Implementation of Geometrically Based Single-Bounce Models for Simulation of Angle-of-Arrival of Multipath Delay Components in the Wireless Channel Simulation Tools, SMRCIM and SIRCIM

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As the demand for wireless communication systems has exploded over the past few years, many researchers have taken on the challenge to model wireless channels more accurately. These models are very useful for enhancing the design of all aspects of wireless communications. Smart antennas and systems used in position location are among the most popular new studies that require signal information such as the amplitude, phase, and angle-of-arrival (AOA) of multipath delay spreads. For proper and efficient implementation of future systems, emerging wireless systems must be able to exploit processing of spatial information. The goal of the work presented in this thesis is to further improve two channel modeling tools, SMRCIM and SIRCIM, by implementing new geometrical models that provide users with angle-of-arrival information as well as amplitude and phase data for wideband wireless communication channels. The new angle-of-arrival models are explained and pseudo code is provided to demonstrate the software implementation of the models. Likewise, the channel models are explained and the usage and results of the simulation tools are described. The SMRCIM and SIRCIM tools are currently being used by researchers throughout the world.
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Chapter 1
Introduction

1.1 Overview

This thesis outlines the development and implementation of new angle-of-arrival (AOA) models in both indoor and outdoor wireless radio channel software simulation tools. Additionally, this thesis expounds upon the theory of propagation of electromagnetic waves in radio frequency (RF) channels, the models utilized in channel simulation software, enhancements made within the software, and the future of the tools. Likewise, specifics of the user interface and the data supplied by the software are discussed.

These software tools, known as SMRCIM (Simulation of Mobile Radio Channel Impulse Response Models) and SIRCIM (Simulation of Indoor Radio Channel Impulse Response Models with Impulse Noise), were originally conceptualized to support simulations of communication systems by providing real-life indoor and outdoor channel impulse response data based on numerous measurement campaigns to construct statistically accurate models. SMRCIM is the outdoor companion of SIRCIM, first conceived and developed by researchers at the Mobile and Portable Radio Research Group (MPRG) of Virginia Polytechnic Institute and State University [24], [52]. With these software packages, labor intensive measurements may now be accurately simulated with the easy to use graphical interface. Likewise, the raw measurement data outputted by the program is organized in a concise directory structure providing the necessary information for all types of wireless communication systems research and design. With these software tools, the user has the ability to create hundreds upon hundreds of wideband and narrowband simulations of real-world measurements based on user selectable parameters.

SMRCIM and SIRCIM offer a graphical user interface based on MATLAB® versions 5.x, and the simulation engines use C/C++ executable code designed to run under Windows 95, 98, or NT. The interface includes powerful menu options for
creating useful displays of channel multipath delay profiles, wideband and narrowband scatter plots, AOA plots, cumulative distribution functions (CDF), and continuous wave (CW) amplitude and phase plots.

This chapter provides a brief introduction to the background of both SIRCIM and SMRCIM including the original research ideas, new models that have been incorporated as the main subject of this thesis, and the motivation for this work. Chapter 2 includes more information about the original research work and serves as a tribute to the work. Chapter 3 discusses, in more detail, the SIRCIM and SMRCIM channel models and implementation. Additionally, Chapter 3 discusses the user input and gives examples of screen shots from both of the programs. Chapter 4 is the main emphasis of the research and work in this thesis. It explains the AOA models in SMRCIM and SIRCIM and discusses the algorithms used to implement the models. Chapter 5 outlines the different types of file outputs that SIRCIM and SMRCIM generate and also provides some example output files. Finally, Chapter 6 provides some example output data and plots generated from the implementation of the AOA models described in Chapter 4.

1.2 Understanding the Generalized Channel

Figure 1.1  Basic Mobile Multipath Environment
Figure 1.1 shows a very simple example of the basic mobile multipath environment [15]. Multipath signals are delayed versions of the originally transmitted signals that are caused due to the multiple number of paths along which the waves travel. Hence the name multipath. Multipath components or multipath signals result at the receiver when electromagnetic waves encounter reflections from large objects, diffraction around large objects, and scattering when transmitted through the wireless channel [15] [38]. All components of the signal experience a different path environment, determining the amplitude $A_{l,k}$, carrier phase shift $\varphi_{l,k}$, time delay $\tau_{l,k}$, angle of arrival $\theta_{l,k}$, and Doppler shift $f_d$ of the $l$th signal component of the $k$th mobile. Generally, these signal parameters are considered to be time-varying.

Gathering all of the information from Figure 1.1, the vector channel impulse response can be expressed with the following equation:

$$
\tilde{h}_l(t, \tau) = \sum_{i=0}^{L(t)-1} A_{i,l}(t) e^{i\varphi_{i,l}(t)} \tilde{a}(\theta_{i,l}(t)) \delta(t - \tau_{i,l}(t))
$$

Eq. 1.1

where $\tilde{a}(\theta_{i,l}(t))$ is the array response vector and $L(t)$ is the number of resolvable paths [15]. Thus, Equation 1.1 defines the spatial channel impulse response made up of the summation of several multipath components, each having its own amplitude, phase, and angle-of-arrival [15]. Note that Equation 1.1 assumes an infinite bandwidth model, because of the delta functions, that can never be physically realized in practice.

---

**Figure 1.2** High Level Block Diagram of a Communication System
With the channel represented as an impulse response, a block diagram of a mobile communication system can be formed as shown in Figure 1.2. Using SMRCIM and SIRCIM, realistic time domain files for $h(t; \tau)$ shown in Figure 1.2 can be created based on extensive measured data reported in the literature, and may be used to model the multipath channel characteristics of a wide range of mobile communication systems.

1.3 Design Issues Corresponding to RF Propagation

Wireless communication system designs can be based on a number of different modulation schemes, coding techniques and data rates if they are digital systems, antenna configurations, and various other aspects. Despite the freedom of choice in these areas, the radio propagation channel environment cannot be completely controlled at all times. Ultimately, a designer will be required to simulate or test designs using the actual channel or a simulation of the channel before the effects of the channel can be mitigated in the design. Accurate, fast, and easy to use design tools based on models derived from measurement data can enable wireless system designers to create communication hardware and systems more efficiently in terms of receiver signal-to-noise ratio (S/N) or bit-error-rate (BER) performance, channel access, handoff, co-channel interference, equalization, diversity, modulation performance trade-offs, and cost.

1.4 Motivation

With the onslaught of the digital revolution, emerging digital, wireless communication systems are demanding higher levels of performance. The common obstacle in achieving such levels in all wireless systems is overcoming the propagation effects of the channel. Many efforts have been made to characterize channels with mathematical models such as those in [23] [28] [53], and yet these models still do not provide sufficiently accurate information for the design of high quality wireless systems. In frequent instances, designers have opted to acquire accurate channel data by performing rigorous measurement campaigns of channels of interest [38].
Over the last ten years, many efforts have been put forth to create accurate models based on real-life measurement campaigns of typical radio channels for both indoor and outdoor environments [29], [37], [49]. The main goal of this work has been to take a step beyond the mathematical models that generally only account for frequency flat fading of signals to provide models that are statistically accurate and account for all types of fading and signal degradation by the surrounding environment. In addition, the direction of this research has been to not only provide statistical characterization of typical indoor and outdoor radio channels, but to also build software simulation tools based on a graphical user interface to provide access to extensive channel impulse responses without the extra cost of having to physically perform channel sounding measurement campaigns.

By providing accurate large scale and small scale propagation fading data, SMRCIM and SIRCIM can be used to study bit error rates, channel access, handoff, co-channel interference, equalization, diversity, and modulation performance in frequency-flat and frequency-selective fading environments. The applications and benefits of having this type of software channel simulation tool are obvious to hardware designers, and university research can thrive with the availability of a plethora of easy to obtain measurements. In fact, the precursor to SMRCIM, SIRCIM, has been used by many researchers in efforts to design and predict the performance of different wireless standards, receivers, coding algorithms, antenna diversity algorithms, etc. Channel impulse response data obtained from SIRCIM was used extensively in [2].

Until recently, the software tool, SMRCIM, had never come to fruition, despite extensive measurements reported in [4], [19], [30], [45], and [48]. The statistical models had been developed at MPRG along the same time frame as those of SIRCIM, but the software was incomplete and based in a DOS environment. In an effort to demonstrate the importance of these simulation tools, this thesis briefly describes the history of the channel modeling software, the present day status of the software tools, and the development of the tools.
1.5 Research Contributions

This thesis encapsulates over a decade of research in the field of propagation in indoor and outdoor environments. The work presented within represents important contributions to the field of wireless communications for both educational and industrial purposes. Below is a brief list of the ideas and results discussed in the remainder of this thesis.

- Easy to use GUI for SMRCIM and SIRCIM
- Automatic configuration utility – (Installation package)
- Increased frequency range from older versions
- Increased number of wavelengths simulated over a local area
- Documentation of output data files
- Faster, more efficient code for SMRCIM and SIRCIM
- Corrections to older versions of SMRCIM
- Industrial applications
- Research applications
- Angle-of-Arrival model implementation
- Support for m.p.h. and k.p.h. in SMRCIM
- Data conversion software with easy to use GUI
Chapter 2

Background Information

2.1 Early Research

Over the past two decades, researchers have strived to analyze radio propagation channels to develop accurate models. In the mid 1970s, work was done by G.L. Turin at the University of California, Berkeley to create initial models of the San Francisco urban/suburban mobile radio channel [37], [56]. Transmitters were to transmit pulses having r.m.s durations of 100ns. These wideband pulses were received in a mobile van containing three receivers and a three-trace oscilloscope. Each second, a pulse was transmitted and the oscilloscope was configured to trigger just before the line-of-sight (LOS) delay time.

After collecting many frames of channel data, the data was reduced and discretized into time bins. The received signal was represented as

\[ p(t) = \Re\{p(t)e^{j\phi}\} \]  

where \( \alpha_i \) is the attenuation factor of the signal received on the i-th path, \( \tau_i \) is the propagation delay induced by the scatterer along the path, \( \theta_i \) is the random phase of the received signal, and \( u(t) \) is the complex envelope of the modulating pulse [37], [56].

Following in the footsteps of Turin, work was performed by Suzuki and Hashemi dealing with fitting measured data to statistical models with the intention of developing a simulation program. Hashemi later combined the data from Turin’s work and the statistical models from Suzuki to design a computer program called SURP (Simulation of Urban Propagation) [17], [37], [55]. This work provided researchers with the ability to simulate discretized received signals, making it possible to use channel models in simulations to predict useful quantities such as SNR, BER, channel dispersion, and other important characteristics [37].
As this area of interest began to intensify, more researchers began analyzing wireless communication channels in new ways. Devasirvatham explored wideband characteristics at 850 MHz in building environments by utilizing spread-spectrum channel sounding equipment. His results offered information about r.m.s. delay spreads and their dependence upon the structure and surroundings of various buildings, providing important information for determining the capacity of the channel [21], [37]. Shortly after Devasirvatham’s findings, Saleh and Valenzuela performed wideband channel sounding in an average two story office building in efforts to continue the modeling of the indoor channel [37], [47]. Using many multipath profiles generated in their research, Saleh and Valenzuela proposed a statistical model of the indoor channel that is widely used in current research.

2.2 Origin of SMRCIM and SIRCIM

Similar to the work explained above, Theodore S. Rappaport performed extensive research at Purdue University in the mid 1980s continuing the characterization of wideband wireless communication channels in factory environments. Rappaport’s goal was to collect radio propagation data from typical factories to identify the characteristics of the factory radio channel [37]. At the time, there were predictions that indoor, wideband, wireless communication systems would be common place in the future. Likewise, Rappaport set forth to determine wideband multipath characteristics and signal fading characteristics by collecting empirical data from several factories in Lafayette, Indiana [37]. This work was later utilized by Scott Y. Seidel at Virginia Polytechnic Institute and State University in 1989 [49].

Seidel determined that models characterizing the impulse responses of factory radio channels would be beneficial for use in simulations for analyzing equalization, diversity, modulation, and coding techniques. Under the direction of Rappaport, as a Masters student, Seidel combined the numerous data files generated in Rappaport’s work to develop statistical models that would be used in software to recreate wideband channel impulse responses along with narrowband fading information. In addition to this
information, Seidel also analyzed other measurement data appearing in the literature at the time to validate consistent trends. As a result, Seidel’s work outlines the development of SIRCIM from the initial stages of analyzing the data, through the generation of the statistical models, and finally to the implementation of the models in software – hence the initial concept of SIRCIM.

In addition to the contributions mentioned above, many students at the Mobile and Portable Radio Research Group of Virginia Polytechnic Institute and State University contributed, over the last 10 years, by continuing the collection of data for increased accuracy of the models and for verification purposes. In the early 1990s, one of these students, W. Huang, along with post-doctoral student M. Feuerstein, combined the empirical data from outdoor measurements to create the first version of the outdoor channel simulation tool, SMRCIM [4], [19], [30], [39], [45], [48].

2.3 Current Status of SMRCIM and SIRCIM

SMRCIM and SIRCIM are currently being used in many research institutions throughout the world and also by many corporations. Among several of the institutions, Georgia Tech, Purdue University, Oklahoma Christian University, the University of Kansas, The Chinese University of Hong Kong, The Korea Advanced Institute of Science and Technology, and many others are using either SMRCIM or SIRCIM or both. Likewise, corporations such as Motorola, Texas Instruments, Tantivy Communications, the Australian Department of Defense, The U.S. Department of Defense, GAT Systems, Stanford Telecom, Southwest Research Institute, ITT Aerospace, Siemens, and many others have obtained these software tools. As a result, the interest in these tools has directly influenced the research discussed in this thesis and the on going RF propagation research at Virginia Polytechnic Institute and State University.
Chapter 3
Channel Models Implemented in SMRCIM and SIRCIM

3.1 Introduction

Unlike wired communication systems that are static and easily characterized, radio channels are highly random, time varying, and difficult to predict. The propagation path in a wireless communication system can vary in real-time from close range, stationary, line-of-sight (LOS) to a heavily obstructed mobile path due to both moving objects and stationary objects [38]. In addition to these non deterministic fluctuations in the channel, the rate at which the channel changes and the rate at which the transmitters and receivers move can all but render the channel unusable, as one may note when talking on a cellular phone in a moving car that enters a tunnel. Needless to say, although wireless systems share the radio channel as a common limiting factor, the channel can be extremely random in nature and thus plays a major role in the design of many wireless communication systems.

Due to these complications, engineers and theoreticians have been researching ways to model and simulate mobile radio channels for years. Many models have been developed based on strictly mathematically based statistics [28]. The most common approach for reproducing channels has been with the implementation of a “Tapped Delay Line [20].” Others include a multiray impulse response model where each ray has independent Rayleigh fading. In this model, two Doppler low-pass filters with white Gaussian noise are used to generate the real and imaginary parts of a flat Rayleigh fading channel [21]. As an alternative to these types of models, researchers have, of late, begun to incorporate realistic measurement data into models to accurately reproduce radio channels. Until recent years, models have been developed but not implemented in software. SMRCIM and SIRCIM are direct results to the flow of research in this area.
3.2 Physical Mechanisms of Propagation

When electromagnetic waves propagate through radio channels, they experience delays and losses due to the channel. A typical radio channel consists of multiple physical propagation paths that individually induce propagation loss and delay to signals. If a line-of-sight (LOS) path exists between the transmitter and receiver antennas, the LOS multipath component will always arrive first. Additional physical paths throughout the environment cause the remainder of the multipath components to arrive later in time. In addition to receiving individual components at different times, there are instances when multipath arrives from more than one path at the exact same time. In such cases, the components will be combined as a resultant of the vector sum of the received signals. Depending on the phases of the signals at the receiver, this may induce fading [29].

Absolute propagation time for a path is determined by the distance between a transmitter antenna and a receiver antenna along a particular path. Since the LOS component arrives first, the relative propagation time of later arriving signals, referred to as excess delay, is defined by the time difference between a multipath component and the LOS component. Dispersion in time affects the quality of digital radio links due to the induced intersymbol interference. Therefore the relative propagation time of multipath components is more important than the absolute propagation time. This is most notable in high data rate communication systems where excess delay can severely reduce system performance [29].

In general, there are three physical mechanisms that affect the propagation of electromagnetic waves in a radio channel as discussed above. These three mechanisms are reflection, diffraction, and scattering [38]. In outdoor environments, tall objects introduce severe diffraction losses due to the sharp change in the shape of the impinging surface. Electromagnetic waves tend to bend around these objects resulting in secondary waves that propagate in random directions from the LOS. When wave fronts strike impeding objects that are large relative to the wavelength of the wave, reflection occurs. When electromagnetic waves propagate through a region of space where small objects are densely located or where small physical bodies extend from a large body, scattering occurs, such as along a rough wall or through dense surroundings, such as a forest [38].
3.3 Channel Impulse Response Function

In an ideal situation the channel impulse response would be measured by probing the channel with a true delta impulse, however this is not physically realizable. Therefore SMRCIM and SIRCIM approximate wideband impulse responses over many local areas, where the complex baseband discrete impulse response is given by Equation 3.1, where

$$h_b(t, \phi_k, \tau_k) = \sum_{k=0}^{63} \alpha_k e^{j\theta_k} p(t - \tau_k)$$

$\phi_k$ is the angle-of-arrival of the multipath components, $p(t)$ is a very narrow pulse and the power of the multipath components $\alpha_k^2$, the relative time delays $\tau_k$, and the phase of each multipath component $\theta_k$ are generated by the simulation tools. Likewise, it is assumed that there is just at most a single multipath component within duration of the pulse $p(t)$ [49]. In addition, the AOA for each multipath component is also generated during wideband simulations based on AOA models discussed in Chapter 4.

3.4 Environment Characterization for SMRCIM

The propagation channel models in SMRCIM allow a user to create spatially-varying wideband channel impulse responses for a general classification of three types of outdoor environments based on real-life measurement data. The three environments modeled within SMRCIM are the URBAN, SUBURBAN, and MICROCELLULAR environments. These models generate simulated data that have statistics analogous to measured data recorded in the different outdoor environments. Each multipath impulse response is simulated over a range of either 40 microseconds for urban and suburban environments [41], [45], [48] or 4 microseconds for microcellular environments [4]. Users can specify the overall link dynamic range, which is defined as the effective isotropic radiated power minus the noise power (EIRP – FkT0B). If a multipath
component has path loss larger than the dynamic range, its level will be below the noise and it cannot be detected.

The wideband impulse responses for all of the outdoor environments are generated in the same manner. However, the models that describe the impulse responses have been altered to represent the specific surroundings. Mathematical descriptions of the models used to generate wideband impulse responses can be found in Appendix B, and are based on empirical fits to measured data described in [19], [49], and [52]. Some typical examples of simulated values for path loss and r.m.s. delay spread at a particular location, denoted in this thesis as $P_n$, are given in Table 3.1. The following sections describe the individual environments.

### Table 3.1 Typical Values for Path Loss and RMS Delay Spread produced by SMRCIM simulations for Urban, Suburban, and Microcellular Environments

<table>
<thead>
<tr>
<th>Component</th>
<th>Median RMS Delay Spread (µs)</th>
<th>Maximum RMS Delay Spread (µs)</th>
<th>$n$</th>
<th>$\sigma$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>1.94</td>
<td>10.64</td>
<td>2.7</td>
<td>11.3</td>
</tr>
<tr>
<td>Suburban</td>
<td>0.92</td>
<td>11.00</td>
<td>2.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Microcellular</td>
<td>0.24</td>
<td>1.08</td>
<td>2.4</td>
<td>6.5</td>
</tr>
</tbody>
</table>

### 3.4.1 Urban Environments

An urban area describes a typical, heavily built up, downtown area within a city. Tall buildings along streets act as reflectors of radio waves, and a line-of-sight path usually does not exist because of the shadowing of nearby buildings. Both the base station and mobile antennas presumably use an omni-directional antenna. A tall (e.g. 50m) base station antenna is used to provide large coverage areas. However, a tall base station antenna may cause many reflections, which are the sources of the multipath signals. The city may be in a mountainous region, so there may be some strong reflections with large delays from the far away mountains.
3.4.2 Suburban Environments

In the context of SMRCIM, a suburban area describes the less built up outskirts of a city. These types of areas may be open farmland located next to small neighborhood subdivisions. There may also be some visible mountains off in the distance. In suburban areas, nearby low buildings cause most of the multipath with small time delays, but the large scatterers, such as isolated large buildings and mountains, generate significant multipath components with large time delays [4], [30].

3.4.3 Microcellular Environments

A microcellular area is considered to be an area such as a campus where cells have been divided into much smaller areas than a typical outdoor cellular system. The size of cells is decreased in such an area primarily to enhance frequency reuse. Consequently, these smaller cells require lower powered base stations with antennas that are closer to the ground. Additionally, microcellular systems, generally, are more likely to have a LOS path.

3.5 Indoor Channel Characterization for SIRCIM

The propagation channel models in SIRCIM allow a user to create spatially-varying wideband channel impulse responses for a general classification of three types of indoor environments based on real-life measurement data obtained in many different buildings. The three building types modeled within SIRCIM are referred to as the OPEN-PLAN, SOFT-PARTITIONED, and HARD-PARTITIONED buildings. All of these models generate outputs that have statistics identical to those of measured data in, [18], [36], and [40] at 1300 MHz, and at other frequencies by many researchers. The models are described in more detail in the following subsections.

Additionally, the radio channel propagation models in SIRCIM allow the user to simulate wideband impulse responses for spatially-varying channels in both line-of-sight (LOS) and obstructed (OBS) areas within buildings from each of the three classifications. From the multipath power delay profiles (square magnitude impulse responses) generated.
in SIRCIM, the user can generate a time series of narrowband fading waveforms or the user can choose from menu options to utilize well-known methods for generating temporal or spatial fading signals such as those discussed in [38].

The wideband impulse responses for all of the indoor models are generated in the same manner. However, the models that describe the impulse responses have been altered to represent specific surroundings. Mathematical descriptions of the models used to generate wideband impulse responses can be found in Appendix B. Some typical examples of values for path loss and r.m.s. delay spread simulated by SIRCIM at a particular location, $P_n$, are given in Table 3.2. The following sections describe the three environments simulated by SIRCIM.

| Table 3.2 Typical Values for Path Loss and RMS Delay Spread produced by SIRCIM simulations for Open-Plan, Hard-Partitioned, and Soft-Partitioned Buildings Over 25 Locations (LOS Denotes Line-Of-Sight Topography, OBS Denotes Obstructed Topography) |
|---------------------------------|---------------------------------|----------|----------|
|                                 | Median RMS Delay Spread (ns)    | Maximum RMS Delay Spread (ns) | $\mu$   | $\sigma$ (dB) |
| Open-Plan LOS                   | 76                              | 172      | 2.0      | 5.0         |
| Open-Plan OBS                   | 109                             | 191      | 2.3      | 5.0         |
| Hard-Partitioned LOS            | 27                              | 144      | 2.3      | 5.4         |
| Hard-Partitioned OBS            | 34                              | 127      | 2.9      | 5.8         |
| Soft-Partitioned LOS            | 24                              | 112      | 2.5      | 5.4         |
| Soft-Partitioned OBS            | 30                              | 114      | 3.1      | 5.8         |

### 3.5.1 Open-Plan Buildings

An open-plan building environment represents spacious buildings such as coliseums, warehouses, factories, gymnasiums, large convention centers, and airport terminals. These areas typically consist of mostly LOS paths and have possibly a few large obstructions at various locations. These obstructions are frequently large, isolated objects, such as machines, shelves of stock, information booths, equipment racks, or various other objects that do not span the entire height from floor to ceiling. In fact, the
best analogy to this type of building is that of a large box having a top on it [24]. A very good example of an open-plan building is a large Walmart store.

### 3.5.2 Hard-Partitioned Buildings

A hard-partitioned building in SIRCIM represents an average multiple floor building such as an office, school, hospital, hotel, etc. consisting of many internal partitions fabricated of reinforced concrete or drywall backed by metal or thick wood studs spaced 16 inches apart. Hallways in these types of buildings are usually six to ten feet wide. The walls separating the different rooms from hallways or walkways span from floor to ceiling, thereby reducing the probability of LOS conditions.

### 3.5.3 Soft-Partitioned Buildings

Soft-partitioned buildings are somewhat similar to open-plan buildings in that they often consist of large open areas. However, these large areas in soft-partitioned buildings are partitioned into office type cubicles constructed of 5-foot-high, movable, cloth covered, plastic dividers. Additionally, the soft-partitioned model assumes that the buildings are multi-story buildings, whereas the open-plan model assumes a single story building with walls extending to the ceiling.

Measurements at frequencies between 850 MHz and 5 GHz reported in [9], [11], [13], [18], [38], [44], [47], and [50] were compared to SIRCIM simulations and found to be very similar. Some of the simulated values for path loss and RMS delay spread are given in Table 3.2.

### 3.6 Model Development for SMRCIM and SIRCIM

#### 3.6.1 Wideband Impulse Response Modeling

Many of the models in SMRCIM and SIRCIM are based on the case of a wireless communications link between a stationary transmitter and a mobile receiver. These models are based on the underlying core statistical models described in [43], [49], [51]. For all measurements, an omni-directional 1.8 dB gain vertical antenna is assumed both
at the transmitter and receiver. In determining the reference path loss, the gain of the antennas is taken into consideration. (see Equation 3.5). For SMRCIM, many measurement data were collected for various geographic environments for the three different types of models, microcellular, urban, and suburban. For SIRCIM, numerous measurement data were gathered in buildings representative of open-plan, soft-plan, and hard-partitioned type establishments. At each location, the receiver was moved over a local area along a straight path. This straight path is referred to as a track. Each location or local area is represented by the variable $P_n$, where $n$ is an index denoting the number of measured locations. Likewise, when simulating measurements in SIRCIM and SMRCIM, $n$ is the index of each of the simulated locations. Corresponding to each $P_n$, there is a nominal transmitter-receiver separation distance referred to as $D_n$. In SIRCIM, there are topography descriptors, denoted $S_m$, associated with each $P_n$ where an index of $m = 1$ indicates a LOS topography and an index of $m = 2$ means that there is at least one obstruction between the receiver and transmitter.

Wideband simulation data are based on statistical models describing the total quantity of multipath components in a received multipath impulse response, the excess delay of each individual multipath component, the amplitude, the instantaneous phase, and the AOA of each of the components. The simulations also consider the motion and the corresponding Doppler spread on individual multipath components, while neglecting slight temporal fading effects caused by objects moving in the channel. Arrival times are determined by a heuristic algorithm that was found to model the observed arrival times better than a Poisson model [49]. Over each local area, the received impulse responses are generated at 19 points spaced at a distance of $\lambda/4$, where $\lambda$ represents one wavelength of the carrier frequency. Likewise, the multipath delay components are separated into 64 discrete time slots referred to as time bins. The resolution of these time bins are dependent on the measurement data used to create the models. In SIRCIM, the time bins have a resolution of $7.8125 \text{ ns}$ for all models, while in SMRCIM, the bins have a resolution of $62.5 \text{ ns}$ for the Microcellular model and $625 \text{ ns}$ for both the Urban and Suburban models. Additionally, users can generate narrowband fading signals based on
the information from the wideband channel impulse response simulation data, or by using well-known methods for generating spatial or temporal fading signals.

Both wideband and narrowband measurements using the fixed transmitters and receivers showed that individual multipath components and narrowband signal strengths fade very slightly (only by a few dB in general) due to motion of other objects in the various channels. Because there is only slight fading when both the transmitter and receiver are stationary, this is evidence that the received multipath components and narrowband signal strengths behave with Ricean (with large K value) or log-normal (with small standard deviation) statistics. When the receiver is in motion, individual multipath components still fade only slightly, but the narrowband signal strengths often exhibit deep fades, sometimes on the order of 30-40 dB. Thus, the impulse response models always assume the receiver is moving over space.

Both SMRCIM and SIRCIM use the probability of the existence of multipath components based on empirical data at a given excess delay to determine the number of multipath components at each discrete location. First, the number of multipath components at each discrete location is determined from a Gaussian distribution based on empirical data. Next, the measured probability of arrival at each excess delay is preserved by using a heuristic technique, described in [49], [51], to determine the excess delays of multipath components. Then, using a log-normal distribution based on a $d^{n(\tau)}$ power law where d is the transmitter-receiver distance in meters and $n(\tau)$ is the excess-delay-dependent power law exponent, the mean amplitude of each multipath component in excess delay bin $\tau_i$ is generated [40]. The free space value of $n(\tau=0)$ would be 2 because power falls off as the square of distance for the free space. However, the value of the path loss exponent depends on the channel characterization as demonstrated in the appendices. For SMRCIM, the multipath component amplitudes at each individual location along a 4.5, 10, 20, 40, or 80λ track are generated from a log-normal distribution with the mean determined from the power law and with a standard deviation...
approximately 8 dB as determined from an empirical distribution given in [48], while in SIRCIM, the standard deviation ranges between 0 and 4 dB as determined from an empirical distribution given in [43], [49]. After simulating the multipath components, the angle-of-arrival for each multipath is simulated using either an Aisle Elliptical or Random Elliptical model as explained in Chapter 4.

Since the multipath models have very high excess delay resolution, an acceptable spatial sample rate is achieved by $\lambda/4$ spacing ensuring the replication of the fading characteristics of individual multipath components over space. In SMRCIM, the resolution for the models is slightly less than for SIRCIM. This is due to the fact that significant multipath components in an outdoor channel can arrive at much greater delays. Depending on the model used in SMRCIM, the resolution is either 62.5ns or 625ns between each multipath component, while the resolution is 7.8125ns for all models in SIRCIM. In SIRCIM, each multipath impulse response is simulated over an excess delay range of 500 ns. This value is utilized because it was the largest excess delay recorded at nearly all indoor locations in [36]. Figure 3.1 shows an example of a typical plot of the multipath delay spread over a local area generated in SIRCIM.

**Figure 3.1 Impulse Response Plot Generated by SIRCIM**
3.6.2 Synthesis of Narrowband Signal from Wideband Impulse Responses

The wideband impulse responses of SMRCIM and SIRCIM were generated based on extensive measurements conducted using either repetitive pulses [41] or a wideband spread spectrum signal [38]. If, instead, a continuous wave signal is transmitted through a channel having its impulse response generated by the simulation tools, the instantaneous complex envelope, \( r(t) \), of the received signal may be represented as a sum of the phasor representations of the individual multipath components within a single power delay profile [38]:

\[
 r(t) = \sum_{i=0}^{N-1} a_i \exp(j\theta_i(t, \tau))
\]  

\text{Eq. 3.2}

where \( a_i \) is the amplitude and \( \theta_i \) is the phase of the \( i \)th multipath component of the profile. This is the result of the convolution of the complex envelope of the CW signal (which is DC) with the complex envelope of the wideband channel impulse response. The magnitude of \( r(t) \) will be the instantaneous received voltage envelope [24].

In order to compute the narrowband (CW) signal strength and carrier phase from the wideband impulse responses, the calculation of phase for each wideband multipath component is required, as shown in Equation 3.2. These computations are performed by interpolating the amplitudes of additional wideband profiles closely spaced between the corresponding 19, 41, 81, 161, or 321 core profiles and synthesizing the phase as the mobile receiver moves over tiny increments of distance along the 4.5, 10, 20, 40, or 80\( \lambda \) track. In a deterministic fashion, the phase change of each multipath component is modeled over a local area as the mobile travels incrementally, based on the simulated angle-of-arrival and small changes in radio path length from a randomly positioned scatterer that remains fixed as the receiver moves. SMRCIM and SIRCIM assume that each multipath component is a result of a reflection from a different fixed scatterer. The phase synthesis process and angle-of-arrival process is described in detail in Appendix A and Appendix B, respectively. After determining the phase for each individual multipath component, Equation 3.2 is used to calculate the instantaneous complex envelope of the
received signal in a local area. Based on the fact that closely spaced impulse responses “collapse” into CW fading responses that obey the same first and second order statistics as real CW measurements, this method has been found to be a very accurate technique, [16], [24], and [51]. The algorithms involving this phase synthesis are discussed in further detail in Chapter 4.

3.6.3 Synthesis of Narrowband Signals Without Wideband Information

All individual multipath components received by the wideband receiver in [36], [40] had an amplitude greater than -56 dBm with a +30 dBm transmitter at 1300 MHz. Any smaller components were treated as noise because they were below a threshold. Thus, in partitioned buildings, since path loss increases more rapidly with distance than in open-plan buildings, the simulation measurement range is smaller than in open-plan buildings. A narrowband receiver, however, has a much narrower noise bandwidth and thus can detect signals below -100 dBm. This permits a much larger simulation coverage range [50]. Another technique, which was also based on measurements, is used to determine the narrowband signal large-scale path loss.

Both SMRCIM and SIRCIM assume a logarithmic increase of mean path loss (in dB) with distance. This can also be thought of as a linear increase of mean path loss in dB with the log of distance. This is modeled as a mean path loss law of $d^n$ where $d$ is the T-R separation between transmitter and receiver, and $n$ indicates the path loss exponent ($n = 2$ for free space). The path loss between a transmitter and receiver at a fixed T-R separation $d$ is assumed to be log-normally distributed about the mean path loss. Thus, the mean path loss in dB is described as [38]:

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right)$$  \hspace{1cm} \text{Eq. 3.3}$$

where free space path loss is assumed between the transmitter and a user specified reference distance, $d_0$. $\overline{PL}(d_0)$ is the reference distance path loss, in dB, and is given by
Equation 3.4, where $d_0$ is the reference distance in meters, $\lambda$ is the wavelength, and $G_T$ and $G_R$ are the gains, in dB, for the transmitter and receiver antennas, respectively. At a particular location, with a T-R separation of $d$ meters, the random path loss is given by Equation 3.5 where $X_\sigma$ is a Gaussian random variable (in dB) having zero mean and $\sigma$ dB standard deviation \[38\]. Table 3.1 and Table 3.2 give values of $n$ and $\sigma$ (the standard deviation in dB about the mean path loss) as functions of surrounding and building type topography, respectively.

With user defined values for $n$ and $\sigma$, in conjunction with Equation 3.4, SIRCIM and SMRCIM can simulate local average path loss values over large scale distances very quickly, without generating the small scale fading signal at a particular location. This aids users in capacity, coverage, and co-channel interference studies because many different received power levels at varying T-R separations can be easily generated.

Using the sum of the squares of two independent Gaussian noise sources which are passed through a low-pass filter having the RF Doppler spectrum for Rayleigh fading, small scale fading of the narrowband signal about the local median signal strength can be generated for moving terminals \[53\]. This process is described in Appendix A, Synthesis of Narrowband Signals, and in \[38\]. In both SMRCIM and SIRCIM, signals may be generated over the 4.5, 10, 20, 40, or 80$\lambda$ track at each location (Small Scale Rayleigh Spatial Fading), or they may be generated for a user-selected time duration (Small Scale Rayleigh Temporal Fading). The user can specify the maximum Doppler frequency which specifies the bandwidth of the RF Doppler spectrum for simulation of temporal fading. Note that, since 4096 (2048 for SMRCIM) time samples are used to create a CW fading waveform, the maximum Doppler and maximum time duration are interrelated.
functions of the carrier frequency, as determined by Equation 3.8. Alternatively, the user can specify an average level crossing rate (LCR) referred to a user-defined threshold level. According to [17], the LCR is the expected rate at which the Rayleigh fading envelope, normalized to the local RMS signal level, crosses a specified level in a positive-going direction. The LCR and the LCR threshold can be related to the maximum Doppler frequency by the following equation:

\[ N_R = \sqrt{2\pi f_m \rho e^{-\rho}} \]  

where \( N_R \) is the number of level crossings per second, \( f_m \) is the maximum Doppler frequency, and \( \rho \) is the LCR threshold [38].

As a final option, the user can enter the mobile velocity, which is related to the maximum Doppler frequency by Equation 3.7. For spatial fading, the user must enter the mobile velocity, which SIRCIM and SMRCIM use to calculate the maximum Doppler frequency.

The selection of the maximum Doppler frequency limits the duration of the temporal waveform, as previously mentioned. For the Rayleigh temporal fading option, SIRCIM generates 4096 (SMRCIM generates 2048) samples of the waveform for the time duration selected by the user. As a result, the sample rate is dependent on the time duration of the fading waveform. In an ideal system, a baseband signal may be reconstructed from sampled values as long as the sampling rate is greater than two times the bandwidth of the signal according to the Nyquist theorem. Because of real world limitations such as not using an ideal pulse shape for the sampling waveform, the sampling rate required for accurate signal reconstruction in a computer simulation can vary from 4 to 16 times the bandwidth of the signal [22]. Thorough testing in the early stages of research has led to the use of a value of 15 times the maximum Doppler
frequency as the sampling rate. Therefore, the maximum number of seconds of fading data which may be generated by SIRCIM is related to the maximum Doppler frequency, \( f_m \), by Equation 3.8 while Equation 3.9 governs the maximum duration in SMRCIM.

\[
\text{max duration (sec)} = \frac{4096}{15f_m} \quad \text{Eq. 3.8}
\]

\[
\text{max duration (sec)} = \frac{2048}{15f_m} \quad \text{Eq. 3.9}
\]

When the transmitter and receiver are stationary, the resulting fading is due to the motion of people or objects around the transmitter or receiver, rather than spatial motion of the receiver. The classical technique by Clarke and Gans is used in this case, to generate small scale fading of the narrowband signal about the local median signal strength [53]. While simulating Rayleigh channels, the programs adjust the minimum and maximum possible values for Doppler frequency based on the setting of the carrier frequency chosen by the user. Then, with the user's selection of Doppler frequency, level crossing rate, or velocity, the CW fading waveform duration is limited such that the total number of time sample points is 4096 in SIRCIM and 2048 in SMRCIM. For Ricean fading at stationary terminals, the user can specify the Ricean K factor which describes the statistical nature of the time variations of CW signal strength. Up to 100 seconds of Ricean fading data may be simulated. Additionally, the user has the option to add or neglect large scale path loss in all CW simulations. If the user chooses to neglect the large scale path loss, the median value of the generated waveform is approximately 0 dB.

### 3.7 User Input

As part of the work involved with the research of the Angle-Of-Arrival simulation algorithms discussed in this thesis, the SMRCIM and SIRCIM user interfaces have been greatly enhanced making them very user friendly. This section presents screen captures from both SMRCIM and SIRCIM along with a description of the user inputs. User
specified building type, transmitter-receiver (T-R) separation distance, surrounding topographical conditions, AOA model parameters, and mobile velocity permit flexible simulations of both wideband and narrowband indoor and outdoor radio channels. Channel simulation results and important parameters such as topography, RMS delay spread, path loss, and T-R separation are displayed and automatically stored on disk for further analysis after the user enters the necessary input parameters.

3.7.1 SIRCIM User Input

3.7.1.1 SIRCIM General Simulation Parameter Entry

When beginning all simulations in SIRCIM, the user is presented with the dialog box shown in Figure 3.1. The dialog box shown in this figure is called the General Simulation Parameters window because it is used to gather information from the user that is necessary and common to both wideband and narrowband simulations. Starting from the top of this dialog box, the user can specify the base name of the files for the simulation run. As discussed in Chapter 5, there are many different files generated from any given simulation. The base name will be used for all of the data files that will have the format base#.ext where base is the base name, # is a number that corresponds to each location, and ext is the extension given to each particular data file as explained in Chapter 5. The next item in this dialog is the number of locations to simulate. SIRCIM performs as many as 999 simulations over a local area per run. This setting allows the user to enter the general parameters once and generate many data files at one time. Following the number of locations to simulate, the user must enter the carrier frequency. SIRCIM simulates multipath channels in a range from 400 MHz to 60 GHz. The next item in the dialog is the close-in reference distance, \(d_0\). Following this parameter, the user can specify the percentage of simulated locations that have a perfect LOS path between the transmitter and receiver.
Another important user choice below the LOS item is that of the number of wavelengths to simulate over the track. The user can select from 4.5, 10, 20, 40, or 80 wavelengths. Next, the user can specify either an Open-Plan, Soft-Plan, or Hard-Partitioned building model by choosing the model from the combo box control labeled Building Type. Finally, the user must specify the transmitter-receiver (T-R) separation distance with the controls located at the bottom of the dialog. The T-R separation can be fixed or the user can provide a range of values from which SIRCIM chooses from a uniformly distributed range of T-R separations based on the user’s input. SIRCIM accommodates T-R separations which range from slightly larger than the reference distance up to 100 meters, making it a powerful research, design, and analysis tool for co-
channel interference studies, modem design, or capacity analysis for future indoor microcellular environments. The maximum allowable T-R separation for wideband impulse response generation is less than 100 meters due to severe shadowing of multipath components and limited dynamic range in wideband communication systems.

3.7.1.2 SIRCIM Wideband Parameter Entry

When performing a wideband simulation, the user will see the dialog box shown in Figure 3.2 immediately after clicking the Continue button on the General Simulation Parameters dialog box. This dialog is necessary for the user to choose an AOA model, as explained in Chapter 4, for use in the simulation. At the top of the dialog box, the user can select between the Random Elliptical or Aisle Elliptical AOA models. The next controls on the dialog box allow the user to select the mobile angular direction from the LOS as it moves over the 4.5, 10, 20, 40, or \(80\lambda\) track. As with the T-R separation, the user can select a constant direction of motion for each simulated location, or the user can select from an uniform random distribution between the selected range for each location. The final control on this dialog box only appears when the user chooses to use the Aisle Elliptical model. The maximum and minimum aisle widths are determined by the smallest multipath delay and the T-R separation distance. Once again, the user can select from an uniform random distribution between the minimum and maximum aisle widths for each location. The aisle width is a parameter that governs the scatterer locations in the Aisle Elliptical model as explained in Chapter 4 and in Appendix B.
3.7.1.3 SIRCIM Input of Narrowband Simulation Parameters

3.7.1.3.1 Generation of Narrowband Signal from Wideband Data Parameter Entry

When narrowband signals are simulated from wideband information, there are two parameters that the user must provide. As shown in Figure 3.3, the user must enter a mobile velocity to take into account the effects of Doppler. The user can choose between a constant velocity for each simulated location or a uniform randomly distributed velocity between a minimum and maximum value for each location. Finally, the user can select the number of interpolation points to calculate when interpolating the amplitudes of additional wideband profiles closely spaced between the 19, 41, 81, 161, or 321 respective core profiles and synthesizing the phase as the mobile receiver moves over tiny increments of distance along the 4.5, 10, 20, 40, or 80\(\lambda\) track.
3.7.1.3.2 Direct Generation of Narrowband Signal Data Parameter Entry

The screen display for entering simulation parameters for directly determined narrowband signals consists of many options, depending on the type of directly determined narrowband signal the user chooses to simulate. The choices available to the user through the drop-down menu are: Large Scale Average Signal Levels, Small Scale Rayleigh Spatial Fading, Small Scale Rayleigh Temporal Fading, and Small Scale Ricean Temporal Fading. In addition, for each of the small scale fading options, the user has the option to add or neglect the large-scale path loss. Figure 3.4 shows the Direct Narrowband Parameters screen display for entering simulation parameters for Large Scale Average Signal Levels, and the possible options available. The path loss exponent, $n$, and the variable sigma in this dialog box correspond to the values of $n$ and $X_\sigma$ from Equation 3.5 respectively. Values of $n$ and $\sigma$, the standard deviation of the log-normal distribution, vary with building type and topography and are user-selectable. The user may enter values for the path loss exponent, $n$, from 1 to 8.0 and values for the standard deviation, $\sigma$, from 0.0 to 20.0 dB. It is the user’s responsibility to enter appropriate simulation parameters. For example, even though it is possible to enter $n = 8.0$ and $\sigma =$
20.0 dB, this is a highly unlikely scenario, as it provides extremely large path loss variation that has yet to be reported in the literature.

![Figure 3.5 SIRCIM Direct Generation of Narrowband Parameters Dialog Box for Large Scale Average Signal Levels](image)

Small scale fading signals represent the time domain waveforms seen within a local area or over a small time window and thus may be simulated over space or time. Small scale fading signals are generated from the square root of the sum of the squares of two low-pass Gaussian signals as described in Appendix A, Section A.2, Synthesis of Narrowband Signals without Wideband Information and in [38]. The small scale signal is normalized such that its median value is 0 dB. This permits superposition of the large-scale path loss value onto the small scale signal which is done for each Pn, when the user toggles the check box at the top of the dialog box. Figure 3.5 shows the Direct Narrowband Parameters screen display for entering simulation parameters for Small Scale Rayleigh Spatial Fading. The mobile velocity may be specified as described for Figure 3.3.
If Small Scale Ricean Temporal Fading is selected, the user must enter both the Ricean K factor and number of seconds of fading data to be generated. Ricean fading is generated as described above for Rayleigh fading, except that a spectral component at DC is added to one of the low-pass Gaussian signals. The level of the distinct component determines the Ricean K factor. The rate of change of the temporally fading signals is fixed to compare favorably with measured data at 1300 MHz presented in [40]. Figure 3.6 shows the Direct Narrowband Parameters screen display for entering simulation parameters for Small Scale Ricean Temporal Fading. The mobile velocity is displayed as a constant value of 0 m/s, since Ricean fading is generated for stationary terminals under the Temporal (fixed ratio) model.
Figure 3.7 SIRCIM Direct Generation of Narrowband Parameters Dialog Box for Ricean Temporal Fading

Figure 3.7 shows one possible screen display of Direct Narrowband Parameters for Small Scale Rayleigh Temporal Fading. If Small Scale Rayleigh Temporal Fading is selected, the user must select the method by which SIRCIM will determine the maximum Doppler frequency for use in the Doppler spectrum. The choices available to the user through the drop-down menu, labeled “Select Doppler Mechanism” are to enter the Doppler frequency directly, enter the mobile velocity, or enter the average LCR. In all cases, the user may enter either a constant value for the parameter, or have SIRCIM generate a uniform random number between the minimum and maximum values. In addition, the user must enter the number of seconds of fading data to be generated. The true maximum time duration of a fading waveform is dependent on the specified maximum Doppler frequency, and is selected automatically by SIRCIM.
Chapter 3 Channel Models Implemented in SMRCIM and SIRCIM

3.7.2 SMRCIM User Input

3.7.2.1 SMRCIM General Simulation Parameter Entry

When beginning all simulations in SMRCIM, the user is presented with the dialog box shown in Figure 3.8. The dialog shown in this figure is called the General Simulation Parameters window because it is used to gather information from the user that is necessary and common to both wideband and narrowband simulations. Starting from the top of this dialog box, the user can specify the base name of the files for the simulation run. As discussed in Chapter 5, there are many different files generated from any given simulation. The base name will be used for all of the data files that will have the format base#.ext where base is the base name, # is a number corresponding to each location, and ext is the extension given to each particular data file as explained in Chapter 5. The next item in this dialog is the number of locations to simulate. SMRCIM performs as many as 999 simulations over a local area per each run. This setting allows the user to enter the general parameters once and generate many data files at one time. Following the number of locations to simulate, the user must enter the carrier frequency.

Figure 3.8 SIRCIM Direct Generation of Narrowband Parameters Dialog Box for Rayleigh Temporal Fading
SMRCIM simulates multipath channels in a range from 400 MHz to 60 GHz. The next item in the dialog is the close-in reference distance, $d_0$.

![SMRCIM General Simulation Parameters Dialog Box](image)

**Figure 3.9 SMRCIM General Simulation Parameters Dialog Box**

Another important user choice below the reference distance is that of the geographic type. The user specifies either an Urban, Suburban, or Microcellular channel model by choosing the model from the combo box control labeled Geographic Type. Another important user choice below the geographic type item is that of the number of wavelengths to simulate over the track. The user can select from 4.5, 10, 20, 40, or 80 wavelengths. Next the user can specify the dynamic range. This gives the user the ability to increase or decrease the noise floor of the channel. If multipath components have a power loss than the dynamic range, they are discarded. Finally, the user must specify the transmitter-receiver (T-R) separation distance with the controls located at the bottom of the dialog. The T-R separation can be fixed or the user can provide a range of
values from which SMRCIM chooses from a uniformly distributed range of T-R separations based on the user’s input. SMRCIM accommodates T-R separations which range from slightly larger than the reference distance up 20 kilometers, making it a powerful research, design, and analysis tool for co-channel interference studies, modem design, or capacity analysis for future indoor microcellular environments. The maximum allowable T-R separation for wideband impulse response generation is less than 20 kilometers due to severe shadowing of multipath components and limited dynamic range in wideband communication systems.

3.7.2.2 SMRCIM Wideband Parameter Entry

When performing a wideband simulation, the user will see the dialog box shown in Figure 3.9 immediately after clicking the Continue button on the General Simulation Parameters dialog box. This dialog is necessary for the user to choose an AOA model, as explained in Chapter 4, for use in the simulation. At the top of the dialog box, the user can select between the Random Elliptical or Aisle Elliptical AOA models. The next controls on the dialog box allow the user to select the mobile angular direction from the LOS as it moves over the 4.5, 10, 20, 40, or 80° track. As with the T-R separation, the user can select a constant direction for each simulated location, or the user can select from an uniform random distribution between the selected range for each location. The final control on this dialog box only appears when the user chooses to use the Aisle Elliptical model. The maximum and minimum aisle widths are determined by the smallest multipath delay and the T-R separation distance. The aisle width parameter is important in determining the scatterers in the model and is explained in Chapter 4 and Appendix B. Once again, the user can select from an uniform random distribution between the minimum and maximum aisle widths for each location.
3.7.2.3 SMRCIM Input of Narrowband Simulation Parameters

3.7.2.3.1 Generation of Narrowband Signal From Wideband Data Parameter Entry

When narrowband signals are simulated from wideband information, there are two parameters that the user must provide. As shown in Figure 3.10, the user must enter a mobile velocity to take into account the effects of Doppler. The user can choose between a constant velocity for each simulated location or a uniform randomly distributed velocity between a minimum and maximum value for each location. Finally, the user can select the number of interpolation points to calculate when interpolating the amplitudes of additional wideband profiles closely spaced between the 19 41, 81, 161, or 321 respective core profiles and synthesizing the phase as the mobile receiver moves over tiny increments of distance along the 4.5, 10, 20, 40, or 80$\lambda$ track.

Figure 3.10  SMRCIM Wideband AOA Parameters Dialog Box
3.7.2.3.2 Direct Generation Of Narrowband Signal Data Parameter Entry

The screen display for entering simulation parameters for directly determined narrowband signals consists of many options, depending on the type of directly determined narrowband signal the user chooses to simulate. The choices available to the user through the drop-down menu are: Large Scale Average Signal Levels, Small Scale Rayleigh Spatial Fading, Small Scale Rayleigh Temporal Fading, and Small Scale Ricean Temporal Fading. In addition, for each of the small scale fading options, the user has the option to add or neglect the large-scale path loss. Figure 3.11 shows the Direct Narrowband Parameters screen display for entering simulation parameters for Large Scale Average Signal Levels, and the possible options available. The path loss exponent, \( n \), and the variable sigma in this dialog box correspond to the values of \( n \) and \( X_\sigma \) from Equation 3.5 respectively. Values of \( n \) and \( \sigma \), the standard deviation of the log-normal distribution, vary with building type and topography and are user-selectable. The user may enter values for the path loss exponent, \( n \), from 1 to 5 and values for the standard deviation, \( \sigma \), from 0.0 to 40.0 dB. It is the user’s responsibility to enter appropriate
simulation parameters. For example, even though it is possible to enter $n = 5.0$ and $\sigma = 40.0$ dB, this is a highly unlikely scenario, as it provides extremely large path loss variation that has yet to be reported in the literature. However, values of $\sigma$ are usually high because there is a wider range of variation and shadowing in outdoor environments.

![Figure 3.12 SMRCIM Direct Generation of Narrowband Parameters Dialog Box for Large Scale Average Signal Levels](image)

Small scale fading signals represent the time domain waveforms seen within a local area or over a small time window and thus may be simulated over space or time. Small scale fading signals are generated from the square root of the sum of the squares of two low-pass Gaussian signals as described in Appendix A and in [38]. The small scale signal is normalized such that its median value is 0 dB. This permits superposition of the large-scale path loss value onto the small scale signal which is done for each $P_n$, when the user toggles the check box at the top of the dialog box. Figure 3.12 shows the Direct Narrowband Parameters screen display for entering simulation parameters for Small Scale Rayleigh Spatial Fading. The mobile velocity may be specified as described for Figure 3.3.
Figure 3.13 shows one possible screen display of Direct Narrowband Parameters for Small Scale Rayleigh Temporal Fading. If Small Scale Rayleigh Temporal Fading is selected, the user must select the method by which SMRCIM will determine the maximum Doppler frequency for use in the Doppler spectrum. The choices available to the user through the drop-down menu, labeled “Select Doppler Mechanism” are to enter the Doppler frequency directly, enter the mobile velocity, or enter the average LCR. In all cases, the user may enter either a constant value for the parameter, or have SMRCIM generate a uniform random number between the minimum and maximum values. In addition, the user must enter the number of seconds of fading data to be generated. The true maximum time duration of a fading waveform is dependent on the specified maximum Doppler frequency, and is selected automatically by SMRCIM.
If Small Scale Ricean Temporal Fading is selected, the user must enter both the Ricean K factor and number of seconds of fading data to be generated. Ricean fading is generated as described above for Rayleigh fading, except that a spectral component at DC is added to one of the low-pass Gaussian signals. The level of the distinct component determines the Ricean K factor. Figure 3.14 shows the Direct Narrowband Parameters screen display for entering simulation parameters for Small Scale Ricean Temporal Fading. The mobile velocity is displayed as a constant value of 0 m/s, since Ricean fading is generated for stationary terminals under the Temporal (fixed ratio) model.
Figure 3.15 SMRCIM Direct Generation of Narrowband Parameters Dialog Box for Ricean Temporal Fading
Chapter 4
Angle-Of-Arrival Models

4.1 Overview

As communication systems have progressively increased in complexity, many new methods have been investigated for increasing performance and capacity. There are many applications that have arisen requiring more in depth information about the propagation of electromagnetic waves. Smart antennas and systems used in position location are among the most popular new studies that require signal information such as the amplitude, phase, and angle-of-arrival (AOA) of multipath delay spreads. For proper and efficient implementation of future systems, emerging wireless systems must be able to exploit processing of spatial information.

Of these three components, knowledge of the AOA of multipath signals is essential to developing signal processing algorithms to take advantage of what has, heretofore, been a nuisance in communication systems. Antenna array systems and RAKE receivers have the ability to recombine the information from multipath components of signals allowing detection with lower bit error rates while using lower transmit power. However, the design of these systems depends heavily on information about the typical channel response. As a result, the research and implementation of AOA models, discussed in this chapter, has been motivated by a real world need for this type of data.

4.2 Multipath Propagation Environment

It is first useful to, once again, illustrate how a transmitted signal interacts with the environment, before discussing the implementation of angle-of-arrival (AOA) models. When electromagnetic waves are transmitted, reflections from large objects, diffraction of the waves around objects, and signal scattering dominate the received signal resulting in the presence of multipath components, or multipath signals, at the receiver. Figure 4.1 depicts a general example of this multipath environment. Each
signal component propagates through a different path, determining the amplitude $A_{l,k}$, carrier phase shift $\phi_{l,k}$, time delay $\tau_{l,k}$, angle of arrival $\theta_{l,k}$, and Doppler shift $f_d$ of the $l$th signal component of the $k$th mobile. Accordingly, each of these signal parameters will be time-varying [15], [27].

![Figure 4.1 The Simplified Multipath Environment](image)

The vector channel impulse response characterizing Figure 4.1 can be expressed as in Equation 4.1, where $\bar{a}(\theta_i(t))$ is the array response vector. Very similar to Equation 3.1, Equation 4.1 is the spatial channel impulse response for the first mobile user and is made up of the summation of several multipath components, each having its own amplitude, phase, and angle-of-arrival [38] where $L(t)$ is the number of multipath components. When antenna arrays are employed, the array response vector is a function of the antenna array geometry and the AOA. This vector normally is described as in Equation 4.2, where $\psi_{l,i}(t) = [x_i \cos(\theta_i(t)) + y_i \sin(\theta_i(t))]\beta$ and $\beta = 2\pi/\lambda$ is the wave number. The variable, $m$, defines the number of elements and $(x_i, y_i)$ is the coordinate of
the \( i \)-th element \([15]\). The distribution of these parameters given in Equation 4.2 is dependent upon the type of environment. More specifically, research has shown that the angle spread of the channel is a function of both the environment and the base station antenna heights. This research has led to the development of spatial models for many different applications \([15]\).

4.3 Spatial Model Development

Several spatial models have been recently developed by Liberti and Rappaport \([26], [27]\) based on the definition of a spatial scatterer density function that aids in deriving the corresponding AOA and time-of-arrival (TOA) density functions. These models are known as Geometrically Based Single-Bounce Models (GBSBM).

Within the GBSBM class of models, two specific models have been proposed. These models are the Geometrically Based Single-Bounce Circular Model (GBSBCM), shown in Figure 4.2, and the Geometrically Based Single-Bounce Elliptical Model (GBSBEM), shown in Figure 4.3.

4.3.1 Geometrically Based Single-Bounce Model

In Figure 4.2, scatterers lie within a radius \( R_m \) about the mobile, with \( R_m < D \) where \( D \) is the distance between the base station and the mobile. The model assumes that, in macrocell environments, antenna heights are relatively large and there is no signal scattering from scatterers near the base station. After an analysis of the geometry of the model, it can be shown that the TOA and AOA probability density functions are derived, respectively as Equation 4.3 and Equation 4.4, where \( c \) is the speed of light, \( \tau \) is the delay.
spread, and $\theta_b$ and $\theta_m$ represent the AOA measured relative to the line-of-sight from the base station and the mobile, respectively [15].

\[ f_{\tau A}(\tau, \theta_b) = \begin{cases} \frac{(D^2 - \tau^2 c^2)(D^2 c + \tau^2 c^3 - 2\tau c D \cos(\theta_b))}{4\pi R_m^2 (D \cos(\theta_b) - \tau c)^3} & : \quad D^2 - 2\tau c D \cos(\theta_b) + \tau^2 c^2 \leq 2R_m \\ D^2 - 2\tau c D \cos(\theta_b) & : \quad \text{else}. \end{cases} \tag{4.3} \]

\[ f_{\tau B}(\tau, \theta_m) = \begin{cases} \frac{(D^2 - \tau^2 c^2)(D^2 c + \tau^2 c^3 - 2\tau c D \cos(\theta_m))}{4\pi R_m^2 (D \cos(\theta_m) - \tau c)^3} & : \quad D^2 - \tau^2 c^2 \leq 2R_m \\ D \cos(\theta_m) - \tau c & : \quad \text{else}. \end{cases} \tag{4.4} \]

4.3.2 Geometrically Based Single-Bounce Elliptical Model

The GBSBEM model was developed by former MPRG student Joe Liberti in 1995 and has since been the center of much of the ongoing research at MPRG [25], [26] as well as throughout the world. In this model, scatterers are assumed to be distributed within an ellipse surrounding the base station and mobile which are located at the foci. The model was based on environments where antenna heights are relatively low, and therefore, scattering near the base station is as likely as multipath scattering near the mobile.
Based on the geometry of the ellipse, only multipath signals that arrive with an absolute delay of less than or equal to $\tau_m$ are accounted for by the model. The parameters $a_m$ and $b_m$ are the semimajor axis and semiminor axis values which are given by

$$a_m = \frac{c \tau_m}{2},$$

$$b_m = \frac{1}{2} \sqrt{c^2 \tau_m^2 - D^2}$$

where $c$ is the speed of light and $\tau_m$ is the maximum TOA to be considered. Smaller ellipses are used when $\tau_i < \tau_m$ [15]. Similar to the GBSBCM model, the joint TOA and AOA probability density function observed at the base station can be derived as Equation 4.5 [15]. Again, $c$ is the speed of light, $\tau$ is the delay spread, and $\theta_b$ and $\theta_m$ are the AOA measured relative to the line-of-sight from the base station and the mobile, respectively. Due to the symmetry of the elliptical model, the joint TOA and AOA will be identical at the mobile. An efficient method of generating multipath delay profiles using the GBSBEM is to uniformly place scatterers in the ellipse and then calculate the corresponding AOA, TOA, and power levels from the coordinates of the scatterer.
4.4 Adaptation of GBSBEM for AOA Simulation

As part of this thesis, research in the implementation of variations of Liberti’s elliptical model have been used in generating SIRCIM and SMRCIM multipath delay profiles having simulated AOA. Two extensions of the GBSBEM have been created in an effort to implement the model in the software tools. The two model variations are referred to as the Aisle Elliptical and the Random Elliptical models.

4.4.1 Aisle Elliptical Model

The Aisle Elliptical model uses intersections of two chords of an ellipse as locations for scattering objects in a wireless channel. Figure 4.4 shows the graphic representation of the model. The ellipse in the model represents the location of all possible scatterers that can generate multipath with a given excess delay, $\tau_m$. The two chords represent an aisle of scatterer objects whose width is $\Delta w$, hence the name Aisle Elliptical. Hallways and rows of buildings along a street are primary examples of the scatterer objects that constitute an “aisle” in the model. For each excess delay time bin in the model, there are four possible locations for scattering objects represented by the

\[
f_{\tau,\theta_b}(\tau,\theta_b) = \begin{cases} 
\frac{(D^2 - \tau^2c^2)(D^2c + \tau^2c^3 - 2\pi^2 D \cos(\theta_b))}{4\pi a_m b_m (D \cos(\theta_b) - \tau c)^3} & \frac{D}{c} \leq \tau \leq \tau_m \\
0 & \text{elsewhere}
\end{cases}
\]

**Eq. 4.5**
points at the intersections of the chords and the representative ellipse. The AOA is then defined as the angle between the LOS direction between transmitter and receiver and the LOS direction between the scatterer and the receiver such that the angle always lies in the range of 0 to $\pm \pi$ radians. Always assuming the receiver to be to the right of the transmitter, when starting at zero radians and rotating in the clockwise direction, the AOA is taken to be positive, while counterclockwise rotation signifies a negative AOA.

The inner ellipse in Figure 4.4, represents the set of all scattering objects that cause multipath components to arrive at the receiver with an excess delay of $\tau_1$. As excess delay increases, the size of the representative ellipse increases. However, the width of the aisle, $\Delta w$, remains constant as does the transmitter to receiver (T-R) separation. Thus this model is useful in environments such as city blocks where there are, often, long rows of buildings side by side and the T-R separation is line of sight. Likewise, the model applies well to indoor situations such as the placement of transmitters and receivers at opposite ends of a long hallway. This provides end fire clustering at 0° and 180° of late-arriving multipath components.

4.4.2 Random Elliptical Model

The Random Elliptical model uses an ellipse to represent the location of all possible scattering objects that can induce multipath components at the receiver with a given excess delay. However, the random model does not constrain the scatterer locations to four points along an aisle, thereby making it useful for representing urban and suburban outdoor environments or open plan indoor environments where multipath is likely to arrive from any direction. Figure 4.5 shows a graphic representation of the Random Elliptical model. Note that the location of the scatterer for each multipath delay time bin is free to fall at any point, randomly, along the corresponding ellipse.
Any time a user performs a wideband channel simulation with SMRCIM or SIRCIM, the user generates AOA data coinciding with the amplitude and time delay response of the channel. This section will explain the process of generating the AOA data. However, before discussing the implementation of the algorithms for simulating AOA data, it is necessary to understand a parameter used in both SMRCIM and SIRCIM called vehicle/mobile direction. Recall that both of the software tools simulate wideband channel impulse responses over what is called a local area. This local area represents a very small (in distance ~4.5, 10, 20, 40, or 80$\lambda$) movement of the receiver along a track while keeping the transmitter stationary. The receiver moves over the respective 19, 41, 81, 161, or 321 discrete points along the track and at each point, the multipath delay spread is simulated for each of the 64 discrete time bins. The vehicle/mobile direction parameter is a necessary input to inform the tools where to place the mobile along the track relative to the geometry of the models.

In the context of SMRCIM and SIRCIM, the vehicle/mobile direction is an angle between 0 and $\pi$ radians. This angle is defined as the angle made between the LOS direction and the 4.5, 10, 20, 40, or 80$\lambda$ track. Figure 4.6 gives a graphical representation of the geometry of the models and the vehicle/mobile direction parameter, denoted as $\alpha$. As can be seen from the figure, a direction of zero radians means that the 4.5, 10, 20, 40,
or $80\lambda$ track starts at the receiver and ends in the LOS direction of the transmitter, while an angle of $\pi$ signifies that the track starts at the receiver and follows in the direction exactly opposite of the LOS direction. Based on the geometry and the symmetry, there is no need to account for both negative and positive angles or a full rotation of $2\pi$ radians.

![Figure 4.6 Graphical Representation of the Vehicle/Mobile Direction Parameter, $\alpha$.](image)

There are several other variables that must also be defined before explanation of the implementation. Figure 4.7 provides the geometry and associated variables for deriving equations used in the AOA simulation algorithms [24]. In the remainder of this chapter, the equations and pseudo-algorithms will reference variables as defined in Figure 4.7.
Additionally, users often wish to have information about the angle-of-departure from the transmitter. Due to the symmetry of this model, it is valid to treat the AOA data as angle-of-departure data where the receiver takes the role of the transmitter and the transmitter acts as the receiver. This makes both SMRCIM and SIRCIM very useful while working with antenna arrays.

### 4.5.1 Aisle Elliptical Model in Wideband Simulations

#### 4.5.1.1 Input Screen and Parameter Entry

Both SMRCIM and SIRCIM provide dialog boxes via the MATLAB GUI engine for entering the necessary parameters to generate simulated AOA data while executing wideband channel simulations. Figure 4.8 shows the Aisle Elliptical parameter window that a user would see while using SMRCIM. At the top of the dialog box, the user can select the Aisle Elliptical model from a combo box control. After selection of the Aisle Elliptical model, user controls for the “Street Width” or “Aisle Width” will become visible, the former being displayed in SMRCIM and the latter in SIRCIM. The vehicle/mobile direction default value is set at a constant 60 degrees for each simulation.
run and the street/aisle width default value is set at a constant equal to the maximum allowable width in meters for a particular run. Users can also select a uniform random value for both of these parameters while providing the upper and lower limits.

The width parameter in this menu, corresponds to the value of $\Delta w$ from Figure 4.7. There are constraints on the maximum and minimum size of this variable. Since the smallest ellipse will be associated with the first multipath delay component, the width cannot exceed the distance, $b$, from the center line of the ellipse to the top. Additionally, the model always assumes there will be four total scatterers along the ellipse as shown in Figure 4.4. Therefore, the width also has to be slightly less than the distance from the centerline to the top of the ellipse and slightly larger than zero.

In an effort to maintain consistency within simulations, the maximum allowable width is set to 98% of $b$ corresponding to the smallest ellipse at the first time bin. This width was arbitrarily chosen to ensure that there are always four cases for locations of scatterers and also to prevent the aisle width from being larger than the width of the smallest ellipse. The first step in determining this maximum allowable width is to first find the smallest excess delay based on the first time bin and the resolution of the model.

Figure 4.8 SMRCIM Wideband Aisle Elliptical AOA Parameter Entry Dialog Box
Therefore, using Equation 4.6, the excess delay of the first time bin is calculated, where binResTime, the time resolution of the bins, depends on the chosen channel model. Next, the excess distance is determined by applying the excess delay to Equation 4.7. Following the calculation of excess distance, the variables \( a \) and \( c \) from Figure 4.7 are calculated with Equation 4.8 and Equation 4.9, where T-Rsep is the separation distance between the transmitter and receiver.

\[
\text{excess delay} = (\text{bin#} - 0.5) \times \text{binResTime} \quad \text{Eq. 4.6}
\]

\[
\text{excess distance} = \text{excess delay} \times C \quad \text{where } C \text{ is speed of light } (3.0 \times 10^8 \text{ m/s}) \quad \text{Eq. 4.7}
\]

\[
a = \frac{1}{2}(T - \text{Rsep} + \text{excess distance}) \quad \text{Eq. 4.8}
\]

\[
c = \frac{1}{2}(T - \text{Rsep}) \quad \text{Eq. 4.9}
\]

Finally, the maximum allowable width is determined by evaluating Equation 4.10 and Equation 4.11.

\[
b = \sqrt{a^2 - c^2} \quad \text{Eq. 4.10}
\]

\[
\Delta w = 0.98 \times b \quad \text{Eq. 4.11}
\]

4.5.1.2 Geometrical Analysis

In deriving the necessary equations for the Aisle Elliptical model, there are four distinct cases corresponding to the four intersections of the aisles with the ellipses. Each of the cases is derived from the geometry in Figure 4.7. Therefore, several variables have been left out of the following figures to provide visual clarity. Note also, that the figures have been drawn out of proportion for ease of viewing. Typically, the 4.5, 10, 20, 40, or 80\( \lambda \) track is very much shorter than the T-R separation because the wavelength is very
small at high frequencies. The subsequent subsections will explain each of the four scenarios.

4.5.1.2.1 Aisle Elliptical Geometry: Case I

As with all of the four cases of the Aisle Elliptical model, the geometry involves placing a set of Cartesian coordinates (\(\hat{x}\) and \(\hat{y}\) axes) over an ellipse such that the origin of the axes is located at the center of the ellipse. Figure 4.9 shows the geometry of Case I of the Aisle Elliptical model. Case I occurs when the scatterer (point S) is located in the upper right quadrant of the ellipse. Therefore, the horizontal distance, x, from the \(\hat{y}\) axis to the scatterer is always a positive value in the \(\hat{x}\) direction. Likewise, the AOA will always be between 0 and \(\pi\) radians for Case I.

![Figure 4.9 Case I Geometry of the Aisle Elliptical Model](image)

After analyzing the geometry of Case I, there are four equations that lead to the AOA of multipath components arriving from the scatterer S at any of the 1941, 81, 161, or 321 evenly spaced, discrete locations along the 4.5, 10, 20, 40, or 80\(\lambda\) track between R and R'. First, it is useful to express the T-R separation as a function of vehicle/mobile direction, initial T-R separation (TRsep\(_0\)), and distance, y, along the local area track.
Equation 4.12 shows the relationship between these parameters. This equation holds for all four cases of the Aisle Elliptical model. The next step in determining the AOA for Case I of the model is calculating the angle $\omega$. Once again, based on the geometry of the model, Equation 4.13 provides the dependence of this angle upon the vehicle/mobile direction, T-R separation, and distance along the local area track. The final step before solving the AOA involves calculating the angle $\theta_4$. Applying Equation 4.14, it is evident

$$TRsep(y, \alpha) = \sqrt{(TRsep_x - y_{ds} \cos \alpha)^2 + (y_{ds} \sin \alpha)^2}$$

where

$$\begin{cases} 
0 \leq \alpha \leq \pi \\
0 \leq y \leq X \lambda \\
dx \in \{1,2,\ldots,Z\} \\
\{X, Z\} \in \{\{4.5,19\},\{10,41\},\{20,81\},\{40,161\},\{80,321\}\}
\end{cases}$$

that this angle is linked to the initial T-R separation (2 x c), the distance along the 4.5, 10, 20, 40, or 80 $\lambda$ track, the vehicle/mobile direction, the horizontal distance, x, and the aisle
\[ \theta_4 = \tan^{-1}\left( \frac{\Delta w + y_{dx} \sin \alpha}{c - x - y_{dx} \cos \alpha} \right) \]

where
\[
\begin{align*}
0 \leq \alpha \leq \pi \\
x > 0 \\
0 \leq y \leq X\lambda \\
dx \in \{1,2,\ldots,Z\} \\
\{X,Z\} \in \{(4.5,19),(10,41),(20,81),(40,161),(80,321)\}
\end{align*}
\]

width, \(\Delta w\). After solving Equation 4.12 through Equation 4.14, the final result for the AOA in Case I is calculated by Equation 4.15.

\[ \text{AOA}_{\text{Case I}} = \theta_4 - \omega \]

4.5.1.2.2 Aisle Elliptical Geometry: Case II

Case II is very similar to Case I in that both cases have the scatterer located on the upper half of the ellipse. Figure 4.10 shows the geometry of Case II of the Aisle Elliptical model. This scenario occurs when the scatterer is located in the upper left quadrant of the ellipse. Therefore, the horizontal distance, \(x\), from the \(\hat{y}\) axis to the scatterer is always a negative value in the \(\hat{x}\) direction. In this case, the AOA will always be greater than or equal to 0, but will be smaller than for Case I.
After analyzing the geometry of Case II, the equations derived for Case I hold equally with Case II with one exception. Since the scatterer lies to the left of the origin, in the negative $\hat{x}$ direction, the bounds on Equation 4.14 are different. Thus, Case II will be identical to Case I after exchanging Equation 4.14 with Equation 4.16.

$$\theta_4 = \tan^{-1}\left(\frac{\Delta w + y_{dc} \sin \alpha}{c - x - y_{dc} \cos \alpha}\right)$$

where

$$\begin{align*}
\{0 \leq \alpha \leq \pi \\
x < 0
\end{align*}$$

Eq. 4.16

4.5.1.2.3 Aisle Elliptical Geometry: Case III

Case III is similar to Case I in that the scatterer is to the right of the origin, but the governing equations are slightly different. Figure 4.11 shows the geometry of Case III of
the Aisle Elliptical model. Case III occurs when the scatterer is located in the lower right quadrant of the ellipse. Therefore, the horizontal distance, $x$, from the $\hat{y}$ axis to the scatterer is always a positive value in the $\hat{x}$ direction. Due to the orientation of the scatterer, the AOA is considered negative for Case III, because the AOA is measured counterclockwise from the LOS (vector from $T$ to $R'$) to the incoming direction of the multipath component (vector from $S$ to $R'$).

![Figure 4.11 Case III Geometry of the Aisle Elliptical Model](image)

Figure 4.11 Case III Geometry of the Aisle Elliptical Model

After analyzing the geometry of Case III and comparing it to that of Case I, two of the four equations must be slightly modified. Note that Equation 4.14 becomes Equation 4.17 after changing the numerator from an addition to a subtraction. This becomes apparent after comparing Figure 4.11 to either Figure 4.9 or Figure 4.10. The angle $\theta_4$ is now measured from the horizontal, dashed line in a counterclockwise direction.
\[
\theta_4 = \tan^{-1}\left( \frac{\Delta w - y_{ds} \sin \alpha}{c - x - y_{ds} \cos \alpha} \right)
\]

Eq. 4.17

where

\[
\begin{align*}
0 &\leq \alpha \leq \pi \\
x &> 0 \\
0 &\leq y \leq X\lambda \\
dx &\in \{1,2,\ldots,Z\} \\
\{X,Z\} &\in \{(4.5,19),\{10,41\},\{20,81\},\{40,161\},\{80,321\}\}
\end{align*}
\]

Additionally, Equation 4.15 must be altered to Equation 4.18 due to the orientation of Case III and Case IV.

\[
AOA_{\text{Case IIIIV}} = -(\theta_4 + \omega)
\]

Eq. 4.18

4.5.1.2.4 Aisle Elliptical Geometry: Case IV

The final scenario, Case IV, is similar to Case II in that the scatterer lies to the left of the origin. However, the equations are identical to those of Case III with the exception of the sign of the variable \(x\). Figure 4.12 shows the geometry of Case IV of the Aisle Elliptical model. Case IV occurs when the scatterer is located in the lower left quadrant of the ellipse. Therefore, the horizontal distance, \(x\), from the \(\hat{y}\) axis to the scatterer is always a negative value in the \(\hat{x}\) direction. Like Case III, the AOA will always be a negative value because of the orientation of the LOS and the direction of arrival of multipath components with respect to the receiver.
With the comparison to Case III, it is evident that Equation 4.17 will become Equation 4.19 for Case IV. And, finally, the AOA for Case IV can be solved by Equation 4.18.

\[
\theta_a = \tan^{-1}\left( \frac{\Delta w + y_{dx} \sin \alpha}{c - x - y_{dx} \cos \alpha} \right)
\]

where

\[
\begin{align*}
0 &\leq \alpha \leq \pi \\
x &< 0 \\
0 &\leq y \leq X\lambda \\
dx &\in \{1,2,\ldots,Z\} \\
\{X,Z\} &\in \{(4.5,19), (10,41), (20,81), (40,161), (80,321)\}
\end{align*}
\]

**Eq. 4.19**

### 4.5.1.3 Implementation of AOA

This section provides a brief pseudo algorithm outlining the program flow used to simulate AOA data with the Aisle Elliptical model. In SMRCIM and SIRCIM, the class member function of the Simulation C++ class, called GenerateAisleEllipticalAOAFiles(), first chooses from 64 random cases as described above for each local area. After determining the case for each multipath delay time bin, the function determines the width of the aisle and the mobile direction based on user input. At this point, the corresponding
equations for each case are used to solve for the AOA. Table 4.1 summarizes the necessary variables used in this function.

**Table 4.1 Description of Variables Used in Aisle Elliptical Model Implementation**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>floating point</td>
<td>half the length of the major axis</td>
</tr>
<tr>
<td>c</td>
<td>floating point</td>
<td>half the T-R separation</td>
</tr>
<tr>
<td>exdel</td>
<td>floating point</td>
<td>relative time of the center of a time bin (excess delay)</td>
</tr>
<tr>
<td>dist</td>
<td>floating point</td>
<td>distance traveled at the speed of light for a given excess delay</td>
</tr>
<tr>
<td>alpha</td>
<td>floating point</td>
<td>mobile/vehicle direction</td>
</tr>
<tr>
<td>mindirec</td>
<td>floating point</td>
<td>minimum mobile/vehicle direction</td>
</tr>
<tr>
<td>maxdirec</td>
<td>floating point</td>
<td>maximum mobile/vehicle direction</td>
</tr>
<tr>
<td>tem</td>
<td>floating point</td>
<td>multipath delay time bin resolution in seconds</td>
</tr>
<tr>
<td>theta4</td>
<td>floating point</td>
<td>absolute value of angle between horizontal and direction of multipath</td>
</tr>
<tr>
<td>e</td>
<td>floating point</td>
<td>ellipse eccentricity</td>
</tr>
<tr>
<td>maxwidth</td>
<td>floating point</td>
<td>maximum aisle width</td>
</tr>
<tr>
<td>minwidth</td>
<td>floating point</td>
<td>minimum aisle width</td>
</tr>
<tr>
<td>x</td>
<td>floating point</td>
<td>absolute value of horizontal distance from origin to scatterer</td>
</tr>
<tr>
<td>y</td>
<td>floating point</td>
<td>absolute value of distance from original receiver location along 4.5, 10,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20, 40, or 80\lambda track</td>
</tr>
<tr>
<td>lambda</td>
<td>floating point</td>
<td>wavelength</td>
</tr>
<tr>
<td>newTR</td>
<td>floating point</td>
<td>distance from transmitter to current receiver for each of 19, 41,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>81, 161, or 321 points along the track</td>
</tr>
<tr>
<td>w</td>
<td>floating point</td>
<td>angle between ellipse centerline and LOS between transmitter and current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>receiver location</td>
</tr>
<tr>
<td>dist</td>
<td>floating point</td>
<td>length of major ellipse axis</td>
</tr>
<tr>
<td>trsep</td>
<td>floating point</td>
<td>original T-R separation</td>
</tr>
<tr>
<td>freq</td>
<td>floating point</td>
<td>carrier frequency</td>
</tr>
<tr>
<td>t</td>
<td>integer</td>
<td>counter for 64 time bins</td>
</tr>
<tr>
<td>dx</td>
<td>integer</td>
<td>counter for 19, 41, 81, 161, or 321 locations along track</td>
</tr>
<tr>
<td>aoa</td>
<td>64 x {19, 41, 81, 161, or 321} array of floating points</td>
<td>AOA for each time bin and track</td>
</tr>
<tr>
<td>cases</td>
<td>64 x 1 array of integers</td>
<td>random cases for each local area</td>
</tr>
<tr>
<td>C</td>
<td>floating point</td>
<td>speed of light in m/s</td>
</tr>
<tr>
<td>deltaw</td>
<td>floating point</td>
<td>vertical distance from ellipse centerline to the scatterer</td>
</tr>
</tbody>
</table>

Incorporating the variables in Table 4.1, the following algorithm shows how the Aisle Elliptical model is implemented in SMRCIM and SIRCIM along a 4.5 wavelength track. Comments are preceded by two (/) slash marks while curly braces {} follow a C/C++ style syntax.
BEGIN:

// PSEUDO ALGORITHM of the C++ function GenerateAisleEllipticalAOAFiles()
// this algorithm first generates 64 random “cases” for each local area, determines the
// width and mobile direction and then uses the equations discussed in Section 4.5 to
// simulate the angle of arrival of the multipath delay components
// In this example, the track length is 4.5 wavelengths

lambda = C / freq      // calculate the wavelength
tem = 62.5 E-9   // assumes the microcellular model in SMRCIM

// assign aisle width based on user input
if (using random aisle width)
{
   deltaw = ½ * uniformly distributed random # between minwidth and maxwidth
}
else
{
   deltaw = ½ * user selected aisle width
}

// assign the mobile direction based on the user input
if ( using random mobile direction )
{
    alpha = uniformly distributed random # between mindirec and maxdirec
}
else
{
    alpha = user selected mobile direction
}

// next, determine the maximum allowable aisle width of the smallest ellipse
// (smallest delay spread). Arbitrarily make the maximum allowable width 98% of ½
// the length of the minor axis of the ellipse
// after substituting Equation 4.6 and 4.7 into Equation 4.8, solve for the variable, a
// note, the bin# is equal to 1 for the smallest delay spread

a = 0.5 * ( 0.5 * tem * C + trsep )

// next solve for the variable c with Equation 4.9
c = 0.5 * trsep

// recalculate the maxwidth
// after substituting Equation 4.10 into Equation 4.11, the calculation is as follows
maxwidth = 0.98 * sqrt( sqrt( a ) – sqrt( c ) )
// make sure the users values for width are less than the allowable amount
if ( deltaw > maxwidth )
{
    warn user
    exit program
}

// generate 64 random cases (uniformly distributed) between 1 and 4
for t=1 to 64
{
    cases[t] = uniform randomly distributed between 1 and 4
}

// use an outer loop to loop through the 19 discrete locations along the track
for dx=1 to 19
{
    y = 4.5 * lambda * ( dx-1 ) / 18
    // user an inner loop to cycle through the 64 time bins
    for t=1 to 64
    {
        exdel = ( t – 0.5 ) * tem
        // excess delay
        exdist = exdel * C
        // C here is speed of light in m/s
        dist = exdist + trsep
        // major axis length
        a = 0.5 * dist
        // this is ½ the major axis
        e = c / a
        // eccentricity (c has already been calculated)

        // calculate x using geometry from Figure 4.7
        // sqrt is the square root function while sqr is the square function
        x = sqrt( ( sqr( a ) – sqr( c ) – sqr( deltaw ) ) / ( 1 – sqr( e ) ) )
        // for case 2 and case 4, make x a negative value
        if ( cases[t] == 2 or 4 )
        {
            x = -x
        }

        // calculate the new T-R separation distance from Equation 4.12
        newTR = sqrt( sqr( trsep – y * cos( alpha ) ) + sqr( y * sin( alpha ) ) )

        // calculate the angle between the original T-R and the newTR
        w = arcsin( y * sin( alpha ) / newTR )

        // if amplitude of multipath component at time t is less than or equal
        // to –200dB, then arbitrarily set aoa[t][dx] = 0 degrees
// otherwise calculate appropriate aoa based on case equations
if ( amplitude < -200dB )
    aoa[t][dx] = 0
else
{
    if ( cases[t] == 1 or 2 )
    {
        // use atan2 function to retrieve 4 quadrant arctangent
        theta4 = atan2(deltaw + y * sin(alpha) , c-x-y * cos(alpha) )
        aoa[t][dx] = theta4 - w
    }
    else if ( cases[t] == 3 or 4 )
    {
        // use atan2 function to retrieve 4 quadrant arctangent
        theta4 = atan2(deltaw - y * sin(alpha) , c-x-y * cos(alpha) )
        aoa[t][dx] = - (theta4 + w)  //angle always negative
        // in the III quadrant, there may be a time when the
        // |AOA| is > 180 ( then the real AOA is 360 + AOA )
        if ( fabs( aoa[t][dx] ) > PI )
        {
            aoa[t][dx] = aoa[t][dx] + 2 * PI
        }
    }
} // end of inner loop of t=1 to 64
}// end of outer loop of t = 1 to 19
// {only have 19 discrete locations along the track because the track length is 4.5
//  wavelengths}

4.5.2 Random Elliptical Model in Wideband Simulations

4.5.2.1 Input Screen and Parameter Entry

Figure 4.13 shows the Random Elliptical parameter window that a user would see while using SMRCIM. At the top of the dialog box, the user can select the Random Elliptical model from a combo box control. The vehicle/mobile direction default value is set at a constant 60 degrees for each simulation run. Users can also select a uniform random value for this parameter while providing the upper and lower limits for the mobile/vehicle direction.
4.5.2.2 Geometrical Analysis

In deriving the necessary equations for the Random Elliptical model, it is essential to understand the geometry of the model. Figure 4.14 shows the graphical representation necessary to derive the equations for simulation of AOA via the Random Elliptical model. Note that the figure has been drawn out of proportion for ease of viewing. Typically, the track is much shorter than the T-R separation because the wavelength is very small at high frequencies.
The ellipse in the Random Elliptical model, as in the Aisle Elliptical model, represents the set of all possible scatterer locations that can induce a multipath delay component at the initial receiver location with a delay of $\tau_i$ seconds. The model is referred to as “random” because the location of the scatterer along the ellipse is chosen based on a uniform random generation of the angle $\theta$. This angle is uniform and random over $2\pi$ radians. The distance of the scatterer, $r$, from the origin to the scatterer is then a function of the size of the ellipse and the angle $\theta$. The AOA is measured in a similar manner as in the Aisle Elliptical model. AOA is considered to be the angle between the vector from the transmitter to the current receiver location along the track, and the vector from that receiver location to the scatterer location.

From Figure 4.14, several equations must be derived to implement this model in SMRCIM and SIRCIM. The $\hat{x}$ and $\hat{y}$ coordinates of the scatterer $S_x$ and $S_y$, respectively, can be determined by Equation 4.20 and Equation 4.21. However, $r$ must be

\[
S_x = r \cos \theta \quad \text{Eq. 4.20}
\]
\[
S_y = r \sin \theta \quad \text{Eq. 4.21}
\]
determined first. Substituting Equation 4.20 and Equation 4.21 into the standard equation for an ellipse, Equation 4.22, provides the means for calculating $r$ and, ultimately, $S_x$ and $S_y$.

$$\frac{S_x^2}{a^2} + \frac{S_y^2}{b^2} = 1 \quad \text{Eq. 4.22}$$

In addition to the $\hat{x}$ and $\hat{y}$ coordinates of the scatterer location, it is useful to specify the coordinates of the transmitter location, original receiver location, and the current receiver location along the track. Table 4.2 lists the coordinates of each of these locations. Using these coordinates, the vectors $\overrightarrow{R'T}$ and $\overrightarrow{SR'}$ are defined in Equation 4.23 and Equation 4.24. Finally, the AOA for the Random Elliptical model is the angle between the two vectors and can be calculated by Equation 4.25 where the operator $\langle \rangle$ represents the dot product of the vectors and the $\| \|$ operator represents the length of the vector.

**Table 4.2 Random Elliptical Model -- Transmitter And Receiver Locations**

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>$\hat{x}$ COORDINATE</th>
<th>$\hat{y}$ COORDINATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>-c</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>c</td>
<td>0</td>
</tr>
<tr>
<td>R'</td>
<td>c-y cos((\alpha))</td>
<td>-y sin((\alpha))</td>
</tr>
</tbody>
</table>

$$\overrightarrow{R'T} = (-2c + y \cos \alpha, y \sin \alpha) \quad \text{Eq. 4.23}$$

$$\overrightarrow{R'S} = (S_x - c + y \cos \alpha, S_y + y \sin \alpha) \quad \text{Eq. 4.24}$$

$$AOA = \pm \cos^{-1} \left( \frac{\langle \overrightarrow{R'S}, \overrightarrow{R'T} \rangle}{\| \overrightarrow{R'S} \| \| \overrightarrow{R'T} \|} \right) \quad \text{Eq. 4.25}$$
4.5.2.3 Implementation

This section provides a brief, pseudo algorithm outlining the program flow used to simulate AOA data with the Random Elliptical model. In SMRCIM and SIRCIM, the class member function of the Simulation C++ class, called GenerateRandomEllipticalAOAFiles(), first chooses from 64 random angles, θ, as described above for each local area. At this point, Equation 4.20 through Equation 4.25 are used to solve for the AOA. Table 4.3 summarizes the necessary variables used in SMRCIM and SIRCIM for this function.
Table 4.3 Description of Variables Used in Random Elliptical Model Implementation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>floating point</td>
<td>half the length of the major axis</td>
</tr>
<tr>
<td>c</td>
<td>floating point</td>
<td>half the T-R separation</td>
</tr>
<tr>
<td>exdel</td>
<td>floating point</td>
<td>relative time of the center of a time bin (excess delay)</td>
</tr>
<tr>
<td>exdist</td>
<td>floating point</td>
<td>distance traveled at the speed of light for a given excess delay</td>
</tr>
<tr>
<td>alpha</td>
<td>floating point</td>
<td>mobile/vehicle direction</td>
</tr>
<tr>
<td>tem</td>
<td>floating point</td>
<td>multipath delay time bin resolution in seconds</td>
</tr>
<tr>
<td>y</td>
<td>floating point</td>
<td>absolute value of distance from original receiver location along 4.5, 10, 20, 40, or 80λ track</td>
</tr>
<tr>
<td>lambda</td>
<td>floating point</td>
<td>wavelength</td>
</tr>
<tr>
<td>dist</td>
<td>floating point</td>
<td>length of major ellipse axis</td>
</tr>
<tr>
<td>trsep</td>
<td>floating point</td>
<td>original T-R separation</td>
</tr>
<tr>
<td>freq</td>
<td>floating point</td>
<td>carrier frequency</td>
</tr>
<tr>
<td>t</td>
<td>integer</td>
<td>counter for 64 time bins</td>
</tr>
<tr>
<td>dx</td>
<td>integer</td>
<td>counter for 19, 41, 81, 161, or 321 locations along track</td>
</tr>
<tr>
<td>aoa</td>
<td>64 x 19, 41, 81, 161, or 321 array of floating points</td>
<td>AOA for each time bin and track</td>
</tr>
<tr>
<td>C</td>
<td>floating point</td>
<td>speed of light in m/s</td>
</tr>
<tr>
<td>Sx</td>
<td>floating point</td>
<td>( \hat{x} ) coordinate of scatterer</td>
</tr>
<tr>
<td>Sy</td>
<td>floating point</td>
<td>( \hat{y} ) coordinate of scatterer</td>
</tr>
<tr>
<td>r</td>
<td>floating point</td>
<td>distance from origin to scatterer</td>
</tr>
<tr>
<td>RTx</td>
<td>floating point</td>
<td>( \hat{x} ) component of vector from current receiver location to transmitter</td>
</tr>
<tr>
<td>RTy</td>
<td>floating point</td>
<td>( \hat{y} ) component of vector from current receiver location to transmitter</td>
</tr>
<tr>
<td>RSx</td>
<td>floating point</td>
<td>( \hat{x} ) component of vector from current receiver location to scatterer</td>
</tr>
<tr>
<td>RSy</td>
<td>floating point</td>
<td>( \hat{y} ) component of vector from current receiver location to scatterer</td>
</tr>
<tr>
<td>magRT</td>
<td>floating point</td>
<td>length of vector from current receiver location to transmitter</td>
</tr>
<tr>
<td>magRS</td>
<td>floating point</td>
<td>length of vector from current receiver location to scatterer</td>
</tr>
<tr>
<td>theta</td>
<td>64 x 1 array of floating points</td>
<td>positive angle between 0 and 2( \pi ) radians measured counter clockwise from the ( \hat{x} ) axis to the vector from the origin to the scatterer location</td>
</tr>
<tr>
<td>mindirec</td>
<td>floating point</td>
<td>minimum mobile/vehicle direction</td>
</tr>
<tr>
<td>maxdirec</td>
<td>floating point</td>
<td>maximum mobile/vehicle direction</td>
</tr>
</tbody>
</table>

Incorporating the variables in Table 4.3, the following algorithm shows how the Random Elliptical model is implemented in SMRCIM and SIRCIM along a 4.5
wavelength track. Comments are preceded by two (/) slash marks while curly braces {} follow a C/C++ style syntax.

BEGIN:

// PSEUDO ALGORITHM of the C++ function GenerateRandomEllipticalAOAFiles()
// this algorithm first generates 64 random angles for each local area, determines the
// location of the scatterers along the ellipse and mobile direction and then uses the
// equations discussed in Section 4.5 to simulate the AOA of the multipath delay
// components In this example, the track length is 4.5 wavelengths
lambda = C / freq      // calculate the wavelength
tem = 7.8125E-9   // assumes a model from SIRCIM

// assign the mobile direction based on the user input
if ( using random mobile direction )
{
    alpha = uniformly distributed random # between mindirec and maxdirec
}
else
{
    alpha = user selected mobile direction
}

// solve Equation 4.9

// generate 64 random angles (uniformly distributed) between 0 and 2π radians
for t=1 to 64
{
    theta[t] = uniform randomly distributed between 0 and 2π
}

// use an outer loop to loop through the 19 discrete locations along the track
// only 19 locations because example is using 4.5 wavelengths
for dx=1 to 19
{
    y = 4.5 * lambda * (dx-1)/ 18
    // user an inner loop to cycle through the 64 time bins
    for t=1 to 64
    {
        exdel = ( t – 0.5 ) * tem     // excess delay
        exdist = exdel * C            // C here is speed of light in m/s
        dist = exdist + trsep        // major axis length
    }
a = 0.5 * dist  \hspace{1cm} // this is $\frac{1}{2}$ the major axis

// sqrt is the square root function while sqr is the square function
b = sqrt( sqr( a ) – sqr( c ) )  \hspace{1cm} // Equation 4.10

// Substitute Equation 4.20 and Equation 4.21 into Equation 4.22 and back
// solve r
r = a * b * sqrt( 1.0 / ( sqr(b) * sqr(cos(theta[t])) + sqr(a) * sqr(sin(theta[t])) ) )

// Solve Equation 4.20
Sx = r * cos ( theta[t] )
// Solve Equation 4.21
Sy = r * sin( theta[t] )

// Using Equation 4.23, solve for RTx and RTy
RTx = -2.0 * c + y  * cos(alpha)
RTy = y  * sin(alpha)

// Using Equation 4.24, solve for RSx and RSy
RSx = Sx – c + y  * cos(alpha)
RSy = Sy + y  * sin(alpha)

// if amplitude of multipath component at time t is less than or equal
// to –200dB, then arbitrarily set aoa[t][dx] = 0 degrees
// otherwise calculate appropriate aoa
if (amplitude < -200dB)
aoa[t][dx] = 0.0
else
  {  // Calculate the numerator of Equation 4.24
    aoa[t][dx] = RTx * RSx + RTy * RSy  \hspace{1cm} // This is the dot product
  
  // Calculate the length of RT vector
  magRT = sqrt( sqr( RTx ) + sqr (RTy ) )

  // Calculate the length of RS vector
  magRS = sqrt( sqr( RSx ) + sqr( RSy ) )

  // Multiply the lengths and store in the variable magRS
  magRS = magRS * magRT

  // Divide the numerator of Equation 4.24 by the denominator
  aoa[t][dx] = aoa[t][dx] / magRS

  // If S is in the bottom left quadrant make it a negative angle
if( INRANGE( theta[t], PI, 1.5 * PI ) )
aoa[t][dx] = -1.0 * acos( aoa[t][dx] )

// If S is in the bottom right quadrant, check to see if AOA is
// positive or negative. If the angle exceeds π radians, then
// the angle will be measured CW and thus be positive
else if( INRANGE( theta[t], 1.5 * PI , 2.0 * PI ) )
{
    // If the absolute value of the slopes of RS and RT are equal
    // then the angle of arrival is considered to be -π radians
    if( fabs( RSy/RSx ) == fabs( RTy/RTx ) )
        aoa[t][dx] = - acos(-1.0)
    // IF the absolute value of the slope of RS is greater than
    // that of RT, then AOA is measured CCW and is thus
    // negative
    else if( fabs( RSy/RSx ) > fabs( RTy/RTx ) )
        aoa[t][dx] = -1.0 * acos( aoa[t][dx] )
}
// Otherwise, AOA is measured CW and is thus positive
else
    aoa[t][dx] = acos( aoa[t][dx] )
}
} // end of inner loop of t=1 to 64
} // end of outer loop of t = 1 to 19
// using 19 because the track length is 4.5 wavelengths

4.6 Generation of Narrowband Phase from Wideband AOA Data

As explained in Chapter 3, SMRCIM and SIRCIM can simulate narrowband
signals using the results of wideband simulations. In the simulation of narrowband
signals, the computation of narrowband (CW) signal strength and carrier phase from the
wideband impulse responses requires calculation of phase for each wideband multipath
component. This calculation is performed along the 4.5, 10, 20, 40, or 80λ track by
interpolating the amplitudes of additional wideband profiles closely spaced between the
19, 41, 81, 161, or 321 core profiles and synthesizing the phase as the mobile receiver
moves over diminutive increments of distance. As the mobile travels incrementally over
a local area, the phase change of each multipath component is modeled in a deterministic
fashion, based on the simulated angle-of-arrival and small changes in radio path length from a pseudo-randomly positioned scatterer which remains fixed as the receiver moves.

### 4.6.1 Geometrical Analysis

In determining the narrowband phase from wideband simulation data, it is necessary to determine the location of the scatterer along the ellipse representing the multipath delay using the simulated AOA of the multipath signal. Figure 4.15 shows the initial geometry used in calculating the narrowband phase. Note that the position of the scatterer, S, can be determined from the first profile when the receiver is located at a focus of the ellipse.

Using both the ellipse equation (Equation 4.22) and the point slope form of the line from the initial receiver location to the scatterer location, the coordinates of the scatter location are calculated, as demonstrated in Figure 4.15. With this in mind, the slope of the line, \( m \), from the receiver to the scatter is given as Equation 4.26

\[
m = -\tan(\text{AOA})
\]

Figure 4.15 Geometry for Determining Narrowband Phase from Wideband AOA
Incorporating the point slope form of the line as given in Equation 4.27 accounts for one equation of two used in solving the scatter coordinates Sx and Sy. Substituting Equation 4.27 into the second equation, Equation 4.22, results in the quadratic equation of the coordinate, Sx, as shown in Equation 4.28. The only unknown variable of Equation 4.28 is then Sx. Using the standard quadratic formula in conjunction with some bounding of possible locations of the scatterer, the value of Sx can be determined for each time delay bin.

In the implementation of this method for determining the scatterer location, there are five separate conditions used to determine Sx. First, if the AOA is 0 radians, the location of the scatter is Sx = -a and Sy = 0 where $|a|$ is $\frac{1}{2}$ the summation of the excess distance induced by the multipath and the T-R separation. If the AOA is $\pm \pi$ radians, then the location of the scatter is Sx = a and Sy = 0. If the value of the AOA is $\pi/2$ radians, then the location of the scatterer is Sx = c and Sy = $b\sqrt{(1-e^2)}$ where $e$ is the eccentricity of the ellipse, $b$ is the length of the minor axis of the ellipse, and c is the horizontal distance from the center of the ellipse to the focus. Likewise if the value of the AOA is $-\pi/2$ radians, then the location of the scatterer is Sx = c and Sy = $-b\sqrt{(1-e^2)}$ There are two more conditions necessary to determine the location of the scatter. If the AOA is an acute angle, the only valid solution of Sx from Equation 4.28 is when Sx is less than c. Finally, if the AOA is an obtuse angle, the only valid solution of Sx from Equation 4.28 is when Sx is greater than c.
4.6.2 Implementation

This section provides a brief, pseudo algorithm outlining the program flow used to generate narrowband phase information from AOA data obtained in wideband simulations. In SMRCIM and SIRCIM, the class member function of the Simulation C++ class, called InitPhase(), first loads the AOA data from the .AOA files in the simulation data directory. The function then proceeds to determine the location of the scatterers for each of the 64 time delay bins. At the same time, it generates the initial phase of the narrowband signal based from a uniform distribution on 0 to $2\pi$ radians. Table 4.4 summarizes the necessary variables used in SMRCIM and SIRCIM for this function.
Table 4.4 Description of Variables Used in Initial Narrowband Signal Synthesis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>floating point</td>
<td>half the length of the major axis</td>
</tr>
<tr>
<td>c</td>
<td>floating point</td>
<td>half the T-R separation</td>
</tr>
<tr>
<td>m</td>
<td>floating point</td>
<td>slope of vector from receiver to scatterer in $\hat{x}$ and $\hat{y}$ coordinates</td>
</tr>
<tr>
<td>exdel</td>
<td>floating point</td>
<td>relative time of the center of a time bin (excess delay)</td>
</tr>
<tr>
<td>exdist</td>
<td>floating point</td>
<td>distance traveled at the speed of light for a given excess delay</td>
</tr>
<tr>
<td>alpha</td>
<td>floating point</td>
<td>mobile/vehicle direction</td>
</tr>
<tr>
<td>tem</td>
<td>floating point</td>
<td>multipath delay time bin resolution in seconds</td>
</tr>
<tr>
<td>y</td>
<td>floating point</td>
<td>absolute value of distance from original receiver location along 4.5, 10, 20, 40, or 80$\lambda$ track</td>
</tr>
<tr>
<td>dist</td>
<td>floating point</td>
<td>length of major ellipse axis</td>
</tr>
<tr>
<td>trsep</td>
<td>floating point</td>
<td>original T-R separation</td>
</tr>
<tr>
<td>t</td>
<td>integer</td>
<td>counter for 64 time bins</td>
</tr>
<tr>
<td>aoa</td>
<td>array of 64 floating points</td>
<td>AOA for each time bin and track</td>
</tr>
<tr>
<td>C</td>
<td>floating point</td>
<td>speed of light in m/s</td>
</tr>
<tr>
<td>ph</td>
<td>array of 100 x 64 floating points</td>
<td>phases of each time delay bin for up to 100 individual interpolation points</td>
</tr>
<tr>
<td>x1</td>
<td>floating point</td>
<td>a possible solution to Equation 4.28</td>
</tr>
<tr>
<td>x2</td>
<td>floating point</td>
<td>a possible solution to Equation 4.28</td>
</tr>
<tr>
<td>Sx</td>
<td>floating point</td>
<td>$\hat{x}$ coordinate of scatterer</td>
</tr>
<tr>
<td>Sy</td>
<td>floating point</td>
<td>$\hat{y}$ coordinate of scatterer</td>
</tr>
<tr>
<td>RSx</td>
<td>floating point</td>
<td>$\hat{x}$ component of vector from current receiver location to scatterer</td>
</tr>
<tr>
<td>RSy</td>
<td>floating point</td>
<td>$\hat{y}$ component of vector from current receiver location to scatterer</td>
</tr>
<tr>
<td>len</td>
<td>array of 64 floating points</td>
<td>length of vector from receiver location along the track to the scatterer</td>
</tr>
<tr>
<td>X</td>
<td>array of 64 floating points</td>
<td>$\hat{x}$ coordinate of scatterer for each time delay bin</td>
</tr>
<tr>
<td>Y</td>
<td>array of 64 floating points</td>
<td>$\hat{y}$ coordinate of scatterer for each time delay bin</td>
</tr>
<tr>
<td>AA</td>
<td>floating point</td>
<td>2$^{nd}$ order polynomial coefficient</td>
</tr>
<tr>
<td>BB</td>
<td>floating point</td>
<td>1$^{st}$ order polynomial coefficient</td>
</tr>
<tr>
<td>CC</td>
<td>floating point</td>
<td>0$^{th}$ order polynomial coefficient</td>
</tr>
</tbody>
</table>

Incorporating the variables in Table 4.4, the following algorithm shows how the initial narrowband signal phase and scatterer location calculations are implemented in...
SMRCIM and SIRCIM along a 4.5 wavelength track. Comments are preceded by two (/) slash marks while curly braces {} follow a C/C++ style syntax.

BEGIN:

// PSEUDO ALGORITHM of the C++ function InitPhase()
// this algorithm first loads AOA data from .AOA files and determines the location of the
// scatterers for each of the 64 time delay bins. At the same time the algorithm generates
// the initial phase of the narrowband signal from a uniform 0 to 2 pi distribution.
// In this example, the track length is 4.5 wavelengths

tem = 7.8125E-9  // assumes a model from SIRCIM

// Find Sx and Sy for each of the time bins
// user an inner loop to cycle through the 64 time bins
for t = 1 to 64
{
    exdel = (t - 0.5) * tem  // excess delay
    exdist = exdel * C  // C here is speed of light in m/s
    dist = exdist + trsep  // major axis length
    a = 0.5 * dist  // this is ½ the major axis

    // sqrt is the square root function while sqr is the square function
    b = sqrt( sqr( a ) - sqr( c ) )  // Equation 4.10
    e = c / a  // eccentricity (c has already been calculated)
    m = -tan( aoa[t][1] )  //Slope of a line from R to S
    // the direction (+ -) will be applied later
    // after checking the region of S

    // solution to a quadratic equation below
    // Solution to Equation 4.28
    AA = sqr( a * m ) + sqr( b )
    BB = -2 * sqr( a * m ) * c
    CC = sqr( a * m * c ) - sqr( a * b )
    x1 = 0.5 * ( -BB + sqrt( sqr( BB ) - 4 * AA * CC ) ) / AA
    x2 = 0.5 * ( -BB - sqrt( sqr( BB ) - 4 * AA * CC ) ) / AA

    // See if |AOA| between 0 and 90 degrees
    if ( INRANGE( fabs( aoa[t][1] ), 0.0, PI/2 ) )
    {
        if ( x1 > c )  // can't have Sx greater than Rx
            Sx = x2
        else

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\[ S_x = x1 \]
\[ Sy = m \cdot (S_x - c) \quad \text{// y-y1 = m \cdot (x-x1) POINT SLOPE FORM} \]

// See if |AOA| between 90 and 180 degrees
if (INRANGE(fabs(aoa[t][1]), PI/2, PI)) {
    if (x1 < c) // can't have Sx less than Rx
        Sx = x2
    else
        Sx = x1
    Sy = m \cdot (Sx - c) \quad \text{// y-y1 = m \cdot (x-x1) POINT SLOPE FORM} 
}

// check extreme points
if (aoa[t][1] == 0.0) //AOA is 0 degrees
    { 
        Sx = -a
        Sy = 0.0
    }

if (fabs(aoa[t][1]) == PI) //AOA is +/- 180 degrees
    { 
        Sx = a
        Sy = 0.0
    }

if (aoa[t][1] == PI/2.0) //AOA is + 90 degrees
    { 
        Sx = c
        Sy = sqrt(sqr(b) * (1.0 - sqr(e)))
    }

if (aoa[t][1] == -PI/2.0) //AOA is - 90 degrees
    { 
        Sx = c
        Sy = -sqrt(sqr(b) * (1.0 - sqr(e)))
    }

// Set the initial phases to be random
ph[0][t] = uniform randomly distributed between 0 and 2\pi
// Vector from R to S ( RSx, RSy )
RSx = Sx - c
RSy = Sy
X[t] = Sx  // Store the scatterer x coordinate for each time bin
Y[t] = Sy  // Store the scatterer y coordinate for each time bin

// Calculate the initial length of vector RS for each time bin
len[0][t] = sqrt( sqr( RSx ) + sqr( RSy ) )
} // end of delay bin loop

After the InitPhase() function calculates the initial phases and scatter locations for each time delay bin, the class member function of the Simulation C++ class, called AddPhaseMakeCW() is called for each profile along the 4.5, 10, 20, 40, or 80\(\lambda\) track. This function synthesizes the narrowband signal from the wideband impulse response by summing the phasor representation of the individual multipath components as discussed in Chapter 3 and in [38]. The carrier phase of the wideband impulse response is necessary for this calculation. Therefore, this function uses the initial phases and scatter locations from the InitPhase() function to complete the calculation of the narrowband signal. The change in phase of each of the multipath components as the mobile moves along the track is calculated by determining the small changes in the radio path length from the scatterer position for each time delay bin.

Incorporating the variables in Table 4.5, the following algorithm shows the remainder of the narrowband synthesis process used in SMRCIM and SIRCIM. Comments are preceded by two (/) slash marks while curly braces {} follow a C/C++ style syntax.
Table 4.5 Description of Variables Used in Final Narrowband Signal Synthesis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>floating point</td>
<td>half the T-R separation</td>
</tr>
<tr>
<td>alpha</td>
<td>floating point</td>
<td>mobile/vehicle direction</td>
</tr>
<tr>
<td>y</td>
<td>floating point</td>
<td>absolute value of distance from original receiver location along 4.5, 10, 20, 40, or 80λ track</td>
</tr>
<tr>
<td>trsep</td>
<td>floating point</td>
<td>original T-R separation</td>
</tr>
<tr>
<td>t</td>
<td>integer</td>
<td>counter for 64 time bins</td>
</tr>
<tr>
<td>index</td>
<td>integer</td>
<td>counter for number of user selected interpolation points</td>
</tr>
<tr>
<td>numPts</td>
<td>integer</td>
<td>user selected number of interpolation points (maximum of 100)</td>
</tr>
<tr>
<td>beta</td>
<td>array of 64 floating points</td>
<td>angle β from Figure 4.7</td>
</tr>
<tr>
<td>C</td>
<td>floating point</td>
<td>speed of light in m/s</td>
</tr>
<tr>
<td>ph</td>
<td>array of numPts x 64 floating points</td>
<td>phases of each time delay bin for up to 100 individual interpolation points</td>
</tr>
<tr>
<td>len</td>
<td>array of numPts x 19, 41, 81, 161, or 321 floating points</td>
<td>length of vector from receiver location along the track to the scatterer calculated in InitPhase()</td>
</tr>
<tr>
<td>X</td>
<td>array of 64 floating points</td>
<td>$\hat{x}$ coordinate of scatterer for each time delay bin</td>
</tr>
<tr>
<td>Y</td>
<td>array of 64 floating points</td>
<td>$\hat{y}$ coordinate of scatterer for each time delay bin</td>
</tr>
<tr>
<td>y</td>
<td>floating point</td>
<td>absolute value of distance from original receiver location along 4.5, 10, 20, 40, or 80λ track</td>
</tr>
<tr>
<td>sumreal</td>
<td>floating point</td>
<td>summation of the real components of the complex envelope</td>
</tr>
<tr>
<td>sumimag</td>
<td>floating point</td>
<td>summation of the imaginary components of the complex envelope</td>
</tr>
<tr>
<td>theta4</td>
<td>floating point</td>
<td>angle as shown in Figure 4.7</td>
</tr>
<tr>
<td>theta5</td>
<td>floating point</td>
<td>angle as shown in Figure 4.7</td>
</tr>
<tr>
<td>phi</td>
<td>floating point</td>
<td>angle as shown in Figure 4.7</td>
</tr>
<tr>
<td>wl</td>
<td>floating point</td>
<td>wavelength induced by the movement of the receiver</td>
</tr>
<tr>
<td>fi</td>
<td>floating point</td>
<td>Doppler frequency due to motion of mobile</td>
</tr>
<tr>
<td>mobvel</td>
<td>floating point</td>
<td>mobile velocity in m/s</td>
</tr>
<tr>
<td>amp</td>
<td>floating point</td>
<td>interpolated wideband amplitude computed in other functions from</td>
</tr>
<tr>
<td>refdist</td>
<td>floating point</td>
<td>reference distance $d_r$ in meters</td>
</tr>
<tr>
<td>freq</td>
<td>floating point</td>
<td>carrier frequency in MHz</td>
</tr>
<tr>
<td>cw</td>
<td>floating point</td>
<td>magnitude of CW wave</td>
</tr>
<tr>
<td>cwph</td>
<td>floating point</td>
<td>phase of CW wave</td>
</tr>
</tbody>
</table>
BEGIN:

// PSEUDO ALGORITHM of the C++ function AddPhaseMakeCW()
// this algorithm takes the output from the InitPhase() function and synthesizes the
// narrowband signal from the wideband impulse response by summing the phasor
// representation of the individual multipath components
// In this example, the track length is 4.5 wavelengths
// refdist in meters  and frequency in MHz
refpl = sqr( 4 * PI * refdist * freq / 300.0 )
c = 0.5 * trsep

// Outer loop to step through the number of interpolation points selected by the user
for index = 1 to numPts
{
    // Inner loop to step through each time delay bin
    for t = 1 to 64
    {
        // calculate the distance along the 4.5λ track
        y = (index - 1) / ( 19 * ( numPts + 1 ) )

        // calculate the angle φ from Figure 4.7
        phi = 2.0 * PI - alpha - beta

        // calculate the new length of the path from the transmitter to the receiver
        // based on the geometry of Figure 4.7
        len[index][t] = sqrt ( sqr ( len[0][t] ) + sqr( y ) - 2.0 * len[0][t] * y * cos( phi ) )

        // calculate the angle θ based on the geometry of Figure 4.7
        theta4 = atan2( ( Y[t] + y * sin( alpha ) ) , (c - X[t] - y * cos( alpha ) ) )

        // calculate the angle θ5 based on the geometry of Figure 4.7
        theta5 = alpha + theta4

        // calculate the Doppler frequency
        fi = freq * 1.0e6 * ( 1.0 + ( mobvel / C ) * cos( theta5 ) )

        // calculate the movement induced wavelength of the signal
        wl = C / fi

        // calculate the change in phase due to movement of the mobile
        ph[index][t] = ph[0][t] + ( len[index][t] - len[0][t] ) * 2.0 * PI / wl
    }
}

// Loop to step through each of the time delay bins to
// store the final phase change after the interpolation
for t = 1 to 64
{
    ph[0][t] = ph[ numPts - 1][t]
    len[0][t] = len[ numPts - 1][t]
}

for index = 1 to numPts
{
    // reset the summations for each interpolation
    sumreal = 0.0;
    sumimag = 0.0;
    for t = 1 to 64
    {
        // sum the real components of the narrowband envelope
        sumreal = sumreal + sqrt( amp[index][t] ) * cos( ph[index][t] )

        // sum the imaginary components of the narrowband envelope
        sumimag = sumimag + sqrt( amp[index][t] ) * sin( ph[index][t] )
    }

    // calculate the magnitude of the CW wave
    cw[index] = ( sqr( sumreal ) + sqr( sumimag ) ) / refpl

    // calculate the phase of the CW wave
    cwpht[index] = atan( sumimag / sumreal )

    // unwrap the phase
    if ( sumreal < 0.0 )
        cwpht[index] = PI + cwpht[index]
    if ( cwpht[index] > PI )
        cwpht[index] = cwpht[index] - 2.0 * PI
}
Chapter 5
Installation and File Formats

5.1 Overview
The types of data supplied by SMRCIM and SIRCIM are very useful in many different levels of wireless system and hardware design. Keeping this in mind, these software packages have been engineered, refined, and well documented as a result of the work presented in this thesis. Since the early inception of these channel modeling programs, as part of the inclusion of the AOA models, the installation procedures have been greatly improved by using a commercial product known as InstallShield® created by InstallShield Software Corporation. Likewise, the graphical user interface has been moved from a DOS based environment into a Microsoft Windows® environment with the reliance upon The MathWorks software package known as MATLAB®. SMRCIM and SIRCIM do not function without MATLAB®. In addition, copy protection has been added by the use of a hardware lock. Essentially, the programs have been enhanced to the level of commercial products with the intention of gaining practical implementation in industry.

This chapter will briefly discuss the installation procedures, initial setup of the programs, and the output file formats. With the information provided in this chapter, a user of these software packages will be able to incorporate the resulting data in a myriad of real world hardware system designs.

5.2 Installation Procedures
As previously stated, new installation setup programs have been written with the assistance of InstallShield™ for both SMRCIM and SIRCIM at Wireless Valley Communications, Inc. These programs are extremely easy to install on any PC running Windows 95, 98 or NT. In a commercial environment, an easy to use installation
program is highly desirable. Following this logic, the following steps outline the installation of both SMRCIM and SIRCIM:

1. Attach the hardware key to the parallel port.
2. Insert Disk #1 into the appropriate floppy drive (e.g., the A: drive).
3. Press the Start button on the Windows taskbar.
4. Select Run…. The Run dialog will then appear.
5. Type a:\setup.exe and press Enter. If the a: drive is not the floppy drive, then substitute the appropriate drive letter for a:. The setup program will then execute. Follow the instructions in the setup program.

The installation setup program requires you to enter in information such as the path in which you would like to install the program files, your name, and your organization name. After entering this information, the program copies the files listed in Table 5.1 into the startup directory. Finally, if MATLAB® has been previously installed on the computer, the setup edits the file startup.m located in the \toolbox\local directory under the main MATLAB® directory.
Table 5.1 SMRCIM and SIRCIM File Listing

<table>
<thead>
<tr>
<th>SMRCIM Files</th>
<th>SIRCIM Files</th>
</tr>
</thead>
<tbody>
<tr>
<td>cdf.MAT</td>
<td>CDF.MAT</td>
</tr>
<tr>
<td>distribbs.MAT</td>
<td>CWLCR.M</td>
</tr>
<tr>
<td>readbin.m</td>
<td>DEFAULT.MAT</td>
</tr>
<tr>
<td>SMRCIM.m</td>
<td>DISTRIBUTS.MAT</td>
</tr>
<tr>
<td>smrCWLCR.m</td>
<td>EXITMENU.M</td>
</tr>
<tr>
<td>smrDEFAULT.MAT</td>
<td>filecheck.m</td>
</tr>
<tr>
<td>smrEXIT.m</td>
<td>GRAPHACW.M</td>
</tr>
<tr>
<td>smrFILE.m</td>
<td>GRAPHAOA.m</td>
</tr>
<tr>
<td>smrFILECHECK.m</td>
<td>GRAPHAOA_TIME.m</td>
</tr>
<tr>
<td>smrGRAPHACW.m</td>
<td>GRAPHAPH.M</td>
</tr>
<tr>
<td>smrGRAPHAOA.m</td>
<td>GRAPHCDF.M</td>
</tr>
<tr>
<td>smrGRAPHAOA_TIME.m</td>
<td>GRAPHCNF.M</td>
</tr>
<tr>
<td>smrGRAPHPH.m</td>
<td>GRAPHCWF.M</td>
</tr>
<tr>
<td>smrGRAPHCDF.m</td>
<td>GRAPHFR.M</td>
</tr>
<tr>
<td>smrGRAPHCWF.m</td>
<td>GRAPHNPL.M</td>
</tr>
<tr>
<td>smrGRAPHNPL.m</td>
<td>GRAPHNSE.M</td>
</tr>
<tr>
<td>smrGRAPHWB.m</td>
<td>GRAPHWB.M</td>
</tr>
<tr>
<td>smrGRAPHWPL.m</td>
<td>GRAPHWPL.M</td>
</tr>
<tr>
<td>smrmat.exe</td>
<td>IMP_HOSP.M</td>
</tr>
<tr>
<td>smrNBFROMWB.m</td>
<td>IMP_OTH.M</td>
</tr>
<tr>
<td>smrNBONLY.m</td>
<td>NBFROMWB.M</td>
</tr>
<tr>
<td>smrNBPARAMS.m</td>
<td>NBONLY.M</td>
</tr>
<tr>
<td>smrSIMULATING.m</td>
<td>NBPARAMS.M</td>
</tr>
<tr>
<td>smrPOLAR.m</td>
<td>readbin.m</td>
</tr>
<tr>
<td>smrSETUP.m</td>
<td>SETUP.M</td>
</tr>
<tr>
<td>smrSIMULATING.m</td>
<td>SIMPARAM.MAT</td>
</tr>
<tr>
<td>smrSIMULATING.m</td>
<td>simulating.m</td>
</tr>
<tr>
<td>smrWBANDNB.m</td>
<td>SIRCIM.M</td>
</tr>
<tr>
<td>smrWBAOA.m</td>
<td>SIRFILE.M</td>
</tr>
<tr>
<td>smrWBONLY.m</td>
<td>sirmat.exe</td>
</tr>
<tr>
<td>smrWTONB.m</td>
<td>sirPOLAR.m</td>
</tr>
<tr>
<td>strsplit.m</td>
<td>STRSPLT.M</td>
</tr>
<tr>
<td>smrREADHD1.xls</td>
<td>WBANDNB.M</td>
</tr>
<tr>
<td></td>
<td>WBAOA.m</td>
</tr>
<tr>
<td></td>
<td>WBONLY.M</td>
</tr>
<tr>
<td></td>
<td>WTONB.M</td>
</tr>
<tr>
<td></td>
<td>READHD1.xls</td>
</tr>
</tbody>
</table>

5.3 Initial Setup Following Installation

When running SMRCIM and SIRCIM for the first time, users must set up the directory where data will be stored. A user must start MATLAB® and then start SMRCIM by typing `smrcim` at the MATLAB® prompt or start SIRCIM by typing `sircim` at the MATLAB® prompt followed by pressing the ENTER key. The main window of the corresponding program will appear. Both SMRCIM and SIRCIM will detect if the user is using the software for the first time and will open the dialog box shown in Figure
5.1. If the users wishes to change the data directory at a later time, the user must select **File** and then **Set Up** from the main menu to open the dialog box shown in Figure 5.1.

![Initial Setup Dialog](image)

**Figure 5.1 Initial Setup Dialog**

This dialog box allows the user to change the data directory to a previously existing directory or to create a new directory to store the data files. Therefore, if the user entered directory does not exist, the software will create it. In addition to creating or changing the simulation directory, the user has the ability to toggle the background color of graphical displays from black to white. This is important for achieving the desired effect for presentation results when using the graphing tools in the software. Clicking the **Change** pushbutton will execute any changes and return the user to the main menu. The data directory may be changed at any time, allowing multiple users to create channel simulation results and store them in different directories. If the directory already exists, any data in the directory will not be deleted or altered.

### 5.4 Output File Formats

Each data file type is denoted by its file extension and all output data files created during a single simulation run are stored in a single subdirectory (called the Data Output Subdirectory) under the data directory as demonstrated above. The subdirectory name is the same as the base name for a simulation as discussed in Chapter 3.
5.4.1 SMRCIM Output File Formats

Before explaining the data that resides in the output files generated by SMRCIM, it is first useful to tabulate the data file types and to provide a listing of the file extension and storage format of the files. Table 5.2 summarizes the output files generated by simulations performed with SMRCIM.

Table 5.2 Table of SMRCIM Output File Types and Extensions

<table>
<thead>
<tr>
<th>File Type</th>
<th>Extension</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wideband channel impulse responses</td>
<td>.BIN</td>
<td>BINARY</td>
</tr>
<tr>
<td>Multipath component phases</td>
<td>.PHS</td>
<td>BINARY</td>
</tr>
<tr>
<td>Angle-of-Arrival of multipath</td>
<td>.AOA</td>
<td>BINARY</td>
</tr>
<tr>
<td>Small scale narrowband signals</td>
<td>.CW</td>
<td>ASCII</td>
</tr>
<tr>
<td>Channel Header1 files</td>
<td>.HD1</td>
<td>ASCII</td>
</tr>
<tr>
<td>Channel Header2 files</td>
<td>.HD2</td>
<td>ASCII</td>
</tr>
<tr>
<td>RMS delay spread values</td>
<td>.RMS</td>
<td>ASCII</td>
</tr>
<tr>
<td>CDF of RMS delay spread</td>
<td>.CDF</td>
<td>ASCII</td>
</tr>
<tr>
<td>Path loss values of wideband signals</td>
<td>.WPL</td>
<td>ASCII</td>
</tr>
<tr>
<td>Path loss values of CW signals</td>
<td>.NPL</td>
<td>ASCII</td>
</tr>
<tr>
<td>Program data</td>
<td>.MAT</td>
<td>BINARY</td>
</tr>
</tbody>
</table>

5.4.1.1 .BIN, .AOA, and .PHS Files

5.4.1.1.1 Overview

When doing any type of wideband simulations, binary files with the extensions .BIN and .AOA are generated. The .BIN files consist of impulse response data (path loss amplitude of each multipath component) stored in a 64 x Z array in binary format, where Z is an integer number of profiles. Since the user has the option of choosing to simulate over various track lengths, Z can take on the following values {19, 41, 81, 161, 321} corresponding to 4.5, 10, 20, 40, or 80λ track lengths. A .BIN file contains the sequential Z wideband impulse responses for a given track local area Pn with a time of 625 nsec (62.5 for microcellular) per time delay bin. Likewise, a bin file is so named because the excess delay range of 40 µs (4 µs for microcellular) for the wideband impulse responses is divided into 64 “bins” of 625 nsec (62.5 nsec for microcellular) duration. Each
multipath component has a power path loss amplitude with respect to the reference distance $d_0$. To obtain the total path loss, the user must add the free space path loss to the values of the power path loss values in this file.

The corresponding .AOA files contain the angle-of-arrival for each multipath component in the .BIN file. In the 64 x $Z$ binary array, the AOA data is stored in radians ranging from 0 to ± $\pi$ radians. The actual AOA represents the angle between a line drawn directly from the transmitter to the receiver at its location along the track and the line drawn directly from the receiver to the scatterer (point S) on the ellipse as discussed in Chapter 4. SMRCIM references AOA as the angle between the LOS and the multipath component seen by the receiver, measured from a line between the transmitter and receiver. For example, start on the line between the transmitter and receiver and rotate towards the line between the scatterer and receiver to the multipath ray. The clockwise direction (as seen from the receiver to the scatterer) is taken as a positive angle while the counter clockwise direction is taken as a negative angle. This is shown graphically in Chapter 4. **NOTE:** When the corresponding path loss of a given time bin is greater than or equal to 200dB, the AOA for that bin is forced to 0 radians.

Similar to .BIN and .AOA files, .PHS files consist of the individual phases of multipath components in a $Z$ x 64 binary array. The .PHS files contain the phase values (in radians) calculated for each individual multipath component in the $Z$ wideband impulse responses over the local area $P_n$. **NOTE:** To save processing time, .PHS files are only created when narrowband (CW) simulations are generated from wideband information. To generate phases of the individual wideband multipath components over a local area, the user must simply run Narrowband from Wideband or Both Wideband and Narrowband simulations.

5.4.1.1.2 Data Extraction

Since .BIN, .AOA, and .PHS files are in binary format to conserve disk space, it is desirable to convert the files to an ASCII form to use with other post processing software or simulations. There are two methods of converting these types of files to ASCII. The
first method utilizes MATLAB. To read binary files in MATLAB, the user can modify the accompanying MATLAB code included in the file `readbin.m`. The code is shown and explained below:

```matlab
%% file sizes =
%% #bins* 8 bytes/double * [ #profiles for 4.5 , 10 , 20 , 40 , 80 wavelengths ]
sizes = 64 * 8 .* [ 19 41 81 161 321 ];
dirstruct = dir( 'filebasename.bin' );
fileid = fopen( dirstruct.name );

%% BINDATA is a variable in MATLAB
switch( dirstruct.bytes )
case sizes(5)
    BINDATA = fread( fileid, [64,321] , 'double');
case sizes(4)
    BINDATA = fread( fileid, [64,161] , 'double');
case sizes(3)
    BINDATA = fread( fileid, [64,81]  , 'double');
case sizes(2)
    BINDATA = fread( fileid, [64,41]  , 'double');
otherwise
    BINDATA = fread( fileid, [64,19]  , 'double');
end

%% we must close files to avoid sharing violations
fclose( fileid ) ;

%% Save the data as double precision ASCII tab delimited
save newfilename_bin.TXT   BINDATA   -ascii  -double  -tabs
```

The text `filebasename.bin` must be replaced in the above code to a valid `.BIN` or `.AOA` filename that you wish to convert to viewable data. Once the code above has been executed in MATLAB, the variable `BINDATA` will be a 64 x Z array in MATLAB that contains the contents of the `.BIN` file. Likewise, a new file named `newfilename.TXT` will be created. The file will contain the 64 x Z array in double precision ASCII form with tab delimited columns. To convert `.PHS` files, interchange the dimensions within the `fread()` statements. For example the first `fread()` statement would be:

```matlab
PHSDATA = fread( fileid, [321,64] , 'double');
```

For more help with MATLAB commands, the user can type `help command` at the MATLAB prompt, where `command` is any valid MATLAB command such as `fread` or `save`.

Another way to convert these files to ASCII text files is to use the file called `readbin.exe` located in the SMRCIM directory. This program can be easily executed by clicking on Readbin from the File pulldown menu of the SMRCIM welcome dialog box. After executing readbin.exe, click the SELECT button to select from `.BIN`, `.AOA`, or `.PHS`
files that you would like to convert to text. Each time you convert files, the converted files will be listed in the listbox labeled “Recently Converted Files:.” Each .BIN file will be transformed into a _bin.TXT file, each .AOA file will be converted into a _aoa.TXT file, and each .PHS file will be transformed into a _phs.TXT file. **NOTE:** The selected .BIN, .AOA, and .PHS files will still exist in their original directories. These text files can be loaded directly into programs such as Microsoft EXCEL™ as tab delimited files or into other simulation programs for further post processing.

### 5.4.1.2 .CW Files

#### 5.4.1.2.1 Overview

Continuous wave (.CW) files are ASCII files used to store information about continuous wave narrowband signals. The .CW files contain the narrowband signal strengths along a 4.5, 10, 20, 40, or 80λ track. When narrowband information is generated from wideband data, the second field of a .CW file is equal to 0.00 and the first field is equal to the number of interpolation points. When narrowband data is determined directly, the first field of a .CW file is a non-zero, internally generated scaling factor based on the second field. The second field, on the other hand, is a user chosen time duration in seconds for a temporal model.

The remainder of the file consists of two columns of data. The first column of data corresponds to the linear narrowband signal power while the second column represents the phase of the waveform. When generating narrowband data from wideband information, the signal power is relative to the local average. Likewise, the values are generated by interpolating between each of the Z profiles. Where Z can take on the following values: {19, 41, 81, 161, 321} corresponding to 4.5, 10, 20, 40, or 80λ track lengths.
**5.4.1.2.2 Field Descriptions**

<table>
<thead>
<tr>
<th>Field #</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Interpolation points</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>Time duration</td>
<td>track length</td>
</tr>
<tr>
<td></td>
<td>Linear Power &amp; Phase</td>
<td>watts</td>
</tr>
</tbody>
</table>

NOTE: In Table 5.3 above, the symbol | in field 2 means that only one of the two options will exist in the file.

**5.4.1.3 HDI Files**

**5.4.1.3.1 Overview**

.HDI files are short ASCII files used to encapsulate important simulation parameters and results when executing all types of simulations. These files contain valuable summary information for each local area during a simulation run. Path loss values are absolute (not referenced to the free space reference distance).

An accompanying Microsoft® EXCEL™ file called sirREADHD1.xls will generate plots of T-R separation versus Delay and Path Loss versus Delay by reading .HDI files and automatically extracting the necessary data. This file is useful in research based comparisons of simulations with real-life measurements of path loss versus delay.

To use the spreadsheet, the user must load it into Excel with all macros enabled. Once the spreadsheet has been loaded, the user must click the button labeled “Read HDI.” This will cause an open file window to appear. With this window, the user can locate the simulation directory containing the .HDI files. Next the user highlights the desired files **(multiple selection available)** to plot and clicks the OPEN button. The macro will then plot the data eliminating the tedious manual tasks.
5.4.1.4 .HD2 Files

5.4.1.4.1 Overview

.HD2 files are short ASCII files used to store important simulation parameters and results when executing narrowband simulations. Therefore, they only exist if some type of narrowband simulation has been run, including a narrowband simulation generated from a wideband simulation. .HD2 files contain valuable summary information for each local area during a narrowband simulation run.

5.4.1.4.2 Field Descriptions

Table 5.5 gives a description of all possible fields of a .HD2 file. Depending on the method of generation of the narrowband information, some of these fields may contain information that is not used. For example, when generating narrowband data from wideband data, the narrowband model (spatial, temporal) is not user-specified.
because of the SMRCIM modeling approach. In such cases, field 8 will default to SPATIAL, and fields 9 and 10 will not be included in the header file. Again, path loss is absolute (not referenced to free space reference distance).

### Table 5.5 .HD2 File Descriptions

<table>
<thead>
<tr>
<th>Field #</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aisle width</td>
<td>meters (m)</td>
</tr>
<tr>
<td>2</td>
<td># interpolated profiles</td>
<td>n/a</td>
</tr>
<tr>
<td>3</td>
<td>Direction of mobile travel</td>
<td>degrees</td>
</tr>
<tr>
<td>4</td>
<td>Mobile Velocity</td>
<td>Max Doppler frequency</td>
</tr>
<tr>
<td>5</td>
<td>Average absolute path loss</td>
<td>dB</td>
</tr>
<tr>
<td>6</td>
<td>Ricean K factor</td>
<td>dB</td>
</tr>
<tr>
<td>7</td>
<td># of secs</td>
<td>channel track length</td>
</tr>
<tr>
<td>8</td>
<td>Narrowband Model {SPATIAL, TEMPORAL}</td>
<td>n/a</td>
</tr>
<tr>
<td>9</td>
<td>For temporal only {Ricean, Rayleigh}</td>
<td>n/a</td>
</tr>
<tr>
<td>10</td>
<td>For temporal only {RHO}</td>
<td>n/a</td>
</tr>
<tr>
<td>11</td>
<td>Conversion {-1,0,1,2,3}</td>
<td>-1=NOT USED 0 = LCR 1=k.p.h. 2=m.p.h. 3=Max Doppler</td>
</tr>
</tbody>
</table>

In field 4, there are three options. The symbol “|” separates the three different types of values and the units on the right correspond to each of these options, respectively. Field 11 distinguishes between these options and also keeps track of which units the user has selected for velocity. **NOTE: If field 4 represents mobile velocity, the value’s corresponding units are always km/hr. Field 11 may have a 2 in it. However, this only tells the graphic portion of the software to display the velocity in m.p.h. and has no effect on the value in field 4.**
5.4.1.4.3 Example

Below is an example of a .HD2 file for a narrowband simulation created from wideband information. Notice that only 9 out of 11 fields exist when narrowband information is generated from wideband information.

30 point interpolation between $\lambda/4$  →  27.000000  ←  27 meter aisle
Mobile velocity 6.7 m/s or 15 m.p.h.  →  13.000000  ←  13.0 degree direction
NOT USED  →  6.705600  ←  Average PL 98.6 dB
USING SPATIAL MODEL  →  98.577673  ←  NOT USED
NOT USED  →  0.000000  ←  velocity in m.p.h.

Since the above example was a SPATIAL model, the KFACTOR, field 6, was not utilized because it is only used in the TEMPORAL fading model for Ricean fading. Likewise, as mentioned earlier, the value in field 4 is in terms of velocity whenever a SPATIAL model is simulated. The above .HD2 example file was created by executing a wideband and narrowband simulation. This is evident because the mobile velocity is greater than zero. For Rayleigh spatial narrowband fading determined directly, the value of mobile velocity is always equal to zero, and for narrowband fading determined from wideband information, the mobile velocity is always greater than zero.
Below is an example of a .HD2 file created from a simulation of directly determined narrowband information. Notice that all of the fields are present. This is a quick indication that the .HD2 file was generated without wideband information.

<table>
<thead>
<tr>
<th>Field</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internally generated scaling factor</td>
<td>0.000000</td>
</tr>
<tr>
<td>Max Doppler Frequency</td>
<td>11</td>
</tr>
<tr>
<td>NOT USED</td>
<td>0.000000</td>
</tr>
<tr>
<td>NOT USED</td>
<td>0.000000</td>
</tr>
<tr>
<td>Average PL</td>
<td>112.335337</td>
</tr>
<tr>
<td>10.502564</td>
<td>10.5 seconds</td>
</tr>
<tr>
<td>RHO = 0</td>
<td>RAYLEIGH fading</td>
</tr>
<tr>
<td>Max. Doppler frequency</td>
<td>3</td>
</tr>
</tbody>
</table>

5.4.1.5 .RMS Files

5.4.1.5.1 Overview

Delay spread files, .RMS files, are ASCII files that contain the delay spread of each wideband impulse response profile. Since there are Z profiles generated in a wideband simulation, where Z is either 19, 41, 81, 161, or 321 corresponding to a 4.5, 10, 20, 40, or 80λ, track, the file consists of Z values for delay spread. Likewise, these files only exist when some type of wideband simulation has been completed.
5.4.1.5.2  Example

Below is an example of a .RMS file, containing the RMS delay spread of each of the 19 impulse response snapshots in an urban channel. The average RMS delay spread for this local area simulation was 3.4 $\mu$s.

```
2728.61
3221.29
5854.62
4220.94
2657.55
2288.75
1110.18
5749.15
1259.34
4106.88
3835.82
4106.88
3835.82
776.08
5661.76
4250.98
1449.28
2817.63
814.96
4344.25
6999.35
```

All units of time in nsec

5.4.1.6  .CDF Files

5.4.1.6.1  Overview

Cumulative distribution files, .CDF files, are ASCII files that contain information about RMS delay spreads of the impulse response data within a local area $P_n$. The first line of a .CDF file is the carrier frequency of the simulation in MHz. The remaining lines in the file consist of two columns of data. The first column of data is the RMS delay spread in microseconds and the second column is the value of the CDF at that delay spread. The value of the CDF at any particular delay spread represents the probability that the RMS delay spread will be less than that particular RMS delay spread value.
5.4.1.7 .WPL & .NPL Files

5.4.1.7.1 Overview

Wideband and narrowband path loss files have the extension .WPL and .NPL, respectively. Both types of files are ASCII text files that contain the corresponding mean path loss exponent, \( n \), and standard deviation, \( \sigma \), of all locations that have been simulated in a single simulation run. Additionally, these files contain the carrier frequency, path loss reference distance, and the value of average absolute path loss at each local area in a simulation run. Wideband and narrowband scatter plots are generated from these files.

5.4.1.7.2 Field Descriptions

Below is a table showing the description of the fields in .WPL and .NPL files. The example file listed in the table was generated by using a microcellular environment.

<table>
<thead>
<tr>
<th>Example File</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7497</td>
<td>Path loss exponent (n)</td>
<td>n/a</td>
</tr>
<tr>
<td>6.4268</td>
<td>Standard Deviation (( \sigma ))</td>
<td>dB</td>
</tr>
<tr>
<td>900.0000</td>
<td>Carrier Frequency</td>
<td>MHz</td>
</tr>
<tr>
<td>1.0000</td>
<td>Path loss reference distance</td>
<td>meters (m)</td>
</tr>
<tr>
<td>10.0000 43.9400</td>
<td>T-R Separation  Path loss</td>
<td>meters (m) dB</td>
</tr>
<tr>
<td>10.0000 45.0400</td>
<td>T-R Separation  Path loss</td>
<td>meters (m) dB</td>
</tr>
<tr>
<td>10.0000 58.0900</td>
<td>T-R Separation  Path loss</td>
<td>meters (m) dB</td>
</tr>
</tbody>
</table>

5.4.1.8 .MAT Files

5.4.1.8.1 Overview

MATLAB files (.MAT files) are used to store various information for the internal operations of SMRCIM. These files should not be altered. If they are corrupted, SMRCIM may not function properly.
5.4.2 SIRCIM Output File Formats

Before explaining the data that resides in the output files generated by SIRCIM, it is first useful to tabulate the file types and to provide a listing of the file extensions and storage formats of the files. Table 5.7 summarizes the output files generated by simulations performed with SIRCIM.

Table 5.7 Table of SIRCIM Output File Types and Extensions

<table>
<thead>
<tr>
<th>File Type</th>
<th>Extension</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wideband channel impulse responses</td>
<td>.BIN</td>
<td>BINARY</td>
</tr>
<tr>
<td>Multipath component phases</td>
<td>.PHS</td>
<td>BINARY</td>
</tr>
<tr>
<td>Angle-of-Arrival of multipath</td>
<td>.AOA</td>
<td>BINARY</td>
</tr>
<tr>
<td>Small scale narrowband signals</td>
<td>.CW</td>
<td>ASCII</td>
</tr>
<tr>
<td>Channel Header1 files</td>
<td>.HD1</td>
<td>ASCII</td>
</tr>
<tr>
<td>Channel Header2 files</td>
<td>.HD2</td>
<td>ASCII</td>
</tr>
<tr>
<td>RMS delay spread values</td>
<td>.RMS</td>
<td>ASCII</td>
</tr>
<tr>
<td>CDF of RMS delay spread</td>
<td>.CDF</td>
<td>ASCII</td>
</tr>
<tr>
<td>Path loss values of wideband signals</td>
<td>.WPL</td>
<td>ASCII</td>
</tr>
<tr>
<td>Path loss values of CW signals</td>
<td>.NPL</td>
<td>ASCII</td>
</tr>
<tr>
<td>Impulse noise data</td>
<td>.NSE</td>
<td>BINARY</td>
</tr>
<tr>
<td>Impulse noise data</td>
<td>.DIS</td>
<td>ASCII</td>
</tr>
<tr>
<td>Impulse noise Header3 files</td>
<td>.HD3</td>
<td>ASCII</td>
</tr>
<tr>
<td>Impulse noise data not below threshold</td>
<td>.DAT</td>
<td>ASCII</td>
</tr>
<tr>
<td>Random impulse noise data</td>
<td>.RND</td>
<td>ASCII</td>
</tr>
<tr>
<td>Repetitive impulse noise data</td>
<td>.REP</td>
<td>ASCII</td>
</tr>
<tr>
<td>Program data</td>
<td>.MAT</td>
<td>BINARY</td>
</tr>
</tbody>
</table>

5.4.2.1 .BIN, .AOA, and .PHS FILES

5.4.2.1.1 Overview

When doing any type of wideband simulations, binary files with the extension .BIN and .AOA are generated. The .BIN files consist of impulse response data (path loss amplitude of each multipath component) stored in a 64 x Z array in binary format, where Z is an integer number of profiles. Since the user has the option of choosing to simulate over various track lengths, Z can take on the following values {19,41,81,161, 321}
corresponding to 4.5, 10, 20, 40, or 80 \( \lambda \) track lengths. A \( .BIN \) file contains the \( Z \) sequential wideband impulse responses for a given track local area \( P_n \) with a time resolution of 7.8125\( \text{ns} \) per time delay bin. Likewise, a bin file is so named because the excess delay range of 500\( \text{ns} \) for the wideband impulse responses is divided into 64 “bins” of 7.8125\( \text{ns} \) duration. Each multipath component has a power path loss amplitude with respect to the reference free space path loss distance \( d_o \). To obtain the total path loss, the user must add the free space path loss to the values in this file.

The corresponding \( .AOA \) files contain the angle-of-arrival for each multipath component in the \( .BIN \) file. In the \( 64 \times Z \) binary array, the AOA data is stored in radians ranging from 0 to \( \pm \pi \) radians. The actual AOA represents the angle between a line drawn directly from the transmitter to the receiver at its location along the track and the line drawn directly from the receiver to the scatterer (point S) on the ellipse as discussed in Chapter 4. SMRCIM references AOA as the angle between the LOS and the multipath component seen by the receiver, measured from a line between the transmitter and receiver. For example, start on the line between the transmitter and receiver and rotate towards the line between the scatterer and receiver to the multipath ray. The clockwise direction (as seen from the receiver to the scatterer) is taken as a positive angle while the counter clockwise direction is taken as a negative angle. This is shown graphically in Chapter 4. **NOTE:** When the corresponding path loss of a given time bin is greater than or equal to 200dB, the AOA for that bin is forced to 0 radians.

Similar to the \( .BIN \) files and \( .AOA \) files, \( .PHS \) files consist of the individual phases of multipath components in a \( Z \times 64 \) binary array. The \( .PHS \) files contain the phase values (in radians) calculated for each individual multipath component in the \( Z \) wideband impulse responses over the local area \( P_n \). **NOTE:** To save processing time, \( .PHS \) files are only created when narrowband (CW) simulations are generated from wideband information. To generate phases of the individual wideband multipath components over a local area, the user must simply run Narrowband from Wideband or Both Wideband and Narrowband simulations.
5.4.2.1.2 Data Extraction

Since .BIN, .AOA, and .PHS files are in binary format to conserve disk space, it is desirable to convert the files to an ASCII form to use with other post processing software or simulations. There are two methods of converting these types of files to ASCII. The first method utilizes MATLAB. To read binary files in MATLAB, the user can modify the accompanying MATLAB code included in the file readbin.m. The code is shown and explained below:

```matlab
%% file sizes =
%% #bins* 8 bytes/double * [ #profiles for 4.5, 10, 20, 40, 80 wavelengths ]
sizes = 64 * 8 .* [ 19 41 81 161 321 ];
dirstruct = dir( 'filebasename.bin' );
fileid = fopen( dirstruct.name );
%% BINDATA is a variable in MATLAB
switch ( dirstruct.bytes )
case sizes(5)
    BINDATA = fread( fileid, [64,321] , 'double' );
case sizes(4)
    BINDATA = fread( fileid, [64,161] , 'double' );
case sizes(3)
    BINDATA = fread( fileid, [64,81] , 'double' );
case sizes(2)
    BINDATA = fread( fileid, [64,41] , 'double' );
otherwise
    BINDATA = fread( fileid, [64,19] , 'double' );
end
%% we must close files to avoid sharing violations
fclose( fileid ) ;
%% Save the data as double precision ASCII tab delimited
save newfilename_bin.TXT   BINDATA   -ascii  -double  -tabs
```

The text `filebasename.bin` must be replaced in the above code to a valid .BIN or .AOA filename that you wish to convert to viewable data. Once the code above has been executed in MATLAB, the variable `BINDATA` will be a 64 x Z array in MATLAB that contains the contents of the .BIN file. Likewise, a new file named `newfilename.TXT` will be created. The file will contain the 64 x Z array in double precision ASCII form with tab delimited columns. To convert .PHS files, interchange the dimensions within the `fread()` statements. For example the first `fread()` statement would be:

```matlab
PHSDATA = fread( fileid, [321,64] , 'double' );
```

For more help with MATLAB commands, the user can type `help command` at the MATLAB prompt, where `command` is any valid MATLAB command such as `fread` or `save`.  

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Another way to convert these files to ASCII text files is to use the file called readbin.exe located in the SIRCIM directory. This program can be easily executed by clicking on Readbin from the File pulldown menu of the SIRCIM welcome dialog box. After executing readbin.exe, click the SELECT button to select from .BIN, .AOA, or .PHS files that you would like to convert to text. Each time you convert files, the converted files will be listed in the listbox labeled “Recently Converted Files:.” Each .BIN file will be transformed into a _bin.TXT file, each .AOA file will be converted into a _aoa.TXT file, and each .PHS file will be transformed into a _phs.TXT file. **NOTE:** The selected .BIN, .AOA, and .PHS files will still exist in their original directories. These text files can be loaded directly into programs such as Microsoft EXCEL as tab delimited files. This makes post processing much easier.

### 5.4.2.2 .CW Files

#### 5.4.2.2.1 Overview

Continuous wave (.CW) files are ASCII files used to store information about continuous wave narrowband signals. The .CW files contain the narrowband signal strengths along a 4.5, 10, 20, 40, or 80λ track. When narrowband information is generated from wideband data, the second field of a .CW file is equal to 0.00 and the first field is equal to the number of interpolation points. When narrowband data is determined directly, the first field of a .CW file is a non-zero internally generated scaling factor based on the second field. The second field, on the other hand, is a user chosen time duration in seconds for a temporal model.

The remainder of the file consists of two columns of data. The first column of data corresponds to the linear narrowband signal power while the second column represents the phase of the waveform. When generating narrowband data from wideband information, the signal power is relative to the local average. Likewise, the values are generated by interpolating between each of the Z profiles. Where Z can take on the following values {19,41,81,161, 321} corresponding to 4.5, 10, 20, 40, or 80 λ track lengths.
5.4.2.2  Field Descriptions

Table 5.8  .CW File Description

<table>
<thead>
<tr>
<th>Field #</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Interpolation points</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>Time duration</td>
<td>secs</td>
</tr>
<tr>
<td>•</td>
<td>Linear Power &amp; Phase</td>
<td>watts</td>
</tr>
<tr>
<td>•</td>
<td></td>
<td>degrees</td>
</tr>
</tbody>
</table>

NOTE: In Table 5.3 above, the symbol | in field 2 means that only one of the two options will exist in the file.

5.4.2.3  .HD1 Files

5.4.2.3.1  Overview

.HD1 files are short ASCII files used to encapsulate important simulation parameters and results when executing all types of simulations. This file contains valuable summary information for each local area during a simulation run. Path loss values are absolute (not referenced to the free space reference distance).

An accompanying Microsoft® EXCEL™ file called sirREADHD1.xls will generate plots of T-R separation versus Delay and Path Loss versus Delay by reading .HD1 files and automatically extracting the necessary data. This file is useful in research based comparisons of simulations with real-life measurements of path loss versus delay. To use the spreadsheet, the user must load it into Excel with all macros enabled. Once the spreadsheet has been loaded, the user must click the button labeled “Read HD1.” This will cause an open file window to appear. With this window, the user can locate the simulation directory containing the .HD1 files. Next the user highlights the desired files (multiple selection available) to plot and clicks the OPEN button. The macro will then plot the data eliminating the tedious manual tasks.
5.4.2.3.2  Field Descriptions

Table 5.9  .HD1 File Description

<table>
<thead>
<tr>
<th>Example File</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>Topography {LOS, OBS}</td>
<td>n/a</td>
</tr>
<tr>
<td>25.00</td>
<td>T-R Separation</td>
<td>meters (m)</td>
</tr>
<tr>
<td>60.53</td>
<td>Average absolute path loss</td>
<td>dB</td>
</tr>
<tr>
<td>56.64</td>
<td>Average RMS delay spread</td>
<td>nanoseconds(ns)</td>
</tr>
<tr>
<td>HARD</td>
<td>Building type {OPEN PLAN, HARD PARTITIONED, SOFT PARTITIONED}</td>
<td>n/a</td>
</tr>
<tr>
<td>PARTITIONED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400.00</td>
<td>Carrier frequency</td>
<td>MHz</td>
</tr>
<tr>
<td>1.00</td>
<td>Path loss reference distance</td>
<td>meters (m)</td>
</tr>
<tr>
<td>120.00</td>
<td>Mobile Direction</td>
<td>degrees</td>
</tr>
<tr>
<td>AisleElliptical</td>
<td></td>
<td>AOA model</td>
</tr>
<tr>
<td>1.00</td>
<td>Street width (if applicable)</td>
<td>meters (m)</td>
</tr>
<tr>
<td>10.0</td>
<td># wavelengths along track { 4.5, 10, 20, 40, 80 wavelengths } (if applicable)</td>
<td>meters (m)</td>
</tr>
</tbody>
</table>

5.4.2.4  .HD2 Files

5.4.2.4.1  Overview

.HD2 files are short ASCII files used to store important simulation parameters and results when executing narrowband simulations. Therefore, they only exist if some type of narrowband simulation has been run, including a narrowband simulation generated from a wideband simulation. .HD2 files contain valuable summary information for each local area during a narrowband simulation run.

5.4.2.4.2  Field Descriptions

Table 5.10 gives a description of all possible fields of a .HD2 file. Depending on the method of generation of the narrowband information, some of these fields may contain data that is not used. For example, when generating narrowband data from wideband data, the narrowband model (spatial, temporal) is not user-specified because of the SIRCIM modeling approach. In such cases, field 7 will default to SPATIAL, and
fields 8 and 9 will not be included in the header file. Again, path loss values are absolute (not referenced to the free space reference distance).

**Table 5.10 .HD2 File Description**

<table>
<thead>
<tr>
<th>Field #</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Building aisle width</td>
<td>meters (m)</td>
</tr>
<tr>
<td>2</td>
<td># interpolated profiles</td>
<td>n/a</td>
</tr>
<tr>
<td>3</td>
<td>Direction of mobile travel relative to aisle</td>
<td>degrees</td>
</tr>
<tr>
<td>4</td>
<td>Mobile Velocity</td>
<td>Max Doppler frequency</td>
</tr>
<tr>
<td>5</td>
<td>Average absolute path loss</td>
<td>dB</td>
</tr>
<tr>
<td>6</td>
<td>Ricean K factor</td>
<td>dB</td>
</tr>
<tr>
<td>7</td>
<td>Narrowband Model {SPATIAL, TEMPORAL}</td>
<td>n/a</td>
</tr>
<tr>
<td>8</td>
<td>For temporal only {Ricean, Rayleigh}</td>
<td>n/a</td>
</tr>
<tr>
<td>9</td>
<td>For temporal only Level Crossing Rate Threshold</td>
<td>dB</td>
</tr>
</tbody>
</table>

In field 4, there are two options. The symbol “|” separates the two different types of values and the units on the right correspond to each of these options, respectively.

**NOTE:** Whenever field 7 is equal to SPATIAL, the values in field 4 correspond to velocity. Whenever field 7 is equal to TEMPORAL, the values in field 4 correspond to max Doppler frequency.

5.4.2.4.3 Example

Below is an example of an .HD2 file for a narrowband simulation created from wideband information. Notice that only 7 out of 9 fields exist when narrowband information is generated from wideband information.

```
50 points interpolations between λ/4
Mobile velocity 5.6 m/s
Either KFACTOR (temporal) or (spatial)  
5.6 meter aisle width 5.574674
40.05 degree mobile direction 50
Average PL 51.6 dB 40.046388
# SPATIAL model 5.600000
0.000000 SPATIAL
51.583513
```
Since the above example was a SPATIAL model, it is obvious that the KFACTOR (field 6) was not utilized because it is only used in the Temporal fading model for Ricean fading. Likewise, as mentioned earlier, the value in field 4 is in terms of velocity whenever a SPATIAL model is simulated. The above .HD2 example file was created by executing a wideband and narrowband simulation. This is evident because the mobile velocity is greater than zero. For Rayleigh spatial narrowband fading determined directly, the value of mobile velocity is always equal to zero, and for narrowband fading determined from wideband information, the mobile velocity is always greater than zero.

Below is an example of an .HD2 file created from a simulation of directly determined narrowband information. Notice that all of the fields are present. This is a quick indication that the .HD2 file was generated without wideband information.

| Internally generated scaling factor | 0.000000 | NOT USED |
| Max Doppler Frequency              | 226      | NOT USED |
| K factor not used                  | 13.000000| Average PL 28.9 dB |
| Rayleigh Temporal Fading           | 0.0000000| Using Temporal Model |

**5.4.2.5 .RMS Files**

**5.4.2.5.1 Overview**

Delay spread files, .RMS files, are ASCII files that contain the delay spread of each wideband impulse response profile. Since there are Z profiles generated in a wideband simulation where Z is either 19, 41, 81, 161, or 321 corresponding to a 4.5, 10, 20, 40, or 80 λ track, the file consists of Z values for delay spread. Likewise, these files only exist when some type of wideband simulation has been completed.
5.4.2.5.2 Example

Below is an example of a .RMS file containing the RMS delay spread of each of the 19 impulse response snapshots. The average RMS delay spread for this local area simulation was 61.4 nanoseconds.

All units of time in nsec

5.4.2.6 .CDF Files
5.4.2.6.1 Overview

Cumulative distribution files, .CDF files, are ASCII files that contain information about RMS delay spreads of the impulse response data within a local area \( P_n \). The first line of a .CDF file is the carrier frequency of the simulation in MHz. The remaining lines in the file consist of two columns of data. The first column of data is the RMS delay spread in nanoseconds and the second column is the value of the CDF at that delay spread. The value of the CDF at any particular delay spread represents the probability that the RMS delay spread will be less than that particular RMS delay spread value.

5.4.2.7 .WPL & .NPL Files
5.4.2.7.1 Overview

Wideband and narrowband path loss files have the extension .WPL and .NPL, respectively. Both of these types of files are ASCII text files that contain the corresponding mean path loss exponent, \( n \), and standard deviation, \( \sigma \), of all locations that have been simulated in a single run. Additionally, these files contain the carrier
frequency, path loss reference distance, and the value of average absolute path loss at each local area in a simulation run. Wideband and narrowband scatter plots are generated from the data in .WPL and .NPL files.

5.4.2.7.2 Field Descriptions

Below is a table showing the description of the fields in .WPL and .NPL files. Notice that the abbreviations OBS and LOS stand for obstructed path and line of sight, respectively.

<table>
<thead>
<tr>
<th>Example File</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8217</td>
<td>Path loss exponent (n)</td>
<td>n/a</td>
</tr>
<tr>
<td>1.2530</td>
<td>Standard Deviation (σ)</td>
<td>dB</td>
</tr>
<tr>
<td>400.0000</td>
<td>Carrier Frequency</td>
<td>MHz</td>
</tr>
<tr>
<td>1.0000</td>
<td>Path loss reference distance</td>
<td>meters (m)</td>
</tr>
<tr>
<td>13.660</td>
<td>T-R Sep. Path loss {OBS,LOS}</td>
<td>meters (m) dB</td>
</tr>
<tr>
<td>3.8200</td>
<td>T-R Sep. Path loss {OBS,LOS}</td>
<td>meters (m) dB</td>
</tr>
</tbody>
</table>

5.4.2.8 .NSE Files

5.4.2.8.1 Overview

.NSE files are binary files that consist of the raw noise amplitude data generated from noise simulations. The impulse noise data is stored in these files using double precision. The size of the file is governed by the length of the impulse noise simulation. To determine the number of amplitude values in the file, the user must divide the simulation duration by the individual bin duration.

5.4.2.8.2 Data Manipulation / Extraction

Similar to .BIN and .PHS files, .NSE files are binary files that require further processing to convert them to ASCII text files. As previously explained, there are two methods to convert binary files to text files, in this case .NSE files to _nse.TXT files. The
first method is to use the file `readbin.exe`. The second method is to use MATLAB code. However, one line in the previously demonstrated code must be changed to use MATLAB. The following example code can be used to convert `.NSE` files to text files using MATLAB: (code also found in readbin.m)

```matlab
fileid = fopen( 'filebasename.nse' );
% PHSDATA is a variable in MATLAB
NSEDATA = fread( fileid, [1,Inf] , 'double' );
% we must close files to avoid sharing violations
fclose( fileid );
% Save the data as double precision ASCII tab delimited
save newfilename_nse.TXT   NSEDATA   -ascii  -double  -tabs
```

The difference in this code from that of section 5.4.2.1.2 is that `.NSE` files consist of one row of data that can have a variable number of columns, therefore the command `fread` uses `[1,Inf]` rather than `[64, Z]` as the dimensions of the variable `NSEDATA`.

5.4.2.9 **.HD3 Files**

5.4.2.9.1 **Overview**

`.HD3` files are ASCII files used to store important simulation parameters and results when executing noise simulations. Therefore, they only exist if an impulsive noise simulation has been run.
### 5.4.2.9.2 Field Descriptions

Below is a description of all possible fields of a .HD3 file and also included is an example file.

**Table 5.12 .HD3 File Description**

<table>
<thead>
<tr>
<th>Example File</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>4e-008</td>
<td>Bin duration</td>
<td>seconds (s)</td>
</tr>
<tr>
<td>125000</td>
<td>Number of bins</td>
<td>bins</td>
</tr>
<tr>
<td>-97.139900</td>
<td>Thermal noise level (kT_o B)</td>
<td>dB</td>
</tr>
<tr>
<td>19.000000</td>
<td>Channel noise factor F_a</td>
<td>dB&gt;kT_o B</td>
</tr>
<tr>
<td>6.000000</td>
<td>Threshold level</td>
<td>dB&gt;kT_o B</td>
</tr>
<tr>
<td>50.000000</td>
<td>Receiver bandwidth (B)</td>
<td>MHz</td>
</tr>
<tr>
<td>apd40</td>
<td>Amplitude distribution used</td>
<td>n/a</td>
</tr>
<tr>
<td>Stores and Offices</td>
<td>Location [Hospitals, Clinics or Stores, Offices]</td>
<td>n/a</td>
</tr>
<tr>
<td>40 GHz</td>
<td>Frequency Band</td>
<td>provide in file</td>
</tr>
<tr>
<td>280.000000</td>
<td>Ambient room temperature (T_o)</td>
<td>degrees Kelvin (K)</td>
</tr>
<tr>
<td>5.000000</td>
<td>Repetitive pulse width</td>
<td>#bins</td>
</tr>
<tr>
<td>100.000000</td>
<td>Repetitive pulse spacing</td>
<td>#bins</td>
</tr>
<tr>
<td>25.000000</td>
<td>Repetitive pulse amplitude</td>
<td>dB&gt;kT_o B</td>
</tr>
<tr>
<td>Empirical, Repetitive Simulation(s)</td>
<td>Type of Simulation</td>
<td>n/a</td>
</tr>
</tbody>
</table>

### 5.4.2.10 .RND, .DIS, .REP, and .DAT Files

#### 5.4.2.10.1 Overview

These four types of noise files are ASCII text files that include information about the absolute start time of impulsive noise pulses, the duration of the pulses, and the amplitude of the pulses. The extensions .REP, .RND, and .DIS are short for repetitive noise, random noise, and distribution noise, respectively. When performing noise simulations, several of these files may or may not be generated depending on certain simulation parameters. Thus, if the user performs a repetitive and random impulsive noise simulation then both a .REP and a .RND file will exist, but not a .DIS file.
The fourth type, known as .DAT files, is a combination of at least two of the three other types of files mentioned above. Therefore, if only one type of simulation is run, for example a random simulation, then only a .RND file exists. No .DAT file would exist in such a case. **NOTE:** If portions of two files overlap in time, the .DAT files represent the overlapping pulses as several pulses. Therefore, the total number of rows in a .DAT file may be slightly larger than the sum of the rows in the files it has combined.

5.4.2.10.2 Field Descriptions

All files with any of these four extensions has the same format. The files are ASCII files with three columns of data. Table 5.13 demonstrates the file format for these files.

**Table 5.13 Field Descriptions for .REP, .RND, .DIS, and .DAT Files**

<table>
<thead>
<tr>
<th>FIELDS</th>
<th>Start of a pulse</th>
<th>Pulse amplitude</th>
<th>Pulse duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNITS</td>
<td>seconds (s)</td>
<td>dB</td>
<td>seconds (s)</td>
</tr>
</tbody>
</table>

5.4.2.11 .MAT Files

5.4.2.11.1 Overview

MATLAB files (.MAT files) are used to store various information for the internal operations of SIRCIM. These files should not be altered. If they are corrupted, SIRCIM may not function properly.
Chapter 6

Conclusion

6.1 Results and Conclusions

The main focus of the work in this thesis has been to commercialize SIRCIM and SMRCIM into a world-class product and to implement the Aisle Elliptical and Random Elliptical AOA models. The development and implementation of these geometrically based single-bounce models, for simulation of Angle-of-Arrival (AOA) of multipath delay components in two revolutionary wireless channel simulation tools, SMRCIM and SIRCIM have been thoroughly explained in Chapter 4. Pseudo algorithms have been provided in Chapter 4 to provide insight for those who wish to expand upon the models. Along with the implementation of the models and the inclusion of the pseudo algorithms, examples of plotted AOA data have been provided in Appendix C.

In the process of developing and implementing these AOA models, SIRCIM and SMRCIM were also enhanced making them very user friendly and professional. The history of SIRCIM and SMRCIM has been presented in this thesis, along with the explanation of the models included in the tools, as given in Appendix A and Appendix B. Likewise, many additions were made to assist users in post processing of simulation data. The program readbin.exe was created to convert data files from binary to ASCII for use in other software packages and Microsoft® Excel™ spreadsheets were created to generate useful plots for users to research propagation. Installation packages were also created as part of the work of this thesis to assist potential users in installing the software.

These software tools, along with the implementation of the two AOA models, provide wireless system designers and hardware developers with easy access to very useful wireless channel data based on many years of research and many real-life measurement data. These programs allow licensed users of the popular mathematics software, MATLAB, to generate lifelike wideband multipath delay profiles having amplitude, phase, and angle-of-arrival information that vary both over time and space by entering in channel parameters such as transmitter to receiver separation distance, carrier frequency, path loss reference distance, distance along a track of ¼ wavelength spaced
profiles, and several other parameters discussed in Chapter 3. Additionally, users can generate narrowband continuous wave signals by synthesizing the signals over the spatial variations of the wideband multipath delay profiles, or by directly generating narrowband signals with predetermined statistical fading characteristics as discussed in Chapter 3.

6.2 Future Work

AOA information has recently become a very hot area for researchers and hardware developers, alike, due to the increased complexity of wireless systems and the heavy demand for higher quality and enhanced performance. Accordingly, SIRCIM and SMRCIM are the first channel simulators to offer AOA information along with amplitude and phase information of multipath signals. However, the AOA information provided by the programs is simulated data based on geometrical models. These models are restricted to the geometry as defined by the user entered parameters. As measurement equipment and testing apparatuses of the future are developed, these models should be enhanced to include empirical data such as the data that was used to develop the multipath delay statistical models. Currently at the Mobile and Portable Radio Research Group of Virginia Polytechnic Institute and State University, measurement equipment has been developed to, in fact, capture AOA data. This equipment consists of an unmanned apparatus that has an antenna that moves along a track while, at the same time, rotating to measure signals arriving from all angles.

As this equipment is in its early stages of development and calibration, measurement results were not available to compare to the simulation results from SMRCIM and SIRCIM. As a future effort, tests should be performed to gather both site-specific and generalized environment empirical data to form comparisons with the geometrical models as well as to discover new AOA models that may be implemented in the software. With more accurate data, system designs will be greatly enhanced in all aspects including antenna design, antenna placement, system capacity, sectoring, interference cancellation, power control, equalization, channel coding, and many others.
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Appendix A

Synthesis of Narrowband Signals

A.1 Synthesis of Phase for Wideband Multipath Components

The synthesis of the phase of each individual multipath component, which incorporates the Doppler shift of each component, allows the computation of narrowband (CW) signal strength and carrier phase. This section describes the method used for synthesizing the phases of individual multipath components. A single-hop path is assumed between the transmitter and receiver, so the locations of possible scatterers that induce a particular excess delay at the receiver form an ellipse with the transmitter and receiver at the foci. If we assume a particular multipath component is located randomly on the ellipse, the change in path length from the scatterer to the specific mobile location is calculated as the mobile moves over very small distances. Based on these changes in radio path length, the phase change of each multipath component may be modeled in a deterministic fashion as the mobile travels incrementally (on the order of millimeters) over a local area. The geometry is shown in Figure A.1 for a particular scatterer location and motion in an arbitrary direction.

Figure A.1 Ellipse of Possible Scatterer Locations Which Induce a Constant Excess Delay

The following discussion describes Figures A.1 and A.2, which show the assumed geometry. All lengths are in meters and all angles are in radians. The transmitter is
located at point T and the receiver at point R. After the receiver moves, its location will be R’.

The angle $\alpha$, which represents the direction of motion, is read in from .HD1 files generated in wideband simulations. $S$ is the location of the scatterer. The location of $S$ is calculated after reading in the angle-of-arrival generated in wideband simulations. The radio path length, $q$, is the distance from the scatterer to the initial receiver location, and $q'$ is the radio path length from the scatterer to the new receiver location. The distance $(c-x)$ represents the distance between the intersection of the chord from the scatterer to T-R (which intersects at a right angle) and the initial receiver location R. The angles $\alpha$ and $\beta$ are variables used to calculate the change in phase as the receiver moves a distance $y$ from R to R’. Note that the distance $y$ is exaggerated for ease of drawing.

![Diagram](image)

**Figure A.2** Geometry Used in Synthesizing Phase Changes of Individual Multipath Components as a Mobile Moves Over Very Small Distances

The “excess distance” traveled by the signal is determined at each excess delay within a profile with respect to the line of sight distance between the transmitter and receiver. Therefore, each excess delay bin has an associated ellipse which represents the locus of all possible locations of scatterers which can induce the excess propagation delay required for that particular bin.
The length of the major axis of the ellipse is defined to be the T-R separation plus
the excess distance:

\[
\text{excess delay} = (\text{bin#} - 0.5) \times \frac{625 \times 10^{-9}}{\text{bin width in seconds}}
\]
\[
\text{excess distance} = \text{excess delay} \times C \quad (C = 3 \times 10^8 \text{ m/s})
\]
\[
\text{length of ellipse} = (2a) = T - R \text{ sep.} + \text{excess distance}
\]

As the receiver goes in motion, the direction of motion with respect to the
transmitter is given by the angle \(\alpha\). We can see from Figure A.2 that the following
equations hold:

\[
(\Delta w)^2 + (c - x)^2 = (a - ex)^2 = q^2
\]
\[
x = \pm \sqrt{\frac{a^2 - c^2 - (\Delta w)^2}{1 - e^2}}
\]

where \(e = \text{eccentricity} = c/a\) \((c = T - R \text{ sep.} / 2)\)

\[
\Rightarrow \quad \beta = \tan^{-1}\left(\frac{\Delta w}{c - x}\right)
\]

The distance the transmitted signal travels between the scatterer and the receiver
in its initial location is:

\[
q = \sqrt{(\Delta w)^2 + (c - x)^2} = (a - ex).
\]

When the receiver moves, it moves a distance \(y\), and the angle between the
direction of motion and the direction of arrival of the wave (at the initial receiver
location) is given by \(\phi = 2\pi - \alpha - \beta\).

Then, the distance the transmitted signal travels between the scatterer and the
receiver at its new location \((R')\) is given by:

\[
q' = \sqrt{q^2 + y^2 - 2qy\cos\phi} \quad \text{(law of cosines)}
\]

The angle \(\theta_4 = \tan^{-1}\left(\frac{\Delta w + y\sin\alpha}{c - x - y\cos\alpha}\right)\) is the angle between the direction of
arrival of the “scattered” signal at the new receiver location, and a line drawn from the
point of the new receiver location perpendicular to the line from the scatterer to the line of sight between the transmitter and the original receiver location. The angle $\theta_s = \alpha + \theta_d$ is the angle between the direction of motion and the direction of arrival of the scattered signal at the new receiver location.

The phases in each bin of the first profile (at a fixed spatial position at the beginning of the 4.5, 10, 20, 40, or 80$\lambda$ track) are randomly generated (independent, identically distributed over $[0, 2\pi]$). The phases of multipath components (when they exist) in corresponding bins of subsequent profiles may be calculated deterministically from the phase of the multipath component in the initial profile. It is well known that received frequency is different from transmitted frequency if the receiver is in motion. This frequency difference is due to a combination of the change in path length between two positions of the receiver and the motion of the receiver (which leads to the Doppler shift). The received frequency may be expressed as $\omega' = \omega + k \cdot v$, where $\omega$ is the transmitted frequency (in radians/second), $k$ is the wave vector, $v$ is the velocity vector (velocity in the direction of motion), and $k \cdot v$ is the dot product, defined to be $k \cdot v \cdot \cos \theta$ ($\theta$ is the angle between $k$ and $v$). It is also known that

$$f \cdot \lambda = c \Rightarrow \frac{\omega \cdot \lambda}{2\pi} = c \Rightarrow c \cdot \frac{2\pi}{\lambda} = \omega = c \cdot k$$

$$k = \frac{d\phi}{dL}$$

where $\phi$ is the phase of the received signal. This leads to the following:

$$ck' = \omega + \frac{2\pi v}{\lambda} \cos \theta$$

$$c \frac{\Delta \phi}{\Delta L} = \omega + \frac{2\pi v}{\lambda} \cos \theta = 2\pi f' + 2\pi f_d$$

where $f_d = \frac{v}{\lambda} \cos \theta$

Finally, this gives the expression for the change in phase between the component in the first profile and the component in subsequent profiles:
\[ \Delta \phi = \frac{2\pi(f + f_d)\Delta L}{c}. \]

In this expression, \( \Delta L \) is the path length difference between \( q \) and \( q' \), \( f_d \) is the Doppler frequency, and \( c \) is the speed of light (3x10^8 m/s). These equations apply for a single multipath component for a receiver moving a very short distance (for example, \( \lambda/100 \) if there are 25 interpolated profiles between each pair \( \lambda/4 \) separated simulated profiles). This procedure is repeated for each multipath component at each excess delay for each small mobile movement.

**A.2 Synthesis of Narrowband Signals without Wideband Information**

For moving terminals, small scale fading of the narrowband signal about the median value is generated as the sum of the squares of two independent Gaussian noise sources which are passed through a low-pass filter that has the RF Doppler spectrum for Rayleigh fading. This LPF, shown in Figure A.3, has a cutoff at the maximum Doppler frequency as determined from the specified velocity:

\[ f_{\text{max}} = \frac{v}{\lambda}. \]

Over many different simulation runs, this recreates a Rayleigh fading channel. Although the fading along a particular track may sometimes not be described by the Rayleigh distribution, the cumulative distribution of fading along several tracks is closely described by the Rayleigh distribution. The small scale signal is generated such that its median signal level is zero dB. By adding the path loss generated by the log-normal distribution with mean described by Equation A.1 and standard deviation \( \sigma \) in dB, the exact narrowband signal level along a 4.5, 10, 20, 40, or 80\( \lambda \) track is found.
Figure A-3  Low Pass Doppler Spectrum for Generating Small Scale CW Signal Strength Along a 4.5° Track Without Knowledge of Wideband Impulse Response

\[
\overline{PL}(d) = \overline{PL}(d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) \quad \text{Eq. A.1}
\]

\[
\overline{PL}(d_0) = 20\log_{10} \left(\frac{4\pi d_0}{\lambda}\right) - G_T - G_R \quad \text{Eq. A.2}
\]
Appendix B
Wideband Channel Models

B.1 SMRCIM MODELS

B.1.1 Urban Areas

Probability of a multipath component appearing at an excess delay in the first profile:

\[
Pr(M_K(T_K)) = \begin{cases} 
  e^{\left(-\frac{(1.6T_s - 1.0)}{10.1}\right)} & 0 \mu s \leq T_K \leq 5.625 \mu s \\
  0.55e^{\left(-\frac{1.6T_s}{24.2}\right)} & 5.625 \mu s \leq T_K < 20 \mu s \\
  0.137 & 20 \mu s \leq T_K < 25.625 \mu s \\
  0.071 & 25.625 \mu s \leq T_K < 40 \mu s
\end{cases}
\]

If there is a multipath component in the previous time bin, \( P_r = 2.5 \times Pr(M_K(T_K)) \). If \( P_r > 1 \), it is set to 1.

Probability of a multipath component appearing at a later profile:

1. If there is a multipath component in the previous profile, then \( P_r = 0.99 \).
2. If there is not a multipath component in the previous profile, then \( P_r = 0.01 \).
The mean path loss exponent of a multipath component at an excess delay:

\[ n(T_k) = \begin{cases} 3.1 & T_k < 0.625 \mu s \\ 3.3 & 0.625 \mu s \leq T_k < 1.25 \mu s \\ 3.4 & 1.25 \mu s \leq T_k < 1.875 \mu s \\ 3.5 & 1.875 \mu s \leq T_k < 2.5 \mu s \\ 3.9 + \frac{1.6T_k - 1}{36} & 2.5 \mu s \leq T_k < 11.875 \mu s \\ 4.3 + \frac{1.6T_k - 18}{185} & 11.875 \mu s \leq T_k < 40 \mu s \end{cases} \]

Large scale fading is log-normally distributed with

\[ \sigma_{\text{large-scale}}(T_K) = 10 dB. \]

The small scale fast fading standard deviation is given as:

\[ \sigma_{\text{small-scale}}(T_K, S_2) = \sqrt{2}. \]

**B.1.2 Suburban Areas**

Probability of a multipath component appearing at an excess delay in the first profile:

\[
\begin{align*}
\Pr(M_K(T_K)) &= 1 - \frac{T_K}{35.7} & 0 \mu s \leq T_K \leq 2.5 \mu s \\
0.93 - \frac{0.4(T_K - 2.5)}{1.5} & 2.5 \mu s \leq T_K \leq 4 \mu s \\
0.55 - 0.3(T_K - 4) & 4 \mu s \leq T_K \leq 4.5 \mu s \\
0.67 - 0.8(T_K - 4.5) & 4.5 \mu s \leq T_K \leq 5 \mu s \\
0.02 + 3.655 e^{-0.536 T_K} & 5 \mu s \leq T_K \leq 10 \mu s \\
0.01 & 10 \mu s \leq T_K \leq 40 \mu s 
\end{align*}
\]
If there is a multipath component in the previous time bin,
\[ P_r = 2.5 \times \Pr(M_k(T_k)). \] If \( P_r > 1 \), it is set to 1.

Probability of a multipath component appearing at a later profile:

1. If there is a multipath component in the previous profile, then \( P_r = 0.99 \).

2. If there is not a multipath component in the previous profile, then \( P_r = 0.01 \).

The mean path loss exponent of a multipath component at an excess delay:

\[
\begin{align*}
n(T_k) &= 3.1 & T_k < 0.625\mu s \\
&= 3.3 & 0.625\mu s \leq T_k < 1.25\mu s \\
&= 3.5 + \frac{1.6T_k - 1}{4} & 1.25\mu s \leq T_k < 2.5\mu s \\
&= 4.1 + \frac{1.6T_k - 1}{180} & 2.5\mu s \leq T_k < 11.25\mu s \\
&= 4.1 + \frac{1.6T_k - 1}{185} & 11.25\mu s \leq T_k < 20.625\mu s \\
&= 5.0 & 20.625\mu s \leq T_k < 40\mu s
\end{align*}
\]

Large scale fading is log-normally distributed with
\[ \sigma_{\text{large-scale}}(T_k) = 12dB. \]

The small scale fast fading standard deviation is given as:
\[ \sigma_{\text{small-scale}}(T_k, S) = \sqrt{2}. \]
B.1.3 Microcellular Areas

Probability of a multipath component appearing at an excess delay in the first profile:

\[ \Pr(M_k(T_K)) = \begin{cases} \frac{15-16T_K}{15} & 0 \mu s \leq T_K \leq 0.9 \mu s \\ \frac{50-16T_K}{300} & 0.9 \mu s \leq T_K \leq 1.8 \mu s \\ 0.002 & 1.8 \mu s \leq T_K \leq 4.0 \mu s \end{cases} \]

If there is a multipath component in the previous time bin, \( P_r = 2.5 \times \Pr(M_k(T_K)) \). If \( P_r > 1 \), it is set to 1.

Probability of a multipath component appearing at a later profile:
1. If there is a multipath component in the previous profile, then \( P_r = 0.99 \).
2. If there is not a multipath component in the previous profile, then \( P_r = 0.01 \).

The mean path loss exponent of a multipath component at an excess delay:

\[ n(T_k) = \begin{cases} 2.6 & T_k < 0.0625 \mu s \\ 2.8 + \frac{16T_k - 2}{4} & 0.0625 \mu s \leq T_k < 0.25 \mu s \\ 3.3 + \frac{16T_k - 1}{18} & 0.25 \mu s \leq T_k < 1.375 \mu s \\ 4.5 + \frac{16T_k - 1}{85} & 1.375 \mu s \leq T_k < 4.0 \mu s \end{cases} \]
Large scale fading is log-normally distributed with

\[ \sigma_{\text{large-scale}}(T_K) = 10 \, dB \, . \]

The small scale fast fading standard deviation is given as:

\[ \sigma_{\text{small-scale}}(T_K, S_2) = \sqrt{2} \, . \]

**B.2 SIRCIM Models**

The terminology for the models presented in this section is identical to that in [18].

**B.2.1 Open Plan Buildings**

\[ \overline{N}_p(S_1, P_n) = \text{Uniform}[9,36] \]

\[ \overline{N}_p(S_2, P_n) = \text{Uniform}[11,37] \]

\[ \sigma_p(S_1, P_n) = 0.492 \times (\overline{N}_p(S_1, P_n) - 4.77) \]

\[ \sigma_p(S_2, P_n) = 0.383 \times (\overline{N}_p(S_2, P_n) - 0.89) \]

\[ \Pr(M_K(T_K, S_1)) = \]

\[ 1 - \frac{T_K}{367} \quad 0ns \leq T_K \leq 110ns \]

\[ 0.65 - \frac{(T_K - 110)}{360} \quad 110ns \leq T_K \leq 200ns \]

\[ 0.22 - \frac{(T_K - 200)}{2142} \quad 200ns \leq T_K \leq 500ns \]

\[ \Pr(M_K(T_K, S_2)) = \]

\[ 0.7 + \frac{T_K}{1000} \quad 0ns \leq T_K \leq 100ns \]

\[ 0.08 + 0.72e^{\frac{(T_K-100)}{75}} \quad 100ns \leq T_K \leq 500ns \]
\[ n(T_k, S_1) = \begin{cases} 
2.5 + \frac{T_k}{39} & T_k \leq 15\text{ns} \\
3.0 + \frac{(T_k - 15.6)}{380} & 15\text{ns} \leq T_k \leq 250\text{ns} \\
3.6 & 250\text{ns} \leq T_k \leq 500\text{ns} 
\end{cases} \]

\[ n(T_k, S_2) = \begin{cases} 
4.55 + \frac{T_k}{536} & T_k \leq 310\text{ns} \\
5.13 & 310\text{ns} \leq T_k \leq 500\text{ns} 
\end{cases} \]

\[ \sigma_{\text{large-scale}}(T_k, S_1) = 4.0\text{dB} \]

\[ \sigma_{\text{large-scale}}(T_k, S_2) = 5.0\text{dB} \]

Ref. Dist. \( \leq D_n \leq 65\text{m} \) for \( S_1 \)

Ref. Dist. \( \leq D_n \leq 50\text{m} \) for \( S_2 \)

### B.2.2 Hard Partitioned Buildings

\[ \overline{N}_p(S_1, P_n) = \text{Uniform}[3,14] \]

\[ \overline{N}_p(S_2, P_n) = \text{Uniform}[2,8] \]

\[ \sigma_p(S_m, P_n) = 0.4 \times \overline{N}_p(S_m, P_n) \]
\[ \Pr(M_K(T_K, S_1)) = \\
\begin{align*}
0.95 - \frac{T_K}{285} & \quad 0ns \leq T_K \leq 100ns \\
0.6e^{-\frac{(T_K-100)}{65}} & \quad 100ns \leq T_K \leq 500ns
\end{align*} \]

\[ \Pr(M_K(T_K, S_2)) = \\
\begin{align*}
0.7 + \frac{T_K}{1000} & \quad 0ns \leq T_K \leq 100ns \\
0.8e^{-\frac{(T_K-100)}{65}} & \quad 100ns \leq T_K \leq 500ns
\end{align*} \]

\[ n(T_K, S_1) = \\
\begin{align*}
3.25 + \frac{T_K}{94} & \quad T_K \leq 200ns \\
5.25 & \quad 200ns \leq T_K \leq 500ns
\end{align*} \]

\[ n(T_K, S_2) = \\
\begin{align*}
4.7 + \frac{T_K}{300} & \quad T_K \leq 300ns \\
5.7 & \quad 300ns \leq T_K \leq 500ns
\end{align*} \]

\[ \sigma_{\text{large-scale}}(T_K, S_m) = 4.0 + 4.0e^{\frac{T_K}{39}} dB \]

Ref. Dist. \[ D_n \leq 40m \] for \( S_m \)

Small scale spatial and temporal correlation coefficients = 0.0
B.2.3 Soft Partitioned Buildings

\[
\overline{N_p}(S_1, P_n) = \text{Uniform}[2, 10]
\]

\[
\overline{N_p}(S_2, P_n) = \text{Uniform}[2, 10]
\]

\[
\sigma_p(S_m, P_n) = 0.4 \times \overline{N_p}(S_m, P_n)
\]

\[
\Pr(M_K(T_K, S_1)) =
\begin{align*}
0.95 - & \frac{T_K}{222} & 0 ns \leq T_K \leq 100 ns \\
0.5e^{-\frac{(T_K-100)}{30}} & 100 ns \leq T_K \leq 500 ns
\end{align*}
\]

\[
\Pr(M_K(T_K, S_2)) =
\begin{align*}
0.7 + & \frac{T_K}{1000} & 0 ns \leq T_K \leq 100 ns \\
0.8e^{-\frac{(T_K-100)}{50}} & 100 ns \leq T_K \leq 500 ns
\end{align*}
\]

\[
n(T_K, S_1) =
\begin{align*}
3.6 + & \frac{T_K}{220} & T_K \leq 250 ns \\
4.7 & 250 ns \leq T_K \leq 500 ns
\end{align*}
\]

\[
n(T_K, S_2) =
\begin{align*}
4.8 + & \frac{T_K}{484} & T_K \leq 250 ns \\
5.3 & 250 ns \leq T_K \leq 500 ns
\end{align*}
\]

\[
\sigma_{\text{large-scale}}(T_K, S_m) = 4.0 + 4.0e^{\frac{T_K}{39}} dB
\]

Ref. Dist. \( \leq D_n \leq 30m \) for \( S_m \)

Small scale spatial and temporal correlation coefficients = 0.0
B.3 Angle-of-Arrival Models

There are two user selectable AOA models in SMRCIM and SIRCIM that can generate AOA data between 0 and $\pm \pi$ radians. These models are the *Aisle Elliptical* model and the *Random Elliptical* model. For reference purposes, the AOA is measured at the receiver by starting with the vector from the transmitter to the receiver and rotating towards the vector from the scatterer to the receiver. For positive AOA, the rotation will be in a clockwise direction, while rotating in a counter clockwise direction yields negative AOA.

![Geometry Used in Synthesizing AOA](image)

**Figure B.1** Geometry Used in Synthesizing AOA

B.3.1 Aisle Elliptical Model

In the Aisle Elliptical Model, the following technique is used to determine the AOA for each multipath component in bin $\tau_i$:

1. Randomly choose one of four intersecting points of the chords separated by the user selected street width ($\Delta w$) for each of 64 time bins $\tau_i$.
2. Using the geometry shown in Figure B.1 and Figure B.2, it can be shown that the AOA is calculated from the following equations:
Cases 1 & 2:

- $x$ positive for case 1
- $x$ negative for case 2

\[
\theta_4 = \tan^{-1}\left( \frac{\Delta w + y \sin \alpha}{c - x - y \cos \alpha} \right)
\]

\[
AOA = \theta_4 - \sin^{-1}\left( \frac{y \sin \alpha}{\sqrt{(2c - y \cos \alpha)^2 + (y \sin \alpha)^2}} \right)
\]

Cases 3 & 4:

- $x$ positive for case 3
- $x$ negative for case 4

\[
\theta_4 = \tan^{-1}\left( \frac{\Delta w - y \sin \alpha}{c - x - y \cos \alpha} \right)
\]

\[
AOA = \sin^{-1}\left( \frac{y \sin \alpha}{\sqrt{(2c - y \cos \alpha)^2 + (y \sin \alpha)^2}} \right) - \theta_4
\]
B.3.2 Random Elliptical Model

1. Choose a random angle, Ω, distributed uniformly on \([0,2\pi]\), for each of 64 time bins \(\tau_i\) as shown in Figure B.3.

2. Using the following information and the geometry in Figure B.1, solve for the \((x,y)\) coordinates of the location of the scatterer for each of the 64 time bins.

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad x = r \cdot \cos\Omega \quad y = r \cdot \sin\Omega
\]

3. Forming vectors from both the receiver to the scatterer (\(RS\)) and from the receiver to the transmitter (\(RT\)), it can be shown that the AOA is calculated with the following equation:

\[
AOA = \pm \cos^{-1}\left(\frac{\langle RS, RT \rangle}{\|RS\| \|RT\|}\right)
\]

4. Perform tests to determine if the AOA is positive or negative based on the slopes of the vectors and the angle Ω.
Appendix C

Sample Output Plots

Figure C.1  SIRCIM – Hard Partition Model – 4.5\(\lambda\) track – Obstructed – 1900MHz – 21.3m T-R separation – Wideband Impulse Response

Figure C.2  SIRCIM – Hard Partition Model – 4.5\(\lambda\) track – Line-Of-Sight – 1900MHz – 15m T-R separation – Wideband Impulse Response
Figure C.3  SIRCIM – Hard Partition Model – 4.5$\lambda$, track – Obstructed – 1900MHz – 21.3m T-R separation – Polar Path Loss vs. AOA

Figure C.4  SIRCIM – Hard Partition Model – 4.5$\lambda$, track – Line-Of-Sight – 1900MHz – 15m T-R separation – Polar Path Loss vs. AOA
Figure C.5  SIRCIM – Hard Partition Model – 4.5λ, track – Obstructed – 1900MHz – 21.3m T-R separation – AOA vs. Delay

Figure C.6  SIRCIM – Hard Partition Model – 4.5λ, track – Line-Of-Sight – 1900MHz – 15m T-R separation – AOA vs. Delay
Figure C.7 SIRCIM – Hard Partition Model – 4.5λ, track – Obstructed – 1900MHz – 21.3m T-R separation – CDF of RMS Delay Spread

Figure C.8 SIRCIM – Hard Partition Model – 4.5λ, track – Line-Of-Sight – 1900MHz – 15m T-R separation – CDF of RMS Delay Spread
Figure C.9  SIRCIM – Hard Partition Model – 4.5λ, track – Obstructed – 1900MHz – 21.3m T-R separation – CW Amplitude and Phase

Figure C.10  SIRCIM – Hard Partition Model – 4.5λ, track – Line-Of-Sight – 1900MHz – 15m T-R separation – CW Amplitude and Phase
Figure C.11 SIRCIM – Hard Partition Model – 4.5$\lambda$ track – 1900 MHz – 10 locations – CDF of CW Amplitude

Figure C.12 SIRCIM – Hard Partition Model – 4.5$\lambda$ track – Obstructed – 1900MHz – 21.3m T-R separation – Mixed Plots
Figure C.13  SIRCIM – Hard Partition Model – 4.5λ track – Obstructed – 1900MHz
15m T-R separation – Mixed Plots

Figure C.14  SIRCIM – Open Plan Model – 4.5λ track – Line-Of-Sight – 900MHz –
30.9m T-R separation – Wideband Impulse Response
Figure C.15  SIRCIM – Open Plan Model – 4.5μ track – Obstructed – 900MHz – 42m T-R separation – Wideband Impulse Response

Figure C.16  SIRCIM – Open Plan Model – 4.5μ track – Line-Of-Sight – 900MHz – 30.9m T-R separation – Polar Path Loss vs. AOA
Figure C.17  SIRCIM – Open Plan Model – 4.5λ track – Obstructed – 900MHz – 42m T-R separation – Polar Path Loss vs. AOA

Figure C.18  SIRCIM – Open Plan Model – 4.5λ track – Line-Of-Sight – 900MHz – 30.9m T-R separation – AOA vs. Delay
Figure C.19  SIRCIM – Open Plan Model – 4.5λ, track – Obstructed – 900MHz – 42m T-R separation – AOA vs. Delay

Figure C.20  SIRCIM – Open Plan Model – 4.5λ, track – Line-Of-Sight – 900MHz – 30.9m T-R separation – CDF of RMS Delay Spread
Figure C.21  SIRCIM – Open Plan Model – 4.5\textdegree, track – Obstructed – 900MHz – 42m T-R separation – CDF of RMS Delay Spread

Figure C.22  SIRCIM – Open Plan Model – 4.5\textdegree, track – Line-Of-Sight – 900MHz – 30.9m T-R separation – CW Amplitude and Phase
Figure C.23  SIRCIM – Open Plan Model – 4.5λ track – Obstructed – 900MHz – 42m T-R separation – CW Amplitude and Phase

Figure C.24  SIRCIM – Open Plan Model – 4.5λ track – 900 MHz – 10 locations – CDF of CW Amplitude

Appendix C  Sample Output Plots
Figure C.25  SIRCIM – Open Plan Model – 4.5\textlambda, track – 900 MHz – 10 locations – Wideband Scatter Plot

Figure C.26  SIRCIM – Open Plan Model – 4.5\textlambda, track – 900 MHz – 10 locations – Narrowband Scatter Plot
Figure C.27  SIRCIM – Soft Partitioned Model – 4.5λ track – Line-Of-Sight – 2100MHz – 21.2m T-R separation – Wideband Impulse Response

Figure C.28  SIRCIM – Soft Partitioned Model – 4.5λ track – Obstructed – 2100MHz – 27.6m T-R separation – Wideband Impulse Response
Figure C.29  SIRCIM – Soft Partitioned Model – 4.5λ track – Line-Of-Sight – 2100MHz – 21.2m T-R separation – Polar Path Loss vs. AOA

Figure C.30  SIRCIM – Soft Partitioned Model – 4.5λ track – Obstructed – 2100MHz – 27.6m T-R separation – Polar Path Loss vs. AOA
Figure C.31  SIRCIM – Soft Partitioned Model – 4.5λ track – Line-Of-Sight – 2100MHz – 21.2m T-R separation – AOA vs. Delay

Figure C.32  SIRCIM – Soft Partitioned Model – 4.5λ track – Obstructed – 2100MHz – 27.6m T-R separation – AOA vs. Delay
Figure C.33  SIRCIM – Soft Partitioned Model – 4.5λ track – Line-Of-Sight – 2100MHz – 21.2m T-R separation – CDF of RMS Delay Spread

Figure C.34  SIRCIM – Soft Partitioned Model – 4.5λ track – Obstructed – 2100MHz – 27.6m T-R separation – CDF of RMS Delay Spread
Figure C.35  SIRCIM – Soft Partitioned Model – 4.5λ track – Line-Of-Sight – 2100MHz – 21.2m T-R separation – CW Amplitude and Phase

Figure C.36  SIRCIM – Soft Partitioned Model – 4.5λ track – Obstructed – 2100MHz – 27.6m T-R separation – CW Amplitude and Phase
Figure C.37 SIRCIM – Soft Partitioned Model – 4.5λ, track – 2100MHz – 10 locations – CDF of CW Amplitude

Figure C.38 SIRCIM – Soft Partitioned Model – 4.5λ, track – 2100MHz – 10 locations – Wideband Scatter Plot
Figure C.39  SIRCIM – Soft Partitioned Model – 4.5λ, track – 2100MHz – 10 locations – Narrowband Scatter Plot

Figure C.40  SIRCIM – Hard Partitioned Model – 80λ, track – Line-Of-Sight – 5500MHz – 27.9ns Delay – Wideband Impulse Response
Figure C.41 SIRCIM – Hard Partitioned Model – 80\(\lambda\), track – Obstructed – 5500MHz – 38.4ns Delay – Wideband Impulse Response

Figure C.42 SIRCIM – Hard Partitioned Model – 80\(\lambda\), track – Line-Of-Sight – 5500MHz – 27.9ns Delay – Polar Path Loss vs. AOA
Figure C.43  SIRCIM – Hard Partitioned Model – 80°, track – Obstructed – 5500MHz – 38.4ns Delay – Polar Path Loss vs. AOA

Figure C.44  SIRCIM – Hard Partitioned Model – 80°, track – Line-Of-Sight – 5500MHz – 27.9ns Delay – AOA vs. Delay
Figure C.45  SIRCIM – Hard Partitioned Model – 80\(\lambda\) track – Obstructed – 5500MHz – 38.4ns Delay – AOA vs. Delay

Figure C.46  SIRCIM – Hard Partitioned Model – 80\(\lambda\) track – Line-Of-Sight – 5500MHz – 27.9ns Delay – CDF of RMS Delay Spread
Figure C.47  SIRCIM – Hard Partitioned Model – 80\(\lambda\), track – Obstructed – 5500MHz – 38.4ns Delay – CDF of RMS Delay Spread

Figure C.48  SIRCIM – Hard Partitioned Model – 80\(\lambda\), track – Line-Of-Sight – 5500MHz – 27.9ns Delay – CW Amplitude and Phase
Figure C.49  SIRCIM – Hard Partitioned Model – 802 track – Obstructed – 5500MHz – 38.4ns Delay – CW Amplitude and Phase

Figure C.50  SIRCIM – Hard Partitioned Model – 4.51 track – 5500MHz – 10 locations – CDF of CW Amplitude
Figure C.51  SIRCIM – Hard Partitioned Model – 4.5\textdegree, track – 5500MHz – 10 locations – Wideband Scatter Plot

Figure C.52  SIRCIM – Hard Partitioned Model – 4.5\textdegree, track – 5500MHz – 10 locations – Narrowband Scatter Plot
Figure C.53  SIRCIM – Open Plan Model – 80λ track – Line-Of-Sight – 2400MHz – 40.7m T-R separation – Wideband Impulse Response

Figure C.54  SIRCIM – Open Plan Model – 80λ track – Obstructed – 2400MHz – 45.4m T-R separation – Wideband Impulse Response
Figure C.55  SIRCIM – Open Plan Model – 80λ, track – Line-Of-Sight – 2400MHz – 40.7m T-R separation – Polar Path Loss vs. AOA

Figure C.56  SIRCIM – Open Plan Model – 80λ, track – Obstructed – 2400MHz – 45.4m T-R separation – Polar Path Loss vs. AOA
Figure C.57 SIRCIM – Open Plan Model – 80\(\lambda\) track – Line-Of-Sight – 2400MHz – 40.7m T-R separation – AOA vs. Delay

Figure C.58 SIRCIM – Open Plan Model – 80\(\lambda\) track – Obstructed – 2400MHz – 45.4m T-R separation – AOA vs. Delay
Figure C.59  SIRCIM – Open Plan Model – 80°, track – Line-Of-Sight – 2400MHz – 40.7m T-R separation – CDF of RMS Delay Spread

Figure C.60  SIRCIM – Open Plan Model – 80°, track – Obstructed – 2400MHz – 45.4m T-R separation – CDF of RMS Delay Spread
Figure C.61 SIRCIM – Open Plan Model – 80\(\lambda\) track – Line-Of-Sight – 2400MHz – 40.7m T-R separation – CW Amplitude and Phase

Figure C.62 SIRCIM – Open Plan Model – 80\(\lambda\) track – Obstructed – 2400MHz – 45.4m T-R separation – CW Amplitude and Phase
Figure C.63  SIRCIM – Open Plan Model – 80\(\lambda\) track – 2400MHz – 10 locations – CDF of CW Amplitude

Figure C.64  SIRCIM – Open Plan Model – 80\(\lambda\) track – 2400MHz – 10 locations – Wideband Scatter Plot
Figure C.65  SIRCIM – Open Plan Model – 80λ, track – 2400MHz – 10 locations – Narrowband Scatter Plot

Figure C.66  SIRCIM – Soft Partitioned Model – 80λ, track – Line-Of-Sight – 25GHz – 16.7m T-R separation – Wideband Impulse Response
Figure C.67  SIRCIM – Soft Partitioned Model – 80\(\lambda\) track – Line-Of-Sight – 25GHz – 16.7m T-R separation – Polar Path Loss vs. AOA

Figure C.68  SIRCIM – Soft Partitioned Model – 80\(\lambda\) track – Line-Of-Sight – 25GHz – 16.7m T-R separation – AOA vs. Delay
Figure C.69 SIRCIM – Soft Partitioned Model – 80\(\lambda\), track – Line-Of-Sight – 25GHz – 16.7m T-R separation – CDF of RMS Delay Spread

Figure C.70 SIRCIM – Soft Partitioned Model – 80\(\lambda\), track – Line-Of-Sight – 25GHz – 16.7m T-R separation – CW Amplitude and Phase
Figure C.71  SIRCIM – Soft Partitioned Model – 80$\lambda$, track – 25GHz – 10 locations – Wideband Scatter Plot

Figure C.72  SIRCIM – Soft Partitioned Model – 80$\lambda$, track – 25GHz – 10 locations – Narrowband Scatter Plot
Figure C.73  SMRCIM – Microcellular Model – 10λ track – 1900MHz – 626m T-R separation – Wideband Impulse Response

Figure C.74  SMRCIM – Microcellular Model – 10λ track – 1900MHz – 774m T-R separation – Wideband Impulse Response
Figure C.75  SMRCIM – Microcellular Model – 10λ, track – 1900MHz – 626m T-R separation – Polar Path Loss vs. AOA

Figure C.76  SMRCIM – Microcellular Model – 10λ, track – 1900MHz – 774m T-R separation – Polar Path Loss vs. AOA
Figure C.77  SMRCIM – Microcellular Model – 10λ, track – 1900MHz – 626m T-R separation — AOA vs. Delay

Figure C.78  SMRCIM – Microcellular Model – 10λ, track – 1900MHz – 774m T-R separation — AOA vs. Delay
Figure C.79 SMRCIM – Microcellular Model – 10\(\lambda\) track – 1900MHz – 626m T-R separation – CDF of RMS Delay Spread

Figure C.80 SMRCIM – Microcellular Model – 10\(\lambda\) track – 1900MHz – 774m T-R separation – CDF of RMS Delay Spread
Figure C.81 SMRCIM – Microcellular Model – 10\(\lambda\) track – 1900MHz – 626m T-R separation – CW Amplitude and Phase

Figure C.82 SMRCIM – Microcellular Model – 10\(\lambda\) track – 1900MHz – 774m T-R separation – CW Amplitude and Phase
Figure C.83  SMRCIM – Microcellular Model – 10\( \lambda \), track – 1900MHz – 10 locations – CDF of CW Amplitude

Figure C.84  SMRCIM – Microcellular Model – 10\( \lambda \), track – 1900MHz – 10 locations – Wideband Scatter Plot
Figure C.85  SMRCIM – Microcellular Model – 10λ, track – 1900MHz – 10 locations – Narrowband Scatter Plot