A Comprehensive In-Building and Microcellular Wireless Communication System Design Tool

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Abstract

Indoor wireless communication systems are becoming increasingly prevalent in work environments. The need to quickly and efficiently provide in-building and microcellular coverage without sacrificing quality is critical to cellular and emerging personal communication system (PCS) operators. Traditionally, indoor wireless communication system design has been carried out by human experts relying on experience to determine a satisfactory system configuration. This thesis describes the algorithms and technical considerations implemented in a comprehensive propagation planning tool, SMT *Plus*, which has been designed to predict the coverage regions of both in-building and microcellular wireless communication systems. The goal of SMT *Plus* is to provide both wireless service providers and equipment manufacturers with an efficient, easy-to-use coverage prediction tool for use in the design of any indoor or campus-wide wireless system. Using site-specific building information combined with on-site signal strength measurements, the tool provides system planners with a highly accurate model of the propagation environment among a group of buildings. SMT *Plus* provides a comprehensive solution to the planning and installation of wireless communication systems in and around buildings.

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Chapter 1

Introduction

1.1 Overview

This thesis describes an interactive software tool suite developed to assist engineers in designing and evaluating in-building and microcellular wireless communication systems. The current tools - SMT *Plus* and Site*Planner* - with the additional tools which have been conceptualized and are under development - Measurement*Builder* and Antenna*Builder* - provide the means to model any single or multi-building environment and simulate the performance of any type of wireless communication system located within the environment [24], [34]. Each building in the environment may contain up to nine stories, with each floor consisting of up to six different types of wall materials. The basic idea behind SMT *Plus* is prediction of path loss as a function of the distance a signal has propagated through an environment along with the number and type of partitions it has intersected along the way. The user of these tools has the ability to customize any aspect of the environment and communication parameters. Coverage predictions made by these tools provide immediate visual feedback on system performance while taking relatively little time to execute. This allows designers to analyze many different system configuration scenarios and evaluate trade-offs very quickly and accurately. The performance of the simulated wireless communication systems at any location in the environment is judged on the basis of coverage area, signal-to-noise ratio, and signal-to-interference ratio. Simple yet highly accurate path loss prediction models are used to predict these.

The SMT *Plus* tool suite requires AutoCAD^R, a popular computer aided design software package, in order to execute properly. All of the tools are written in C/C++, and are designed to operate within AutoCAD. All of the code is portable and operates identically on any computing platform supporting AutoCAD.

This chapter provides a brief introduction to several issues relating to the design of in-building wireless communication systems. Chapter 2 presents a detailed description of the design approach for the SMT *Plus* tool suite, along with a brief overview of AutoCAD. The overall structure of the SMT *Plus* tool suite is provided, and a discussion of the reasoning behind using AutoCAD as the foundation of the project. The next four chapters describe the components comprising the SMT *Plus* tool suite. Chapter 3 discusses the Site*Planner* tool, provides an overview of its functionality, and outlines the methods for obtaining the necessary site-specific information to use in the simulations. Chapter 4 discusses the SMT *Plus* simulation tool. A discussion of path loss models and their implementation in SMT *Plus* is given, and an overview of the user interface is provided. Chapter 5 discusses Measurement*Builder*, a member of the SMT *Plus* tool suite currently under development. The incorporation of measurements into the tool suite is discussed. Chapter 6 discusses Antenna*Builder*, another member of the SMT *Plus* tool suite under development. A discussion of the visualization and use of three dimensional antenna radiation patterns is given. Finally, Chapter 7 summarizes this thesis and the contributions made herein. Suggestions for future directions of this work are outlined, including the design of custom antennas and the automatic optimization of the site-specific database to maximize the accuracy of the SMT *Plus* simulations.

Four appendices are provided. Appendix A outlines the source files for the SMT *Plus* simulation tool. Appendix B outlines the source files for the Site*Planner* simulation tool. Finally, Appendices C and D supply a description of the commands supported by versions 1.0 of SMT *Plus* and Site*Planner* respectively.

1.2 In-Building and Multi-Building Communication Systems

The portable wireless communication industry is currently experiencing a period of tremendous growth with no foreseeable decline in the near future. This growth is not limited to one country or region, but is truly global in scale. The potential market for the deployment of wireless personal communication systems is literally in the billions of dollars. This results in tremendous interest in any research effort dealing with the deployment of wireless communication systems.

A major goal of current wireless communication research and development is in the area of integrated services. Such services will share resources to allow all types of data and voice information to be conveyed between users, regardless of their respective locations. Implementing a wired system of this type presents a daunting task. Installing the necessary wiring throughout the site is tedious and expensive. If the system needs to be reconfigured later, additional time and resources are required to rework the existing wiring. Even when satisfactorily installed, a wired system of this type affords users very little mobility [8], [20]. Those using the system are forced to conform to the system configuration. That is, the user must move to the data instead of having the data brought to the user. Considering all of these factors, a wireless alternative becomes the ideal path toward reaching the goal. A wireless communication system does not incur any of the overhead costs associated with wired systems brought about by reconfiguration. Upgrading or reconfiguring a wireless system is simply a matter of replacing or upgrading several pieces of equipment located in a centrally located position. Once deployed, users are free to use the wireless communication system and move about freely, suffering no restrictions on data access.

As the demand for high quality wireless communication systems grows, and as competition among wireless service providers increases, the ability to provide wireless services inside buildings and between buildings will be required. Beyond this, the ability to provide a seamless transition of communication between the outdoor macrocellular communication system and the in-building wireless communication system will be necessary. This is beginning to spark tremendous interest in the development of in-building wireless communication systems [27]. Such systems have the potential of significantly improving point-to-point communications among employees and equipment in commercial environments. The importance of these systems is in the ability to share information without regard for where the receiver of the information is located. In the conventional wired communication system, information can be sent only if the location of the desired receiver is known ahead of time along with the means to contact that location. The development of modern cellular communication systems is just the beginning of a global information infrastructure that will merge data, voice, and video transmission services into a single, convenient system.

Figure 1.1 shows an example of how wireless communication systems can be distributed in a building to help achieve this goal. In the typical scenario, the wireless communication equipment would be connected to the conventional wired communication backbone. This enables access not only to others sharing the wireless communication link, but also to the external world via the wired communication networks. If seamless communication is provided with the external wireless communication system, information can be exchanged without interruption while transitioning between indoor and outdoor environments.

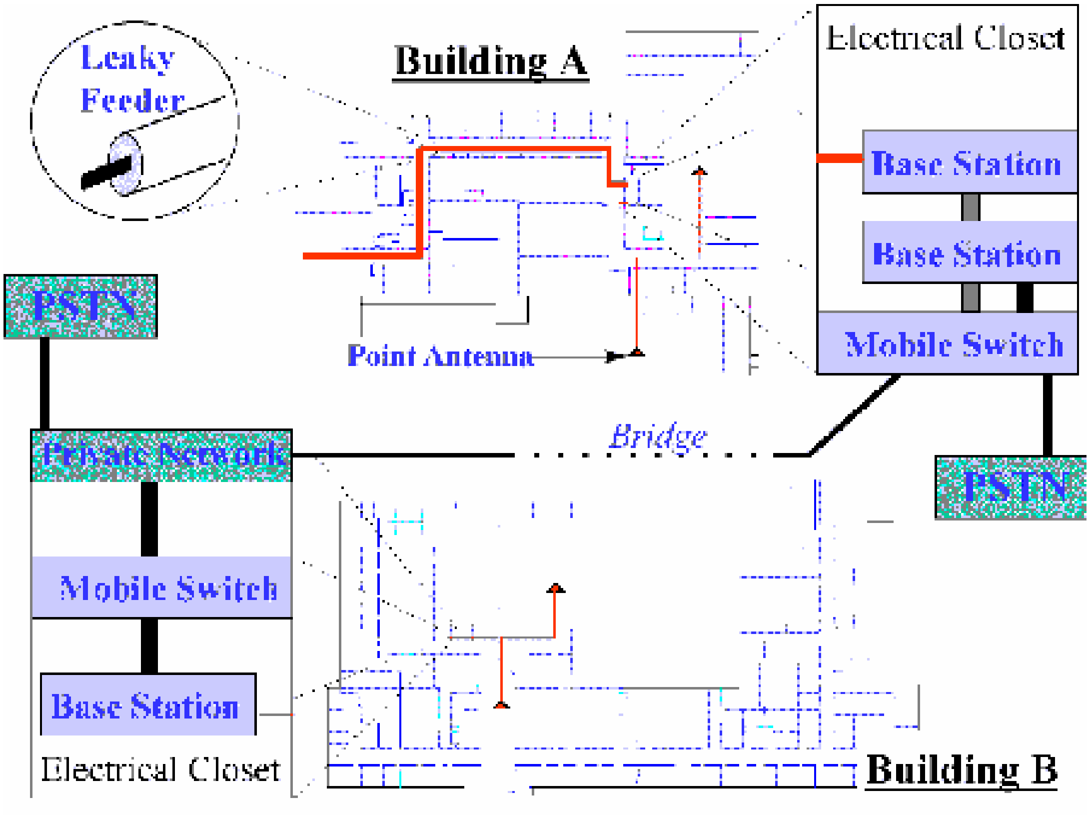


Figure 1.1: Sample in-building wireless communication system implementation linking two buildings together via a "bridge" between the privately switched telephone network of one building and the mobile switch of the other. Note that both mobile switches are connected to the Public Switched Telephone Network (PSTN).

1.3 The In-Building and Multi-Building Radio Propagation Channel

In-building wireless communications presents several challenges to designers. A line of sight path between transmitter and receiver rarely exists. Instead, signals are attenuated and reflected by walls, doors, and other physical obstructions within the building. The movement of equipment and users also affects the propagation channel, resulting in a continually changing and difficult-to-predict propagation environment.

Multipath and shadowing effects are among the greatest obstacles in-building wireless systems need to deal with. In multipath propagation, the transmitted signal arrives at the receiver via several different paths. These paths are the result of reflection, scattering, diffraction, and refraction effects incurred on the transmitted signal by obstructions in the environment [5], [18], [28]. These obstructions may be stationary objects such as walls, or very mobile objects such as people or machinery. Because the paths are not necessarily the same length, the receiver has the added problem that the transmitted signal components are arriving at different times. In narrowband communication systems, the existence of multipath signal components causes Rayleigh fading to occur at the receiver [28]. The end result is that as movement occurs, either among mobile obstructions in the environment or with the receiver, the signal strength observed at the receiver varies with time.

Shadowing is also caused by obstructions in the environment, but is generally associated with signal blockage due to large, immobile objects such as walls or buildings. The variation in received signal strength due to shadowing tends to occur slowly with changes in receiver location [28].

Interference is another major problem in-building wireless systems need to overcome. In wideband communication systems, multipath delays affect the received signal quality, but in this case it assumes the form of frequency selective fading [28]. Digital wireless communication systems are susceptible to interference as a result of multiple signal components. A signal component may arrive at the receiver at the same instance in time as a component from a previously transmitted signal. The interference between the signal components is known as inter-symbol interference (ISI). This ISI increases with the signaling rate, thus limiting the maximum data rate for any unequalized wireless communication system [28].

Another problem arises when two or more users are using the same communication channel while in relatively close proximity. This results in co-channel interference [4], [18], [28]. Co-channel interference can be reduced during the design phase of the in-building system through optimal channel assignment and base station antenna location strategies [4], [28], [33]. Such strategies are designed to minimize the chance multiple users will interfere with one another.

In an urban setting containing densely packed building structures, a similar propagation channel environment appears. The same obstructions and potential hazards identified in the in-building case apply, only on a larger scale. A wireless system designed to provide communication services inside and between multiple buildings suffers from the same potential downfalls as one designed solely for in-building use.

1.4 Design Issues Related to In-Building and Multi-Building Wireless Communication System Design

Characterizing the radio propagation channel environment is the first step in designing a wireless communication system. Once all the propagation hazards have been identified, the system can be designed to overcome them. Given this, there is a huge interest in understanding the propagation of radio waves within and between buildings, especially in the 800 MHz to 6 GHz frequency bands [14]. Recently, several statistical channel models have evolved based upon extensive measurement campaigns in single and multistory buildings [7], [9], [10], [13], [17], [21], [22], [29], [30]. Although much of this work has been centered around 900 MHz, several measurement campaigns to characterize the propagation channel at other frequencies have also been performed [12]. Literature surveys of radio propagation between, into, and within buildings are in [1], [12], [20], and [32]. Fast and accurate design tools based on the models derived from these sources can enable wireless system designers to create communication systems more efficiently in terms of scale, frequency planning, performance, and cost.

1.5 Motivation

In the past several years, considerable effort has been channeled into the creation of tools for aiding in the implementation of in-building wireless communication systems. Many such systems rely on examining experimental measurements that test signal characteristics throughout the entire region. Measurement data are used in rough statistical models in order to provide a more accurate representation of the propagation environment. Communication systems developed in this manner often result in higher implementation costs and a less efficient overall functionality [29].

To overcome the limitations of this design approach, prediction tools relying on more precise statistical models have been developed [26]. Although useful in projecting system performance from a statistical perspective, many such systems do not deal with specific details concerning the physical environment in which the wireless system is being deployed. Somewhat broad assumptions regarding details such as building material and layout are made when performing the statistical analysis. In order to develop more efficient and precise design tools, this type of information needs to be accounted for.

Recently, a software tool utilizing much of this information has been developed at Virginia Tech. The Site Modeling Tool (SMT) is a graphical propagation prediction tool relying on actual building layouts and material selection combined with statistical propagation models to gauge wireless system performance [24], [34]. SMT has the ability to graphically display the predicted coverage regions of arbitrarily positioned transceivers inside of a building. The coverage regions are displayed directly on top of the existing building floor plan, providing the user with the opportunity to visualize the effect of the building structure on the predicted coverage region. Transceivers can be placed, removed, or moved into user-specified locations within the building floor plan, allowing the developer to see the effects of each change on the system performance. However, SMT does not provide the means to easily acquire the site-specific information in a usable format. This can be particularly frustrating to the wireless system designer, who does not want to be encumbered with such details. No support for varying antenna types or the incorporation of measurements is provided with SMT. Measurements provide not only the means of verifying the predictions made by a design tool such as SMT, but can also be incorporated directly into the simulations being performed.

This thesis describes a series of major extensions to the SMT system designed to enhance the usability and performance of the tool. Taken as a whole, these extensions are known as the SMT *Plus* tool suite [34].

Ray tracing techniques can be used to predict wideband power delay profiles, and from this the local wideband or narrowband loss from transmitter to receiver can be obtained [11]. These methods, while very accurate and powerful, are computationally intensive. Typical implementations tend to require a great deal of highly accurate site-specific information and computing power in order to generate usable results. Instead, SMT uses relatively simple distance and partition-dependent path loss models to perform simulations [30], [34]. These models provide reasonable accuracy without the computational complexity of a true brute force ray tracing method. Much less site-specific information is needed for statistical models as well.

The original SMT system forms the foundations of the SMT *Plus* design effort. However, although much of the same functionality of SMT exists in SMT *Plus*, the underlying implementation has been drastically modified. Many new features have been added, and several stand alone software tools that complement one another have been developed. In terms of efficiency, usability, and power, SMT *Plus* is a significant step beyond SMT. A sample SMT *Plus* simulation is given in Figure 1.2.

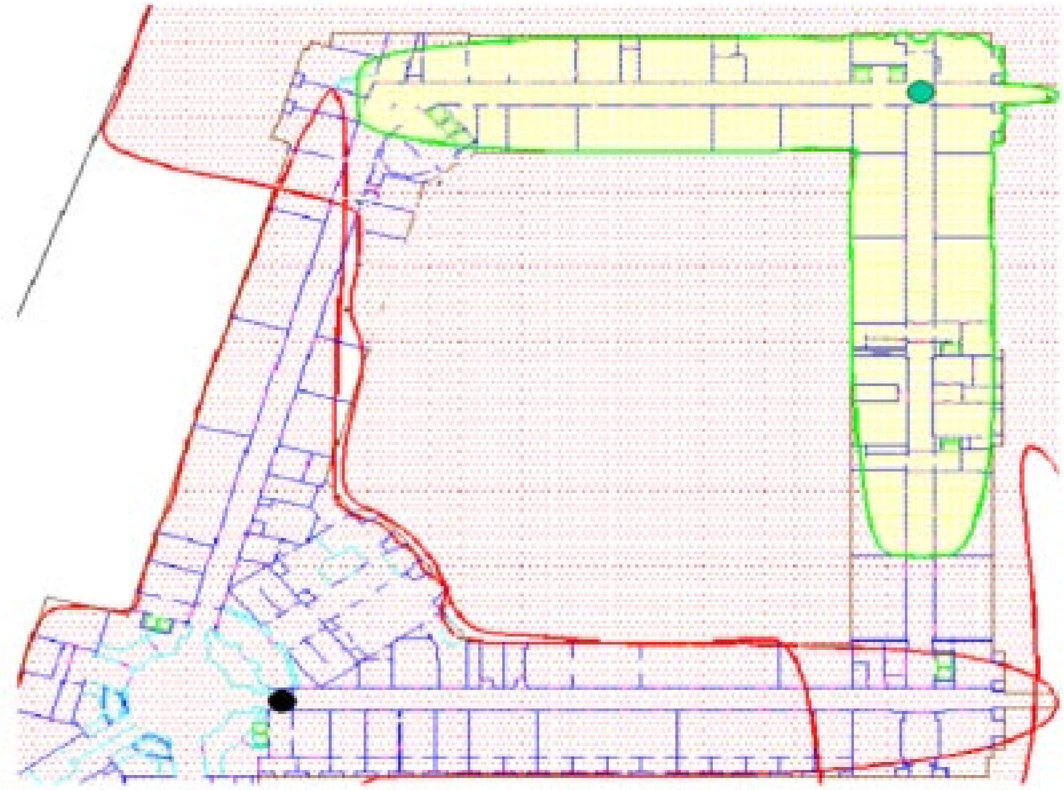


Figure 1.2: Sample SMT *Plus* in-building simulation result involving the simultaneous prediction of the coverage area for two base station antennas. Both are operating at 870 MHz with a transmit frequency of 100 mW and a bandwidth of 30 kHz. The yellow contour marks the region where received signal strength is greater than -75 dBm. The red contour marks the region where the received signal strength is greater than -100 dBm. The building is approximately 400 meters on each side, with an open courtyard in the center.

1.6 Research Contributions

This thesis represents the culmination of two years of research in the field of in-building and microcellular wireless communication system design. The results presented herein represent major contributions to the field. Some of the ideas and results to be found in the remainder of this thesis include:

- A comprehensive wireless communication system design tool based upon statistical path loss models is presented in Chapter 4. The design tool is at least an order of magnitude faster and more efficient than any known in-building or microcellular system design tool, and provides both researchers and engineers alike with a powerful system for analyzing wireless communication systems.

- A site-specific database development tool is presented in Chapter 3. This tool represents a leap forward in wireless communication system simulation by providing the means to acquire the necessary database of information. No other existing site-specific simulation tool known has such a feature readily available. This helps overcome the difficulty inherent in site-specific simulation tools, allowing researchers and engineers to concentrate on performing simulations rather than spending time developing the database.

- Research in the construction and utilization of site-specific databases for wireless communication system design has been greatly extended by this work. Future site-specific wireless communication system design tools will greatly benefit from this research.

- Two new statistical path loss prediction models are proposed and discussed in Section 4.2. These models were developed and tested during an extensive measurement campaign discussed in Section 5.2.1.

- The statistical path loss models discussed in [21] and [29], which were originally developed to be used with in-building systems only, have been extended to include multiple buildings in a microcellular system design. This is discussed in Section 4.6.

- The ability to quickly reconstruct three dimensional antenna radiation patterns and export the data in a format usable by any simulation tool has been developed. This is discussed in Chapter 6.

- The incorporation of antenna radiation patterns into the statistical path loss models presented in [21] and [29] has been investigated.

- The ability to accurately simulate leaky feeder antenna has been researched, and several methods for doing so are proposed in Section 6.4.2.

- The use of measurements in the optimization of the statistical path loss models used by SMT *Plus* has been thoroughly investigated and is discussed in Chapter 5. This provides an incredibly powerful research and design capability to the SMT *Plus* tool suite.

- The ability to easily and efficiently store measurement data directly into the same site-specific database used by the simulation tools has been added, as discussed in Chapter 5.

These and many other contributions are presented in this thesis.

Chapter 2

Simulation of Wireless Communication Systems

2.1 Overview

The original SMT path loss prediction tool described in [24] was viewed as the starting point for this thesis. Much of the work described in this thesis is either an improvement or an addition to the core SMT system. Although SMT was a fairly robust system in its own right, considerable potential was present to take the same basic ideas and create a much more powerful, comprehensive simulation tool which could be applied to the design of any in-building wireless communication system.

2.2 Project Goals

The initial goals of the SMT *Plus* project were as follows:

- SMT *Plus* must be able to calculate and display transceiver coverage areas within a modeled environment.

- The system must be as efficient and user friendly as possible, while not sacrificing computational accuracy.

- The user must be able to place and simulate any number of transceivers within the environment.

- The system must be portable to as many different computing platforms as possible.

- The source code must be designed using software engineering principles to allow for future expansion.

Through the course of the research and interaction with engineers designing wireless communication systems commercially, the initial goals expanded and became much more ambitious.

- The site-specific information required for the tool should be kept to a minimum as a convenience to the user. However, this should not impact the accuracy or performance of future simulations.
- The system must be able to generate a usable model of the environment regardless of the source of the site-specific data.
- The burden of correctly formatting the site-specific information should be as easy as possible.
- Few limitations should be placed on any aspect of the resulting design tools.
- Support for incorporating measurements into the wireless system design process should be added. Measurement data should be used to maximize the accuracy of simulations through comparisons of measured and predicted data.
- The system should be able to work with antenna patterns to enhance the ability to simulate any wireless communication system.

The overall goal was to create a commercial quality wireless system design tool applicable to any in-building communication system design.

2.3 System Components

From the list of goals given in Section 2.2, the system has been broken into four distinct packages. Each tool deals either with the issue of site modeling, simulation, measurements, or antennas. Each of the resulting tools can function independently, but directly complement one another when viewed as a whole. The separate components comprising the SMT *Plus* tool suite are discussed below.

2.3.1 Site-Specific Modeling

To address the issue of creating the database of site-specific information necessary for the simulations, a software package known as Site*Planner* has been created. Site*Planner* is an interactive software package which steps the user through the creation of the site-specific databases used by the simulation tools. Regardless of the information source or quantity, Site*Planner* assists a user in massaging the description of a building or multiple buildings into a format usable in later simulations. This tool frees the wireless system designer to concentrate on performing simulations and analyzing the results. Site*Planner* is discussed in detail in Chapter 3.

2.3.2 Simulation

The path loss prediction models utilized by the original SMT are simple yet highly accurate. For this reason, they form the core of the prediction techniques used in this next generation of simulation tools. An interactive software tool known as SMT *Plus* has been created which uses the path loss prediction techniques to assist a user in wireless system planning. A much improved algorithm for performing path loss predictions has been implemented in SMT *Plus*, making it several times faster than its predecessor. Many new features and an improved user interface also make SMT *Plus* a much better overall design tool. SMT *Plus* is discussed in detail in Chapter 4.

2.3.3 Measurements

The importance of measurements in any wireless communication system design cannot be overstated. Measurement data can be used in all stages of the design process, from initial planning to final deployment and validation. An interactive software tool known as Measurement*Builder* has been developed to interface SMT *Plus* to a number of commercial RF measurement devices. Most popular commercial RF measurement equipment provide some mechanism for storing recorded measurement data into a text file on a computer. Measurement*Builder* takes advantage of this, providing a mechanism for importing these text files and storing the measurement data directly onto the building layout. Once the measurements are imported, they may be displayed, or used by SMT *Plus* to optimize the coverage calculations. This is done through a comparison of the measured signal strength with the predicted signal strength at the same location, and then by optimizing the values of partition losses to minimize the error over the entire model. Measurement*Builder* is discussed in detail in Chapter 5.

2.3.4 Antenna Patterns

The original SMT design tool assumed that isotropic antennas were being used in all simulations [24]. While this is reasonable for omnidirectional antennas, directional antennas, leaky feeder, and other antenna types cannot be accurately represented in that manner. However, in order to account for the antenna pattern in the simulation, design tools such as SMT *Plus* need to have access to the full three dimensional antenna pattern. This information is not readily available from antenna manufacturers. To help resolve this issue, an interactive software program known as Antenna*Builder* has been developed. Antenna*Builder* provides the means to reconstruct the three dimensional radiation pattern of an antenna using either the two dimensional pattern data provided by the manufacturer or special closed form equations capable of approximating the pattern. The fully rendered pattern may be displayed to the user in order to visually verify the pattern, or exported and stored in a special three dimensional antenna pattern file. This file provides all the information needed by design tools such as SMT *Plus* and brute force ray tracing systems to fully simulate the effect of the antenna on the communication system design. Antenna*Builder* is discussed in detail in Chapter 6.

2.4 System Development

2.4.1 The AutoCAD Foundation

AutoCAD release 12 and release 13 were chosen as the development frameworks for all four members of the SMT *Plus* tool suite for several reasons.

1. Many commercial buildings have computerized floor plans in some format that may be imported into AutoCAD and manipulated by a tool such as Site*Planner*.

2. Programs written for the AutoCAD environment may be easily ported to any computing platform that supports AutoCAD. This provides a much higher degree of portability than could otherwise have been achieved.

3. Using a package such as AutoCAD as an application framework frees the developer from worrying over the details of the user interface. AutoCAD handles most of the work involved in creating a graphical user interface.

4. The full power of AutoCAD, including three dimensional modeling and rendering, is available to the developer.

5. The AutoCAD programming environment, though difficult to master, is quite extensive.

Given this combined with the already strong relationship between the Virginia Tech College of Engineering and AutoDesk, AutoCAD makes a good choice for the foundation of the SMT *Plus* tool suite.

2.4.2 AutoCAD Development Environment

The SMT *Plus* tool suite has been developed using the Advanced Development System (ADS) and the Advanced Runtime Extension (ARX) programming environments available for AutoCAD. Beginning with AutoCAD release 10, AutoDesk provides these extensive development systems to assist third party developers in creating software extensions to AutoCAD. These take the form of C and C++ libraries with the necessary header files and documentation for utilizing them. The object libraries contain routines for accessing AutoCAD commands and manipulating any aspect of a drawing file from within another program.

The basic development process involves writing a C or C++ routine which calls functions within the AutoCAD development environment, followed by compiling and linking the routine with the AutoCAD object libraries. From within AutoCAD, the routine can be invoked and executed the same as any other standard command. Full support is provided to enable these routines to open and control dialogue boxes, manipulate the AutoCAD menu structure, or access programs and files outside of AutoCAD.

The only true limitation of processes developed for AutoCAD is the requirement that a full version of AutoCAD be present. The applications in the SMT *Plus* tool suite cannot function unless first invoked from within an executing AutoCAD session.

Chapter 3

Site Modeling

3.1 Overview

A common problem in in-building wireless system planning is creating digitized building floor plans in a format usable by the propagation simulation system. To carry out site-specific propagation predictions, properly formatted, digitized building floor plans are required. To solve this problem, a stand alone software tool known as Site*Planner* has been developed. Site*Planner* is an interactive software tool that assists a user to acquire and properly format building floor plans for use by SMT *Plus*. Site*Planner* uses AutoCAD as a graphical shell for the user interface. The objective behind the design of Site*Planner* is to reduce the amount of AutoCAD experience needed by a user in order to generate SMT *Plus* building floor plans. Depending on the amount of existing building information available, a user selects one of several different options for developing the building floor plan. Each option provides step-by-step interactive assistance for building a floor plan in AutoCAD in the correct format for SMT *Plus*. By providing a buffer between the user and the required low level AutoCAD commands, Site*Planner* reduces the time required to construct and format building floor plans. Existing SMT *Plus* floor plans may also be easily modified using Site*Planner*. Site*Planner* executes independently of SMT *Plus* to design and construct building layouts. The usefulness of Site*Planner* as a stand alone package is minimal. However, when used with SMT *Plus*, Site*Planner* is a powerful tool for creating or editing building layouts intended for use in future SMT *Plus* simulations.

Site*Planner* is a mouse driven software package designed to be quick and easy to use, and which executes from within AutoCAD. All Site*Planner* commands are accessible with the mouse either through dialog boxes, which appear in response to user actions or via the Site*Planner* menus which are located both at the top and on the right hand side of the screen. Appendix D lists each Site*Planner* command and gives a short description of its function. Site*Planner* is available for any computing platform which supports AutoCAD release 12 or 13 and SMT *Plus* 1.0. If a computing platform has the minimum system requirements for executing AutoCAD, Site*Planner* will function properly. Site*Planner* does not place any demands on a computing platform beyond what is required by AutoCAD.

3.2 SMT *Plus* Building Database Structure

In order for SMT *Plus* to function properly, an AutoCAD building floor plan in the correct format must be available. Due to the path loss prediction models used in SMT *Plus*, the only information embedded within a floor plan formatted for use by SMT *Plus* is the amount of attenuation incurred upon a signal which passes through a partition. Section 4.2 provides information on the path loss prediction models incorporated into SMT Plus. All additional information, such as ceiling height and floor temperature, is added by the user and maintained by SMT *Plus* separately. Therefore, the primary information Site*Planner* is concerned with is the correct assignment of attenuation factors to each partition within the floor plan.

AutoCAD provides a method of logically organizing drawing entities into groups known as *layers*. Layers may be thought of as transparencies on an overhead projector. Each transparency contains the drawn entities associated with the given layer. By making a layer active, its transparency is added onto the stack on the projector; by making a layer inactive, the transparency is removed. Therefore, all drawn entities which exist on active layers are visible, whereas those on inactive layers are not. However, even though certain entities may not be visible because they reside on inactive layers, they are still components of the current drawing. In general, layers allow users to manipulate large groups of data in a very efficient manner.

3.2.1 Differentiating Floors and Partition Types

SMT *Plus* uses layers to differentiate between different types of partitions in a building floor plan. Currently, eight different classes of partitions are supported by SMT *Plus*: Primary, Secondary, Medium, Hard, Glass, Earth, External, and Custom. Each partition type has a specific level of attenuation this is incurred on signals which pass through the partition [34]. Attenuation values are assigned within SMT *Plus* by the user. Site*Planner* is only concerned with grouping all partitions of a certain type which will share the same attenuation factor onto the same layer within AutoCAD. SMT *Plus* expects to find these partitions grouped

Table 3.1: SMT *Plus* Supported Partition Types

Partition Type	AutoCAD Layer Name
Primary	FLOORx
Secondary	SPARTx
Medium	MPARTx
Hard	HPARTx
Glass	GPARTx
Earth	EPARTx
External	XPARTx
Custom	CPARTx

onto their own distinct layers (i.e., all entities of type Primary exist on the Primary partition layer). In addition, each floor in a building maintains a set of partition layers separate from those of all other floors. Each layer is given a name which SMT *Plus* uses to distinguish one layer from another. The type of partitions a layer contains can be determined from the name. Table 3.1 summarizes the naming scheme employed by SMT *Plus* and Site*Planner*. The small x following each layer name corresponds to the number of the floor for which the layer exists (e.g., layer SPART3 will contain all of the Secondary partitions for the third floor). Therefore, the first five characters in the layer name differentiates between partition types, while the final numeric digit differentiates between building floors.

Partitions can be visually distinguished within Site*Planner* by color. Each partition type has an associated default color. A fully formatted SMT *Plus* drawing will provide immediate visual feedback on the number and type of each partition found within the building. Figure 3.1 shows a typical building floor plan after having been formatted for use in SMT Plus. Each line represents a partition, and all lines of the same color share the same attenuation properties.

When a partition is converted from one type to another, two steps take place. First, the partition moves from its existing layer to the layer corresponding to the desired partition type. Secondly, the color of the partition changes to match that of the destination type. Likewise, when a partition is drawn, it is placed on the layer corresponding to its type, and is given the correct color. It is in this manner that all aspects of the building are modeled for SMT *Plus* in Site*Planner*.

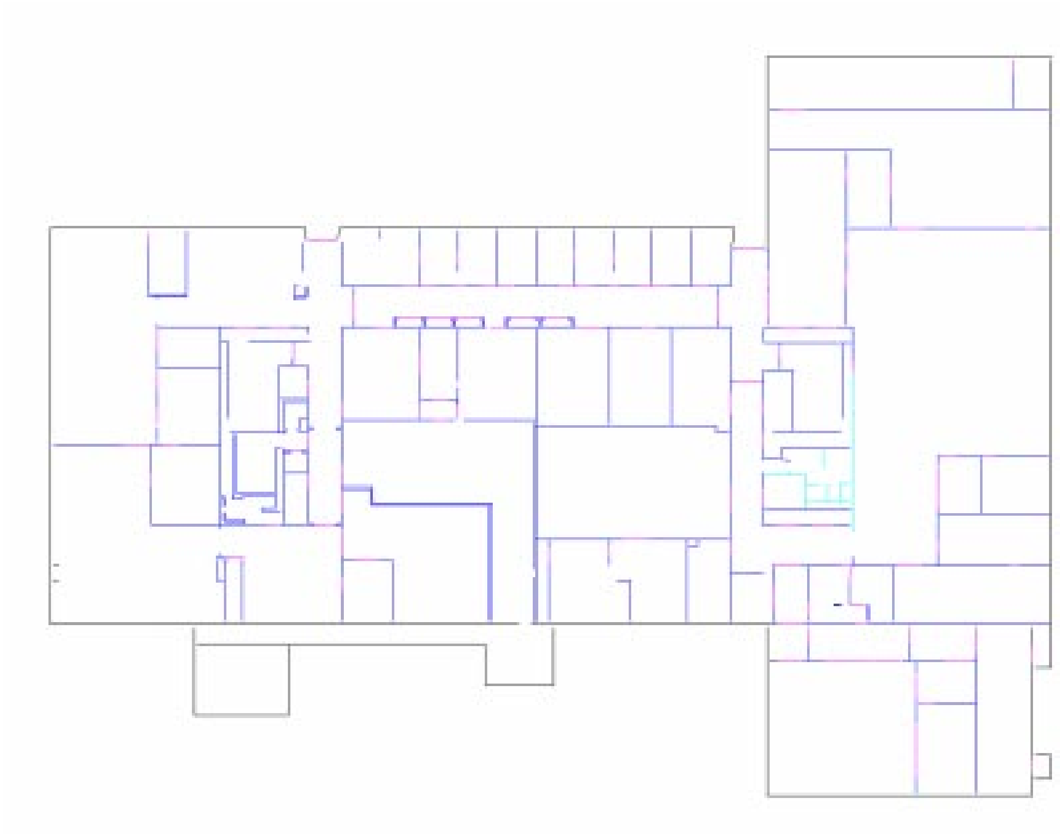


Figure 3.1: Sample SMT *Plus* formatted building layout. Each line represents an obstruction in the building, and all lines of the same color share the same signal attenuation characteristics.

3.2.2 Three Dimensional Building Layout

Separate building floors are distinguished within AutoCAD by the current layer name. AutoCAD displays the current layer name on the screen at all times. When a user changes to a different floor via either a SMT *Plus* or Site*Planner* command, the drawing entities associated with the desired floor are displayed on the screen. The current layer name is automatically set to be FLOORx, where x is the number of the floor being displayed. Thus, although only a two dimensional image is displayed to the user, a three dimensional building floor plan is created by Site*Planner* and utilized by SMT *Plus*. This technique minimizes the effort required on the part of the user in formatting the building layout, as an actual three dimensional model is not constructed. The end result, however, is a virtual three dimensional model for SMT *Plus* to work with.

3.2.3 Limitations of Site*Planner*

Site*Planner* is limited in the types of building structures which it can model. This is due to the limitations in the types of structures which the path loss prediction models used by SMT *Plus* support. SMT *Plus* 1.0 assumes that all rooms on a given floor have the same ceiling height. Obviously, this is not the case for elevator shafts, staircases, large auditoriums, etc. However, since SMT *Plus* does not support such drawing entities on a floor plan, neither does Site*Planner*. Whenever such entities occur in a drawing being formatted with Site*Planner*, either remove them from the drawing completely or, preferably, simply format them as rooms on the floor of the building. For instance, an elevator becomes a small room present on each floor of the building.

Another limitation is in the ability to model multiple buildings. SMT is designed to be an in-building wireless communication system simulation tool [23], [24]. Although multiple buildings can be incorporated into the same drawing using Site*Planner*, no mechanism currently exists to distinguish among them. SMT *Plus* will treat the building database as if all entities were of the same building. Figure 3.2 shows a sample SMT *Plus* drawing containing two buildings. See Section 4.6 for a discussion of multi-building simulation in SMT *Plus*.

3.3 Site*Planner* Building Layout Development Routes

Site*Planner* approaches the development of an SMT *Plus* building floor plan from several different routes. Each route is distinguishable from the others based upon the amount of information already available for a building. For example, if a user already has an AutoCAD drawing of a floor plan, there is no need to draw the floor plan from scratch. The user is free to pick which development route to take, a choice Site*Planner* prompts for when it is first executed. Figure 3.3 shows the dialog box displayed to the user when Site*Planner* first executes. Once the decision is made, Site*Planner* takes the user interactively through the steps which are required to progress along the chosen route. A description of each development route is given below.

Edit existing SMT format drawing This development route enables a user to make edits to an existing drawing already formatted correctly for SMT *Plus*.

Create-Assemble new floor plan This development route enables a user to create an SMT *Plus* format drawing by either editing scanned images of the building blue print or sketching the building plan.

Figure 3.2: Sample SMT *Plus* drawing containing two buildings.

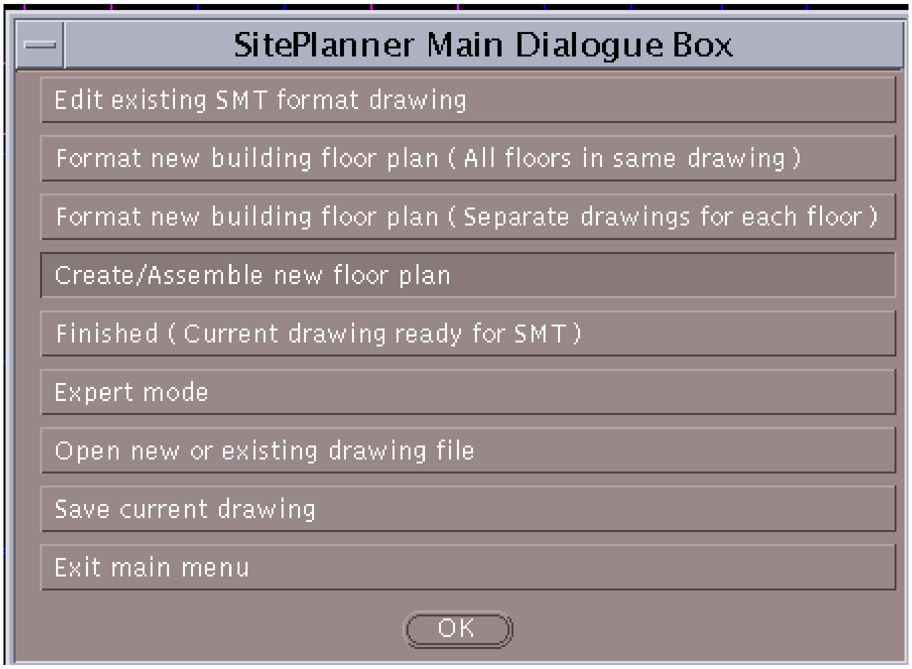


Figure 3.3: Site*Planner* Opening Dialogue Box

Format new building floor plan This development route enables a user to create an SMT *Plus* format drawing from existing digitized floor plans created in a drawing package such as AutoCAD. The approach to this development route varies depending on whether the developer has a separate digitized floor plan for each story in the building, or whether a single digitized drawing contains all floors of the building. Given an AutoCAD floor plan similar to Figure 3.4, the resulting SMT *Plus* format drawing will appear similar to Figure 3.5. Much of this development route concentrates on removing unnecessary information from the drawing.

Expert mode This option is for experienced users of AutoCAD. This breaks out of the interactive Site*Planner* design loop and provides direct access to the Site*Planner* commands discussed in Appendix D. Otherwise, Site*Planner* strictly controls the entire development process.

Figure 3.4: Unformatted AutoCAD drawing of a building floor plan.

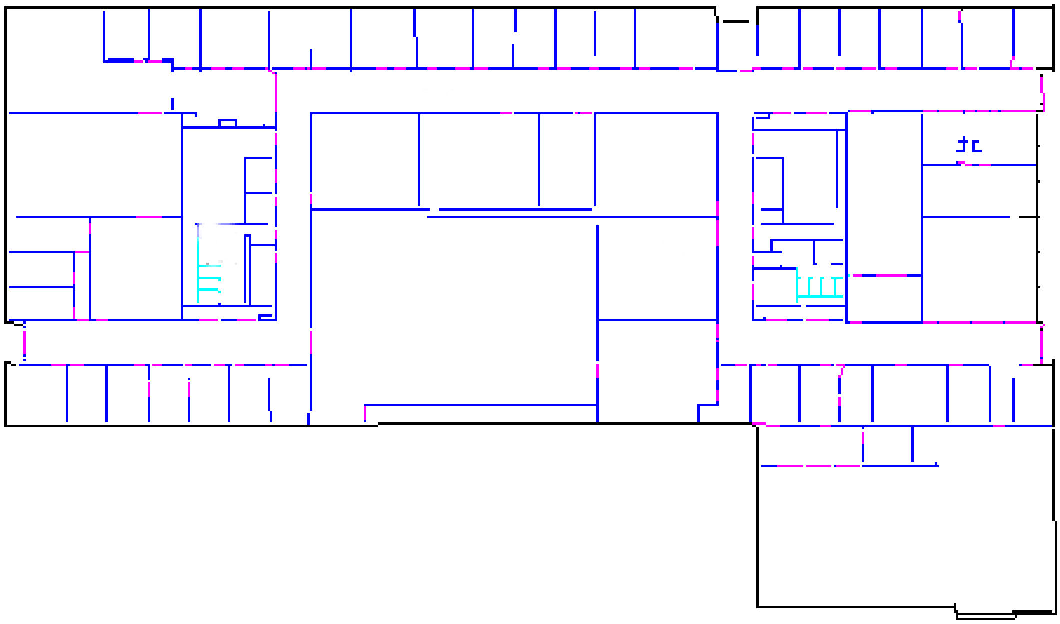


Figure 3.5: SMT *Plus* formatted AutoCAD drawing of a building floor plan.

Chapter 4

The SMT *Plus* Simulation Tool

4.1 System Overview

SMT *Plus* is an interactive software tool designed provide radio coverage and system design support for installers and designers of in-building wireless communication systems. Developed as an extension to AutoCAD, SMT *Plus* allows a user to display the floor plan of a building, position base station and interference source antennas on the floor plan, and view predicted coverage contours for each source. The user may interactively select from different propagation models and environment types, and can set communication parameters to match any desired indoor radio system. SMT *Plus* supports multifloor buildings, although only one floor is visible at any time. The tool is intended to be user friendly and requires little knowledge of AutoCAD. In order to reduce computation times, simple yet highly accurate point-to-point propagation models are used by the system.

SMT *Plus* 1.0 is the commercially licensable implementation of the SMT *Plus* project. It is available for any IBM compatible 486 or better personal computer, or any workstation platform which supports AutoCAD release 12 or 13. AutoCAD release 12 or 13 must be installed and operational on a system before SMT *Plus* will function properly. During normal operation, SMT *Plus* 1.0 does not place any demands on a computing platform beyond what is required by AutoCAD during normal operation. At the time of this writing, over fifteen companies and universities such as Motorola, Ericsson, Mobile Systems International, and Southwestern Bell have licensed SMT *Plus* version 1.0 from Virginia Tech Intellectual Properties, Inc., a non-profit branch of Virginia Tech.

4.2 RF Channel Modeling

4.2.1 Large-Scale Path Loss Prediction Models

SMT *Plus* makes use of large-scale path loss prediction models in predicting the coverage area of transmitting antennas. Four of these models, developed at MPRG, are discussed in [24], [28], [29], and [34]. These are generally referred to as the Distance Dependent Single Floor, Distance Dependent Multifloor, Partition Dependent, and Distance Dependent with Floor Attenuation models [24], [34]. Two additional models are proposed in this thesis, and the number of environmental parameters utilized in the path loss models has been greatly extended.

Basically, each model is a series of point-to-point path loss prediction equations which take into account the operating parameters of transmitting base stations and the physical building environment. Table 4.1 lists the parameters used in the following discussion.

4.2.1.1 Basic Path Loss Calculation

A commonly used estimation of mean path loss, $\overline{PL}$, is [24], [28], [34]

$$\overline{PL}(d) = PL(d_o) + 10 \times n \times log_{10}\left(\frac{d}{d_o}\right), \text{ [dB]} \tag{4.1}$$

where $PL(d_o)$ is the path loss at a reference distance d_o, which is typically selected to be one meter. An expression for $PL(d_o)$ is defined as [28]

$$PL(d_o) = 20 \times log_{10}\left(\frac{4\pi d_o}{\lambda}\right), \text{ [dB]} \tag{4.2}$$

Equation 4.1 assumes that mean path loss $\overline{PL}$ is a function of the distance d raised to the power n, the path loss exponent, from the transmitting source. In this case, n refers to the path loss behavior observed for a signal in a particular environment (e.g., $n = 2.0$ in free space). The reference distance d_o is normally selected so that it is within the far field of the transmitting antenna.

The distribution of local large-scale path loss around $\overline{PL}(d)$ as defined in Equation 4.1 is often log-normal, as in [24], [28]

$$PL(d) = \overline{PL}(d) + X_\sigma, \text{ [dB]} \tag{4.3}$$

The accuracy of the model used in predicting path loss can be quantitatively measured by analyzing the standard deviation σ in dB of the zero mean log-normal random variable X_σ.

Table 4.1: Parameters Used in Path Loss Prediction Equations

Parameter	**Description**	**Units**
BW	RF bandwidth	Hz
C	Received signal strength	dBW
C_{min}	minimum required C	dBW
C/I	Signal-to-interference ratio	dB
$(C/I)_{min}$	minimum required C/I ratio	dB
C/N	Signal-to-noise ratio	dB
$(C/N)_{min}$	minimum required C/N ratio	dB
CNF	Channel Noise Factor	dB
d	Distance between transmitting antenna and receive point	m
d_o	Reference distance	m
FAF	Floor attenuation factor	dB
FSM	Feasibility safety margin	dB
$G_t(\theta, \phi)$	Transmitter antenna gain	dB
k	Boltzmann's constant ($\approx 1.38 \times 10^{-23}$)	J/K
λ	Carrier wavelength	m
N	Total noise power	dBW
n	Mean path loss exponent	—
$n\,(multifloor)$	Mean path loss exponent for the multifloor models	—
P_{custom}	Number of custom partitions in path	—
P_{earth}	Number of earth partitions in path	—
P_{extern}	Number of external partitions in path	—
P_{glass}	Number of glass partitions in path	—
P_{hard}	Number of hard partitions in path	—
P_{med}	Number of medium partition in path	—
$P_{primary}$	Number of primary partitions in path	—
P_{second}	Number of secondary partitions in path	—
PAF_{custom}	Attenuation factor for custom partitions	dB
PAF_{earth}	Attenuation factor for earth partitions	dB
PAF_{extern}	Attenuation factor for external partitions	dB
PAF_{glass}	Attenuation factor for glass partitions	dB
PAF_{hard}	Attenuation factor for hard partitions	dB
PAF_{med}	Attenuation factor for medium partitions	dB
$PAF_{primary}$	Attenuation factor for primary partitions	dB
PAF_{second}	Attenuation factor for secondary partitions	dB
PL	Path loss	dB
$\overline{PL}$	Mean path loss	dB
P_t	Transmit power	dBW
P_n	Thermal noise power	dBW
T_o	Absolute room temperature	K
$X_{overlap}$	Percent overlap between two RF channels	—
X_σ	Zero mean log-normal variable with standard deviation σ dB	dB

The models used in this work are modifications of Equation 4.1 in order to obtain an improved fit of predicted versus measured path loss.

4.2.1.2 Distance Dependent Path Loss Model

The Distance Dependent Path Loss Model is valid for predicting path loss across one or more floors of a building [34]. This model only takes into account the distance along a straight path the carrier signal travels from the transmitting source. Partitions, floor boundaries, and any other obstructions are ignored.

For simulations in which the transmitting antenna and receiving point are located on the same floor, the expression for the Distance Dependent model becomes [24], [34]

$$\overline{PL}(d) = PL(d_o) + 10 \times n \times log_{10}\left(\frac{d}{d_o}\right), \text{ [dB]} \tag{4.4}$$

which is identical to Equation 4.1. In free space, the path loss exponent n assumes the value 2.0. However, in order to minimize the standard deviation between the predicted and measured values, the value of n can be modified. Through extensive measurement campaigns, typical values of n have been identified for a variety of building environments [29]. These are given in Table 4.2.

Table 4.2: Typical values for the path loss exponent n based on building environment.

Type of Building	**Value of Path Loss Exponent**
Office	2.8
Factory	2.2
Grocery Store	1.8
Retail Store	2.2

For multifloor simulations, the expression for the Distance Dependent model becomes [24], [34]

$$\overline{PL}(d) = PL(d_0) + 10 \times n(multifloor) \times log_{10}\left(\frac{d}{d_o}\right), \text{ [dB]} \tag{4.5}$$

which is virtually identical to Equations 4.1 and 4.4. This uses a different path loss exponent, $n(multifloor)$, to account for the effects of ceilings on signal propagation. The $n(multifloor)$ parameter attempts to account for the path loss which occurs when a signal passes through a given number of floors as well as the distance it has traveled from the transmitting source. Table 4.3 lists typical values for the multifloor path loss exponent which have been determined through extensive measurement campaigns [29].

Table 4.3: Typical values for the multifloor path loss exponent, $n(multifloor)$, based on the number of floors separating the transmitting antenna and receiving point.

Number of Intervening Floors	**Value of the Multifloor Path Loss Exponent**
1 Floor	4.2
2 Floors	5.0
3 Floors and up	5.3

4.2.1.3 Partition Dependent Path Loss Model

The Partition Dependent Path Loss Model is valid only for the case where both the transmitting antenna and receiving point are located on the same floor of a building. For this model, predicted path loss depends upon the number and type of physical obstructions the carrier signal passes through [29]. Generally, free space propagation (i.e., the value of the path loss exponent n in Equation 4.1 is 2.0) is assumed between obstructions [29], [24]. However, this work makes no assumptions regarding the value of the path loss exponent, and a user of SMT *Plus* may specify any value for n.

Each obstruction in the modeled environment is assigned to one of eight different partition types, as discussed in Chapter 3. Each partition type has an associated partition attenuation factor (PAF), which is a measure of the amount of loss in dB that occurs when a signal passes through a single partition of the given type. The larger the PAF value, the greater the loss incurred on the signal. The work described in [29] used only two partition classifications, while the work in [34] extended this to six classifications. To provide even more flexibility in the modeling of in-building environments, this work extends the number of partition types to eight. The typical attenuation factors assigned to each are given in Table 4.4, and considers the findings from [24] and [29].

The expression for the Partition Dependent Path Loss Model, given a variable path loss exponent and eight possible partition types, is shown in Equation 4.6.

$$\begin{aligned}
\overline{PL}(d) \;=\;& PL(d_o) + 10 \times n \times log_{10}\left(\frac{d}{d_o}\right) + \\
& \Big[(P_{primary} \times PAF_{primary}) + (P_{second} \times PAF_{second}) + (P_{med} \times PAF_{med}) + \\
& (P_{hard} \times PAF_{hard}) + (P_{glass} \times PAF_{glass}) + (P_{extern} \times PAF_{extern}) + \\
& (P_{earth} \times PAF_{earth}) + (P_{custom} \times PAF_{custom})\Big], \text{ [dB]} \qquad (4.6)
\end{aligned}$$

Table 4.4: Typical partition attenuation factor (PAF) values in dB used in the Partition Attenuation Path Loss Model.

Partition Type	Attenuation Factor (dB)
Primary	2.4
Secondary	1.4
Medium	2.0
Hard	4.0
Glass	3.0
External	20.0
Earth	20.0
Custom	2.0

4.2.1.4 Distance Dependent with Floor Attenuation Model

The Distance Dependent with Floor Attenuation Model is valid only for multifloor simulations. This model takes into account the number of floors that a carrier signal has passed through in determining coverage areas as well as the distance the signal has traveled from the transmitting antenna. Unlike the pure Distance Dependent Model which modifies the path loss exponent n, this model uses an additional parameter known as the floor attenuation factor (FAF) to account for floor attenuation. The value of the FAF depends directly upon the number of floors separating the transmitting antenna from the receiving point. Table 4.5 provides typical floor attenuation values derived during extensive in-building measurement campaigns [29].

Table 4.5: Typical floor attenuation factor (FAF) values for use in the Distance Dependent with Floor Attenuation Path Loss Model.

Number of Intervening Floors	Attenuation Factor (dB)
1 Floor	13.2
2 Floors	18.1
3 Floors	24.0
4 Floors	27.0
5 Floors or more	27.1

Previously, free space propagation was assumed for this path loss model [24], [29]. However, this work leaves the path loss exponent n modifiable in order to achieve greater freedom in minimizing the difference between measurements and predictions, as discussed in Section 5.2.2.2. The resulting expression for the Floor Dependent with Floor Attenuation Path Loss

Model is given in Equation 4.7.

$$\overline{PL}(d) = PL(d_o) + 10 \times n \times log_{10}\left(\frac{d}{d_o}\right) + FAF, \text{ [dB]} \tag{4.7}$$

4.2.1.5 Floor Dependent Model

The Floor Dependent Path Loss Model is a proposed multifloor path loss model developed as a result of this research. This model attempts to combine the Distance Dependent with Floor Attenuation Model with the Partition Attenuation Model in order to create a hybrid multifloor path loss model. The resulting model takes into account the number of floors the carrier signal has passed through in a straight path between the transmitting antenna and the receiving point, as well as the number and type of partitions intersected on the floor of the receiving point. That is, only partitions which exist on the same floor as the receiver are considered by this model. Tables 4.4 and 4.5 provide typical values of floor and partition attenuation factor values. The resulting path loss expression is given in Equation 4.8.

$$\begin{aligned}\overline{PL}(d) \quad = \quad & PL(d_o) + 10 \times n \times log_{10}\left(\frac{d}{d_o}\right) + FAF \\ & \Big[(P_{primary} \times PAF_{primary}) + (P_{second} \times PAF_{second}) + (P_{med} \times PAF_{med}) + \\ & (P_{hard} \times PAF_{hard}) + (P_{glass} \times PAF_{glass}) + (P_{extern} \times PAF_{extern}) + \\ & (P_{earth} \times PAF_{earth}) + (P_{custom} \times PAF_{custom})\Big], \text{ [dB]}\end{aligned} \tag{4.8}$$

4.2.1.6 Modified Floor Dependent Model

The Modified Floor Dependent Path Loss Model is a proposed multifloor path loss model developed as a result of this research. During the course of the measurement campaign described in Chapter 5, all of the multifloor path loss models discussed thus far were rigorously applied to a building model and the results compared with the actual measured data. It was noticed during the optimization process described in Section 5.2.2.2 that the Floor Dependent Path Loss Model described in Section 4.2.1.5 provided a much better matching between measured and predicted when only a subset of the total partition types were used in the calculation of Equation 4.8. By only accounting for the partitions typically found along the outer wall of the building (e.g., the outer wall, windows, etc.), a better fit of the predicted data to the measurement data was achieved. The resulting expression for this model is given in Equation 4.9.

$$\begin{aligned}\overline{PL}(d) &= PL(d_o) + 10 \times n \times log_{10}\left(\frac{d}{d_o}\right) + FAF + \\ &\Big[(P_{extern} \times PAF_{extern}) + (P_{earth} \times PAF_{earth}) + \\ &(P_{glass} + PAF_{glass})\Big], \text{ [dB]} \end{aligned} \tag{4.9}$$

4.2.2 Link Budget Calculation

4.2.2.1 Predicting Received Signal Strength

Using the path loss models described in Section 4.2.1 and knowledge of the transmitting source characteristics, the coverage area of any antenna can be predicted. The site-specific database provides the environmental information needed by the path loss models, such as the location of partitions. By positioning transmitting antennas within the site-specific model and specifying source parameters such as carrier frequency and transmit power, the received signal power at any point in the database can be predicted. Equation 4.10 provides the calculation of received signal power [28].

$$C = P_t + G_t(\theta, \phi) - \overline{PL}(d), \text{ [dBW]} \tag{4.10}$$

4.2.2.2 Accounting for Noise

The thermal noise power P_n seen by a receiver at any point within the modeled environment is given by [28], [34]:

$$P_n = 10 \times log_{10}\left(k \times T_o \times BW\right), \text{ [dBW]} \tag{4.11}$$

From Equation 4.11, the total noise power at any receiving point is calculated as [24], [34]:

$$N = P_n + CNF, \text{ [dBW]} \tag{4.12}$$

The channel noise factor (CNF) is specified by the user and provides a means of quantifying any noise present other than thermal noise. A qualitative measurement, signal-to-noise ratio (C/N), can now be defined as [24], [34]:

$$(C/N)\mid_{dB} = C - N, \text{ [dB]} \tag{4.13}$$

Equation 4.13 enables the prediction of signal-to-noise at any location in the modeled database.

4.2.2.3 Accounting for Interference

An interference source is any transmitting source whose signal affects in any way the desired carrier signal being simulated. Consider m active interference sources present in a region, each having a transmit power P_i and located at a distance d_i from a receiving point. The interference power I_i seen at the receiving point due to any single active interference source is [34]:

$$I_i = P_i - \overline{PL}(d_i) + X_{overlap}, \text{ [dBW]} \tag{4.14}$$

In Equation 4.14, $X_{overlap}$ is an adjustment factor determined from the percentage of overlap between the channel bandwidth of the interference source and that of the desired carrier signal. The actual calculation of $X_{overlap}$ was developed using the same techniques utilized in industry. Given a transmitting source having a transmit frequency f_{ts} and channel bandwidth BW_{ts}, and an interference source having a transmit frequency f_{is} and channel bandwidth BW_{is}, their respective spectrum is shown in Figure 4.1. The spectrum of both the base station source and interference source are modeled as being rectangular. The center of the rectangle is the transmit frequency, while the opposite ends of the rectangle are at positions equal to the transmit frequency plus or minus half the channel bandwidth.

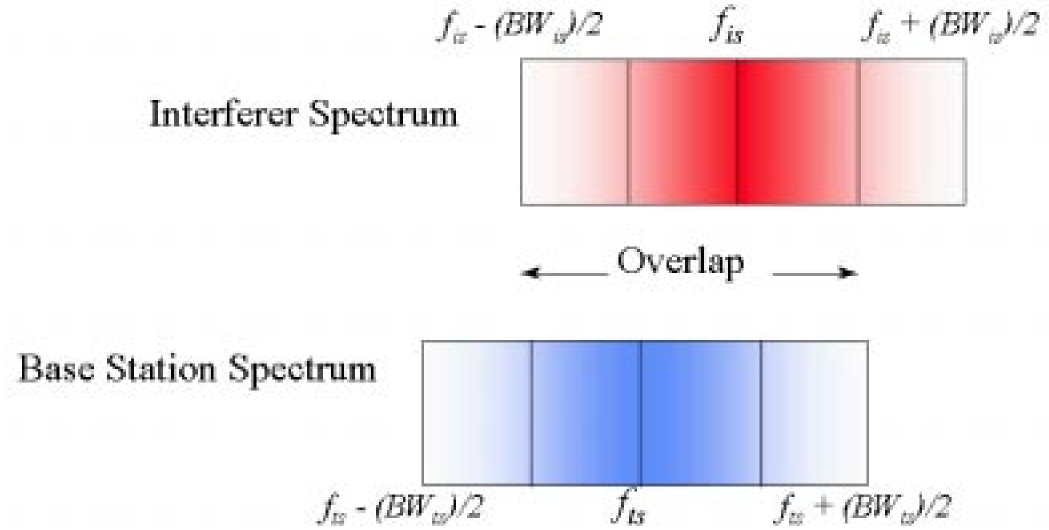


Figure 4.1: Using channel spectral density to model interference source effects in SMT *Plus*.

Each rectangle is then divided into fourths, with each section representing 25 percent of the total area of the rectangle (i.e., 25 percent of the channel bandwidth). The amount of overlap between the base station channel and the interference source channel, in 25 percent blocks, is then determined. For example, in Figure 4.1, 100 percent overlap exists between the interference source and base station channels. If the channel of the base station was shifted slightly to the left (or its channel bandwidth BW_{ts} was made smaller) such that the upper block of the interference was not overlapped, only 75 percent overlap between the two would occur. The decision to use blocks of 25 percent for determining overlap was done in order to reduce the overall calculation time.

Once the percent overlap is determined, the calculation of $X_{overlap}$ becomes [34]:

$$X_{overlap} = 10 \times log_{10}\left(X_{overlap}\right), \text{ [dB]} \tag{4.15}$$

In Equation 4.15, $X_{overlap}$ is some multiple 0.25 between 0.25 and 1.0. In the event that no overlap exists between the channels, no interference is seen at the receiving point.

The total interference power I seen at a receiving point due to m active interference sources is given can now be calculated [34].

$$I = \sum_{i=1}^{m} I_i, \text{ [dBW]} \tag{4.16}$$

The overall signal-to-interference ratio (C/I) can now be calculated at any receiving point in the modeled database using Equation 4.17 [34].

$$(C/I)\mid_{dB} = C - I, \text{ [dB]} \tag{4.17}$$

4.3 Coverage Contour Creation Algorithm

From Sections 4.2.2.1, 4.2.2.2, and 4.2.2.3, the ability to predict received signal power, signal-to-noise, and signal-to-interference given any transmitting antenna and a receiving point is provided. By specifying boundary conditions on Equations 4.10, 4.13, and 4.17, coverage regions can be formed on the site-specific databases, the edges of which correspond to the set boundary conditions. Figure 4.2 provides an example of how this is done in SMT *Plus*.

A base station antenna is positioned within the site-specific database as discussed in Section 4.7.3. Parameters are assigned to it, and boundary conditions are specified. A contour boundary is drawn, marking the point in the database at which the boundary condition is satisfied. For example, if a boundary condition of -100 dBm received signal power is specified for Equation 4.10, a contour boundary is drawn directly on the site-specific database marking the points at which the predicted received power is equal to -100

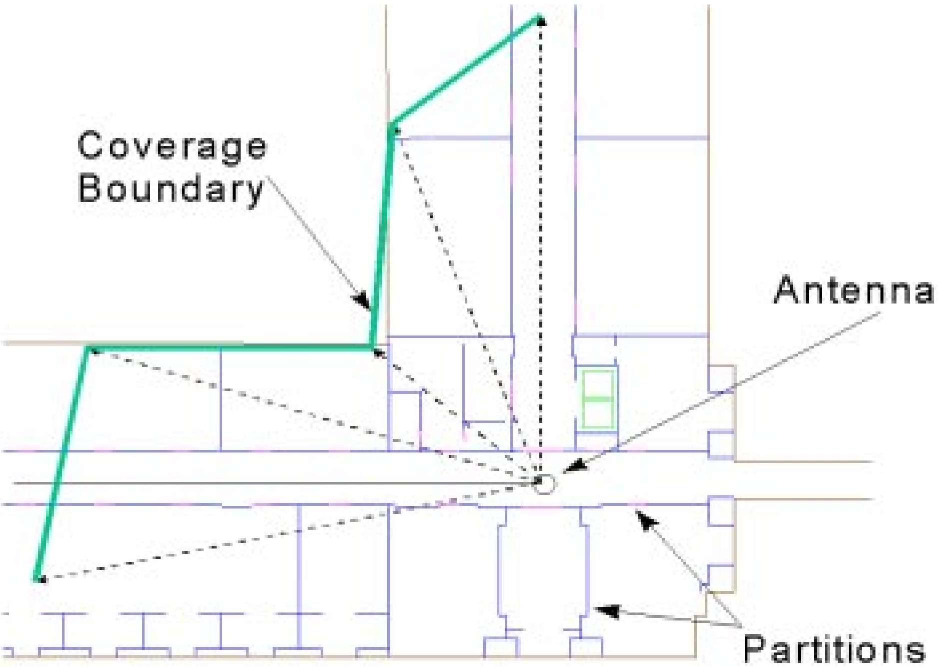


Figure 4.2: Predicting the coverage region of a base station antenna on a site-specific database in SMT *Plus*.

dBm. In this manner, coverage regions for received signal strength, signal-to-noise, and signal-to-interference can be visualized for any modeled base station antenna placed in a site-specific database.

The algorithm used to identify the vertices of the coverage contours is a form of binary search. If a straight path is drawn from the transmitting antenna to the limit of the site-specific database, the predicted path loss along the path steadily increases with distance from the transmitting antenna. Therefore, if the path is discretized into a series of points, where each point represents the predicted path loss to that point in the database, the path can be thought of as a sorted array. Each successive element in the array is greater than the previous one in terms of its path loss value. Locating the specified boundary conditions is then simply a matter of searching through the sorted array. A binary search algorithm is used to do this [15]. In SMT *Plus*, the user has full control of the step size and resolution of the search.

4.4 Accuracy Assessment

An important issue is that of the accuracy with which SMT *Plus* estimates coverage regions. This is not only related to the type of propagation model used in the prediction, but also on the accuracy of the building floor plan being used.

For the indoor propagation prediction models used by SMT *Plus* a standard deviation (σ) of ±5.8 dB has been reported for the entire data set from which the models were obtained [29]. This implies that 67.7 percent of actual measurements would lie within 5.8 dB of the predicted mean path loss [24]. For both of the Distance Dependent path loss models considered together, a σ of ±16.3 dB has been reported [29]. For the single floor Distance Dependent model considered by itself, σ reduces to ±12.9 dB. For the Partition Dependent path loss model, a σ of ±4.1 dB has been reported [29]. Estimates of σ for the Distance Dependent with Floor Attenuation Factors model range from ±1.5 to ±7.0 dB in one building, and between ±2.9 and ±7.2 dB in another [29]. All of these reported values of σ agree well with those reported by other researchers.

In addition, a large measurement campaign described in Section 5.2.1 was carried out during the course of this research. In-building and building penetration measurements were performed and compared with the results of the SMT *Plus* predictions. From these measurements, the overall σ for the entire building, using the both Partition Dependent and Floor Dependent with Partition Attenuation path loss models, was ±7.3 dB. This agrees quite well with the theoretical accuracy.

4.5 Utilizing Antenna Patterns

Currently, SMT *Plus* assumes that every base station antenna is isotropic. That is, the value of $G_t(\theta, \phi)$ in Equation 4.10 is always zero. This is due to the difficulty in acquiring the three dimensional antenna pattern needed to accurately simulate a real antenna. With the creation of the Antenna*Builder* software tool described in Chapter 6, special antenna pattern files can be created supplying the three dimensional radiation pattern for any antenna. These files, similar in format to Figure 6.16, supply the antenna gain, $G_t(\theta, \phi)$, in three dimensions. With this information, the actual antenna pattern can be substituted into Equation 4.10, and, thus, any antenna can be simulated within SMT *Plus*. This functionality has not been completely implemented into SMT *Plus* at this time, but the foundation for doing so is in place.

4.6 Validity of Multi-Building Simulations

The path loss equations described in Section 4.2.1 were developed from measurement campaigns performed in a variety of buildings [24], [29]. The three primary components of these models are the path loss exponent, the number of floors separating the transmitting antenna and receiving point, and the number of partitions between the transmitting antenna and receiving point. The site-specific database to which these models are applied are simple collections of partitions arranged relative to one another as they appear in the actual building, as shown in Figure 3.5. Nothing in the actual equations themselves is specific to an indoor environment, however.

Consider an urban environment in which buildings are located relatively close to one another. By modeling the buildings as collections of partitions and floors, a site-specific database can be created. Figure 4.3 shows two buildings modeled in the exact same manner as the one shown in Figure 3.5.

The same path loss models can be applied to the multi-building database as to the single building one. The calculations are carried out in exactly the same manner. Thus, a site-specific database which contains multiple buildings is treated as simply being one large building upon which the path loss models are being applied. In this fashion, the in-building path loss models described in Section 4.2.1 can be applied to microcellular communication system design.

4.7 Using SMT *Plus*

4.7.1 Overview of Features

SMT *Plus* allows the user to predict signal coverage and interference contours for base station transmitters. SMT *Plus* does this by simulating the RF coverage throughout the building at a number of uniformly spaced receiver points encircling the base station antenna. Since the system has been developed as an extension to AutoCAD, the user interface relies heavily on AutoCAD to provide an interactive operating environment. A mouse and keyboard are used as input devices, and visual feedback is provided, all via AutoCAD. Some of the main provisions of SMT *Plus* are listed below.

- Because AutoCAD serves as the foundation of the system, full AutoCAD functionality is available to the user.

- The user can interactively add, reposition, or delete any number of base stations and interference source antennas at any time during SMT *Plus* operation.

Figure 4.3: Formatted site-specific database containing two buildings.

- Interference sources are modeled as independent base stations with their own set of operating parameters. The amount of overlap that is seen between interference sources and base stations directly impacts the interference power seen at any given point in a building as discussed in Section 4.2.2.3.

- All communication parameters for any base station or interference source are user configurable. In addition, SMT *Plus* includes many of the most common wireless standards as pre-existing parameter sets which can be used within a model.

- The user can initiate the calculation of coverage contours for all or individual base station antennas that have been placed on a floor plan. These regions are highlighted graphically and in color on the floor plan. The user may also clear all or individual coverage contours if desired.

- Received signal strength coverage contour and signal-to-noise/signal-to-interference (CNR/CIR) coverage contours may be predicted by the system. The user is free to set the boundary limits of these contours, and may selectively activate or deactivate the calculation of each for any base station.

- The user can select an environment type, such as office building or warehouse, each of which has corresponding radio propagation path loss model which affects the prediction of coverage areas [29], [34].

- The user can experiment with different path loss models. The path loss models implemented in SMT *Plus* are described in Section 4.2.

- The user can interactively set values for the path loss parameters. For partition attenuation calculations, SMT *Plus* supports up to six different types of partitions which may exist in a building.

- The user may change the displayed contour resolution to improve SMT accuracy or calculation time.

- If working with a multifloor building, the user may move between floors, place base stations and interference source antennas on different floors, and view the resulting coverage contours on any floor in the building. The distance between floors (i.e., ceiling height) may be altered for any given floor. However, at the beginning of any SMT *Plus* session all floors are assigned a default ceiling height of 3.3 meters. If a different ceiling height is desired, it must be explicitly changed by the user. SMT *Plus* supports predictions for up to nine consecutive floors in a single building. If more than nine floors are desired, a sliding window approach must be taken, where only nine floors of a building are modeled at a time in SMT *Plus*.

Each of the preceding capabilities are provided by several specially developed SMT *Plus* commands. These commands are accessible via the SMT *Plus* menu or AutoCAD command prompt, and are discussed in Appendix C.

4.7.2 Assigning Environmental Parameters

SMT *Plus* enables a user to specify information concerning the site-specific database which impacts the coverage calculations discussed in Section 4.2. The path loss exponent, floor and partition attenuation factors, and the ceiling height and temperature of each floor are all customizable parameters. The SMT *Plus* commands ENVPARM, FAF/nMF, FLR_INFO, and PAFVAL enable the user to set these parameters. See Appendix C for a listing of SMT *Plus* specific commands for accessing and customizing these database parameters..

4.7.3 Positioning and Modeling Base Stations

4.7.3.1 Placing Base Station and Interference Source Antennas

The user locates base station antennas on the building layout through the BASESTAT command. Once activated, wherever the user clicks with the mouse within the drawing becomes the location of a new base station. In this manner, base station antennas can be created and visually positioned within a building floor plan. Similarly, interference source antennas are created and placed using the Int_Src command. Sources can be moved or deleted at will. Figure 4.4 shows a building layout with base station and interference source antennas positioned on it. Antennas located on building floors other than the currently displayed floor are either crossed out or shown with less intensity to differentiate them from those on the current floor. This provides immediate visual feedback on which sources are on the current floor.

4.7.3.2 Assigning Source Properties

A user may adjust the parameters of both base stations and interference sources using the Src_Info command. This will prompt the user to select either a base station or interference source antenna, and proceeds to display a dialog box similar to that in Figure 4.5. This presents detailed information concerning the operating characteristics of the selected source. The values on the right side of the dialog box correspond to the actual parameters assigned

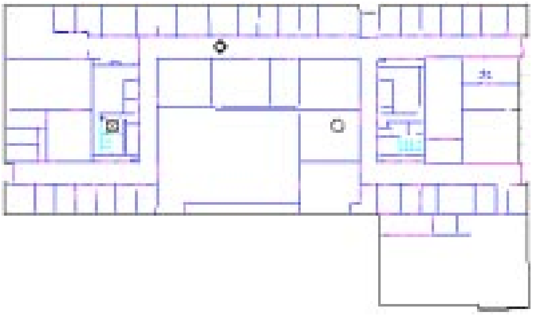


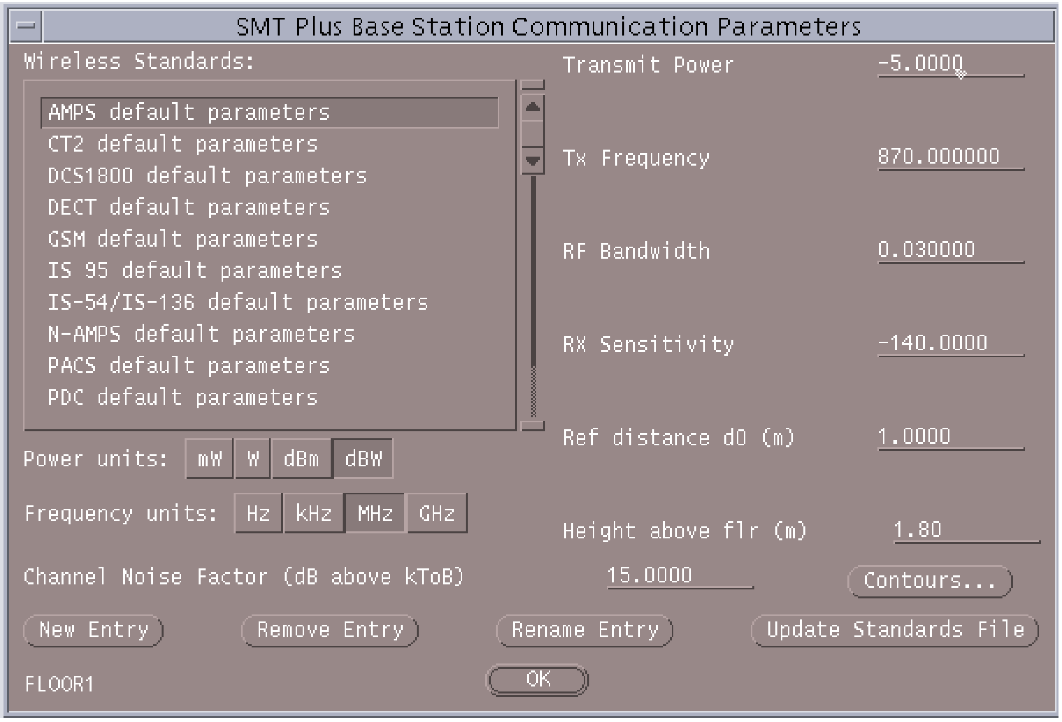
Figure 4.4: Building layout with a base station antenna, represented by a circle, and an interference source antenna, represented by a diamond, having been placed on the current floor. Another base station antenna, represented by a circle that has been crossed out, has been positioned on some other floor of the building.

to the source. The wireless standards listed on the left side corresponds to pre-established collections of the parameters on the right side of the dialog box. Please refer to the SRC_INFO command in Appendix C for more information on the specification of source characteristics, which is one of the most critical commands to the proper functioning of SMT Plus.

4.7.3.3 Wireless Standards

The calculations which SMT *Plus* performs depend upon transmitting base station parameters such as transmit power, frequency, RF bandwidth, and receiver parameters such as receiver sensitivity as discussed in Section 4.2. In using SMT *Plus*, entire sets of these parameters were developed and incorporated into the simulation of indoor wireless systems. To support this, SMT *Plus* provides the means to save and restore the parameter sets which are developed for particular systems or simulation runs. This is done via a text file named STANDARD.DAT, which contains information on all previously developed and stored wireless system parameters. SMT *Plus* reads STANDARD.DAT for stored parameter sets when it first initializes. These parameter sets are referred to as wireless standards within SMT *Plus*. The user has the ability to alter existing standards, create new standards, and remove existing standards. Standards are distinguished from one another by short descriptions given to them by the user as they are created.

Default wireless parameter sets have been developed for twelve of the most common wireless communication standards – AMPS, CT2, DCS-1800, DECT, GSM, IS-54/IS-136, IS-95, N-AMPS, PACS, PDC, PHS, and IEEE 802.11. These default parameter sets are always available to the user. In the event something happens to the STANDARD.DAT file, SMT


SMT Plus Base Station Communication Parameters

Transmit Power -5.0000

Tx Frequency 870.000000

RF Bandwidth 0.030000

RX Sensitivity -140.0000

Ref distance d0 (m) 1.0000

Height above flr (m) 1.80

Power units: dBW

Frequency units: MHz

Channel Noise Factor (dB above kToB) 15.0000

FLOOR1

Figure 4.5: SMT *Plus* BASE STATION PROPERTIES dialogue box.

PLUS recreates it using the default wireless parameter sets. The listing of STANDARD.DAT given in Appendix A details the default parameters used by SMT *Plus* for each of the above wireless communication standards.

In working with parameter sets, it is very important to understand that all base stations and interference source of the same named parameter set (i.e., the same wireless standard) share the exact same parameters. For example, if two base stations are created with the parameter set *AMPS default settings* and the transmit power of one of the base stations is changed, the transmit power of the other base station is automatically changed as well. To avoid this, a separate set of parameters must be established and assigned to the second base station. Any number of active base stations of any selected wireless standard may be placed within a building floor plan.

4.7.4 Assigning Simulation Boundaries

SMT *Plus* grants the user full control over the prediction of coverage regions. This is done by allowing the user to set boundary conditions on the coverage calculations discussed in Section 4.2. Once a base station antenna is positioned within the drawing database, as discussed in Section 4.7.3.1, boundary conditions may be placed on the coverage regions to be predicted for the antenna using the SRC_INFO command. Specifications on the coverage contours (i.e., number of vertices, resolution of the boundary, etc.) may be set using the RESOLUT command. See Appendix C for a description of these SMT *Plus* commands and more information on their usage.

4.7.5 Visualizing Simulation Results

After all base station and interference source antennas have been positioned in the building and have had their parameters defined as discussed in Section 4.7.3.2, a simulation can be performed. The first step is to select the desired propagation prediction model to apply. SMT *Plus* incorporates five different propagation models, each of which is discussed in Section 4.2.1. These can be selected using the MODEL command described in Appendix C. Once the desired single and multifloor models are selected, various other parameters associated with them may need to be specified. For instance, if the Partition Dependent path loss model is being used, the attenuation factors for each of the partitions in the drawing can be set using the PAFVAL command. Likewise, the value of the environmental path loss exponent can be set for the Distance Dependent model using the ENVPAR command. More information on this can be found in Section 4.7.2. The desired boundary conditions are specified as discussed in Section 4.7.4.

Once the desired simulation has been configured, coverage areas are predicted and coverage contours are generated. Contours are used to mark the physical location within the building database at which the user specified boundary conditions were satisfied. Figure 4.6 gives an example of a predicted set of coverage contours from an actual SMT *Plus* simulation. Depending on whether or not a given base station antenna is located on the currently displayed floor, SMT *Plus* automatically applies either the selected single floor or multifloor propagation model (i.e., the single floor models are used for base stations on the currently displayed floor, while the multifloor models are used for those which are not).

Whenever a coverage prediction is conducted for a given base station antenna, the coverage contours of that base station on the current floor are erased. However, coverage contours predicted for the base station on other floors in the drawing will not be erased. Coverage contours can be manually erased by the user if necessary.

SMT *Plus* makes use of a dynamic color allocation scheme which assigns a unique color to a coverage contour based upon the contour boundary limits specified by the user using the SRC_INFO command. All contours in a drawing which are of the same color share the same boundary conditions. What each color represents can be determined using the LEGEND

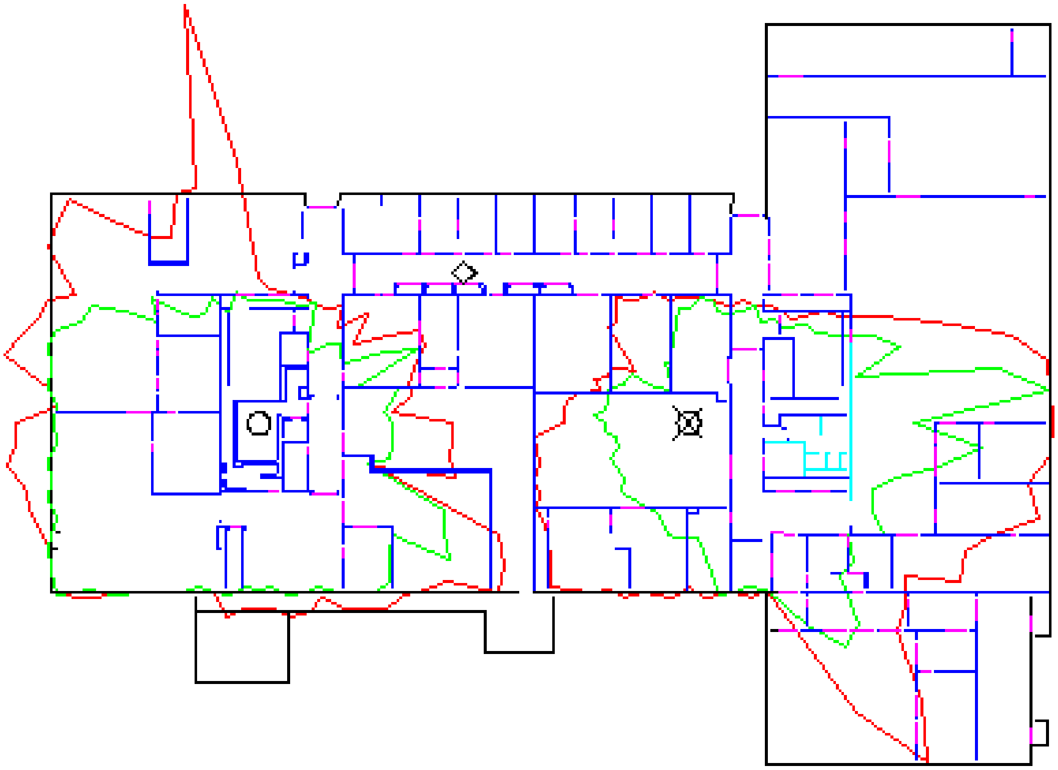


Figure 4.6: Sample coverage contours for two base station antennas on separate floors and a co-channel interference source predicted by SMT *Plus*. Note the effect of the co-channel interference source on the coverage area of the two base station antennas.

command, which will display a dialog box listing colors and what they symbolize. In very large simulations, it is possible that there will be many overlapping coverage contours. To help sort these out, the DISPLAY command allows certain types of contours to be turned off. For example, all RSSI contours can be made invisible. This will help reduce the clutter which may be generated on the screen.

Chapter 5

Combining Measurements With Coverage Predictions

5.1 Overview

Acquiring and analyzing RF measurement data is vital to any successful wireless communication system deployment. Measurements provide the means of gauging the radio propagation environment, and enable users to verify the results of prediction and simulation tools such as SMT *Plus*. Support for accommodating measurement data has been successfully added to the SMT *Plus* tool suite in the form of an interactive software package known as Measurement*Builder*.

During the fall of 1996, a comprehensive coverage analysis of a large, five story government building in the Washington, D.C., area was undertaken. The goal of this analysis was to fully test the SMT *Plus* tool in an actual wireless communication system design. Building floor plans were acquired and formatted using the Site*Planner* tool, and initial simulations were performed. At that time, it became obvious that there were some limitations to the design process. As shown in Section 4.2, the coverage calculations being performed by SMT *Plus* require knowledge of the attenuation properties of the building partitions [23], [30], [34]. However, in new building environments there is no way to have such information without first taking measurements throughout the building. This measurement campaign and the corresponding features added to SMT *Plus* to manipulate the measurement data led to the development of Measurement*Builder*. The remainder of this section is devoted to discussing the capabilities of Measurement*Builder* and describing its use in wireless system design.

5.2 Development of Measurement*Builder*

5.2.1 The Measurement Campaign

On November 30 and December 1, 1996, a large, five story government building in Washington, D.C., was the site of a large radio site survey. The objectives of the measurement campaign were to refine the partition attenuation factors for use in future SMT *Plus* simulations and expose any sections of the building which exhibit unusual propagation characteristics. During this campaign, detailed RF measurements were made throughout the building complex using cellular (870 MHz) and PCS (1870 MHz) base station transmitters located in seven positions within the building. The seven locations were selected based upon possible equipment access points and their desirability in terms of providing uniform building coverage. Key locations, such as areas with a history of poor wireless communications, were identified and included in the selected subset of base station antenna sites.

While the base station was transmitting a narrowband tone at known power and frequency, received signal strength (RSSI) measurements were taken throughout every floor and hallway in the building. This included several conference rooms, offices, and elevators. Data were taken continuously and stored in log files at two second intervals while the measurement equipment was walked throughout the building. In addition, approximately two hundred specific positions throughout all floors of the building were identified as measurement points for each base station antenna location at both cellular and PCS frequencies.

5.2.1.1 Measurement Equipment Overview

The equipment used in the measurement campaign consisted of two transmitters, each of which simultaneously broadcast 0.1 Watts (20 dBm) at 870 MHz and 1870 MHz, and a single, two channel receiver which captured the average received signal strength (RSSI) for both frequencies simultaneously at two second intervals. A schematic of the hardware set-up is shown in Figure 5.1.

The transmitters used for the measurements consisted of two calibrated signal generators: one, a HP 8648C, transmitting an 870 MHz continuous wave (CW) signal, and the other, a Fluke 6062A, transmitting an 1870 MHz CW signal. The outputs of the signal generators were then amplified by ZHL-1042J power amplifiers, and broadcast through 4-inch discone antennas matched to 50 Ohm impedances. The antennas were elevated to ceiling height, which was approximately fifteen to eighteen feet depending on the location. The output of the signal generators was carefully adjusted so that the net transmitted power,

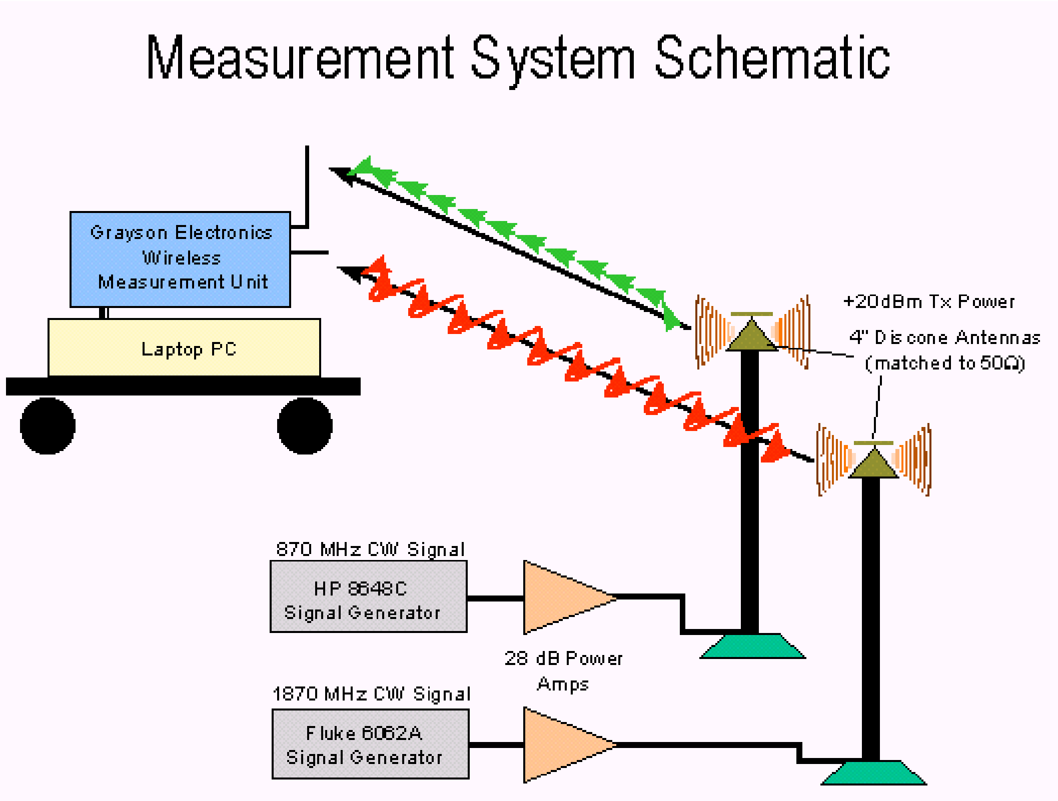


Figure 5.1: Hardware setup for the measurement campaign.

accounting for cable and antenna losses, was exactly 20 dBm at both cellular (870 MHz) and PCS (1870 MHz) frequencies.

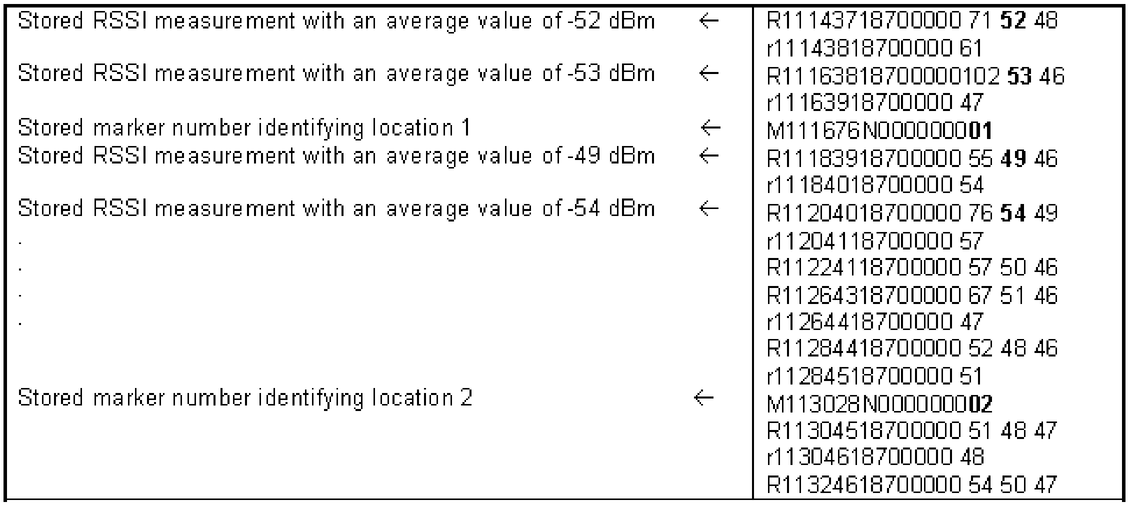
The receiver used for the measurements was an Allen Telecom (Grayson Electronics Division) SpectrumTracker^R Wireless Measurement System unit with two receiver channels. The input limits on the receiver ranged from a maximum input power of -42 dBm to the channel noise floor, which was in this case approximately -110 dBm. The RSSI values were stored in real time in a text file on a laptop computer. The ability of SpectrumTracker to simultaneously record measurement data from two channels and store it into a text file which could be analyzed at a later time was one of the principle reasons for using it as the receiver.

The measurement receiver automatically converts received signal strengths to digital values, and sends those values to a computer via a standard computer serial port. The receiver was connected via serial cable to a standard laptop computer, where outputs from the receiver were stored in data files. Received data collection was controlled by Allen Telecom SpectrumTracker(R) software. SpectrumTracker allows the user to define which frequencies are scanned for signal strength, how long the signal is averaged before a signal strength is recorded, and how often signal strength measurements are recorded. In this case, measured values were linearly averaged over a two second interval, with the final average value recorded in the data file every two seconds. This averaging removes any small-scale fading that might be present in the signal.

5.2.1.2 Recording Measurement Data

Once the equipment was configured and calibrations were verified at each base station location, signal strength measurements were made throughout the building complex. Received signal strength measurements were made on every floor and every hallway of the building for each base station location.

With the transmitters continuously broadcasting, the two channel receiver was walked throughout the building recording RSSI measurements for the selected frequencies. The RSSI measurement was based on linearly averaged received power over a two second interval. These average measurements were recorded every two seconds to data log files during a brisk walk through the entire building complex. In addition, the Grayson SpectrumTracker receiver has the capability of storing an incremental marker within the data log file. A marker provides the ability to associate measurement data in the log file with the physical locations in the building at which the data were collected. If the locations at which the markers were written are recorded, markers can be used as a reference for relating the



Stored RSSI measurement with an average value of -52 dBm	←	R11143718700000 71 **52** 48
		r11143818700000 61
Stored RSSI measurement with an average value of -53 dBm	←	R11163818700000102 **53** 46
		r11163918700000 47
Stored marker number identifying location 1	←	M111676N0000000**01**
Stored RSSI measurement with an average value of -49 dBm	←	R11183918700000 55 **49** 46
		r11184018700000 54
Stored RSSI measurement with an average value of -54 dBm	←	R11204018700000 76 **54** 49
.		r11204118700000 57
.		R11224118700000 57 50 46
.		R11264318700000 67 51 46
.		r11264418700000 47
		R11284418700000 52 48 46
		r11284518700000 51
Stored marker number identifying location 2	←	M113028N0000000**02**
		R11304518700000 51 48 47
		r11304618700000 48
		R11324618700000 54 50 47

Figure 5.2: Sample SpectrumTracker data log file from the on-site measurement campaign.

measurement data in the log file to the positions at which they were taken. Throughout the measurement campaign, markers were taken and their positions recorded on a printed building floor plan referred to as a data log sheet. With seven base station locations and over two hundred specific receiver locations for each, approximately 1600 marker locations were taken and recorded.

5.2.2 Characterizing the Building Propagation Environment

5.2.2.1 Importing Measurement Data

The result of the on-site measurement campaign was a large volume of data pertaining to the actual measured propagation environment of the building. This information was in the form of SpectrumTracker log files. Figure 5.2 displays a portion of a measured log file taken on the second floor of the building.

Figure 5.3 shows a portion of the corresponding data log sheet recorded for the log file in Figure 5.2. The numbers marked on the data log sheet correspond to the marker numbers recorded in the SpectrumTracker log file. As discussed in Section 5.2.1.2, this provides the ability to locate the position at which the measurements in the data log file were taken.

In order to be able to visually compare the recorded measurement data with SMT *Plus* predictions, the ability to automatically import the SpectrumTracker data log files and store the measurement data onto the building floor plan in SMT *Plus* was developed. The measured data points corresponding to each stored marker in the data log file were

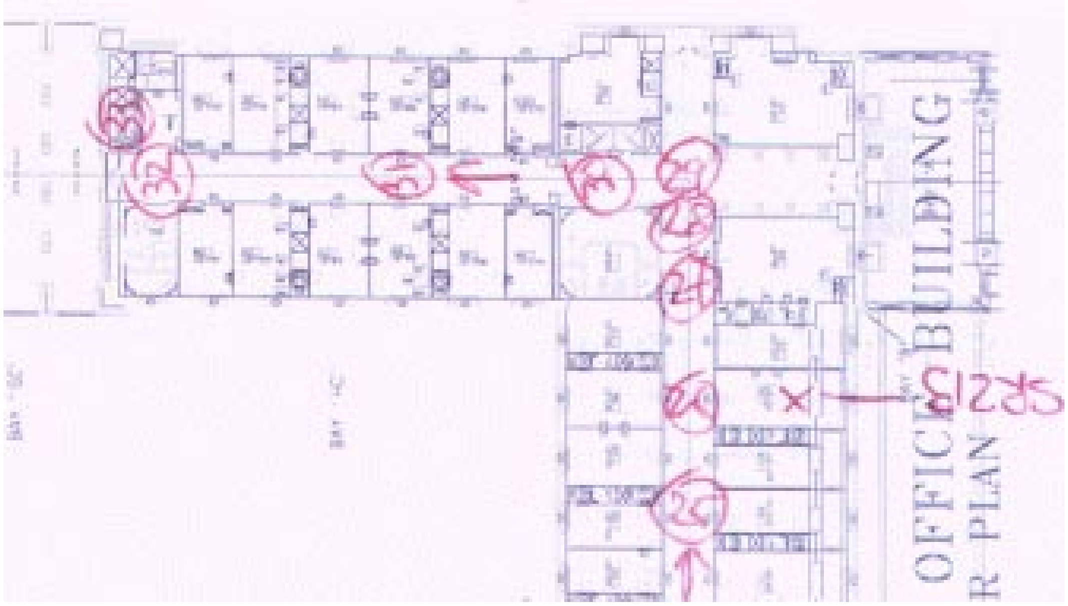


Figure 5.3: Portion of a data log sheet recorded during the on-site measurement campaign. The handwritten numbers correspond to marker locations in the data log file.

imported and stored directly onto the SMT *Plus* floor plans. The recorded position of the marker on the data log sheet was used as the location in the building database to store the corresponding measurement data. The data log file was parsed by the import routines, and the user was prompted to select the location on the building floor plan at which the measurement data was to be stored. Figure 5.4 shows the second floor building plans with the imported measurement points.

Having the measurement data recorded directly on the building floor plan alone is an invaluable resource to a wireless system designer. This also provides users of SMT *Plus* with the ability to visually compare simulation results with the actual recorded measurements. Figure 5.5 gives an example of visually verifying an SMT *Plus* simulation.

5.2.2.2 Optimizing SMT *Plus* Simulations Using Measurement Data

The purpose of the measurement campaign was to acquire enough information to quantify the attenuation characteristics of the building partitions. The goal was to identify the path loss parameters which would optimize the coverage predictions being performed by SMT *Plus*. With over 1600 stored measurement points across seven different base station locations for a five story building, there was a sufficient database to explore various optimization approaches.

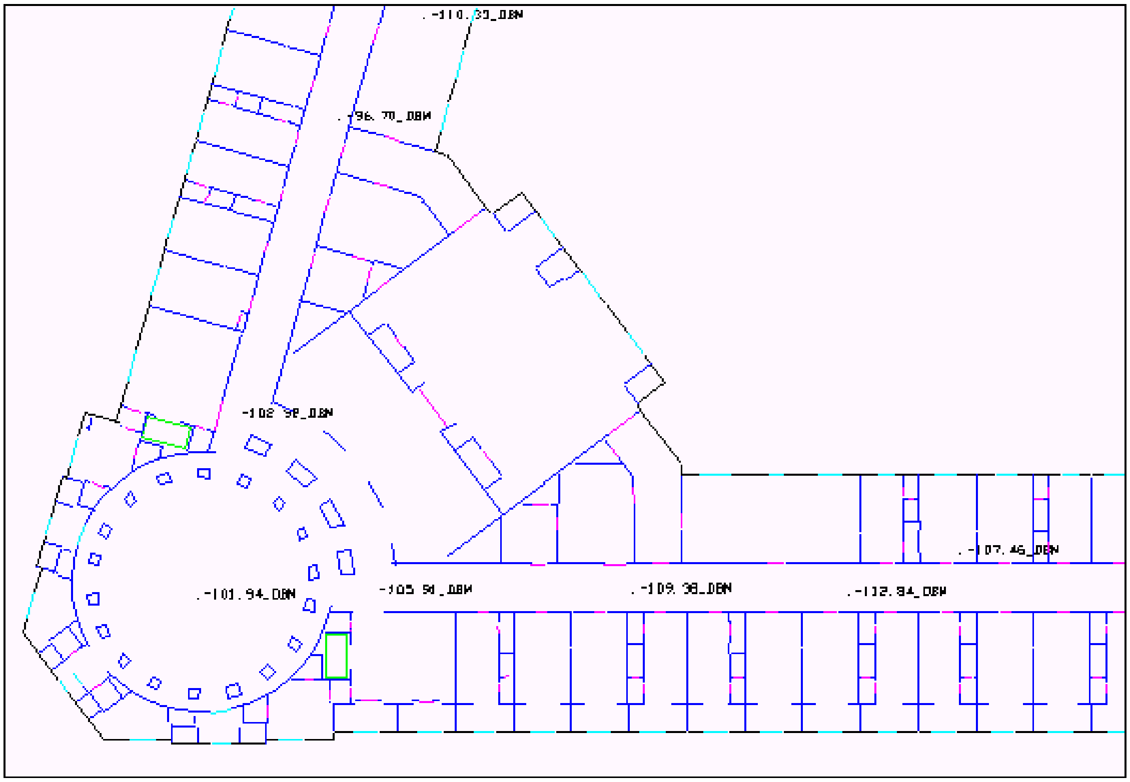


Figure 5.4: Portion of the building second floor with the local average PCS measurements stored directly on the floor plan within SMT *Plus*.

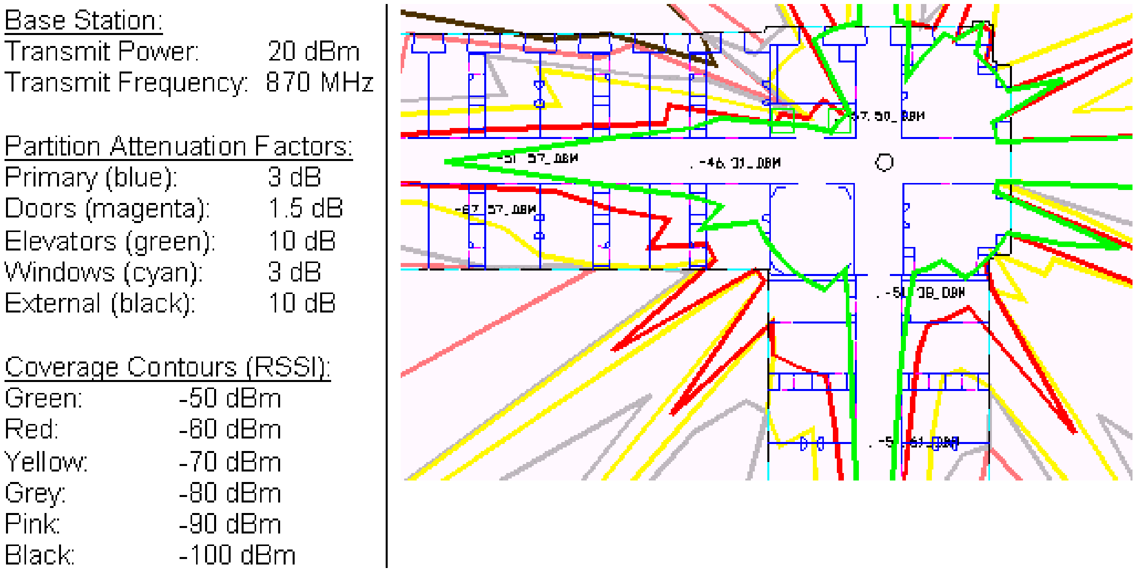
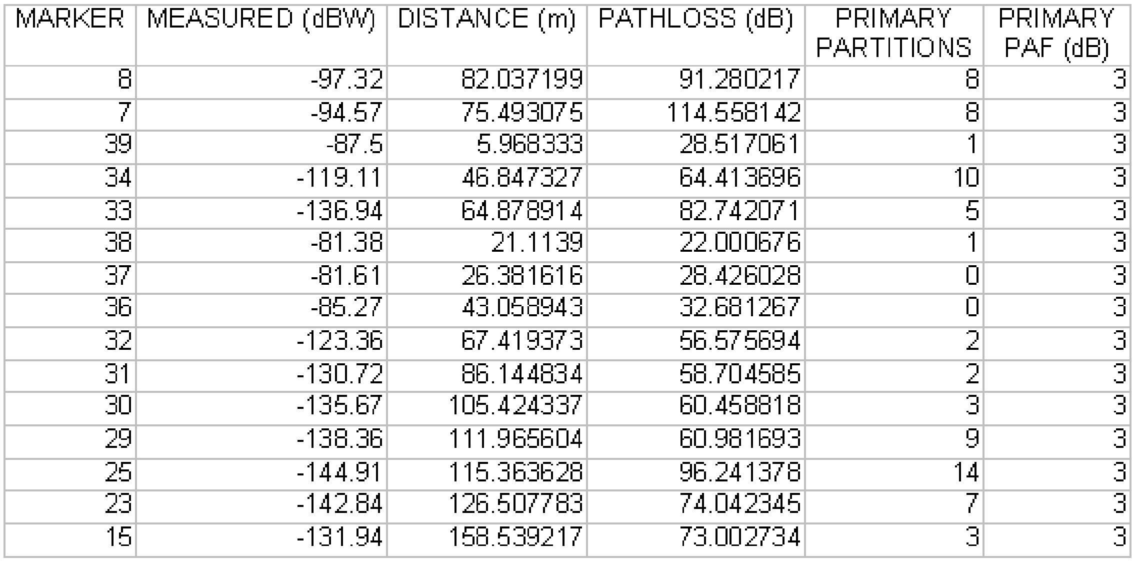


Figure 5.5: Comparing SMT *Plus* simulation results with recorded measurement data.

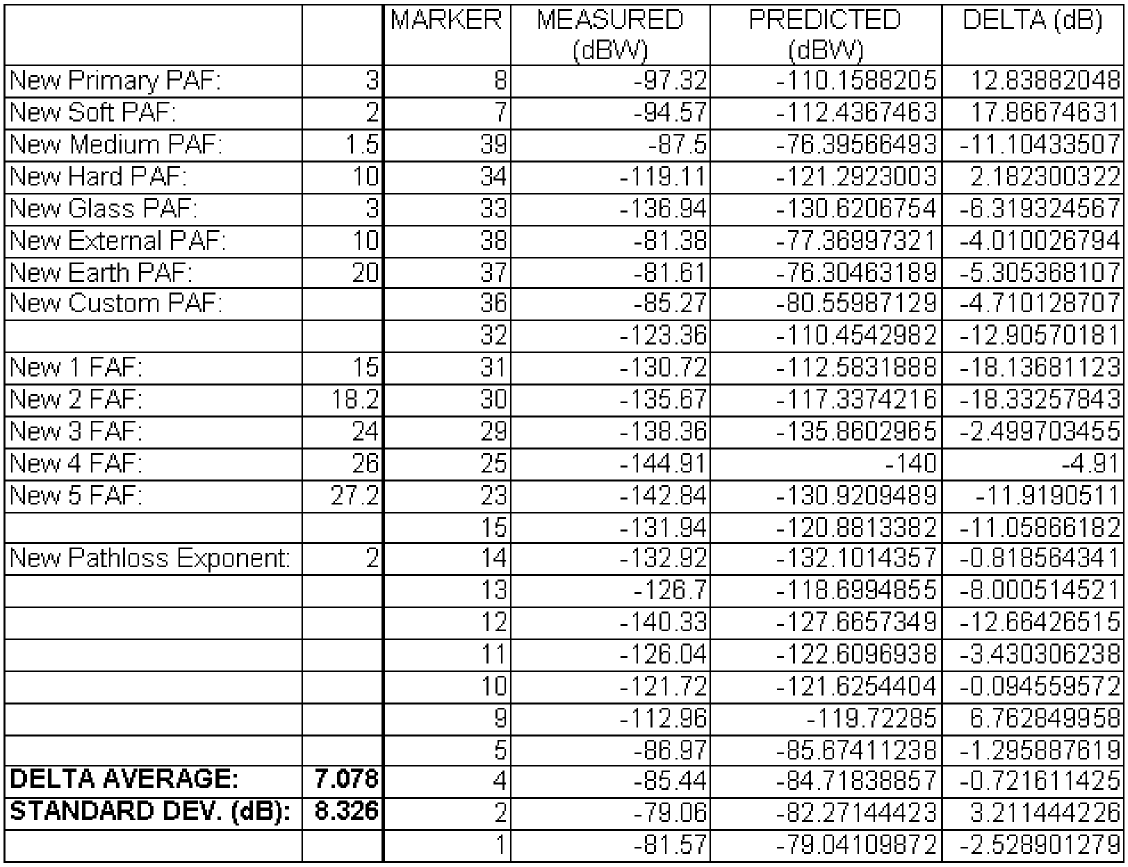


MARKER	MEASURED (dBW)	DISTANCE (m)	PATHLOSS (dB)	PRIMARY PARTITIONS	PRIMARY PAF (dB)
8	-97.32	82.037199	91.280217	8	3
7	-94.57	75.493075	114.558142	8	3
39	-87.5	5.968333	28.517061	1	3
34	-119.11	46.847327	64.413696	10	3
33	-136.94	64.878914	82.742071	5	3
38	-81.38	21.1139	22.000676	1	3
37	-81.61	26.381616	28.426028	0	3
36	-85.27	43.058943	32.681267	0	3
32	-123.36	67.419373	56.575694	2	3
31	-130.72	86.144834	58.704585	2	3
30	-135.67	105.424337	60.458818	3	3
29	-138.36	111.965604	60.981693	9	3
25	-144.91	115.363628	96.241378	14	3
23	-142.84	126.507783	74.042345	7	3
15	-131.94	158.539217	73.002734	3	3

Figure 5.6: Portion of a measurement analysis spreadsheet used in the optimization of SMT *Plus* calculations.

The ability to export columnar text files containing all the pertinent information for performing a link budget calculation between the base station antenna and a measurement point was added to SMT *Plus*. Files of this sort were created for each base station site and for each frequency at which measurements were recorded. These text files were easily imported into any popular commercial spreadsheet. The resulting spreadsheet contains forty-nine columns of data. The data ranged from the base station properties and characteristics to the number and type of partitions intersected in the path between the base station antenna and each measurement point in the drawing file. Figure 5.6 shows a portion of one of these spreadsheets.

Once all of the measurement data was in the form of spreadsheets, a detailed analysis of the propagation environment was undertaken. All of the information necessary for doing computer generated coverage prediction calculations and their comparisons to actual measured data was available, and the equations outlined in Section 4.2 for doing so were added to the spreadsheets. By doing this, the RSSI predictions of SMT *Plus* for each marker location can be directly compared to the actual measured RSSI value at that location. By manipulating the values of the attenuation factors for the partitions and floors, a closer agreement between the predictions and the actual measurements can be achieved. The basic idea is to achieve the smallest standard deviation in dB possible while maintaining a minimum average difference (i.e., closest to zero dB) between the predicted and measured



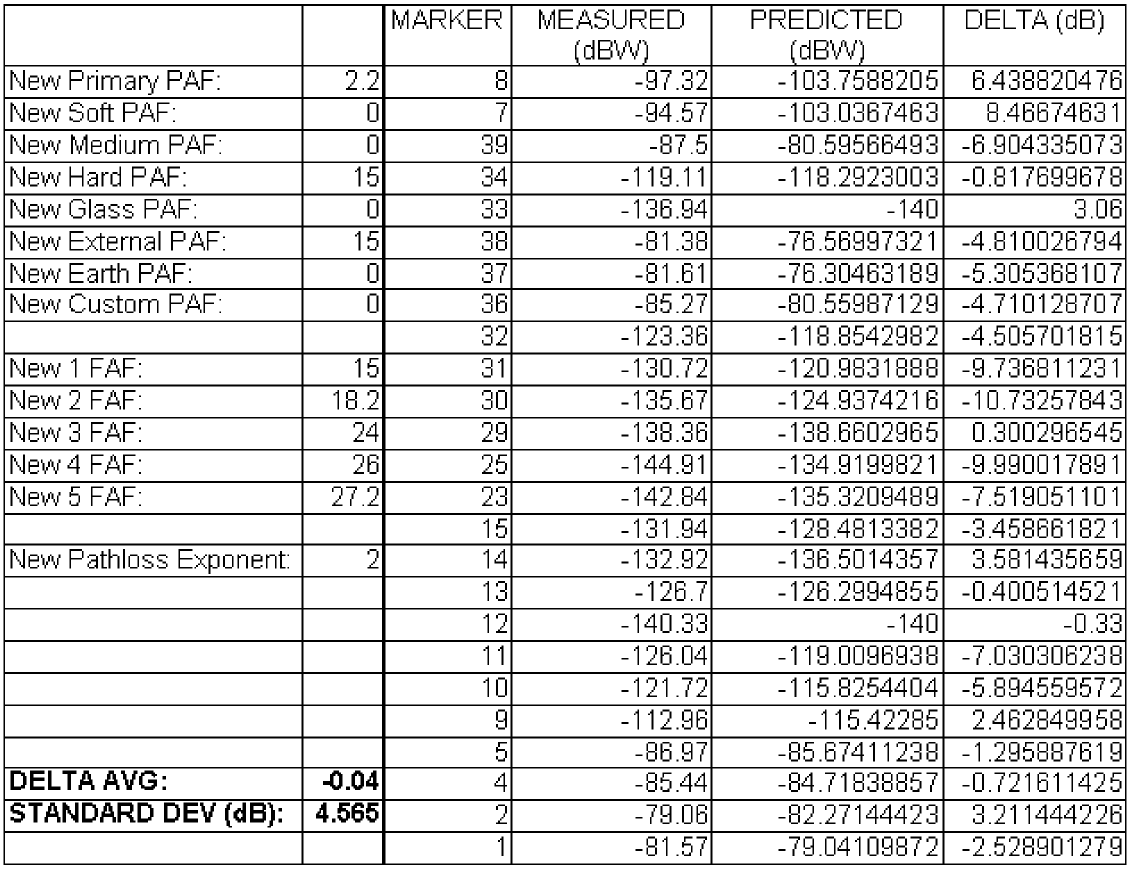
		MARKER	MEASURED (dBW)	PREDICTED (dBW)	DELTA (dB)
New Primary PAF:	3	8	-97.32	-110.1588205	12.83882048
New Soft PAF:	2	7	-94.57	-112.4367463	17.86674631
New Medium PAF:	1.5	39	-87.5	-76.39566493	-11.10433507
New Hard PAF:	10	34	-119.11	-121.2923003	2.182300322
New Glass PAF:	3	33	-136.94	-130.6206754	-6.319324567
New External PAF:	10	38	-81.38	-77.36997321	-4.010026794
New Earth PAF:	20	37	-81.61	-76.30463189	-5.305368107
New Custom PAF:		36	-85.27	-80.55987129	-4.710128707
		32	-123.36	-110.4542982	-12.90570181
New 1 FAF:	15	31	-130.72	-112.5831888	-18.13681123
New 2 FAF:	18.2	30	-135.67	-117.3374216	-18.33257843
New 3 FAF:	24	29	-138.36	-135.8602965	-2.499703455
New 4 FAF:	26	25	-144.91	-140	-4.91
New 5 FAF:	27.2	23	-142.84	-130.9209489	-11.9190511
		15	-131.94	-120.8813382	-11.05866182
New Pathloss Exponent:	2	14	-132.92	-132.1014357	-0.818564341
		13	-126.7	-118.6994855	-8.000514521
		12	-140.33	-127.6657349	-12.66426515
		11	-126.04	-122.6096938	-3.430306238
		10	-121.72	-121.6254404	-0.094559572
		9	-112.96	-119.72285	6.762849958
		5	-86.97	-85.67411238	-1.295887619
DELTA AVERAGE:	**7.078**	4	-85.44	-84.71838857	-0.721611425
STANDARD DEV. (dB):	**8.326**	2	-79.06	-82.27144423	3.211444226
		1	-81.57	-79.04109872	-2.528901279

Figure 5.7: Portion of the measurement analysis spreadsheet showing the accuracy of the SMT *Plus* predictions while utilizing default propagation parameters.

values over all floors and hallways.

In Figure 5.7, a portion of a measurement analysis spreadsheet is shown with the SMT *Plus* default attenuation properties in place for each partition type. Note the poor standard deviation of ±8.326 dB and average delta value of 7.078 dB between the predictions and the measured data in bold. This enables the user to gauge the accuracy of the predictions SMT *Plus* makes using those default attenuation values. After manually manipulating the attenuation properties and other coverage prediction variables, a much better matching between predicted and measured data results. This is shown in Figure 5.8. Note the standard deviation in this case is ±4.565 dB with an average difference of only 0.04 dB.

As can be seen from Figure 5.7 and 5.8, by manipulating the partition attenuation factors, the error between the simulations and the measured data can be greatly reduced. This same process of matching measured RSSI values with predictions was repeated for all



		MARKER	MEASURED (dBW)	PREDICTED (dBW)	DELTA (dB)
New Primary PAF:	2.2	8	-97.32	-103.7588205	6.438820476
New Soft PAF:	0	7	-94.57	-103.0367463	8.46674631
New Medium PAF:	0	39	-87.5	-80.59566493	-6.904335073
New Hard PAF:	15	34	-119.11	-118.2923003	-0.817699678
New Glass PAF:	0	33	-136.94	-140	3.06
New External PAF:	15	38	-81.38	-76.56997321	-4.810026794
New Earth PAF:	0	37	-81.61	-76.30463189	-5.305368107
New Custom PAF:	0	36	-85.27	-80.55987129	-4.710128707
		32	-123.36	-118.8542982	-4.505701815
New 1 FAF:	15	31	-130.72	-120.9831888	-9.736811231
New 2 FAF:	18.2	30	-135.67	-124.9374216	-10.73257843
New 3 FAF:	24	29	-138.36	-138.6602965	0.300296545
New 4 FAF:	26	25	-144.91	-134.9199821	-9.990017891
New 5 FAF:	27.2	23	-142.84	-135.3209489	-7.519051101
		15	-131.94	-128.4813382	-3.458661821
New Pathloss Exponent:	2	14	-132.92	-136.5014357	3.581435659
		13	-126.7	-126.2994855	-0.400514521
		12	-140.33	-140	-0.33
		11	-126.04	-119.0096938	-7.030306238
		10	-121.72	-115.8254404	-5.894559572
		9	-112.96	-115.42285	2.462849958
		5	-86.97	-85.67411238	-1.295887619
DELTA AVG:	**-0.04**	4	-85.44	-84.71838857	-0.721611425
STANDARD DEV (dB):	**4.565**	2	-79.06	-82.27144423	3.211444226
		1	-81.57	-79.04109872	-2.528901279

Figure 5.8: Portion of the measurement analysis spreadsheet showing the accuracy of the SMT *Plus* predictions with optimum propagation parameters.

floors in the building and indoor-to-outdoor signal leakage measurements with very similar results. By combining the measured data for all floors, global optimum floor and partition attenuation factor values matching measured to predicted values for global building coverage calculations were achieved for the building. This quantified the accuracy of the SMT *Plus* simulations in the building, which would not otherwise have been possible prior to the deployment of the final system.

5.2.2.3 Results of the Measurement Campaign

After optimizing the simulations being performed by SMT *Plus* using the measurement data analysis spreadsheets, the overall accuracy of the simulations was found to have a mean standard deviation of ±7.3 dB. This involved all measurement points across all floors for all base station locations. This matches fairly closely with the theoretical accuracy discussed in Section 4.4.

It is interesting to note that a closer matching of predictions to measurements occurred when the number of modeled partition types in the building was decreased. Removing doors and windows from the building database improved the accuracy of the simulations. Whether this was an artifact of the architecture of the building or the approach taken to model the building in SMT *Plus* needs to be investigated in the future.

The measurement campaign provided major contributions to the SMT *Plus* tool suite. The foundations of Measurement*Builder* were created due to the demands of the project. As a result of the ability to manipulate measurements and incorporate them directly into AutoCAD drawings, the power and flexibility of SMT *Plus* is greatly enhanced. Using measurement data in the calculations SMT *Plus* performs provides a means of gauging the accuracy of those predictions. This enables a user to optimize the path loss parameters used in SMT *Plus*. The end result is the closest possible matching between the predictions SMT *Plus* provides and the actual measurement information.

5.3 Measurement*Builder*

5.3.1 System Overview

Measurement*Builder* was created as a link between prediction and measurements, which is necessary to maximize the performance of tools such as SMT *Plus*. A powerful stand alone tool in its own right, Measurement*Builder* currently enables users to import stored measurement data into an AutoCAD building floor plan and manipulate that data in a variety of ways. Users of SMT *Plus* can then make use of the information to optimize the simulations being performed as described in Section 5.2.2.2.

Chapter 6

Three Dimensional Antenna Radiation Patterns

6.1 Overview

The SMT *Plus* design software and developing ray tracing tools promise an unprecedented amount of site-specific information regarding the performance of communication systems. At the core of each of these modeling tools is the need to simulate the operation of the wireless hardware used to create the communication link between transmitter and receiver. One of the key components in the performance of this link is the antenna. Being able to quickly simulate the effect of antennas without sacrificing accuracy is crucial to the overall usefulness site-specific tools [5], [11], [35]. To effectively model an antenna in a three dimensional environment, information on the antenna radiation pattern in three dimensions is needed. Currently, commercial antenna manufacturers do not provide this degree of information.

The following chapter presents a novel software tool that enables a wireless communication system designer to visualize the three dimensional radiation pattern of any antenna. The tool, Antenna*Builder*, is being developed to complement wireless communication system simulation programs such as SMT *Plus*, providing efficient access to the three dimensional antenna pattern information.

6.2 Project Goals

To properly design future wireless systems, it will be necessary to have access to easy to use, powerful visualization tool for representing the three dimensional radiation pattern of any standard antenna given the basic information available from the antenna manufacturer. Several desirable features in such a tool are listed below.

- Well-designed, object oriented program code to ease any future extensions to the tool.
- Portability between a variety of computing platforms.
- An intuitive graphical user interface suitable for experienced RF engineers and beginning students alike.
- A configurable viewpoint to allow the user to view the antenna pattern from a variety of perspectives.
- The ability to draw from a variety of input formats in reconstructing the three dimensional pattern.
- The ability to export the reconstructed pattern into a format suitable for use in wireless communication system simulation tools such as SMT *Plus*.

This thesis has undertaken the development of Antenna*Builder*, a tool that meets the above objectives. Most of the goals mentioned above have already been successfully met, and remaining issues will be pursued by future students. The remainder of this chapter discusses the progress that has been made on Antenna*Builder*.

6.3 Three Dimensional Antenna Pattern Visualization

This section describes the basic algorithms incorporated into Antenna*Builder* for generating three dimensional antenna patterns. The type of algorithm used depends upon the type of antenna being modeled along with the source of information regarding the radiation pattern. All of the algorithms depend upon some initial knowledge of the radiation pattern.

6.3.1 Two Dimensional Azimuth and Elevation Planar Patterns

Typically, commercial antenna vendors supply information regarding the antennas they manufacture in the form of the radiation pattern in one or more planes intersecting the antenna [5], [19], [35]. These planes are typically referred to as the azimuth and elevation plane, respectively [35]. Given the coordinate system shown in Figure 6.1, the azimuth plane may be formed by the xy-axis (i.e., holding θ equal to 90°), while the elevation plane may be formed by the xz-axis (i.e., holding ϕ equal to 90°) [19], [35]. In other terminology,

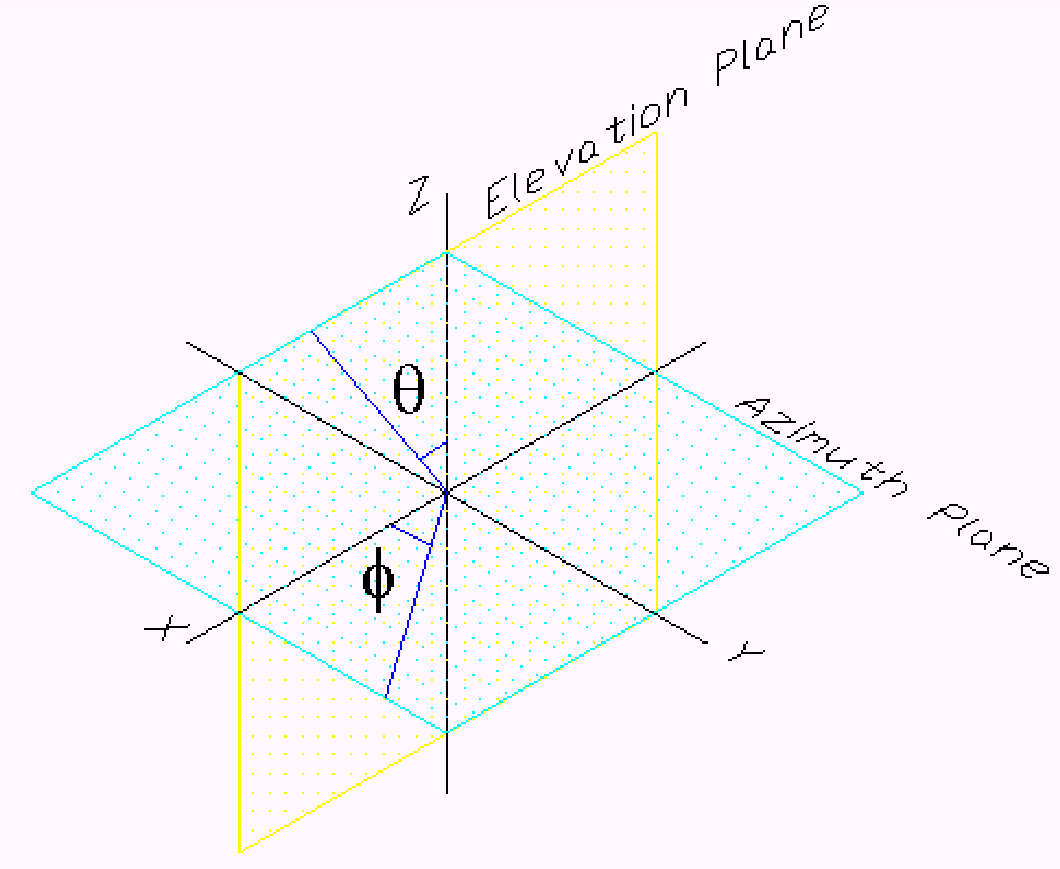


Figure 6.1: Azimuth and elevation planes on a Cartesian axis.

the azimuth plane is referred to as the horizontal plane, while the elevation plane is referred to as the vertical plane [3], [5].

Given a quarterwave dipole antenna centered at the origin, the radiation pattern extends outward in all directions similar to Figure 6.2. Commercial antenna vendors typically measure the gain pattern by sweeping 360 degrees around the antenna in the azimuth and elevation planes [5], [19], [25], [35]. The result is identical to slicing the antenna gain pattern by the two planes. These planar slices, when removed and viewed individually, look similar to Figures 6.3 and 6.4. Effectively, the antenna radiation gain pattern in those two dimensions is isolated and recorded. This data is then discretized and supplied in the form of antenna pattern files, which provide the measured gain values corresponding to specific θ and ϕ directions. Figures 6.5 and 6.6 give an example of a typical planar pattern and the corresponding discretized pattern file supplied by one such vendor.

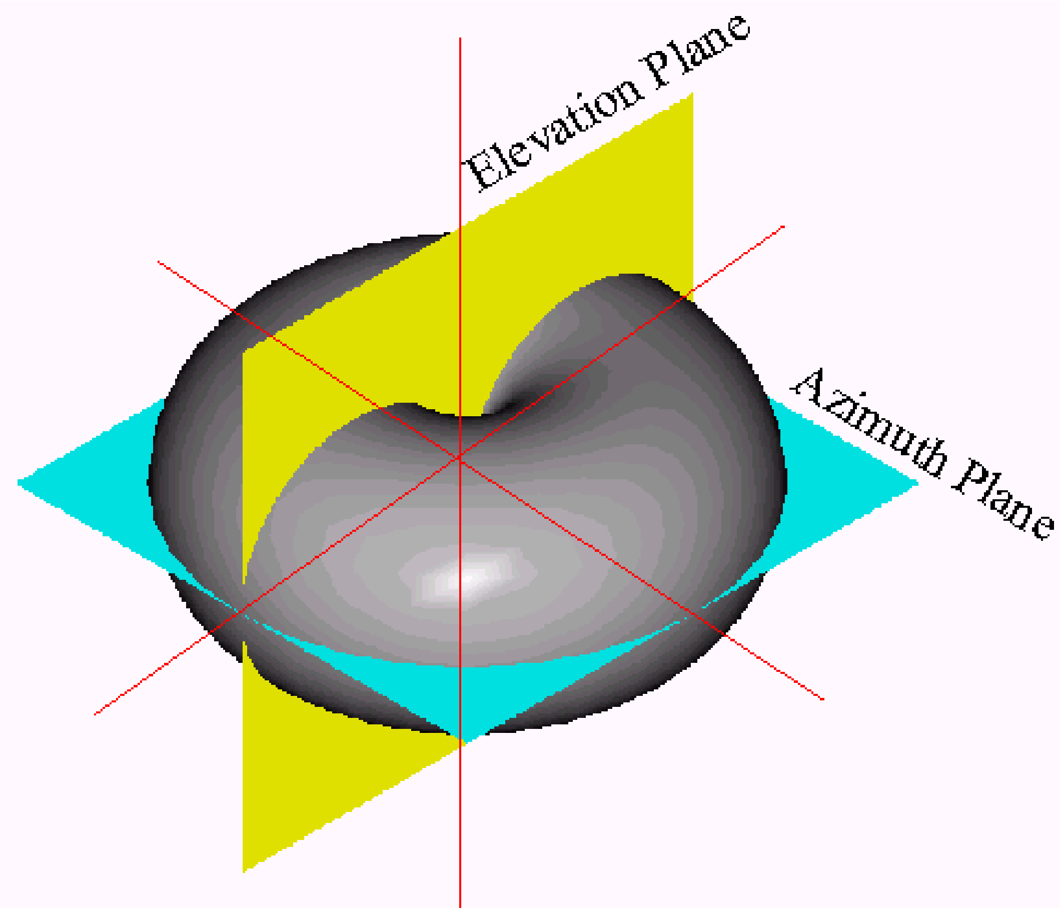


Figure 6.2: A quarterwave dipole antenna radiation pattern.

6.3.2 Antenna Pattern Reconstruction Algorithms

6.3.2.1 Elliptical Fit by Quadrant Method of Antenna Pattern Reconstruction

The technique described below is a variation on the traditional elliptical fit algorithm for reconstructing the original three dimensional radiation pattern from two planar radiation patterns [19], [25], [35]. Although not as fast as the elliptical fit algorithm, a much better reconstruction of the original pattern can result. This technique also avoids the computational overhead of working directly with electromagnetic fields to represent the radiation pattern [5], [16], [25]. Figure 6.7 shows the two planar cuts of Figure 6.5 and 6.6 discretized into the individual measurement points stored in the antenna pattern files. In the figure, the two patterns are aligned in three dimensions with respect to each other exactly as they were measured.

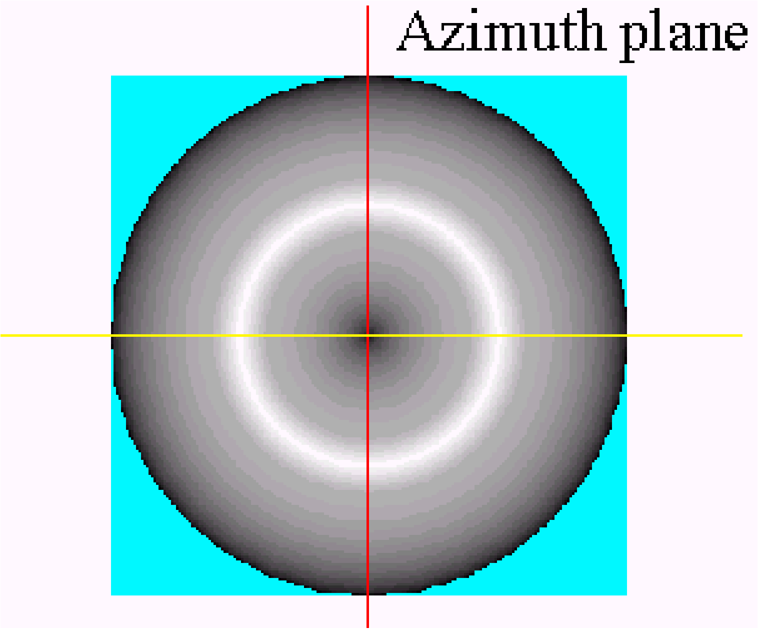


Figure 6.3: Dipole antenna radiation pattern in the azimuth plane.

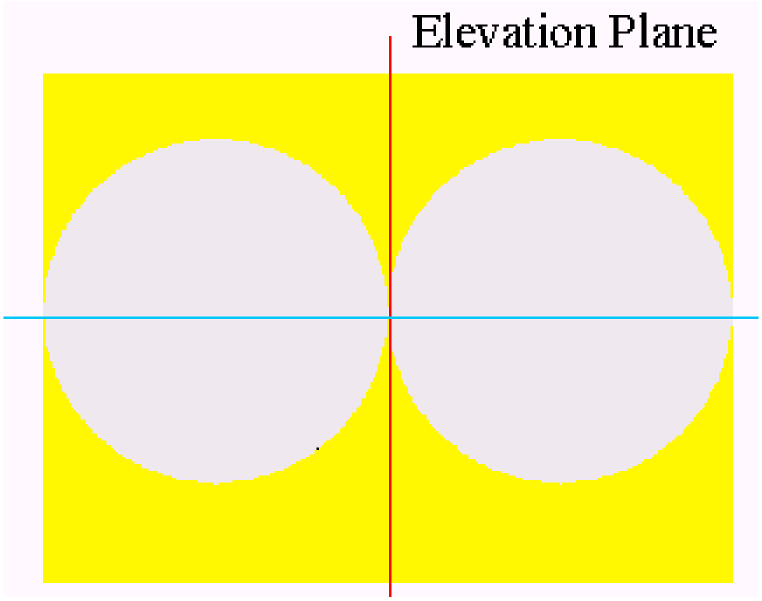


Figure 6.4: Dipole antenna radiation pattern in the elevation plane.

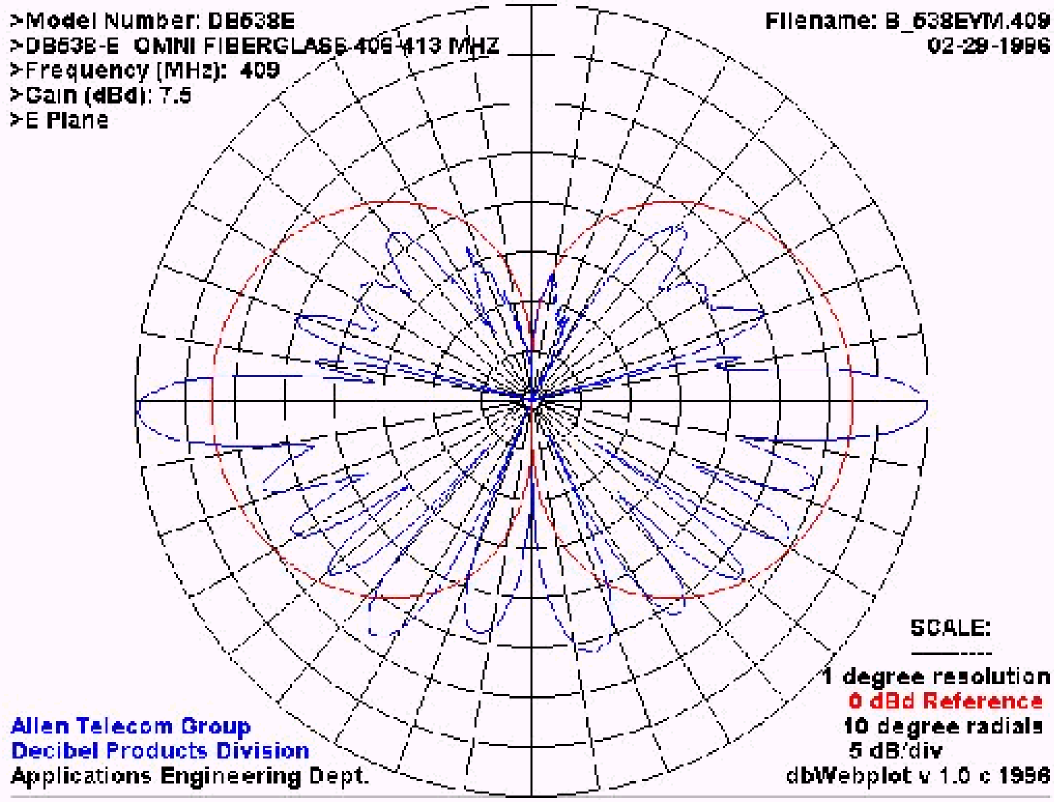
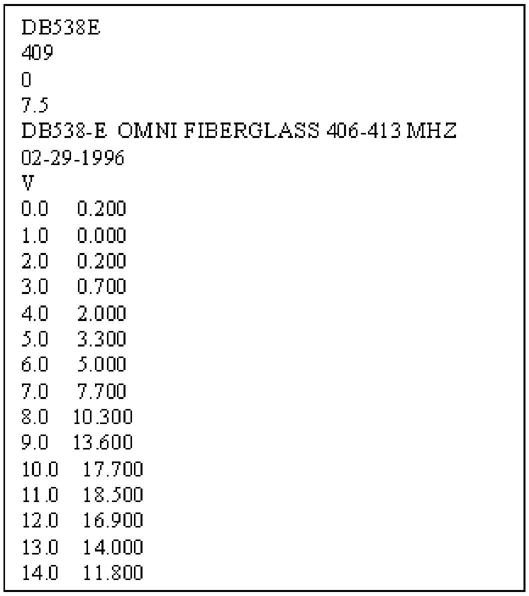


Figure 6.5: Typical elevation plane pattern. Taken from Decibel Products DB538E public domain antenna file Web page.



```
DB538E
409
0
7.5
DB538-E OMNI FIBERGLASS 406-413 MHZ
02-29-1996
V
0.0    0.200
1.0    0.000
2.0    0.200
3.0    0.700
4.0    2.000
5.0    3.300
6.0    5.000
7.0    7.700
8.0   10.300
9.0   13.600
10.0   17.700
11.0   18.500
12.0   16.900
13.0   14.000
14.0   11.800
```

Figure 6.6: Portion of the antenna pattern file corresponding to the elevation plane pattern. Taken from Decibel Products DB538E public domain antenna file Web page.

Figure 6.8 shows the same graph reoriented such that the x-axis is coming out of the page. Assuming that the angular resolution of the azimuth and elevation cuts is the same (i.e., both pattern files contain the same number of gain points), if we slice the figure in the yz-plane at each discrete azimuth point, we should receive a figure that closely resembles Figure 6.8. Figure 6.9 shows another representation of this.

Every slice in the yz-plane will consist of two points from the azimuth plane and two from the elevation plane. Given an angular resolution of n degrees, where n divides 360 degrees evenly, the number of yz-planar slices which can be formed is:

$$\frac{360^\circ}{2n^\circ} - 1 \tag{6.1}$$

The minus one is a result of the maximum and minimum dimension of the pattern along the x-axis resolving into a single point instead of four discrete points as in Figure 6.8.

Referring to Figures 6.8 and 6.10, the three dimensional pattern is reconstructed using the elliptical fit by quadrant algorithm. Letting each azimuth and elevation point pair bordering the same quadrant of the graph in Figure 6.10 represent the major and minor axis of an ellipse, an equation can be derived of the form:

$$\frac{Y^2}{Y'} + \frac{Z^2}{Z'} = 1 \tag{6.2}$$

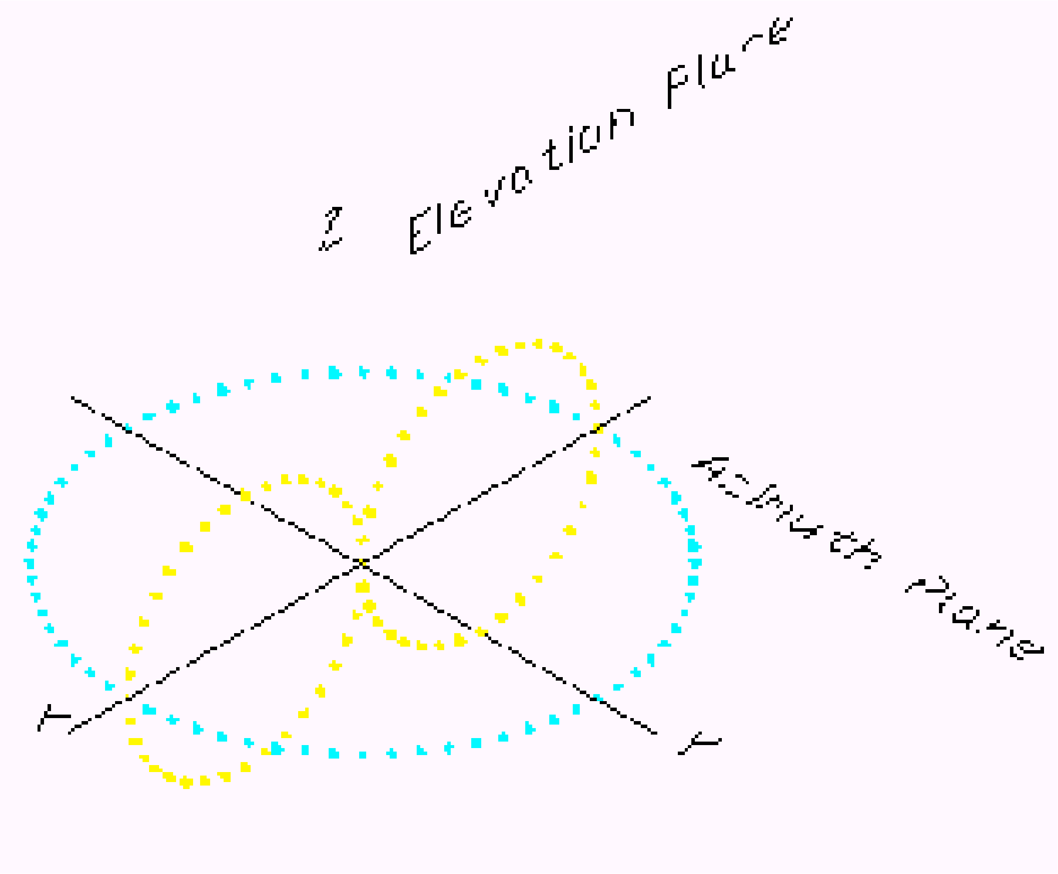


Figure 6.7: Discretized azimuth and elevation antenna patterns for the quarterwave dipole antenna.

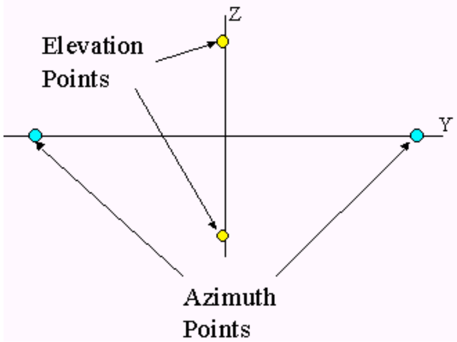


Figure 6.8: Planar cut through the yz-plane.

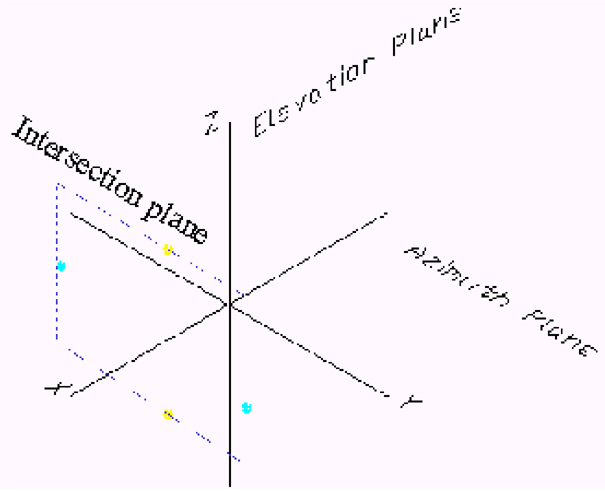


Figure 6.9: Three dimensional perspective of the yz-planar cut

where Y' and Z' are the perpendicular distances from the discrete gain points to the axes.

This provides a continuous function for describing the pattern arc connecting the azimuth and elevation point in that quadrant. By repeating this for all four quadrants, a plot closely resembling Figure 6.11 is created. By repeating the entire procedure for each yz-planar cut, a series of quarter-elliptical curves spaced along the x-axis outline the reconstructed three dimensional antenna gain. This is shown in Figure 6.12.

It is obvious from Figure 6.12 that there is a problem. The reconstructed pattern does not exactly match the actual pattern shown in Figure 6.2. This is due to the application of the elliptical fit algorithm to an omnidirectional antenna pattern. An omnidirectional antenna is one whose azimuth radiation pattern approximates a circle [35]. The elliptical fit algorithm is designed to accommodate directional antenna patterns, but it cannot adequately model all omnidirectional antennas. The following section discusses the method Antenna*Builder* uses to accurately model omnidirectional patterns.

6.3.2.2 Closed Form Equations in Antenna Pattern Reconstruction

Section 6.3.2.1 assumed that the discrete azimuth and elevation planar antenna gain pattern data were acquired from individual antenna pattern files similar to the one in Figure 6.6. Many common types of antennas can have one or both of their planar pattern data, or their complete three dimensional radiation pattern, described by one or more closed form equations [16], [19], [25], [35]. Generally, these antennas are of the omnidirectional variety,

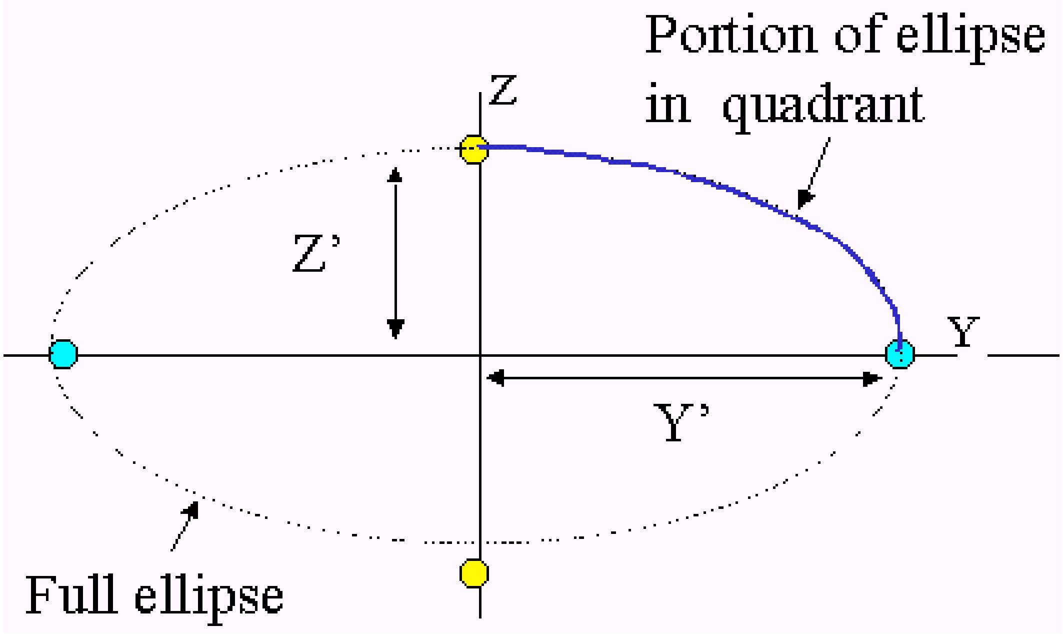


Figure 6.10: Applying the elliptical fit by quadrant algorithm. Only the portion of the ellipse within the quadrant being analyzed is kept. This forms the basis for the three dimensional pattern reconstruction within this yz-planar slice.

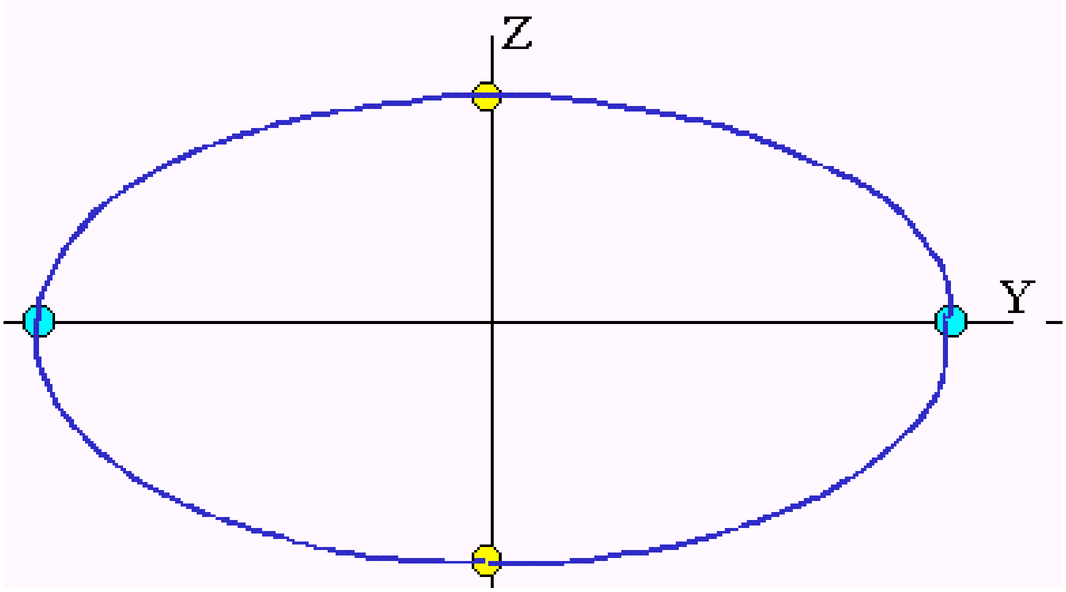


Figure 6.11: Resulting plot after applying the elliptical fit by quadrant algorithm to each quadrant in the yz-plane.

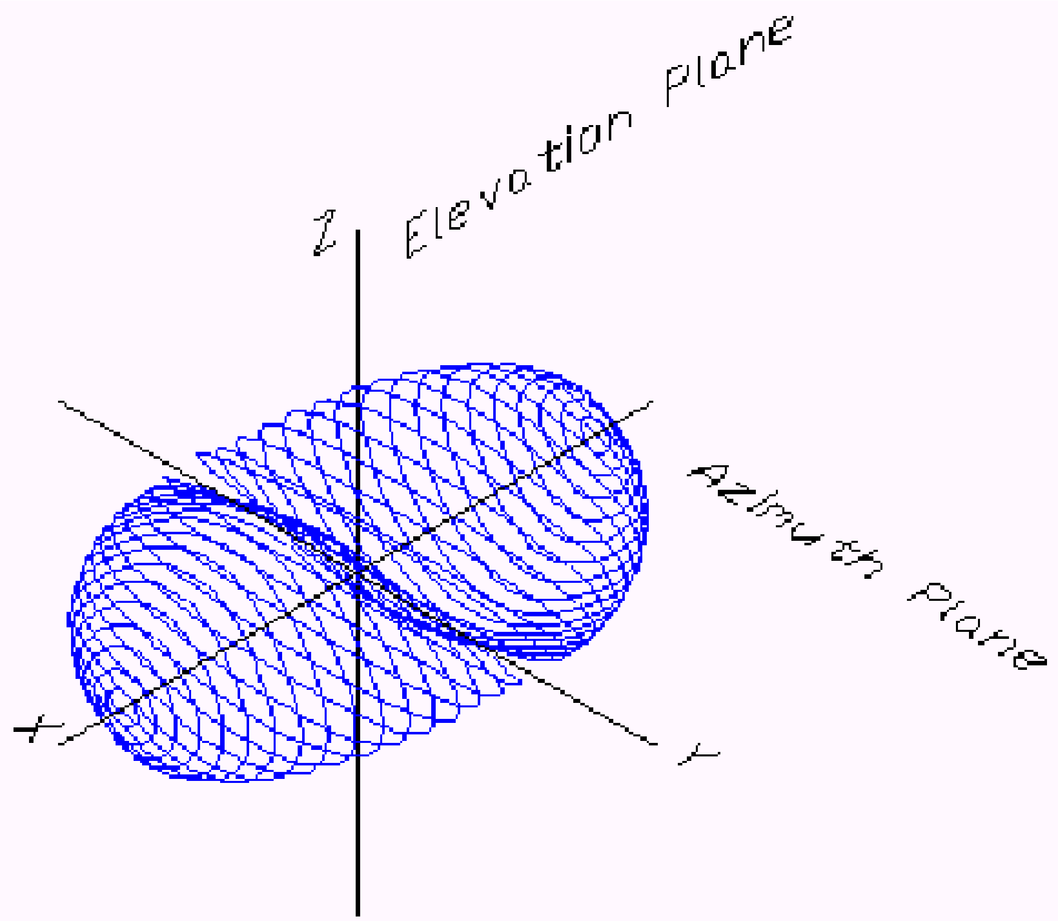


Figure 6.12: Three dimensional perspective after applying the elliptical fit by quadrant algorithm.

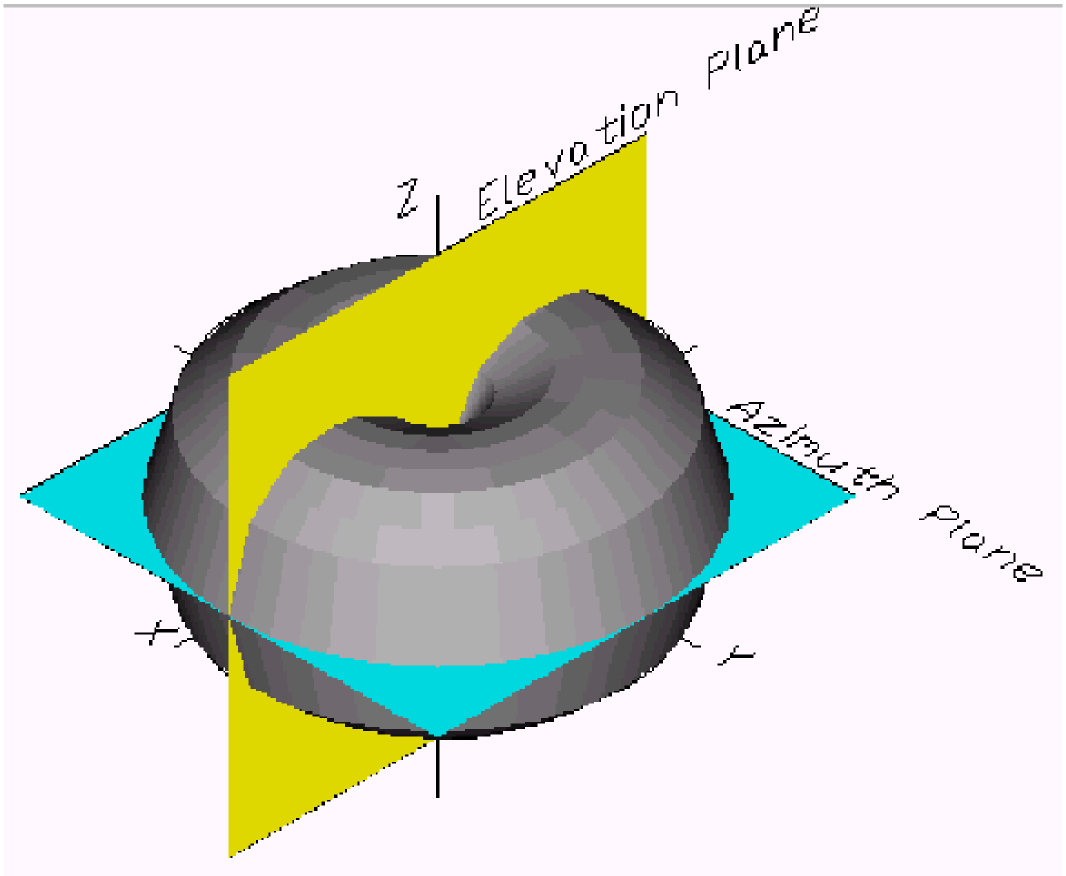


Figure 6.13: Reconstructed omnidirectional pattern for a quarterwave dipole antenna using closed form equation approximations.

meaning that the azimuth planar pattern closely resembles a circle as shown in Figure 6.3. By supplying a single equation that accurately describes the full three dimensional antenna pattern, the technique discussed in Section 6.3.2.1 is no longer necessary. The display of the three dimensional radiation pattern becomes a matter of simply graphing the equation.

Applying this technique to the antenna pattern shown in Figure 6.2, the reconstructed three dimensional antenna pattern produced by Antenna*Builder* is shown in Figure 6.13. This is a much more acceptable result than that given in Figure 6.13. Increasing the angular resolution at which the closed form equation is evaluated results in a much smoother approximation of the pattern at the expense of increased calculation time.

Several omnidirectional antennas and their associated closed form pattern equations are given in Table 6.1. Since the gain of omnidirectional antennas in the azimuth plane approximates a circle, only the equation describing the pattern as θ varies is given. The derivation for these equations may be found in [5], [16], [19], [25], and [35].

6.3.3 Three Dimensional Pattern Reconstruction Accuracy

Quantifying the accuracy of the three dimensional pattern reconstruction algorithm given in Section 6.3.2.1 compared to actual measurements has not yet been thoroughly investigated, and this is a topic of future research. It is initially evident that the antenna boresight should be aligned in one of the planes for which a planar pattern slice is available in order for the elliptical fit by quadrant method to succeed. This is an artifact of the reconstruction algorithm, which does not account for spurious sidelobes that do no fall in either the azimuth or elevation planes.

6.4 Antenna*Builder* Implementation

6.4.1 System Overview

Antenna*Builder* is the software implementation of the three dimensional antenna pattern reconstruction algorithms given in Section 6.3.2 and represents the culmination of the discussions in Sections 6.1 and 6.2. Written in C++, Antenna*Builder* is an interactive program that uses AutoCAD as a graphical shell. All display routines and interaction with the user is handled from within AutoCAD. The object-oriented design approach was taken to allow greater flexibility in extending or manipulating the design by future researchers. The existing system meets the majority of the goals put forth in Section 6.2.

6.4.1.1 Working with Antenna*Builder*

Figure 6.14 provides a screen capture of the Antenna*Builder* user interface. From this graphical user interface, all of the Antenna*Builder* functionality is available. Figure 6.15 shows the specific screen presented to a user when initially modeling a new antenna.

The minimum information required by Antenna*Builder* is a description of the antenna pattern in the azimuth and elevation planes. This is done either by selecting from the list of closed form equations or specifying a file source for the azimuth and elevation radiation pattern information similar to that shown in Figure 6.6. From the dialogue box shown in Figure 6.15, a user specifies the source of the pattern information for the azimuth and elevation planes, or the omnidirectional equation to use in reconstructing the three dimensional pattern.

Once the azimuth and elevation pattern sources are specified, additional information, such as the angular resolution of the three dimensional pattern, maximum antenna gain,

Table 6.1: Sample omnidirectional antennas and their associated closed form equation approximations in dB.

Isotropic Antennas

$$Gain(\theta) = 0 \text{ , for all } \theta. \tag{6.3}$$

Quarterwave Dipole/Biconic

$$Gain(\theta) = 20log_{10}\left|\frac{\cos(0.25\pi\cos(\theta)) - \cos(0.25\pi)}{\sin(\theta)}\right| \tag{6.4}$$

for $0^\circ < \theta < 180^\circ, 180^\circ < \theta < 360^\circ$, 0 elsewhere

Halfwave Dipole/Biconic

$$Gain(\theta) = 20log_{10}\left|\frac{\cos(0.5\pi\cos(\theta))}{\sin(\theta)}\right| \tag{6.5}$$

for $0^\circ < \theta < 180^\circ, 180^\circ < \theta < 360^\circ$, 0 elsewhere

Quarterwave Monopole/Discone

$$Gain(\theta) = 20log_{10}\left|\frac{1.4782\cos(0.5\pi\cos(\theta))\sin(2.5\sin(\theta))}{\sin(\theta)}\right| \tag{6.6}$$

for $0^\circ < \theta < 180^\circ, 180^\circ < \theta < 360^\circ$, 0 elsewhere

Halfwave Monopole

$$Gain(\theta) = 20log_{10}\left|\frac{1.2015\Big[\cos(\pi\cos(\theta)) + 1\Big]\sin(2.75\sin(\theta))}{\sin(\theta)}\right| \tag{6.7}$$

for $0^\circ < \theta < 180^\circ, 180^\circ < \theta < 360^\circ$, 0 elsewhere

Fullwave Biconic

$$Gain(\theta) = 20log_{10}\left|\frac{\cos(\pi\cos(\theta)) + 1}{\sin(\theta)}\right| \tag{6.8}$$

for $0^\circ < \theta < 180^\circ, 180^\circ < \theta < 360^\circ$, 0 elsewhere

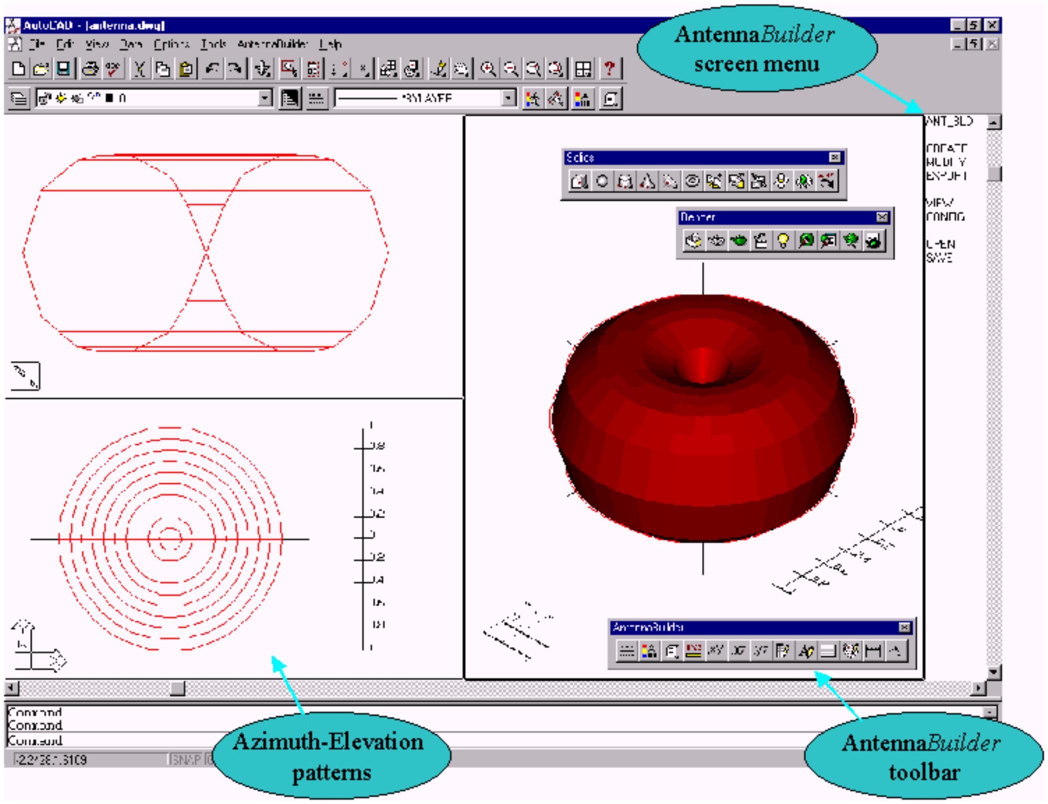
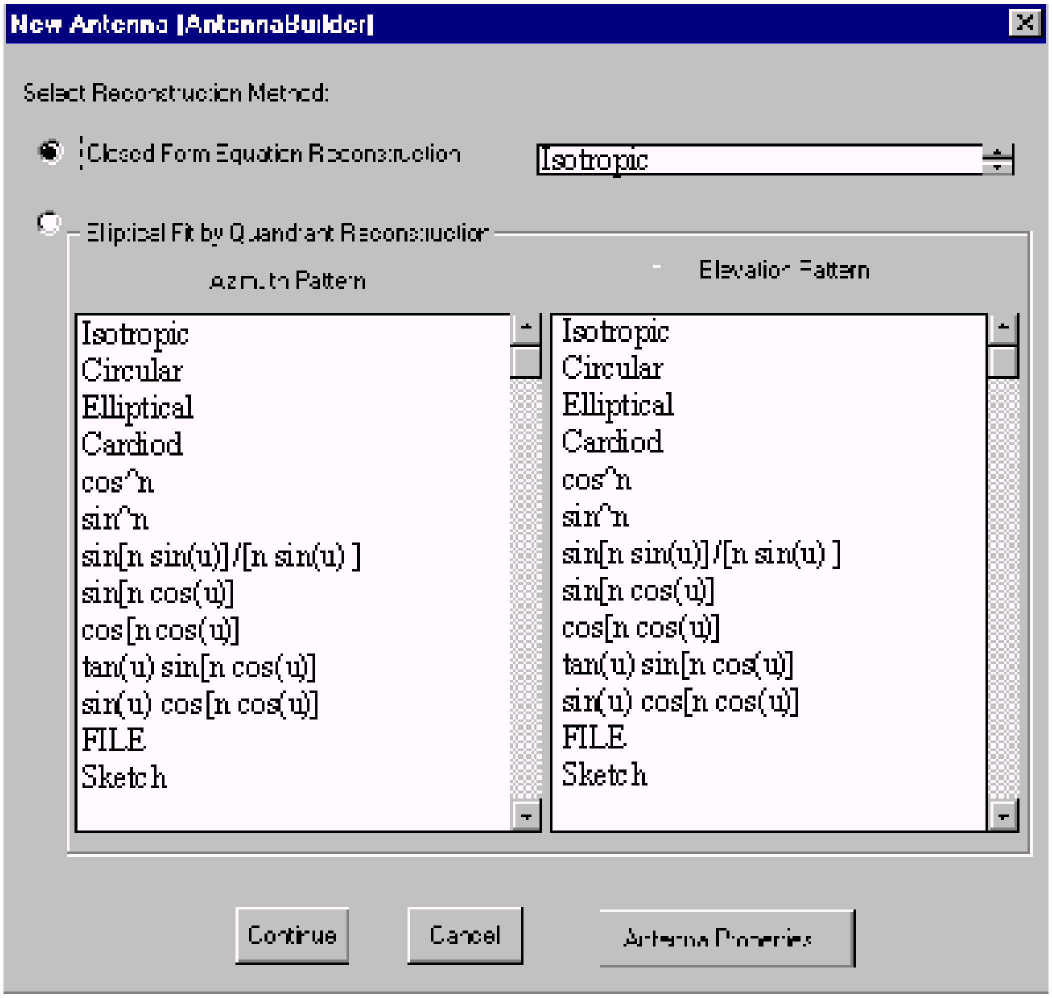


Figure 6.14: Screen capture of Antenna*Builder*.



New Antenna [AntennaBuilder]

Select Reconstruction Method:

● Closed Form Equation Reconstruction — Isotropic

○ Elliptical Fit by Quandrant Reconstruction

Azimuth Pattern	Elevation Pattern
Isotropic	Isotropic
Circular	Circular
Elliptical	Elliptical
Cardiod	Cardiod
cos^n	cos^n
sin^n	sin^n
sin[n sin(u)]/[n sin(u)]	sin[n sin(u)]/[n sin(u)]
sin[n cos(u)]	sin[n cos(u)]
cos[n cos(u)]	cos[n cos(u)]
tan(u) sin[n cos(u)]	tan(u) sin[n cos(u)]
sin(u) cos[n cos(u)]	sin(u) cos[n cos(u)]
FILE	FILE
Sketch	Sketch

Figure 6.15: Sample Antenna*Builder* pattern selection dialogue box.

and orientation of the antenna boresight, may be required inputs from the user depending on the pattern sources selected.

6.4.1.2 Three Dimensional Antenna Pattern Visualization

Once the sources for the azimuth and elevation patterns are specified, the three dimensional antenna pattern is reconstructed using the processes described in Section 6.3.2. Antenna*Builder* displays the reconstructed pattern in AutoCAD by mapping a surface mesh to the outer edge of the pattern. Although relatively slow, the advantage of this technique is in the visualization of the pattern. Figure 6.14 shows the sample rendered pattern of Figure 6.2 produced by Antenna*Builder* and viewed from three different orientations. There are no limitations on the viewing perspectives available to the user. Antenna*Builder* allows the three dimensional pattern to be viewed from any angle and orientation, and, as shown in Figure 6.14, multiple perspectives can be viewed simultaneously.

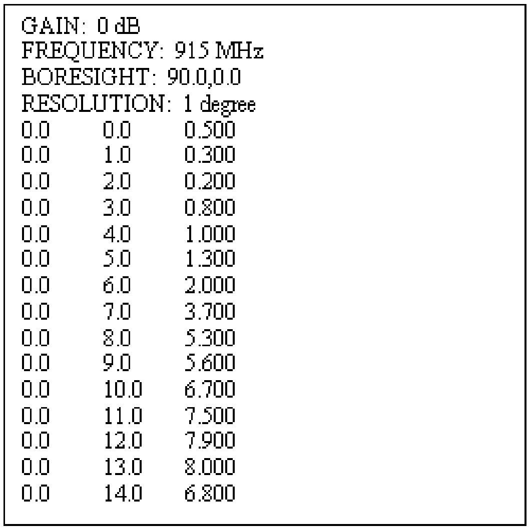
6.4.1.3 Integration With Wireless Communication System Design Tools

A large part of the motivation for Antenna*Builder* concerns the ability to complement emerging wireless communication simulation tools. The ability to export the reconstructed antenna pattern information into a format usable by ray tracing tools meets that objective. Antenna*Builder* stores the reconstructed pattern information into a single three dimensional pattern file. This file is very similar in format to the two-dimensional planar pattern files discussed in Section 6.3.1, but supplies a full three dimensional description of the pattern. Additional work needs to be done in defining the exact format of the three dimensional antenna pattern files, but Figure 6.16 provides an sample file format being integrated into the SMT *Plus* design tool.

This supplies the SMT *Plus* design tool with three dimensional gain pattern information needed to perform highly accurate simulations. When an antenna is placed within SMT *Plus*, the radiation pattern is applied via a three dimensional antenna pattern file. SMT*Plus* then takes the gain information supplied by the pattern file and applies it to the link budget calculations of Section 4.2.

6.4.2 Modeling Leaky Feeder Antenna

The reconstruction techniques described in Section 6.3.2 assume the antenna being modeled is a point antenna. The radiation pattern of a point antenna can be modeled as having originated from a single point in space, generally taken to be the center of the radiating



```
GAIN: 0 dB
FREQUENCY: 915 MHz
BORESIGHT: 90.0,0.0
RESOLUTION: 1 degree
0.0     0.0     0.500
0.0     1.0     0.300
0.0     2.0     0.200
0.0     3.0     0.800
0.0     4.0     1.000
0.0     5.0     1.300
0.0     6.0     2.000
0.0     7.0     3.700
0.0     8.0     5.300
0.0     9.0     5.600
0.0     10.0    6.700
0.0     11.0    7.500
0.0     12.0    7.900
0.0     13.0    8.000
0.0     14.0    6.800
```

Figure 6.16: A portion of a sample three dimensional antenna pattern file exported from Antenna*Builder*. The first two numeric columns provide the proper θ and ϕ direction in degrees relative to the user-specified antenna boresight, and the final column provides the antenna gain in dB.

antenna [5], [16], [19], [35]. However, not all antennas share this characteristic. This presents a problem with the approach taken by Antenna*Builder* that must be addressed.

In in-building wireless communication systems, a type of antenna known as leaky feeder or radiax cable is becoming very popular. Basically, leaky feeder antenna takes the form of a length of coaxial cable whose outer layer of insulation has been stripped off in tiny slices which are evenly spaced down the length of the cable. This enables signal energy to escape the cable and radiate into the environment. Figure 6.17 gives an diagram of a leaky feeder cable.

Deploying leaky feeder antennas helps ensure total building coverage the same as if a large number of point antennas were distributed throughout the interior. Several different types of wireless technologies can make use of the same leaky feeder cable simultaneously, making it even more attractive for multiple in-building wireless systems.

The first steps towards successfully modeling leaky feeder antenna in Antenna*Builder* have been taken. The approach taken in Antenna*Builder* is to model leaky feeder as a series of point antennas evenly spaced along the cable. Discussions with experts in industry have suggested that each point antenna can then be modeled as an omnidirectional antenna. That is, each point antenna is considered to have its own distinct radiation pattern. Further, since each slice is virtually identical, each simulated point source shares the same radiation

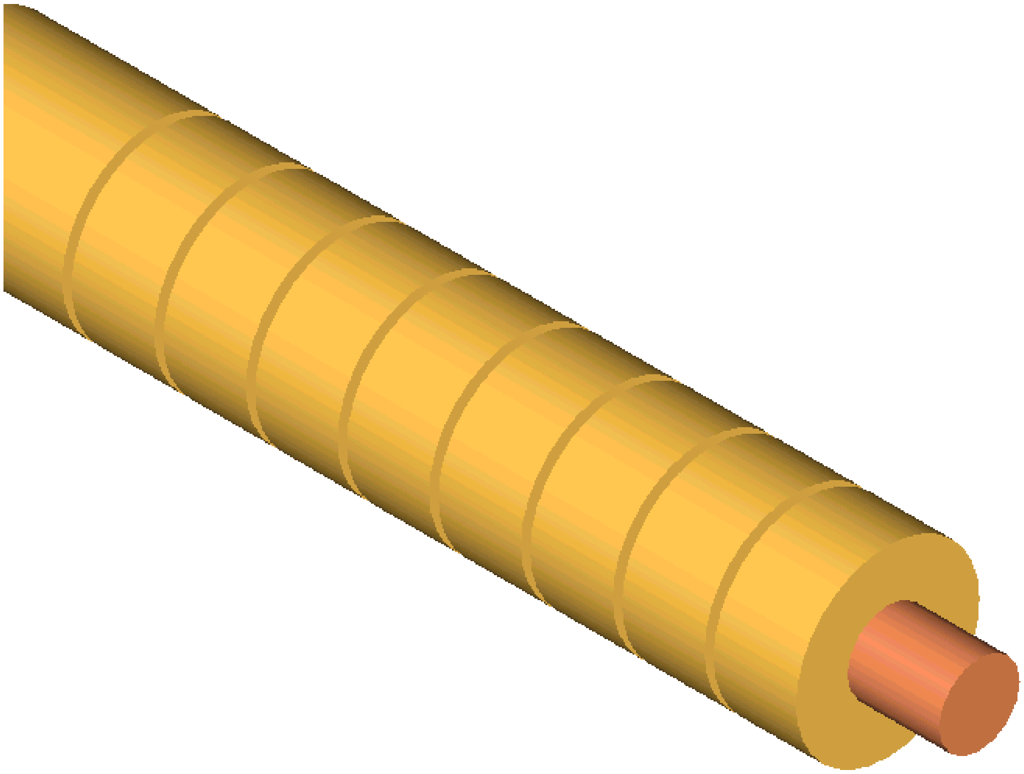


Figure 6.17: Diagram of leaky feeder cable. The slices through the insulation spaced along the length of the cable allow signals to radiate into the environment.

pattern. Due to cable loss, each successive point source further from the base station transmits with less power, but the same radiation pattern applies. Therefore, modeling leaky feeder antennas within Antenna*Builder* requires a user to specify a source for the omnidirectional pattern of each point source along with a line loss to apply for every unit length of the cable. With this information, the radiation pattern of the leaky feeder cable can be visualized as shown in Figure 6.18. In Figure 6.18, the radiation pattern resulting from having modeled three identical point antennas, each with the same quarterwave dipole pattern as in Figure 6.2, is shown. By exporting the leaky feeder antenna pattern from Antenna*Builder* into a three dimensional pattern description file similar to Figure 6.16, design tools such as SMT *Plus* can then begin using leaky feeder antennas in their own simulations.

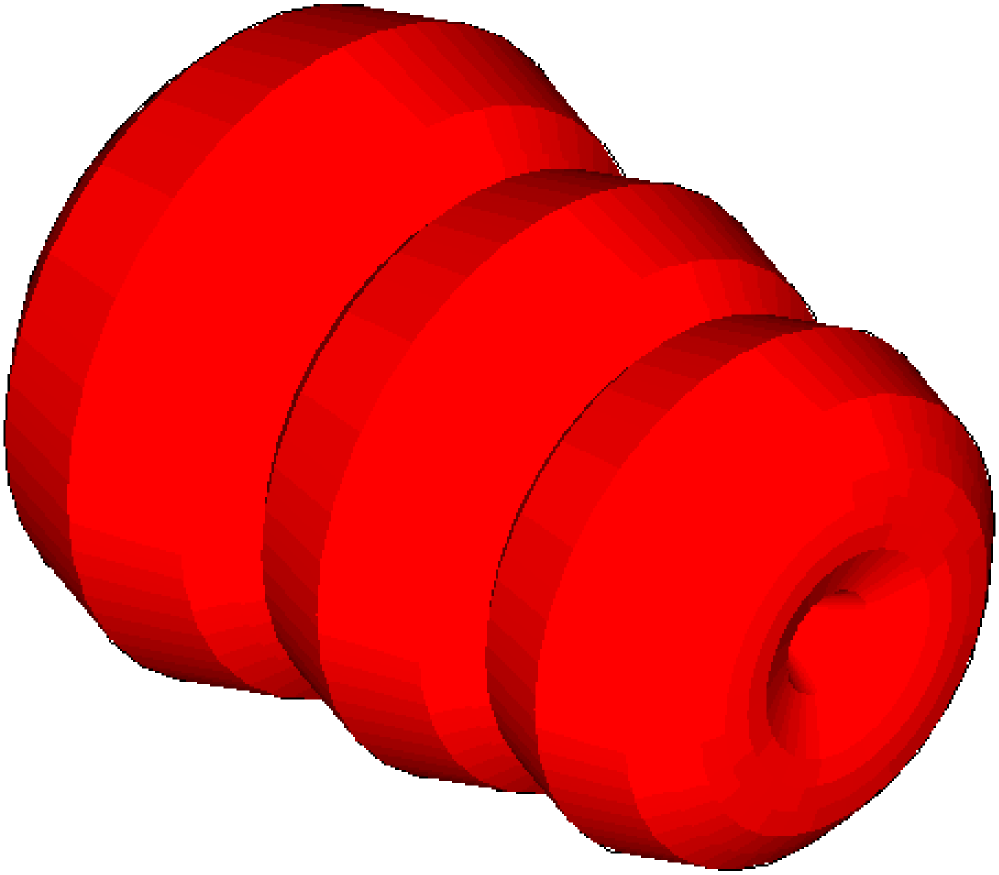


Figure 6.18: Radiation pattern for a leaky feeder antenna modeled as three evenly spaced quarterwave dipole antennas. The decrease in gain along the length of the cable is the result of cable loss.

Chapter 7

Conclusion

7.1 Results and Conclusions

This thesis report describes the SMT *Plus* tool suite developed to provide a comprehensive design approach to the deployment of wireless communication systems. The system provides full interactive support for developing and formatting the required site-specific database in AutoCAD, regardless of the quantity or source of initial information. These databases take the form of specially constructed AutoCAD drawings of building floor plans. Buildings up to nine stories can be modeled, and multiple building simulations can be performed as outlined in Section 4.6. Although the building layout is three dimensional, only one floor is visible to the user at any one time. Buildings are modeled as being collections of partitions. Partitions are differentiated from one another based on the name assigned to them and the building floor on which they are located.

A user can place any number or type of base station antennas and interference sources within the modeled region. Direct support is provided for many of the most common types of wireless communication standards, but a user is free to develop their own custom standards for use in simulations. Antenna coverage regions can be predicted using the techniques discussed in Section 4.2. These regions are displayed directly on the site-specific database, providing immediate visual feedback on system performance. Any number of coverage regions can be drawn for each antenna. Coverage regions are predicted using user specified boundary conditions on received signal strength, signal-to-noise ratio, or signal-to-interference ratio. The algorithm for generating these coverage regions has been greatly improved and is several times faster than the previous implementation in the original SMT.

Measurement data has been fully integrated into the SMT *Plus* tool suite. Measurement information may be visually displayed and compared to predicted data, or exported and manipulated within measurement analysis spreadsheets to maximize the accuracy of the simulations. This optimization process involves the user iteratively changing the values of the path loss parameters until an acceptable agreement between predicted and measured data is reached.

The foundation is in place for implementing antenna patterns within the SMT *Plus* simulation tool or future ray tracing tools. Three dimensional antenna radiation patterns can be reconstructed using the two dimensional planar radiation data supplied by commercial manufacturers or through special closed form equations. The reconstructed pattern is visualized as a rendered solid within AutoCAD which can be rotated and viewed from any orientation. The ability to export reconstructed patterns into special antenna pattern files capable of storing three dimensional pattern information provides the means for simulation tools such as SMT *Plus* to make use of the reconstructed pattern information.

Most of the project goals outlined in Section 2.2 have been satisfactorily accomplished. The system is very easy to use, efficient, and provides the means to do commercial grade wireless system design. A previous version of the SMT *Plus* tool suite consisting of SMT *Plus* 1.0 and Site*Planner* 1.0 has been made commercially available as Virginia Tech intellectual property. Over twenty licenses have been distributed thus far to companies in all areas of the wireless communications industry.

The research contributions made by this work can be summarized as follows:

- Two new multifloor path loss models for use in in-building and microcellular wireless communication system design have been proposed. These are discussed in Section 4.2 and verified by measurements as discussed in Sections 4.2.1.6 and 5.2.2.3.
- The statistical path loss models proposed and discussed in [21] and [29] have been extended to include microcellular wireless communication system design.
- The SMT *Plus* design tool discussed in Chapter 4 represents a dramatic step forward in speed and accuracy of wireless communication system design.
- The Site *Planner* design tool discussed in Chapter 3 represents a first in the area of site-specific modeling for the sole purpose of wireless communication system simulation.
- Measurements have been combined with the empirical modeling capabilities of SMT *Plus* with great success.
- The ability to quickly and easily acquire a large quantity of RF measurements and optimize the SMT *Plus* simulations to account for the data has been implemented as

described in Chapter 5. This opens new doors in terms of the design and validation of wireless communication systems.

- A new technique for reconstructing the three dimensional gain pattern of an antenna has been proposed in Chapter 6.
- The ability to account for the antenna pattern has been added to the empirical models of [21] and [29].
- The applicability of the empirical models of Section 4.2 to leaky feeder antenna has been investigated.

7.2 Recommendations for Future Work

The SMT *Plus* tool suite is a rich foundation for future research in the field of propagation prediction. There are many avenues of considerable research potential which have yet to be explored. Likewise, there are several features which need to be more fully developed in SMT *Plus*. Several of these are outlined in this section.

SMT *Plus* still lacks a full implementation of antenna patterns in the simulations it performs. The ability to import the three dimensional antenna pattern files created by Antenna*Builder* is present, but the ability to simulate the antenna has not yet been implemented. This is a straightforward task, however, involving only the addition of the antenna gain to the link budget calculations described in Section 4.2. Leaky feeder antenna presents a special modeling problem in SMT *Plus*. A direct implementation of leaky feeder involves modeling the cable as a series of point antennas. This easily becomes a slow, time-consuming calculation to perform that does not correspond with the SMT *Plus* goal of fast, efficient wireless communication system design. Therefore, an alternative implementation is desirable. Through conversations with experts in industry, the current method of quickly modeling leaky feeder involves using SMT *Plus* and simulating the cable as if it were actually two point antennas – one at the beginning of the cable where the signal is strongest and one at the end where the signal is weakest. By analyzing the coverage supplied by these two point sources, a rough estimate of the effectiveness of the leaky feeder antenna is gained. This process appears somewhat limited in usefulness, and additional research is underway to develop a third alternative implementation in SMT *Plus*.

A large research field involves the use of SMT *Plus* in antenna design. By combining the *predicted* received signal strength profiles of SMT *Plus* with the *desired* received signal strength profile for a modeled region, the required gain characteristics of an antenna can be determined. In this scenario, a user places a transmitting source at the desired location in the building and then provides information regarding the required signal levels in other parts of the database. For example, a minimum of -100 dBm received signal strength may be required in all parts of the building. This would allow SMT *Plus* to solve the link budget calculations of Section 4.2 for the antenna gain parameter, with the end result being the minimum required antenna gain pattern to match the required signal levels. Designing custom antenna patterns, the ability to optimize the orientation of a positioned antenna, and the ability to select the most desirable antenna from some form of antenna database have considerable research potential.

Additional work currently underway involves extending Measurement*Builder* to support a variety of popular commercial measurement devices. This will result in making the tool much more user friendly and convenient by providing compatibility with the commercial RF measurement devices. An area of research just initiated is taking advantage of the direct serial connection available with several RF measurement devices. Previously, the process of importing measurement data has revolved around the ability to import a stored data log file and correlate measurement data points with a database location. This requires a two step process of acquiring the measurements and then placing them into SMT *Plus*. With a direct serial connection to the RF measurement device, it is possible for Measurement*Builder* to read measurement data in real time. A user could walk around with a portable measurement unit and palmtop computer recording measurements. The palmtop would display the building floor plan, removing the need for a data log sheet. Storing a position marker could involve simply pointing at the location on the screen.

Currently, the optimization of SMT *Plus* simulations involves manually manipulating path loss parameters while comparing measured and predicted data. It may be possible for the same process to be accomplished automatically within SMT *Plus*. That is, given measured data stored within the building database, SMT *Plus* should be able to automatically compare the measured and predicted values and optimize the path loss parameters without the need for manual user intervention.

Another area with strong research potential is the ability to automatically predict the optimal number and locations for antennas in SMT *Plus*. Several ideas for approaching this problem are presented in [24] and [33]. This problem becomes compounded by the introduction of antenna patterns and orientations. Performing automatic channel assignment based upon minimizing co-channel interference effects, and extending the SMT *Plus* database to support true multi-building modeling are other areas which need to be investigated.

The SMT *Plus* tool suite presents a comprehensive wireless communication system design tool, but, as can be seen from this section, there are still many features and areas of research which are deserving of investigation. The modeling capabilities of SMT *Plus* have not yet reached their limits.

Bibliography

[1] J. B. Andersen, T. S. Rappaport, and S. Yoshida, ”Propagation Measurements and Models for Wireless Communications Channels,” *IEEE Communications Magazine*, vol. 33, no. 1, Jan. 1995.

[2] K. L. Blackard, T. S. Rappaport, and C. W. Bostian ”Impulsive Noise in Personal Communication Systems,” *IEEE Journal on Selected Areas in Communications*, vol. 11, no. 7, pp. 991-1000, Sept. 1993.

[3] R.A. Brickhouse and T.S. Rappaport, ”A Study of Parasitic Cellular Frequency Reuse,” Masters Thesis, Virginia Tech, September 11, 1995.

[4] R.A. Brickhouse and T.S. Rappaport, ”Urban In-Building Cellular Frequency Reuse,” *IEEE Globecom '96*, UK, November 1996.

[5] R.E. Collin, *Antennas and Radio Wave Propagation*, McGraw-Hill, New York, 1985.

[6] P.M. Cartwright and K.W. Sowerby, ”Estimating Regions of Service in Wireless Indoor Communication Systems,” *Virginia Tech 4th Symposium on Wireless Personal Communications Proceedings*, pp. 12.1-12.11, June 1994.

[7] D.C. Cox, R.R. Murray, and A.W. Norris, ”800 MHz Attenuation Measured in and Around Suburban Houses,” *AT&T Bell Laboratories Technical Journal*, vol. 63, pp. 921-954, July 1984.

[8] D.C. Cox, ”Universal Portable Radio Communications,” *IEEE Transactions on Vehicular Technology*, vol. 34, no. 3, pp. 117-121, August 1985.

[9] D.M.J. Devasirvatham, M.J. Krain, and T.S. Rappaport, ”Radio Propagation Measurements at 850 MHz, 1.7 GHz, and 4.0 GHz Inside Two Dissimilar Office Buildings,” *Electronics Letters*, vol. 26, no. 7, pp. 445-447, 1990.

[10] D.M.J. Devasirvatham, C. Bannerjee, R.R. Murray, and T.S. Rappaport, "Four Frequency Radiowave Propagation Measurements of the Indoor Environment in a Large Metropolitan Commercial Building," *IEEE Globecom '91*, Phoenix, AZ, pp. 1282-1286, December 1991.

[11] G. Durgin, N. Patwari, T. S. Rappaport, "An Advanced 3D Ray Launching Method for Wireless Propagation Prediction", *IEEE Vehicular Technology Conference '97*, Phoenix, AZ, pp. 785-789, May 1997.

[12] H. Hashemi, "The Indoor Radio Propagation Channel," *IEEE Proceedings*, vol. 81, no. 7, pp. 943-968, July 1993.

[13] D.A. Hawbaker and T.S. Rappaport, "Indoor Wide Band Radio Wave Propagation Measurements at 1.3 GHz and 4.0 GHz," *Electronics Letters*, vol. 25, pp. 1800-1802, October 1990.

[14] W. Honcharenko, H.L. Bertoni, J.L. Dailing, J. Qian, and H.D. Lee, "Mechanisms Governing Propagation Between Floors in Buildings," *IEEE Transactions on Antennas and Propagation*, vol. 41, no. 6, pp. 787-790, June 1993.

[15] E. Horowitz, S. Sahni, and S. Anderson-Freed, *Fundamentals of Data Structures in C*, Computer Science Press, New York, 1993.

[16] J. D. Kraus, *Antennas*, McGraw-Hill, New York, 1988.

[17] J.F. Lafortune and M. Lecours, "Measurement and Modeling of Propagation Losses in a Building at 900 MHz," *IEEE Transactions on Vehicular Technology*, vol. 39, no. 2, pp. 101-108, May 1990.

[18] W.C.Y. Lee, *Mobile Communications Engineering*, McGraw-Hill, New York, 1982.

[19] Y.T. Lo and S.W. Lee, *Antenna Handbook: Theory, Application, and Design*, Von Nostrand Reinhold, New York, 1988.

[20] D. Molkdar, "Review on Radio Propagation Into and Within Buildings," *IEEE Proceedings*, vol. 138, no. 1, pp. 61-73, February 1991.

[21] A.J. Motley and J.M. Keenan, "Radio Coverage in Buildings," *British Telecom Technology Journal*, vol. 8, no. 1, pp. 19-24, January 1990.

[22] R.D. Murch, J.H.M. Sau, and K.W. Cheung, "Improved Empirical Modeling for Indoor Propagation Prediction," *IEEE Vehicular Technologies Conference Proceedings*, pp. 1737-1740, July 1995.

[23] M. A. Panjwani, A. L. Abbott, T. S. Rappaport, and J. Haagh, "An Interactive System for Visualizing Wireless Communication Coverage within Buildings," *Virginia Tech 4th Symposium on Wireless Personal Communications Proceedings*, pp. 14.1-14.12, June 1994.

[24] M. A. Panjwani, A. L. Abbott, T. S. Rappaport, "Interactive Computation of Coverage contours for Wireless Communication in Multifloored Indoor Environments," *IEEE Journal of Selected Areas of Communication*, vol. 14, no. 3, pp. 420-430, April 1996.

[25] D.M. Pozar, *Antenna Design Using Personal Computers*, Artech House, Dedham, Massachusetts, 1985.

[26] T.S. Rappaport et al., "Statistical Channel Impulse Response Models for Factories and Open Plan Radio Communication System Design, " *IEEE Transactions on Communications*, vol. 39, no. 5, pp. 794-806, May 1991.

[27] T. S. Rappaport and R. A. Brickhouse, "A Study of Urban In-Building Cellular Frequency Reuse", *IEEE Personal Communications Magazine*, vol. 4, no. 1, pp. 19-23, February 1997.

[28] T. S. Rappaport, *Wireless Communications Principles and Practices*, Prentice-Hall, Inc., New Jersey, 1996.

[29] S. Y. Seidel and T. S. Rappaport, "914 MHz Path Loss Prediction Models for Indoor Wireless Communications in Multifloored Buildings," *IEEE Transactions on Antennas and Propagation*, vol. 40, no. 2, pp. 207-217, Feb. 1992.

[30] S. Y. Seidel, T. S. Rappaport, M. J. Feuerstein and K. L. Blackard, "The Impact of Surrounding Buildings on Propagation for Wireless In-Building Personal Communications System Design," *IEEE Vehicular Technology Conference Proceedings*, Denver, CO, pp. 814-818, May 1992.

[31] S. Y. Seidel, "Site-Specific Propagation Prediction for Wireless In-Building Personal Communications System Design," Ph.D. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA, Feb. 1993.

[32] S.Y. Seidel and T.S. Rappaport, "Site-Specific Propagation for Wireless In-Building Personal Communication System Design," *IEEE Transactions on Vehicular Technology*, vol. 43, no. 4, pp. 879-891, November 1994.

[33] H. D. Sherali, C. M. Pendyala, and T. S. Rappaport, "Optimal Location of Transmitters for Micro-Cellular Radio Communication System Design," *IEEE Journal on Selected Area in Communication*, vol. 14, no. 4, pp. 662-673, May 1996.

[34] R. R. Skidmore, T. S. Rappaport, A. L. Abbott, "Interactive Coverage Region and System Design Simulation for Wireless Communication Systems in Multifloored Indoor Environments: SMT Plus," *IEEE International Conference on Universal Personal Communications*, Boston, MA, pp. 646-650, September 1996.

[35] W. L. Stutzman, G. A. Thiele, *Antenna Theory and Design*, John Wiley and Sons, New York, 1981.

[36] R. A. Valenzuela, "Antennas and Propagation for Wireless Communications," *IEEE 46th Vehicular Technology Conference*, vol 1, pp. 1-5, Atlanta, GA, May 96.

Appendix A

SMT *Plus* Source Code File List

A.1 SMT *Plus* Source Code Files

This section lists the source code files which comprise SMT *Plus* 1.0.

building.c Source file containing routines for accessing the site-specific building database.

building.h Header file for building.c

colors.c Source file containing routines for controlling displayed colors.

colors.h Header file for colors.c

comm.c Source file implementing the path loss prediction routines.

comm.h Header file for comm.c

constant.h Global constants and macros.

contour.c Source file handling the drawing and displaying of coverage contours.

contour.h Header file for contour.c

error.c Source file containing routines for displaying error messages.

error.h Definitions for all error messages.

file.c Generic file parsing routines.

file.h Header file for file.c

functbl.h Contains the AutoCAD function call table for SMT *Plus*.

smt.c Primary source file for SMT *Plus*.

standard.c Source file implementing the handling of wireless standards.

standard.h Header file for standard.c

transcvr.c Source file handling the placement and specification of base station antennas.

transcvr.h Header file for transcvr.c

usrcmd.c Source file implementing generic AutoCAD user commands.

usrcmd.h Header file for usrcmd.c

A.2 AutoCAD Related SMT *Plus* Files

This section lists the files required to interface SMT *Plus* with AutoCAD.

acadsmt.mnu AutoCAD menu file containing SMT *Plus* commands.

afval.dcl Path loss exponent specification dialogue box.

alert.dcl Alert message dialogue box.

chmodeq.dcl Dialogue box selecting path loss model to use.

cntr_res.dcl Contour resolution dialogue box.

colors.dcl Color legend dialogue box.

display.dcl Customize displayed parameters dialogue box.

fafval.dcl Floor attenuation factor dialogue box.

faterr.dcl Fatal error message box.

floor.dcl Floor parameters dialogue box.

intsinfo.dcl Interference source specification dialogue box.

model.dcl Wireless standard specification dialogue box.

nmfval.dcl Multifloor path loss exponent selection dialogue box.

query.dcl Query message dialogue box.

traninfo.dcl Base station specification dialogue box.

warn.dcl Warning message box.

A.3 Files Related to SMT *Plus* Simulations

standard.dat Text file storing the list of currently available wireless standards and their associated parameter sets.

The default STANDARD.DAT file which accompanies SMT *Plus* 1.0 is shown below.

```
/**************************************************************/
/* STANDARD.DAT          Copyright Virginia Tech  March 3, 1996 */
/* This file contains a full description of the various         */
/* wireless standards supported by SMT.  The first twelve       */
/* entries are the default standards and should not be changed. */
/* The remaining entries, if any are those added by the user    */
/* thru normal use.  This file may also be edited by hand to    */
/* add or remove entries, but this is not recommended.  Instead,*/
/* new entries should be developed within SMT Plus 1.0 and then */
/* stored to this file using the Store to File button.          */
/* The format of this file is as follows:                       */
/* -----------      - Separator                                 */
/* DESCRIPTION:     - Description of the standard               */
/* TX_POWER:        - Base station transmit power (dBW)         */
/* TX_FREQUENCY:    - Base station transmit frequency (Hz)      */
/* RF_BANDWIDTH:    - Channel bandwidth (Hz)                    */
/* CHANNEL_NOISE:   - Channel noise factor (dB)                 */
/* RX_SENSITIVITY:  - Receiver sensitivity (dBW)                */
/* RSSI:            - Received Signal Strength (dBm)            */
/* C/N_MINIMUM:     - Signal-to-noise contour limit (dB)        */
/* C/I_MINIMUM:     - Signal-to-interference contour limit (dB) */
/* CARRIER_RECVD:   - Carrier strength contour limit (dBW)      */
/* SAFETY_MARGIN:   - Feasibility safety margin (dB)            */
/*                                                              */
/* SMT Plus 1.0 assumes that all of the above fields are        */
/* present for each model, and that they are specified in the   */
/* order listed above.                                          */
/**************************************************************/


--------------------------------
```

```
DESCRIPTION:     AMPS default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    870000000.000000
RF_BANDWIDTH:    30000.000000
CHANNEL_NOISE:   15.000000
RX_SENSITIVITY:  -140.000000
RSSI:            -90.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     18.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     CT2 default parameters
TX_POWER:        -23.000000
TX_FREQUENCY:    945000000.000000
RF_BANDWIDTH:    100000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -137.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     20.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     DCS1800 default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    1850000000.000000
RF_BANDWIDTH:    200000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -135.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     12.000000
SAFETY_MARGIN:   0.000000
```

```
--------------------------------
DESCRIPTION:     DECT default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    1900000000.000000
RF_BANDWIDTH:    1728000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -125.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     20.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     GSM default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    950000000.000000
RF_BANDWIDTH:    200000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -135.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     12.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     IS 95 default parameters
TX_POWER:        -10.000000
TX_FREQUENCY:    840000000.000000
RF_BANDWIDTH:    1250000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -130.000000
RSSI:            -80.000000
C/N_MINIMUM:     0.000000
C/I_MINIMUM:     7.000000
SAFETY_MARGIN:   0.000000
```

```
--------------------------------
DESCRIPTION:     IS-54/IS-136 default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    890000000.000000
RF_BANDWIDTH:    30000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -140.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     15.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     N-AMPS default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    870000000.000000
RF_BANDWIDTH:    10000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -143.000000
RSSI:            -80.000000
C/N_MINIMUM:     9.000000
C/I_MINIMUM:     12.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     PACS default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    1950000000.000000
RF_BANDWIDTH:    300000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -130.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     13.000000
```

```
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     PDC default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    1500000000.000000
RF_BANDWIDTH:    25000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -141.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     14.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     PHS default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    1900000000.000000
RF_BANDWIDTH:    300000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -130.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     13.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     IEEE802.11 default parameters
TX_POWER:        -20.000000
TX_FREQUENCY:    915000000.000000
RF_BANDWIDTH:    1000000.000000
CHANNEL_NOISE:   7.000000
RX_SENSITIVITY:  -130.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
```

```
C/I_MINIMUM:     10.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     PCS
TX_POWER:        -10.000000
TX_FREQUENCY:    1870000000.000000
RF_BANDWIDTH:    30000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -140.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     10.000000
SAFETY_MARGIN:   0.000000

--------------------------------
DESCRIPTION:     CELLULAR
TX_POWER:        -10.000000
TX_FREQUENCY:    870000000.000000
RF_BANDWIDTH:    30000.000000
CHANNEL_NOISE:   10.000000
RX_SENSITIVITY:  -140.000000
RSSI:            -80.000000
C/N_MINIMUM:     10.000000
C/I_MINIMUM:     10.000000
SAFETY_MARGIN:   0.000000
```

Appendix B

Site*Planner* Source Code File List

B.1 Site*Planner* Source Code Files

This section lists the source code files which comprise Site*Planner* 1.0.

assist.c Source file containing generic, useful AutoCAD functions.

assist.h Header file for assist.c

build2d.c Source file containing routines for manipulating the building floor plan.

build2d.h Header file for build2d.c

constant.h Global constants and macros.

error.c Source file containing routines for displaying error messages.

error.h Header file for error.c

export.c Source file implementing several drawing export routines.

export.h Header file for export.c

format.c Source file containing routines for formatting the building floor plan.

format.h Header file for format.c

ftbl2d.h Contains the AutoCAD function call table for Site*Planner*.

import.c Source file containing several drawing import routines.

import.h Header file for import.c

smt2d.c Primary source file for Site*Planner*.

B.2 AutoCAD Related Site*Planner* Files

This section lists the files necessary to interface Site*Planner* with AutoCAD.

acadsite.mnu AutoCAD menu file containing Site*Planner* commands.

alert2d.dcl Alert message dialogue box.

begin.dcl Initial top-level dialogue box.

build.dcl Building feature manipulation dialogue box.

chgpart.dcl Building formatting dialogue box.

floor2d.dcl Floor control dialogue box.

legend.dcl Color legend dialogue box.

numflrs.dcl Building floor dialogue box.

query2d.dcl Query message dialogue box.

select.dcl Entity selection dialogue box.

tools.dcl Siteit Planner toolkit dialogue box.

warn2d.dcl Warning message box.

Appendix C

SMT *Plus* Command Reference

This appendix describes the SMT *Plus* 1.0 commands available to the user via the menu or directly from the AutoCAD command prompt.

ALL_GLOBAL Simulates all base station antennas in the drawing, predicting coverage areas for each on the every floor in the building using the user specified single or multifloor propagation model. The types of coverage areas predicted depends upon what the user selected to be generated using the SRC_INFO command.

AREA Prompts the user to select a coverage contour using the mouse. The area enclosed within the contour in square meters and the perimeter of the contour in meters is displayed. This command is not limited to coverage contours, as any closed polygon may be selected with the same result.

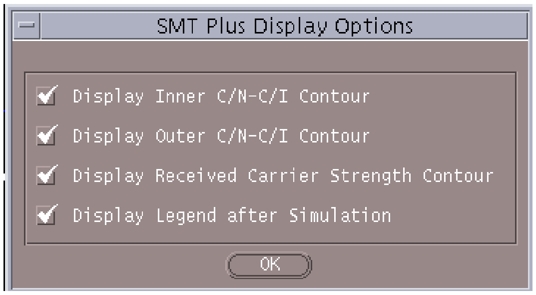
BASESTAT Allows the user to create and place base stations antennas anywhere within the displayed floor plan. When selected, this command loops continually; thereafter, a base station of the current standard is placed wherever the user clicks the mouse. The command may be exited by either pressing enter, clicking the right mouse button, or pressing *Control-C*. To change the communication parameters of an existing base station, see the SRC_INFO command.

CLEAR Erases all coverage contours on the currently displayed floor.

CLEAR_1 Erases the coverage contours on the displayed floor for a selected base station.

DISPLAY Displays the dialog box shown in Figure C.1.

Selecting any of the first three check boxes controls whether or not the corresponding contours of all base stations in the drawing are displayed. This does not control



SMT Plus Display Options

☑ Display Inner C/N-C/I Contour
☑ Display Outer C/N-C/I Contour
☑ Display Received Carrier Strength Contour
☑ Display Legend after Simulation

Figure C.1: SMT *Plus* DISPLAY dialogue box.

whether or not the contours are calculated, only whether they are visible. The last check box controls whether or not the color legend appears automatically following each simulation.

DEL_ALL Deletes all base stations and interference sources from the current drawing. A prompt will appear to make sure that this is the intended action.

DOWN This command is analogous to panning down. All drawing entities are moved upwards on the screen.

DWN_1_FL Shifts the current view down one building floor.

ENVPARM Selecting this command displays the following dialog box shown in Figure C.2.

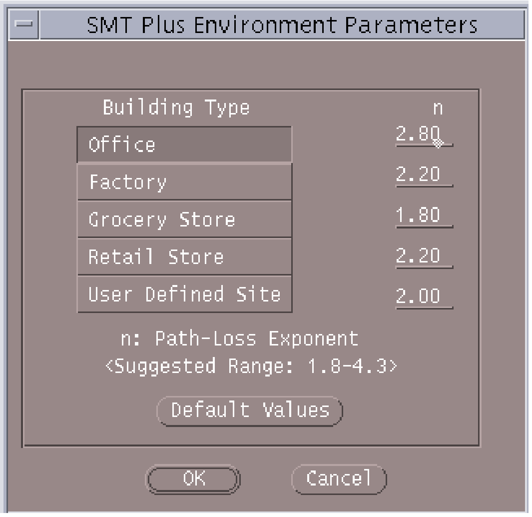
This enables the user to specify the type of building the current drawing represents and to specify what the value of the path loss exponent.

EXIT Exit SMT Plus.

FAF/nMF If the currently selected multifloor propagation model is the Distance Dependent model, the dialog box shown in Figure C.3 is displayed to the user.

This allows the n(multifloor) path loss exponent value to be specified for use in the coverage contour predictions. A Default button is provided to return all edited values to the original defaults.

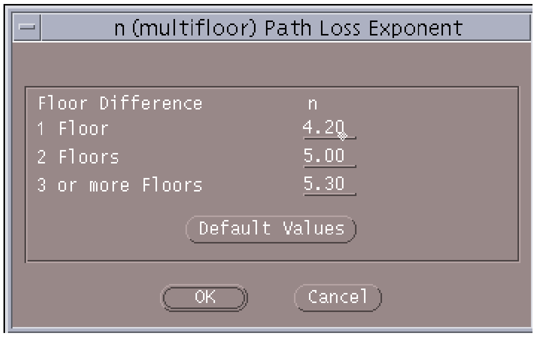
If the currently selected multifloor propagation model is anything other than the Distance Dependent Model, the dialog box shown in Figure C.4 is displayed to the user.



Building Type	n
Office	2.80
Factory	2.20
Grocery Store	1.80
Retail Store	2.20
User Defined Site	2.00

n: Path-Loss Exponent
<Suggested Range: 1.8-4.3>

Figure C.2: SMT *Plus* Environmental Parameters dialogue box.



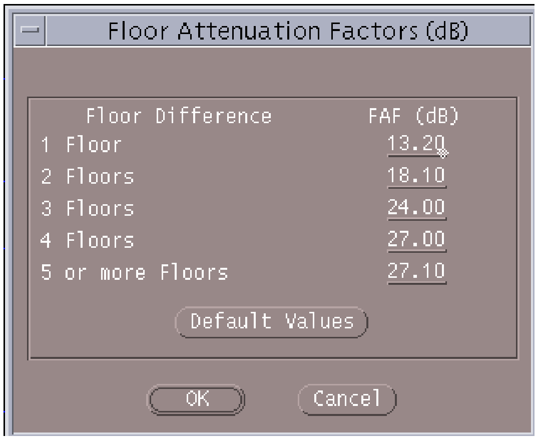
Floor Difference	n
1 Floor	4.20
2 Floors	5.00
3 or more Floors	5.30

Figure C.3: SMT *Plus* Multifloor Path Loss Exponent dialogue box.

This allows the user to edit the floor attenuation properties of the building. A Default button is provided to return all edited values to the original defaults.

FLR_INFO Activates the dialog box shown in Figure C.5 which displays relevant information regarding the current floor. The two editable fields of this dialog box are Ceiling Height and Room Temperature. Currently, SMT Plus assumes a ceiling height of 3.3 meters and a room temperature of 290 kelvin for every floor in the building on startup. This command gives the user the ability to change these default values.

The ceiling height parameter is used in the multifloor propagation prediction models, while room temperature is used in the single floor propagation models only.



Floor Difference	FAF (dB)
1 Floor	13.20
2 Floors	18.10
3 Floors	24.00
4 Floors	27.00
5 or more Floors	27.10

Figure C.4: SMT *Plus* Floor Attenuation Factor dialogue box.

Ceiling Height (m) 3.3

Room Temperature 290.0000

Figure C.5: SMT *Plus* Floor Information dialogue box.

HIDE_FLR Prompts the user to enter the number of the floor to hide. If the floor is visible, all entities on that floor are hidden from view.

INT_SRC Allows the user to create and place interference sources anywhere within the displayed floor plan. When selected, this command loops continually; thereafter, an interference source is placed wherever the user clicks the mouse. The command may be exited either by pressing enter, clicking the right mouse button, or pressing *Control-C*.

LEFT This command is analogous to panning left, as all drawing entities are shifted to the right.

LEGEND Displays a dialog box similar to Figure C.6 which provides a description of what each color in the drawing represents. Only six different colors are displayed at any one time; the More Colors button on the dialog box provides access to the remaining colors.

Figure C.6: SMT *Plus* COLOR LEGEND dialogue box.

As with all dialog boxes, the color legend is movable. In addition, the color legend box remembers its previous position and always reappears in its last location when selected.

MODEL Displays a dialog box which enables a user to select which propagation prediction model discussed in Section 4.2 will be used in the simulation.

OPEN Open an SMT *Plus* format drawing. Once the drawing is loaded, SMT *Plus* reloads itself.

PAFVAL This command displays the dialog box shown in Figure C.7 which allows the user to specify the values for the partition attenuation factors. A Default button is provided to return all edited values to the original defaults.

Figure C.7: SMT *Plus* PARTITION ATTENUATION FACTOR dialogue box.

RESOLUT Displays a dialog box enabling a user to set the parameters of the contour draw algorithm discussed in Section 4.3.

RIGHT This command is analogous to panning right, as all drawing entities are shifted to the left.

SAVE Save the current drawing. The original drawing should never be overwritten as SMT *Plus* does not have the capability of saving a simulation in its current state and return to it at a later date. Instead, the value of this command is in saving a snap shot of the state of the system as it currently exists, either for future reference or plotting.

SCL_SRC Changes the displayed size of all antenna icons. This should only need to be done on platforms with very small screen sizes, such as laptop computers. The displayed size of base stations and interference sources has no effect on the coverage prediction calculations.

SHOW_FLR Prompts the user to enter a floor number. All entities on that floor are made visible. This is useful when doing a visible comparison of the coverage areas of the same base station antenna across multiple floors.

SIM_ALL Simulates all base station antennas in the drawing, predicting coverage areas for each on the *current* floor using the user specified single or multifloor propagation model. The types of coverage areas predicted depends upon what the user selected to be generated using the SRC_INFO command.

SIM_ONE Simulates a selected base station antenna, predicting coverage areas for it on the *current* current floor using the user specified single or multifloor propagation model. The types of coverage areas predicted depends upon what the user selected to be generated using the SRC_INFO command.

SINGLE_GLOBAL Simulates a selected base station antenna, predicting its coverage areas on the every floor in the building using the user specified single or multifloor propagation model. The types of coverage areas predicted depends upon what the user selected to be generated using the SRC_INFO command.

SRC_DEL Deletes a user selected base station or interference source antenna.

SRC_INFO Displays information on the selected base station or interference source in a dialog box similar to the one shown in Figure 4.5.

The list displayed under the *Wireless Standards* heading shows the wireless standards which are available for selection. As a standard is selected with the mouse, its corresponding parameters are displayed in the remaining fields in the dialog box. These parameters may be changed by the user. The standard which is selected when this dialog box is exited is assigned to the selected base station or interference source. It is important to realize that all base stations and interference sources of the same wireless standard share the exact same parameters. When a parameter of a standard is changed, the parameters of all sources of that particular standard are changed as well. Therefore, any changes made in this dialog box have a global impact on base stations and interference sources in the drawing.

The two rows of buttons below the wireless standards list specify what units the displayed parameters are in. As different units are selected, the displayed values of the parameters are changed to match the desired units. The absolute value of the parameter will not change.

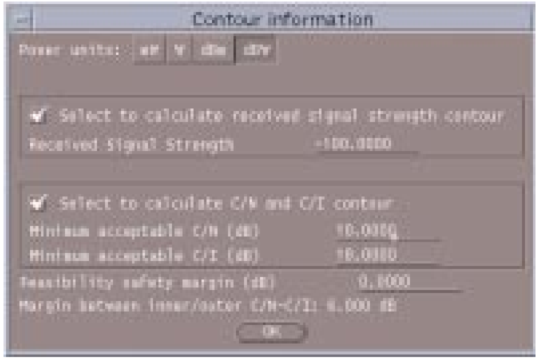
The *New Entry* and *Remove Entry* buttons handle the creation and deletion of wireless standards respectively. Creating a wireless standard means adding an entry to the list and supplying parameters to associate with the new standard. Deleting a standard removes the entry from the list.

The *Rename Entry* button enables a user to change the description of a model as it is displayed in the *Wireless Standards* list.

The *Update Standards File* button exports all of the information regarding the wireless standards to a data file named STANDARD.DAT. This data file is read when SMT Plus is first run to provide the list of standards and parameters which are available for modeling. The default STANDARD.DAT file supplied with SMT *Plus* is given in Appendix A.

In the lower left hand corner of the box is a text string which lists which floor of the building the selected base station is located upon.

The *Contours...* button displays the dialog box shown in Figure C.8, which displays information regarding the contours of the selected base station.



☑ Select to calculate received signal strength contour

Received Signal Strength -100.0000

☑ Select to calculate C/N and C/I contour

Minimum acceptable C/N (dB) 10.0000

Minimum acceptable C/I (dB) 10.0000

Feasibility safety margin (dB) 0.0000

Margin between inner/outer C/N-C/I: 6.000 dB

Figure C.8: SMT *Plus* BASE STATION CONTOUR DRAW PARAMETERS dialogue box.

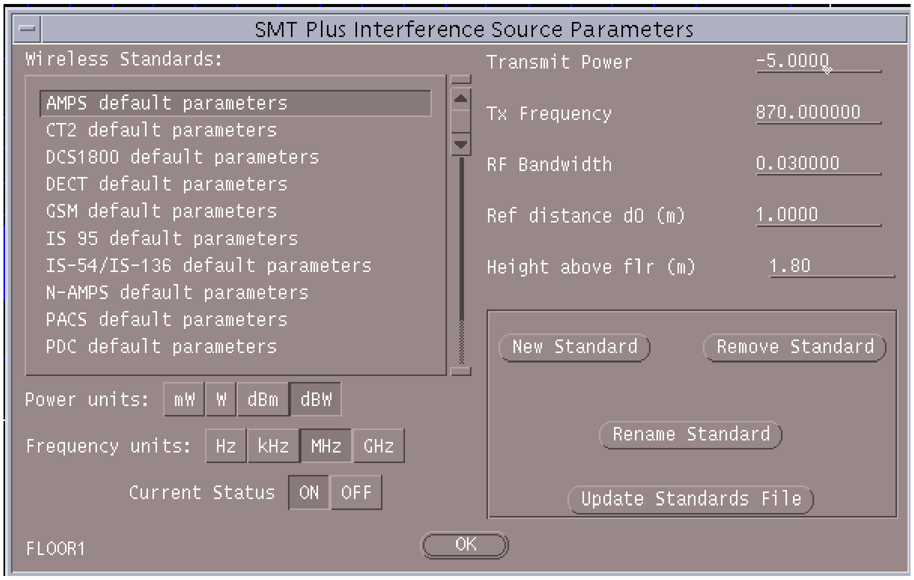
Within this dialog box, the desired boundaries of the coverage contours can be specified for both the Received Signal Strength and the CNR/CIR contours. The units of power for the Received Signal Strength can be specified using the buttons at the top of the box.

In specifying the boundary for the CNR/CIR coverage contours, the values are being specified for the outer contour. That is, the boundary for the inner CNR/CIR contour is dependent upon both the values specified here and the margin separating the inner and outer contours. This margin is displayed in the above dialog box, and may be specified by the user using the Resolut command.

To calculate the given contours, select the check box next to each one. When a simulation is performed, whether or not these check boxes are selected is used to determine which types of coverage contours to predict for the current base station.

The Feasibility Safety Margin is a means of instilling a margin of error into the simulation. The impact of this is discussed in Section 4.2.

If an interference source was selected instead of a base station as above, the dialog box shown in Figure C.9 would have been displayed. Interference sources are modeled the same as base stations in SMT *Plus* [24], [34]. Because of this, interference sources share the same set of wireless standards as base stations. However, only a subset of the parameters necessary to describe base stations are required to describe interference sources.



Transmit Power -5.0000

Tx Frequency 870.000000

RF Bandwidth 0.030000

Ref distance d0 (m) 1.0000

Height above flr (m) 1.80

Figure C.9: SMT *Plus* Interference Source Properties dialogue box.

Each of the fields in the Interference Source Parameters dialog box is identical to those found in the Base Station Parameters dialog box described above.

Interference sources can be turned on and off by selecting the corresponding button in the *Current Status* field.

SRC_MOVE Allows a user to select a base station or interference source and physically relocate it to any position on the currently displayed floor.

STANDARD This command enables a user to specify the parameters associated with a wireless standard, define new standards or delete existing ones, and set the currently active wireless standard. Upon selection, a dialog box similar to Figure 4.5 is displayed. Using this dialogue box is the same as described under the SRC_INFO command with the exception that the *Contour...* button is inaccessible.

START Executes SMT Plus.

UP This command is analogous to panning up, as all drawing entities are shifted down slightly.

UP_1_FLR Shifts the current view up one building floor.

ZOOM Provides the user the ability to zoom in or out on the viewed portion of the drawing.

ZOOMIN Zooms in on the current view slightly.

ZOOMOUT Zooms out on the current view slightly.

Appendix D

Site*Planner* Command References

The following section outlines the various commands available in Site*Planner* 1.0. Each command is available from on the Site*Planner* toolbar and from the AutoCAD prompt. A detailed description of the command is given.

ACCURACY Allows the user to change the drawing grid spacing by prompting for a new value. By changing the grid spacing, the user can change the precision with which activities within Site*Planner* are performed. Using these drawing guides, perfectly straight lines may be constructed and objects may be repositioned with much greater accuracy. By default, the grid is not visible when Site*Planner* first executes.

ALIGN Steps the user through lining up each of the floors in the building vertically so that they correctly overlap each other. Each floor is aligned using the floor directly beneath it as a visual guide.

BEGIN Activates the top level dialog box which lists the available development paths for constructing a building floor plan as discussed in Section 3.3.

CHG_PART Prompts the user to select partitions from the current view, then changes the partitions into the user selected type. Note that the partitions shown in the drawing need not be of any existing format.

DONE Checks the finished drawing to ensure it is in a format which SMT *Plus* can use. Note that this does not necessarily mean that the drawing is correct; only that SMT *Plus* will be able to use it. The drawing is checked to insure that, given the number of stories the user initially specified for the building, all such floors have been added to the building and that each floor contains valid partitions. The user will be prompted for information regarding what has or has not been done to the drawing. This insures no required formatting steps have been inadvertently skipped by the user in creating the floor plan.

DOWN This command is analogous to panning down. All drawing entities are moved upwards on the screen.

DRAWPRIM Draws a Primary partition between two user selected points on the current floor.

DRAWCUST Draws a Custom partition between two user selected points on the current floor.

DRAWEXT Draws an External partition between two user selected points on the current floor.

DRAWHARD Draws a Hard partition between two user selected points on the current floor.

DRAWMED Draws a Medium partition between two user selected points on the current floor.

DRAWSEC Draws a Secondary partition between two user selected points on the current floor.

DWN_1_FLR Shifts down one floor in the drawing.

ERASE Allows the user to select entities in the drawing and then erases them. Erased entities can be retrieved using the UNDO command, but the UNDO must immediately follow the erase.

EXPLODE Polygons and polylines (open polygons) are common drawing entities; however SMT *Plus* expects all drawing entities to be lines. This command separates all polylines and polygons in the current drawing into separate lines. This is done automatically during the initialization phase of Site*Planner*.

HIDE_FLR Prompts the user to enter the number of the floor to hide from view. This effectively makes all drawing entities associated with the building floor invisible to the user.

IMP_DXF This command is used when assembling a drawing from existing digitized drawing files, preferably created through the FORMAT...WITH EACH FLOOR A SEPARATE DRAWING development route. The user is prompted to enter the name of the drawing file to import. It is assumed that the entities in the drawing being imported have already been formatted correctly for use by SMT *Plus*. If this is not the case, or for some reason the assembled drawing is not correct, the drawing can be saved and reformatted using the FORMAT... WITH ALL FLOORS IN SAME DRAWING development route.

IMP_IMG This command allows the user to import a scanned image of a building floor plan, in Encapsulated Postscript (EPS) format, into AutoCAD in order to trace over it. The user is prompted for the name of the file to import and the floor on which to place it. Once imported, the user can trace over the building floor plan using the Draw commands.

LEFT This command is analogous to panning left, as all drawing entities are shifted to the right.

LEGEND Displays the color legend used by the current drawing.

MOVE Allows the user to move a single entity or selected group of entities, an entire floor, or the entire drawing.

POSITIVE This command physically relocates the entire building such that a user selected reference point is set to be the origin point (0,0,0). All building coordinates are referenced to this point.

PRT_INFO Displays information (type, floor, length, etc.) regarding a user selected entity.

RIGHT This command is analogous to panning right, as all drawing entities are shifted to the left.

SCALE Enables the user to scale selected entities, an entire floor, or the entire drawing. To do so, the user selects two points in the drawing and enters what the expected distance between the two points is. Site*Planner* then scales the selected entities such that the distance in the drawing matches the actual distance in the real building.

SETSNAP Allows the user to specify the method by which points in the drawing will be selected using the mouse. This is only relevant when the user is prompted to select a point within the drawing. The default value for Snap is NONE, which means that whenever the user is prompted to select a point, the location of wherever the mouse is clicked is returned. If ENDPOINT is selected, however, the nearest end point of the line closest to the point indicated by the user is returned as the selected point. Similarly, if CENTER is selected, the center of the nearest line is returned as the selected point.

SHOW_FLR Prompts the user to enter a floor number, and makes all entities on that floor visible.

TGL_GRID Toggles the displayed drawing grid on and off.

TGL_SNAP Toggles the snap-to-grid on and off. For greater drawing accuracy, it is recommended that snap-to-grid remain on. By setting the grid spacing to a smaller value, more precise points may be selected.

UNDO Takes away the previous user action. Undo is limited to actions which affect the drawing directly.

UP This command is analogous to panning up, as all drawing entities are shifted down slightly.

UP_1_FLR Shifts up one floor in the drawing.

VIEW_ALL Make the entire drawing visible at one time.

XPORTDXF Exports the current AutoCAD drawing into a portable text based file format known as Drawing Interchange Format (DXF) format. A DXF file is a textual description of the drawing in a format that is interchangeable between most graphical systems. In Site*Planner*, this export is usually done with the purpose of later importing the file as a component of another floor plan (i.e., importing a DXF file describing the second floor of a building into the final building layout).

ZOOM Provides the user the ability to change the viewed portion of the drawing.

ZOOMIN Zooms in on the current view slightly.

ZOOMOUT Zooms out on the current view slightly.

Author's Biographical Sketch

Roger R. Skidmore was born on May 9, 1972 in Pennington Gap, VA. He received his B.S. degree in computer and electrical engineering from Virginia Tech in 1995. During the course of his undergraduate degree, he participated in the cooperative education program, spending three semesters working with Ericsson in Lynchburg, VA. From 1995 to the present, he has worked as a graduate research assistant for the Mobile and Portable Radio Research Group. His research interests center around in-building and microcellular wireless communication systems, including wireless LAN, wireless PBX, and wireless local loops. He is currently pursuing a doctorate with Dr. Theodore S. Rappaport at Virginia Tech.