687	7	29	209	14.86
8	fixed	none	30	15	133	19	0	7	121	0.19
8	fixed	none	30	15	149	117	2	9	150	1.34
8	fixed	none	30	15	190	376	3	19	176	3.86
8	fixed	none	30	15	175	877	4	36	196	8.33
8	fixed	none	30	15	206	1647	8	38	210	14.69
8	fixed	none	30	12	133	18	1	6	121	0.28
8	fixed	none	30	12	149	108	0	14	150	1.06
8	fixed	none	30	12	184	355	1	18	176	3.47
8	fixed	none	30	12	177	839	5	29	196	8.11
8	fixed	none	30	12	203	1624	8	31	210	14.52
8	fixed	none	40	21	135	23	0	2	121	0.23
8	fixed	none	40	21	157	130	1	11	150	1.36
8	fixed	none	40	21	174	417	3	11	175	4.24
8	fixed	none	40	21	186	943	2	19	196	8.67
8	fixed	none	40	21	204	1729	3	28	208	14.79
8	fixed	none	40	18	132	21	0	1	121	0.21
8	fixed	none	40	18	159	128	0	11	150	1.24
8	fixed	none	40	18	179	414	5	14	175	4.41
8	fixed	none	40	18	186	941	4	26	196	8.85
8	fixed	none	40	18	211	1717	6	36	209	14.99
8	fixed	none	40	15	132	21	0	2	121	0.21
8	fixed	none	40	15	161	124	2	9	150	1.41
8	fixed	none	40	15	177	388	3	12	176	3.97
8	fixed	none	40	15	176	922	3	17	196	8.61
8	fixed	none	40	15	220	1704	4	26	209	14.89
8	fixed	none	40	12	134	17	1	2	121	0.27
8	fixed	none	40	12	149	123	0	5	150	1.20
8	fixed	none	40	12	180	390	2	13	176	3.89
8	fixed	none	40	12	167	905	1	13	196	8.27
8	fixed	none	40	12	215	1660	5	19	209	14.47

8	fixed	none	50	21	132	26	0	1	121	0.26
8	fixed	none	50	21	155	140	0	5	149	1.36
8	fixed	none	50	21	177	444	0	9	175	4.18
8	fixed	none	50	21	189	971	6	11	194	9.30
8	fixed	none	50	21	204	1759	3	19	208	15.00
8	fixed	none	50	18	133	26	0	1	121	0.26
8	fixed	none	50	18	157	138	1	1	150	1.44
8	fixed	none	50	18	178	430	3	6	175	4.36
8	fixed	none	50	18	184	961	3	10	194	8.92
8	fixed	none	50	18	205	1739	3	19	208	14.86
8	fixed	none	50	15	134	21	1	0	121	0.31
8	fixed	none	50	15	157	132	2	5	150	1.48
8	fixed	none	50	15	172	421	1	6	175	4.07
8	fixed	none	50	15	188	945	1	11	196	8.59
8	fixed	none	50	15	212	1714	4	14	208	14.77
8	fixed	none	50	12	133	19	0	3	121	0.19
8	fixed	none	50	12	149	123	0	3	150	1.20
8	fixed	none	50	12	174	406	2	4	176	4.04
8	fixed	none	50	12	166	913	3	13	196	8.54
8	fixed	none	50	12	222	1704	3	18	209	14.58
8	fixed	none	60	21	130	30	0	1	121	0.30
8	fixed	none	60	21	159	156	0	0	149	1.51
8	fixed	none	60	21	186	461	0	1	175	4.33
8	fixed	none	60	21	182	1008	0	1	194	9.01
8	fixed	none	60	21	198	1801	0	3	207	15.01
8	fixed	none	60	18	132	26	1	2	121	0.36
8	fixed	none	60	18	157	150	0	1	149	1.46
8	fixed	none	60	18	185	456	0	3	175	4.29
8	fixed	none	60	18	185	999	0	3	194	8.93
8	fixed	none	60	18	202	1791	1	7	207	15.03
8	fixed	none	60	15	131	25	1	2	121	0.35
8	fixed	none	60	15	154	144	0	2	150	1.40
8	fixed	none	60	15	174	447	0	4	175	4.21
8	fixed	none	60	15	189	984	1	3	194	8.91
8	fixed	none	60	15	201	1756	0	7	208	14.69
8	fixed	none	60	12	131	25	1	2	121	0.36
8	fixed	none	60	12	156	137	1	1	150	1.43
8	fixed	none	60	12	177	436	0	2	175	4.11
8	fixed	none	60	12	182	961	1	5	194	8.72
8	fixed	none	60	12	206	1743	1	4	208	14.69

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