Chapter 3

System Hardware and Calibration

High data rate wireless communication systems require wideband propagation measurements to facilitate collection of channel statistics and development of appropriate channel models. The sliding correlator measurement technique, also referred to as swept time-delay cross-correlation (STDCC) method [Par89], has been widely used for channel sounding. This chapter introduces a similar wideband direct-sequence spread spectrum (DSS) channel sounding system that is extensively used in all measurement campaigns presented in this dissertation. The chapter also describes the operation of the channel sounder hardware and briefly discusses the significance of various test equipment. Relevant details of the transmitting and receiving antennas (operating at 38GHz and 60GHz) used in the measurement campaigns are also included.

Back-to-back and free-space (FS) calibration measurements are described and their relevance to measurement campaigns is explained. Equipment setup for calibration measurement, sequence of calibration measurements, sample calibration data, derivation of calibration constants and end-to-end link budget analysis for calculating Path Loss statistics are also presented.

3.1 The Channel Measurement System

The channel sounder hardware, used in this research, is required for measuring Power Delay Profile (PDP) snapshots to facilitate characterization of the wireless channel. Researchers at the Mobile and Portable Radio Research Group (MPRG) have developed a spread spectrum sliding correlator channel sounder (SCS) capable of operating in a wide band of frequencies (Cellular, PCS and LMDS) [Chr00]. The equipment has been an integral part of numerous measurement campaigns including the one described in this dissertation ([New96_1],[Xu99],[Xu00], [Gre01]).

Recently, Dr. Durgin modified the MPRG channel sounder to facilitate fully automatic computer-controlled operation that provides a high degree of error-free operation and enhances the scientific value of measured propagation statistics [Gre99]. Chris Anderson has also designed and developed 11-bit and 18-bit 400MHz PN sequence generators for operation with the channel sounder. This has increased the RF bandwidth of the system from 200MHz to 800MHz thereby imparting a greater temporal multipath resolution capability of 2.5ns to the system. This corresponds to a spatial multipath resolution capability of about one meter. However, the 38GHz and 60GHz front-end transmitter and receiver units, used with the channel sounder during the measurement campaigns, limit the maximum RF bandwidth to 200MHz.

3.1.1 System Hardware at 38 and 60 GHz

The block diagrams of the transmitter and receiver sections of the SCS channel sounding system configured for operation at 38GHz are shown in Figure 3.1. The Rubidium Oscillators in the transmitter and the receiver subsystems produce 10MHz reference clock signals that are fed to the HP83630A synthesized sweeper and HP8648C signal generator, respectively. In either of the two configurations (operation at 38GHz or 60GHz), the synthesized sweeper in the transmitter section is used to generate a continuous wave Intermediate Frequency (IF) in the range of 5.2GHz to 5.6GHz. A wideband power divider is used to divide the total input signal power equally into two channels. The IF signal from one of these channels is fed to the transmitting antenna block and is used to generate the LO frequency for the up-conversion mixer.

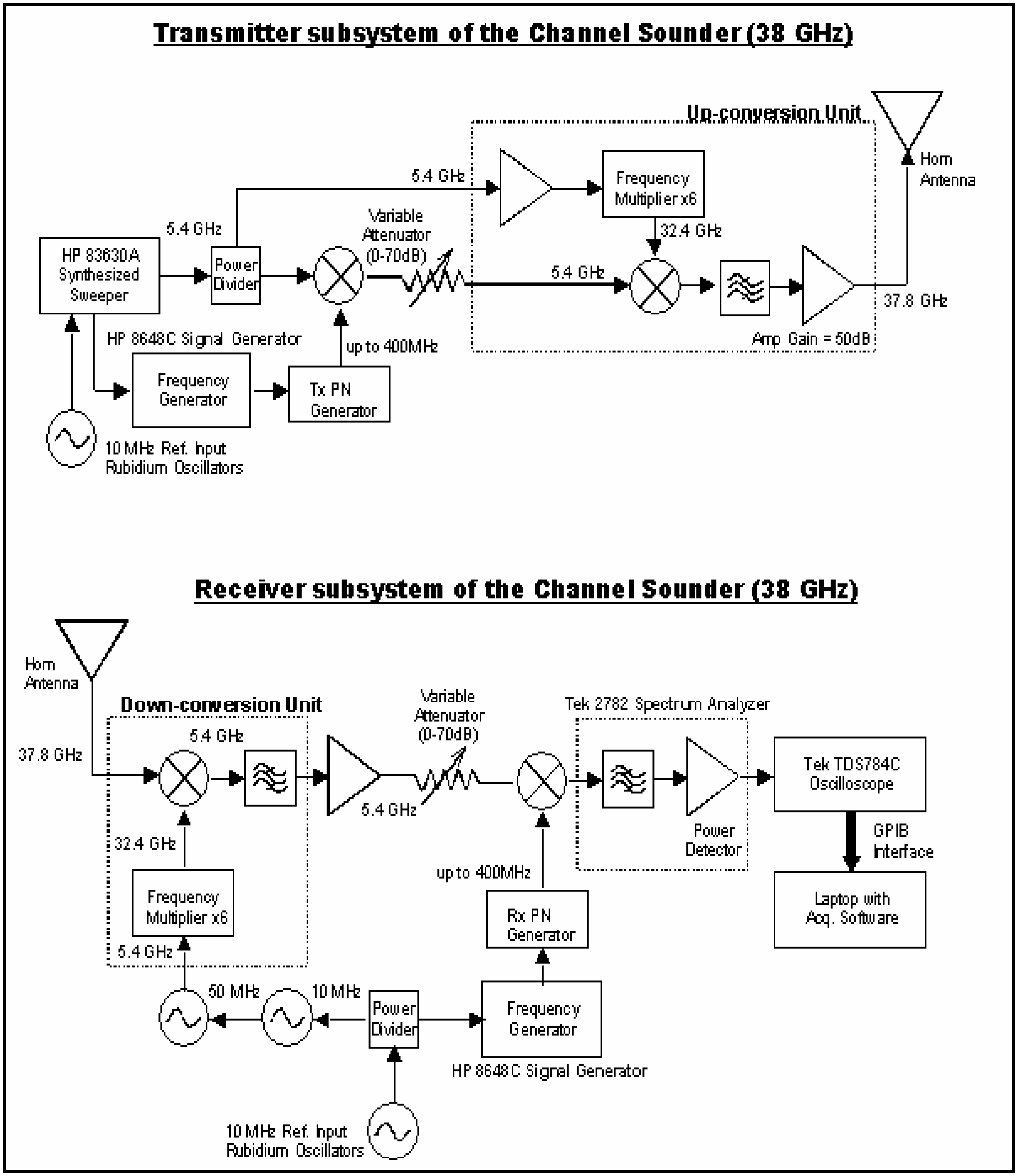

Figure 3.1 Block Diagram of Transmitting and Receiving subsystems of the Channel Sounder

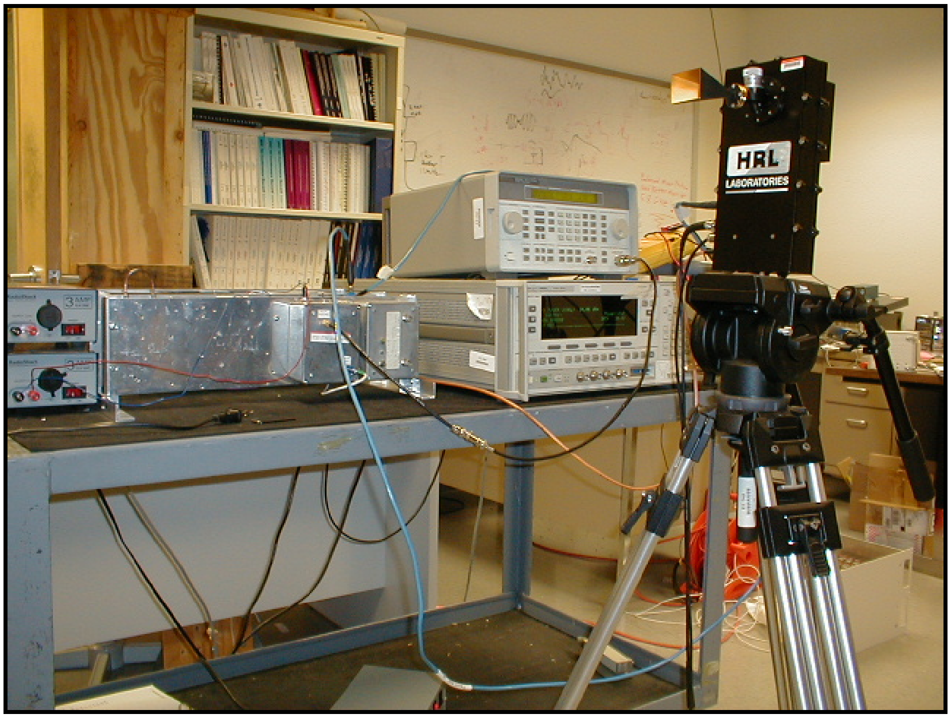

Figure 3.1.(a) Channel Sounder Transmitter Subsystem.

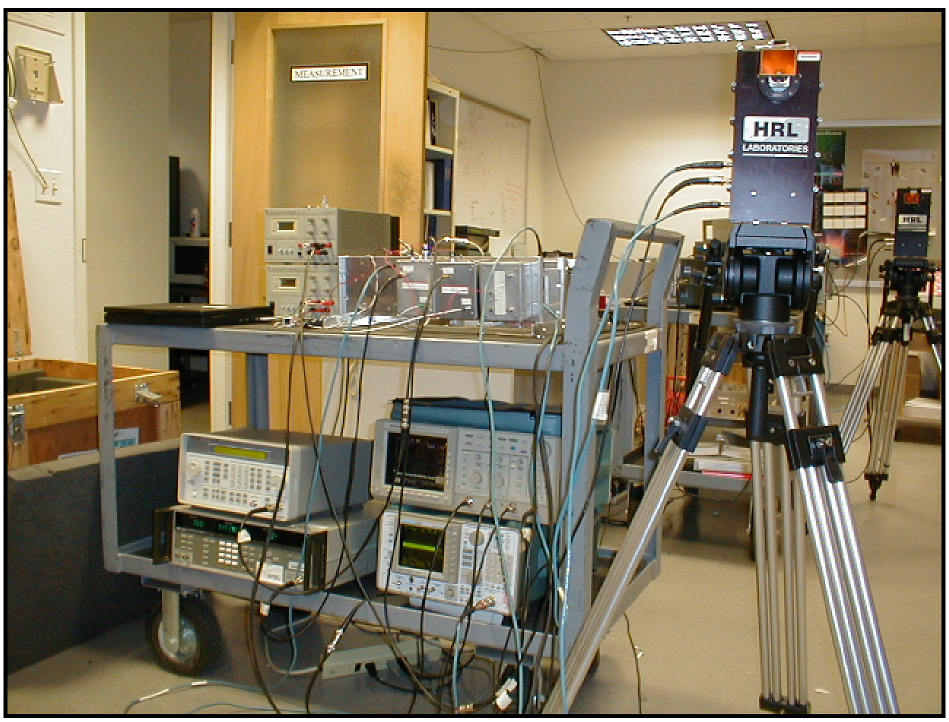

Figure 3.1.(b) Channel Sounder Receiver Subsystem.

In this research, the Pseudo-Noise (PN) Sequence Generator is clocked at 100MHz to provide a 200MHz RF sounding signal (10ns temporal resolution) and the output PN sequence is mixed with the IF signal from the second power divider channel. In Figure 3.1, the mixer that follows the power divider unit has a maximum power rating of 13dBm. Therefore the power fed into the power divider by the HP 83630A synthesized sweeper unit is maintained at 16dBm.

The circuit diagrams of the PN sequence generators (11 bit and 18 bit) are shown in Figure 3.2. The system in its present configuration employs the 11-bit PN sequence generator. Figure 3.3 shows the output of the 11-bit transmitter PN sequence generator and the correlation of transmitter and receiver PN sequences [Chr00].

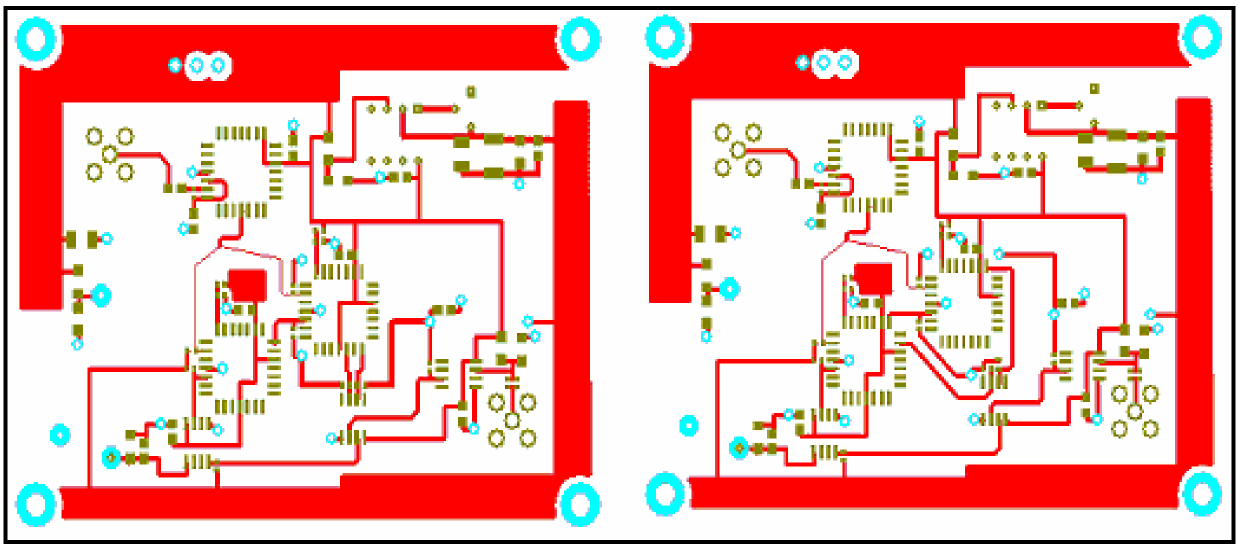

Figure 3.2 PN Sequence Generator Designs (11 bit (left) and 18 bit (right)) [Chr00]

With reference to Figure 3.1, the power divider output signal (for 38GHz configuration) is multiplied six times to provide a local oscillator (LO) frequency for the up-conversion mixer in the transmitting antenna block of the channel sounder. In other words, the IF signal effectively gets multiplied by a factor of seven in the transmitter. The resultant signal at 37.8GHz has a bandwidth of 200MHz. The signal is then passed through a band pass filter followed by an amplifier before it is radiated in free space. The overall gain of the conversion unit is 50dB and the maximum allowable input power into the up conversion unit is -29dBm. The transmitter therefore transmits a maximum power of 21dBm.

The receiver section, also shown in Figure 3.1, has the requisite down conversion and de-spreading circuitry. The signal received by the parabolic horn antenna (for 38GHz configuration) is down converted to the IF followed by band pass filtering and amplification. A variable attenuator is provided to facilitate manual signal power control followed by de-spreading of the signal. The output of the Receive PN Sequence Generator (clocked at 99.99MHz) is used to de-spread the signal using a mixer. A spectrum analyzer set in the zero-span mode serves both as a down converter and envelope detector and feeds the signal to the oscilloscope that displays the Power Delay Profile. The zero-span Spectrum Analyzer also allows the Power Delay Profiles to be saved into a laptop computer via a GPIB interface. All System Configuration settings including IF and Spectrum Analyzer Detection frequencies for all the measurement campaigns are explained in detail in Section 3.3. For more general details relevant to the design and implementation of the channel sounder, please refer [New96] and [Xu99].

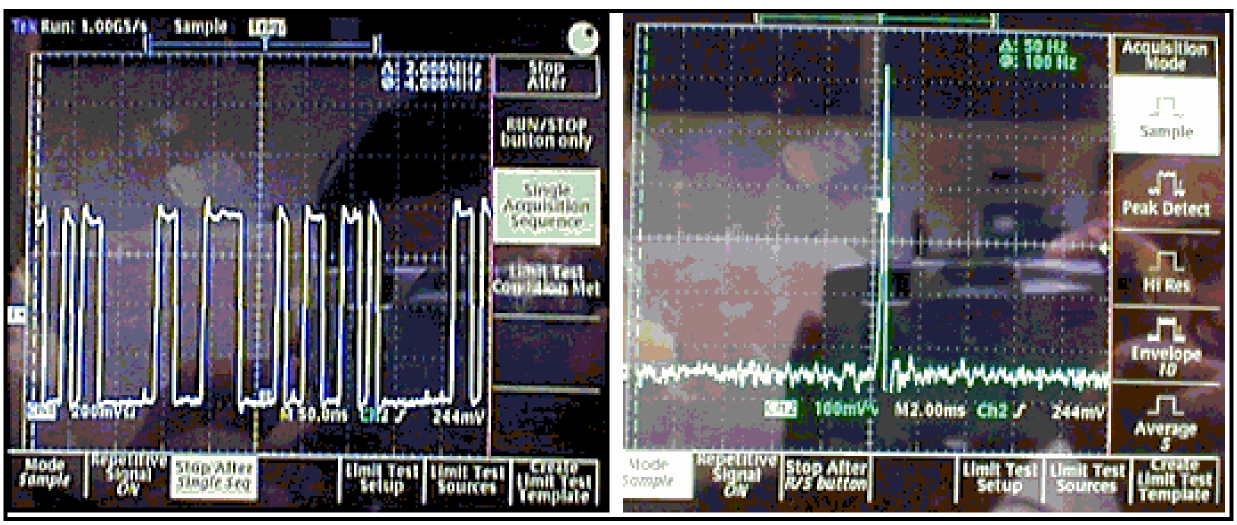

Figure 3.3 Rx PN Sequence snapshot and correlation peak between Tx and Rx PN sequences (r)

With reference to Figure 3.1, the main differences between the 38GHz and 60GHz system configurations are in the up and down conversion circuitry. Apart from using customized transmit and receive antennas for each of the two configurations, in the 60GHz setup, the IF signal is multiplied by a factor of ten. The resultant 54GHz signal serves as the LO frequency for the up-conversion mixer in the transmit antenna subsystem. Thus, the original IF signal (from the synthesized sweeper) is effectively multiplied by a factor of eleven before it is fed to band pass filters. The bandwidth of the signal is 200MHz and the frequency is 59.4GHz. The band pass filtering is followed by amplification within the transmitting antenna block before the RF signal is radiated in free space. In the receiving antenna block, the 10MHz reference signal from Rubidium Oscillators is used to generate a 5.4GHz continuous wave signal. This signal is multiplied by a factor of ten to serve as the LO frequency for the down-conversion mixer in the receiver antenna subsystem. The down-converted signal at 5.4GHz, with a bandwidth of 200MHz, is band pass filtered, and amplified followed by de-spreading and detection.

3.1.2. Antennas

For the 38 GHz setup, the transmitting antenna is a horn with a maximum gain of 19dB and half power beam widths of 45° and 6.5° in azimuth and elevation, respectively. The receiver antenna is a parabolic reflector with a maximum gain of 39dB and half power beam widths of 1.5 in both azimuth and elevation. Figures 3.4 (a) and (b), respectively show the theoretical transmitting and receiving antennas operating at 38 GHz [Xu99].

For the 60 GHz setup, the transmitting antenna is an open-ended wave-guide with a maximum gain of 6.7dB and a half power beam width of 90° in azimuth. The receiver antenna is a horn antenna with a maximum gain of 29dB and a half power beam width of 7°. Figure 3.5 shows the transmitting antenna operating at 60GHz and the corresponding antenna pattern [Xu00]

3.1.3. Measurement Parameters

Small scale fading describes the rapid fluctuations of the amplitude of radio signals over a short period of time or travel distance [Rap99]. In order to be able to model a typical wireless channel, one must eliminate small-scale fading effects from the recorded propagation data, before correct channel statistics can be calculated. A local average of the wideband PDP can provide a typical channel response. Recording multiple snapshots of Power Delay Profiles over a large period of time or over a local area, and performing statistical average on the data, facilitates temporal characterization and removal of small-scale fading effects from the recorded propagation data.

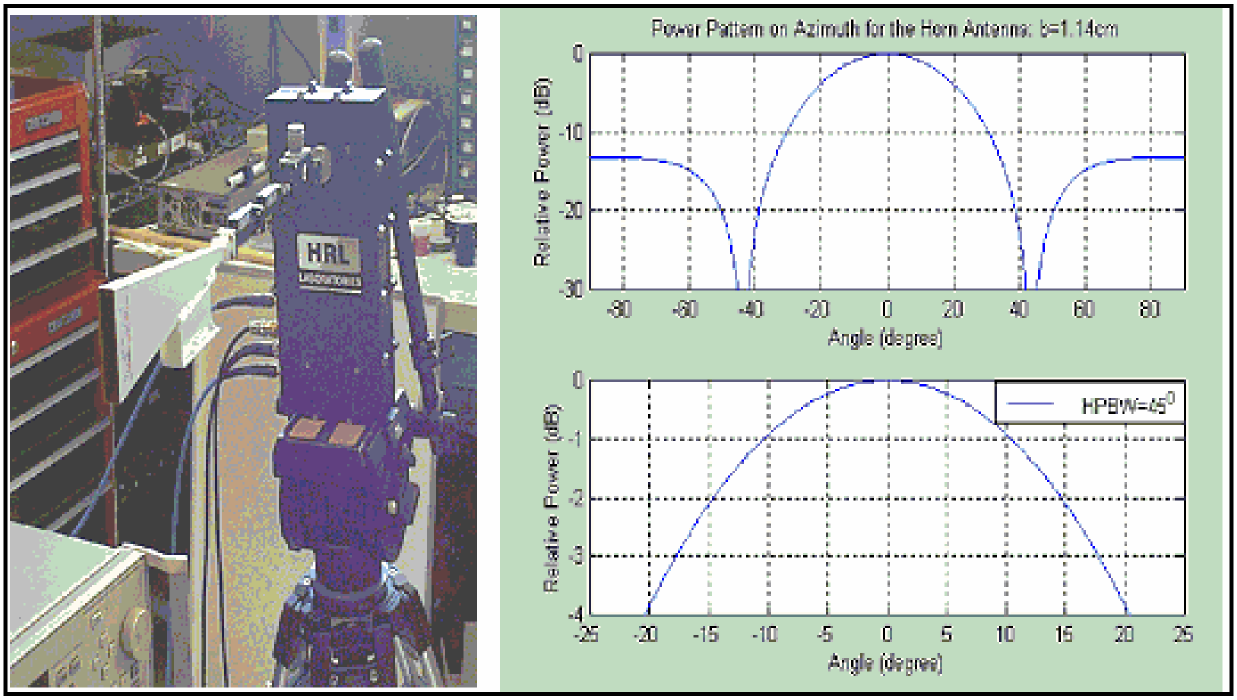

Figure 3.4.(a) Horn Transmitting Antenna (38GHz) and corresponding antenna pattern [Xu99]

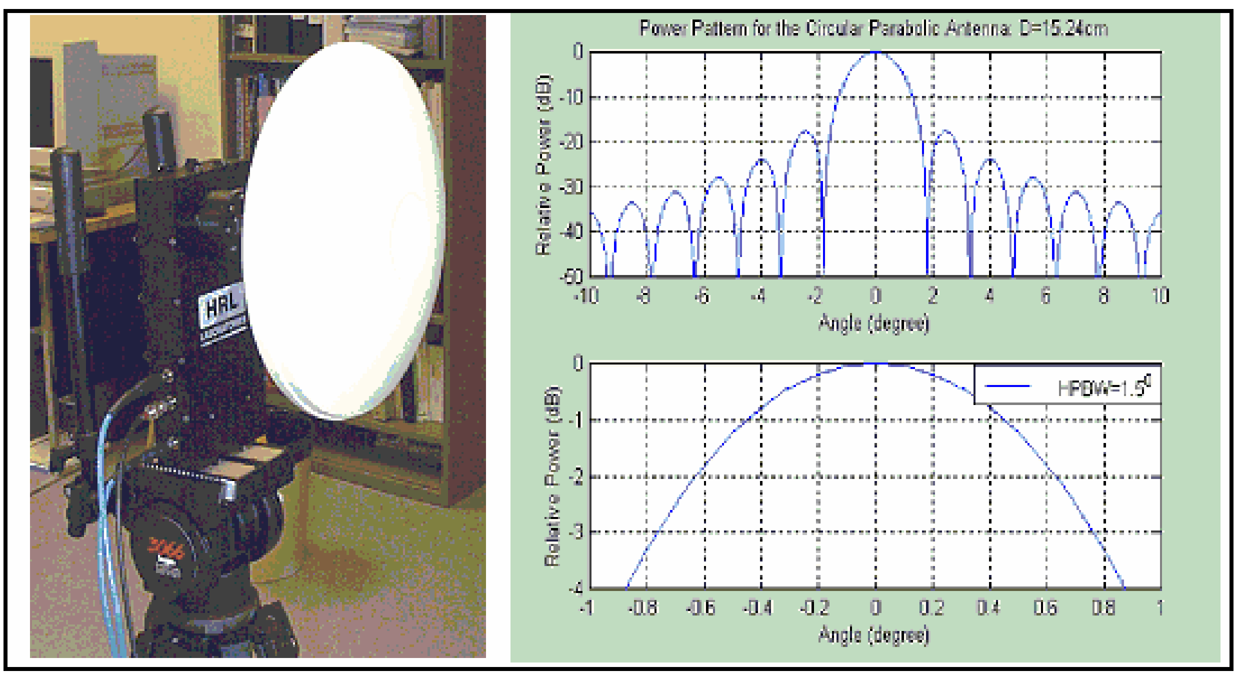

Figure 3.4.(b) Horn Receiving Antenna (38GHz) and corresponding antenna pattern. [Xu99]

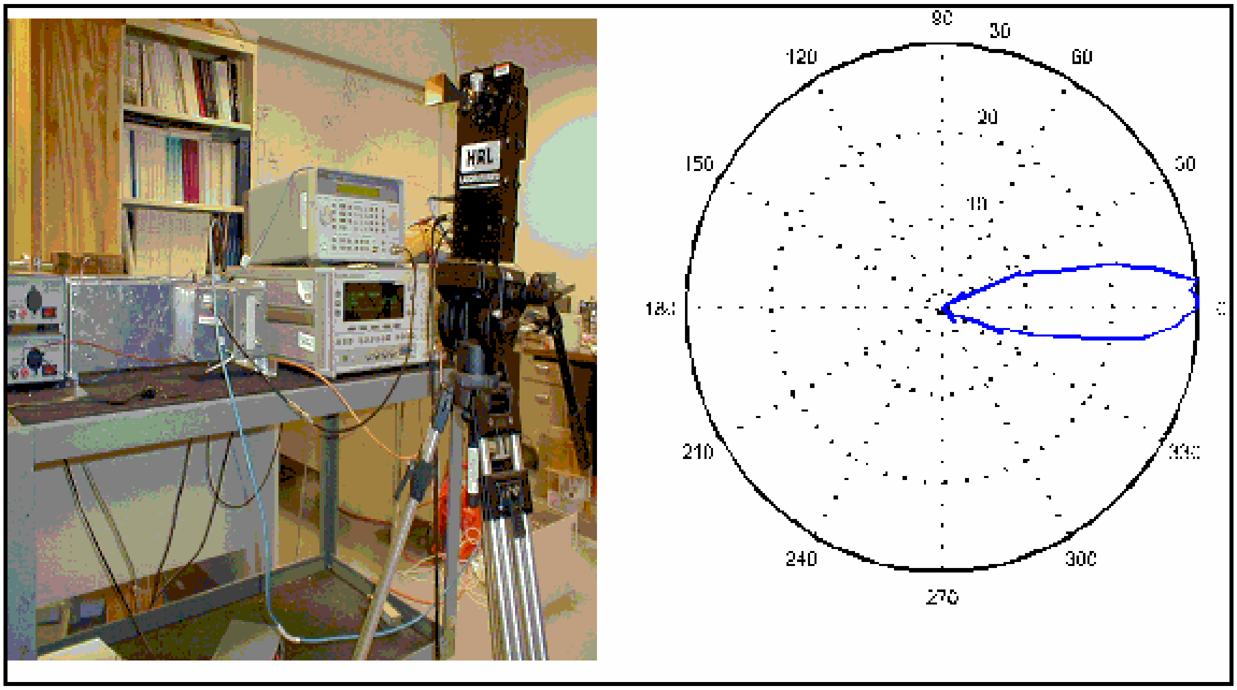

Figure 3.5 Transmitter Horn Antenna (60GHz) and corresponding Antenna Pattern [Xu00]

In this research, the Sliding Correlator Channel Sounding system is configured to record multiple snapshots of Power Delay Profiles during each measurement sequence. Specifically, the data acquisition software of the channel sounder is configured to record 25 PDP snapshots back-to-back for every measurement sequence. Accordingly, the data processing software is configured such that it performs temporal averaging of all the recorded PDPs in the measurement sequence and thereby eliminate small-scale signal fading effects. The software then calculates the channel statistics from the averaged Power Delay Profile.

The minimum time between two successive measurements is determined by the time interval between two consecutive correlations of the transmitter and receiver PN sequences. This time difference is given by the following expression [Hao00]

$$T = N\mathbf{z} \;/\; f_{Tx} = N / (f_{Tx} - f_{Rx}) \qquad \textbf{Equation 3.1}$$

where, N is the PN code length, ζ is the channel sliding factor, and f_{Tx} and f_{Rx}, respectively, represent transmit and receive PN chip rates. The difference between the transmit chip rate and the receive chip rate values is referred to as the frequency offset. In this research, 11-bit PN sequence generators are used (PN code length is 2047) and the transmit PN chip rate, f_{Tx} , is maintained at 100Mcps.

It can be seen from Equation 3.1 that there exists a tradeoff between the frequency offset and the PDP measurement speed. The transmit chip rate and receive chip rate values must be as close as possible so as to preserve correlation properties of the PN sequences. With an increase in the frequency offset, fewer PN chips will be aligned at the peak correlation time and therefore result in lower correlation peak and higher correlation noise [Hao00]. However, according to equation 3.1, a higher frequency offset will reduce the time between successive PDP measurements and hence permit faster recording of Power Delay Profiles. In this research, the receive PN chip rate was maintained at 99.99Mcps to facilitate a measurement speed of 5 PDPs per second. The corresponding sliding factor value is 10000.

3.2 Calibration

System Calibration is the most important part of any measurement campaign because it allows the user to verify and validate the functionality of the system hardware and software. System verification consists of thorough examination of functioning of every component, cable connection, and test equipment, followed by performance evaluation of the integrated system. In addition, operation of data acquisition software and the data processing software is also evaluated as a part of the verification process. System validation consists of comparison of system performance statistics and propagation measurement results with analytically derived models and results.

The channel sounder test equipment settings (attenuation, amplification, channel sounding frequency, etc.) and cable connections between components may change during different measurement campaigns. The calibration measurements, performed before measurement campaigns, serve to accurately characterize the behavior of the system for given set of system parameters. Also, performing calibration measurements in the beginning, and at the end of a measurement campaign (under identical conditions), and then comparing them with each other, allows the user to detect drift in the system performance, and counteract the same, if any. At lower cellular and PCS frequencies, usually extensive back-to-back calibration is performed. The process involves de-mounting of the antennas and connecting the transmitter and receiver subsystems directly via a set of fixed and variable attenuators. Free Space Calibration performed at LMDS frequencies, on the other hand, involves separation of transmitting and receiving antennas in free space by a distance greater than the Fraunhofer distance and performing calibration measurements. This ensures that both the antennas are in their respective far fields. Fresnel Zone radius is also calculated and antenna heights are adjusted suitably to take care of LOS and first order Fresnel clearance. The significance of Fraunhofer distance and Fresnel Zone radius is explained in Section 3.3.1.

3.2.1. Back-to-back Calibration Measurements

In back-to-back calibration, the transmitter and receiver subsystem of the channel sounding test equipment are connected directly via a set of fixed and variable attenuators. Figure 3.6 shows a simplified block diagram of the channel sounding equipment setup during back-to-back calibration measurements. The transmitter subsystem consists of power dividers, up conversion mixer, amplifiers, attenuators and cables. Similarly, the receiver subsystem consists of amplifiers, down conversion mixer, attenuators and cables.

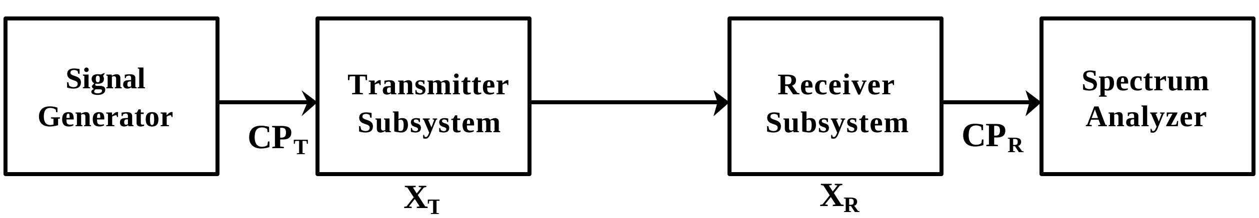

Figure 3.6 Block diagram of channel sounding equipment during back-to-back calibration.

In Figure 3.6,

CP_T = Total power transmitted by the Signal Generator during calibration (in dBm)

X_T = Cumulative Transmitter Subsystem Loss Value (in dB)

X_R = Cumulative Receiver Subsystem Loss Value (in dB)

CP_R = Total power received at the Spectrum Analyzer during calibration (in dBm)

The expression that relates all the above variables is given by Equation 3.2.

$$CP_R = CP_T - X_T - X_R \quad \textbf{Equation 3.2}$$

During a calibration sequence, at a given frequency and given set of parameters, we can record the values for variables CP_T and CP_R. Consequently, the sum of cumulative transmitter and receiver subsystem losses can be expressed by Equation 3.3.

$$X_T + X_R = CP_T - CP_R \quad \textbf{Equation 3.3}$$

During actual propagation measurements, as can be seen from Figure 3.7, the transmitting and receiving antennas are introduced in the system and the length of the radio link is 'D' meters.

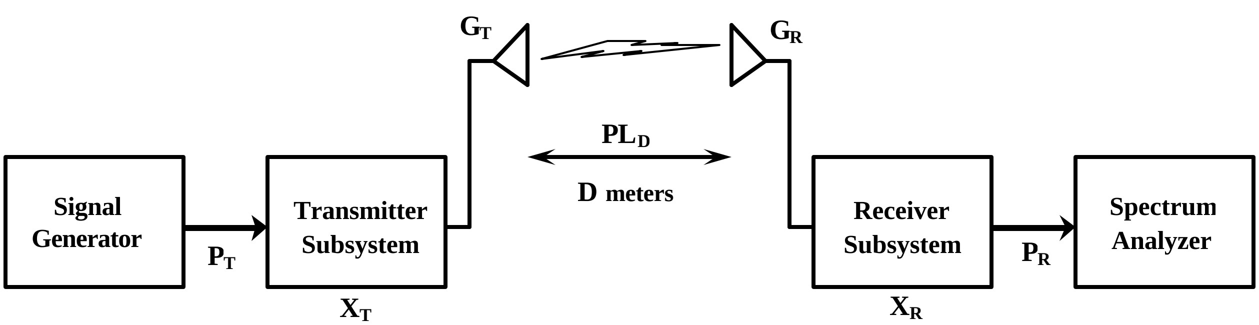

Figure 3.7 Block diagram of channel sounding equipment during propagation measurements.

In addition to the parameters defined above, let the remaining parameters be defined as follows

P_T = Total power transmitted by the Signal Generator during measurements (in dBm)

P_R = Total power received at the Spectrum Analyzer during measurements (in dBm)

G_R = Receiver Antenna Gain (in dB)

G_T = Transmitter Antenna Gain (in dB)

PL_D = Absolute Path Loss over a radio link of length D meters (in dB)

The expression that relates the above set of variables is given by Equation 3.4.

$$P_R = P_T - X_T + G_T - PL_D + G_R - X_R \qquad \textbf{Equation 3.4}$$

During propagation measurements, we can record values for parameters P_T and P_R and assuming that antenna gain values, G_T and G_R, are also known, we can calculate the Absolute Path Loss over a link length of D meters by using Equation 3.5. Note that Equation 3.3 is substituted in Equation 3.4 to derive Equation 3.5.

$$PL_D = P_T - P_R + G_T + G_R - (CP_T - CP_R) \qquad \textbf{Equation 3.5}$$

Thus back-to-back calibration permits calculation of absolute path loss values.

3.2.2. Free-Space (FS) Calibration Measurements

During wireless propagation measurements, the transmitting and receiving antenna units are placed in their respective far fields. Therefore, the antenna units must be placed in far fields during free-space calibration measurements as well. To accomplish this, the transmitting and receiving antennas are separated in free-space by a distance greater than the Fraunhofer distance. Fresnel Zone radius is also calculated and antenna heights are adjusted to ensure LOS and first order Fresnel clearance for calibration measurements. Significance of Fraunhofer distance and Fresnel Zone radii with respect to calibration measurements, and equations for calculating the same are presented in Section 3.3.1.

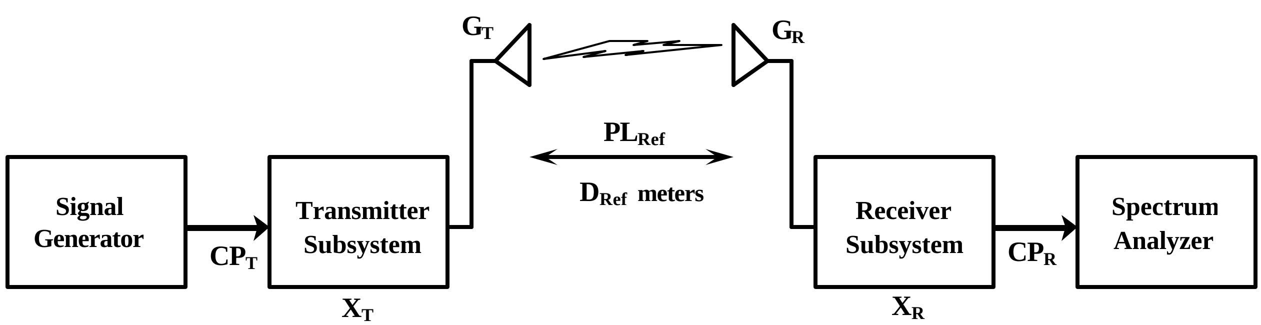

Figure 3.8 Block Diagram of channel sounding equipment during FS calibration.

In the figure,

CP_T = Total power transmitted by the Signal Generator during calibration (in dBm)

X_T = Cumulative Transmitter Subsystem Loss Value (in dB)

X_R = Cumulative Receiver Subsystem Loss Value (in dB)

G_R = Receiver Antenna Gain (in dB)

G_T = Transmitter Antenna Gain (in dB)

PL_{Ref} = Absolute Path Loss over a reference calibration distance, D_{Ref}. (in dB)

CP_R = Total power received at the Spectrum Analyzer during calibration (in dBm)

The expression that relates the above set of variables is given by Equation 3.6.

$$CP_R = CP_T - X_T + G_T - PL_{Ref} + G_R - X_R \qquad \textbf{Equation 3.6}$$

During FS calibration measurements, we can record the values for parameters CP_T and CP_R. It is evident that Path Loss value for the reference calibration distance, PL_{Ref}, is independent of antenna type or gain values. Let us assume that antenna gain values, G_R and G_T, are not known. Then Equation 3.6 may be rearranged as

$$G_T + G_R - PL_{Ref} - (X_T + X_R) = CP_R - CP_T \qquad \textbf{Equation 3.7}$$

During actual propagation measurements, as can be seen from Figure 3.7, the radio link between the transmitting and receiving antennas is 'D' meters long. The received signal power at the Spectrum Analyzer can be expressed by Equation 3.4. By substituting Equation 3.7 into Equation 3.4, we get an expression for the absolute path loss value as follows:

$$PL_D = P_T - P_R + CP_R - CP_T + PL_{Ref} \qquad \textbf{Equation 3.8}$$

It is evident from Equation 3.8 that absolute path loss (for a radio link 'D' meters long) can be expressed as a sum of known constant values and the reference path loss value. Also, one must note that it is not at all necessary to know the antenna gain values to be able to calculate the path loss values. In other words, the FS calibration process allows calculation of path loss statistics independent of the antenna types or gain values. The reference path loss value, PL_{Ref} can be computed theoretically (with path loss exponent value equal to 2) and added to the relative path loss values calculated by Equation 3.8 to obtain absolute path loss values. This assumption is valid because calibration measurements are performed in a controlled, benign, free-space LOS environment that is devoid of any reflected multipath components. Equation 3.9 can be used to calculate the path loss value for the reference calibration distance, where ? is the wavelength.

$$PL_{\mathrm{Ref}} = 20\log_{10}\left(\frac{4pD_{\mathrm{Ref}}}{l}\right) \qquad \textbf{Equation 3.9}$$

3.3 FS Calibration for Measurement Campaigns

The following subsections explain FS calibration measurements performed during propagation measurement campaigns at 38GHz and 60GHz bands of frequencies. Calibration measurements for both Path Loss as well as Frequency Diversity measurement campaigns are explained.

3.3.1. Calibration Equipment Setup

During wireless propagation measurements, the transmitting and receiving antenna units are placed in their respective far fields. Therefore, to facilitate accurate characterization of channel sounder behavior, during free space calibration measurements, the transmitting and receiving antennas must be in their respective far fields. The far field, or Fraunhofer region, of a transmitting antenna is defined as the region beyond the far field distance d_f, which is related to the largest linear dimension of the transmitter antenna aperture and the carrier wavelength [Rap99]. The Fraunhofer distance can be expressed by Equation 3.10. In the expression, D is the largest physical linear dimension of the antenna and l is the signal wavelength. For true far field, the Fraunhofer distance, d_f, must also be much greater than D, and the wavelength ?.

$$d_f = 2D^2/l \qquad \textbf{Equation 3.10}$$

The spatial separation of the transmitting and receiving antennas for free space calibration is also affected by the Fresnel Zone clearance. Fresnel Zones represent successive regions where secondary waves have a path length from the transmitter to receiver which are $nl/2$ greater than the total path length of a line-of-sight path [Rap99]. The successive Fresnel zones have the effect of alternately providing constructive and destructive interference to the total received signal. The radius of the nth Fresnel zone circle is denoted by r_n and can be expressed by Equation 3.11 where d_1 and d_2 represent distances from the transmitter and receiver antennas respectively.

$$r_n = \sqrt{\frac{n d_1 d_2 l}{d_1 + d_2}} \qquad \textbf{Equation 3.11}$$

Consequently, the antenna separation distances and antenna heights must be carefully chosen to allow for LOS clearance and minimization of reflection from ground.

For example, the vertical and horizontal aperture dimensions of the horn antenna shown in Figure 3.5 are 3.6cm, and 4.6cm, respectively. The maximum linear aperture dimension for a rectangular horn antenna is the antenna aperture diagonal. For the specific antenna under consideration, this length can be mathematically calculated as 5.8cm. At 60GHz, the signal wavelength is 0.50cm and hence the corresponding Fraunhofer distance, calculated using Equation 3.10 is 1.34 meters. Also, if we assume a total distance of separation of 40 meters between the transmitter and receiver antennas (d_1, d_2 = 20m), from Equation 3.11, the minimum Fresnel radius (n = 1) can be calculated as 0.23 meters. This implies that the antenna heights and their positions must be chosen such that there exists a clear LOS with no obstructions in the first Fresnel zone. For this specific example, the curved surface of a hypothetical cylinder with LOS as its center and radius of 0.23 meters, defines the first Fresnel zone.

Fraunhofer distances for 38GHz and 60GHz antennas are less than two meters and thus, for all calibration measurements, the reference distance of separation is fixed at four meters. The corresponding minimum Fresnel radius for either of the frequencies is less than one meter. Antenna heights were thus maintained at 1.5 meters above ground throughout the free-space calibration measurements to allow sufficient LOS clearance. The calibration measurements must be performed in a benign environment such that there are no strong stationary or mobile reflectors in the vicinity of the equipment. This allows the system to stay clear of multipath components reflected from ground, adjacent walls and other nearby objects. In this research, all the calibration measurements were performed in the fourth floor hallway of the Durham Hall.

During calibration measurements, the transmitting and receiving antennas units are appropriately positioned, leveled and aligned accurately. The equipment is secured and the entire region is cordoned off using a 'caution tape'. However, before any calibration measurement, all of the transmitter and receiver equipment must be powered on and operated for a period of at least 30 minutes. This warm-up period allows the equipment to reach a steady-state operating temperature. The losses, gains, and noise figures for many of the system components depend on operating temperature and hence measurements performed in haste can produce erroneous results that change over time.

3.3.2. Sequence of Calibration Measurements and Calibration Data

In this research, clear-sky frequency diversity measurements, and path loss measurements during different weather events, are performed at three different locations on the Virginia Tech campus. The motivation and objective of these propagation measurements is presented in Chapter 1 and a detailed measurement plan is discussed in Chapter 4. This section presents the sequence of short-distance free-space propagation measurements, performed at different frequencies for calibration of the Channel Sounder.

All the steps followed during Path Loss calibration measurements and Frequency Diversity calibration measurements are outlined in Sections 3.3.2.1 and 3.3.2.2, respectively. The significance of calibration data with reference to broadband wireless propagation measurements is also explained. Link Budget Analysis to facilitate calculation of path loss statistics, and sample calibration data files are presented in Sections 3.3.2.3 and 3.3.2.4.

3.3.2.1 38GHz and 60GHz Path Loss Calibration Measurements

During calibration measurements in the hallway, once the antennas are positioned and leveled and the system has achieved steady state, the receiver is accurately aligned with the transmitter antenna such that the power received by the receiving antenna is maximized. After verifying the functionality of the system, the calibration data recording process is initiated. For the 38GHz configuration, the steps are as follows:

1. At the transmitter subsystem, a continuous wave signal at 5.4GHz (16dBm power) is generated using the HP83630A synthesized sweeper. The HP8648C signal generator is configured to generate a 100MHz reference signal to clock the Tx PN Sequence Generator. For either of the two polarizations (vertical or horizontal), the spread spectrum signal is up converted to 37.8GHz followed by amplification and radiation into free space by the directional horn antenna. The External Variable Attenuator (EA) is maintained at 0dB.
2. The Receiver Antenna Subsystem, with polarization in agreement with the transmitter subsystem, amplifies and down converts the signal. The External Variable Attenuator (EA) at the receiver is used to introduce attenuation so as to limit the input power into the Tek 2782 Spectrum Analyzer. The maximum input power rating for the spectrum analyzer is 30dBm. The detection frequency and span for the spectrum analyzer are set at 5.4GHz and 0Hz respectively. The Tek TDS784C Oscilloscope is configured to sample the power delay profile at 100Ksamples per second and a computer controlled PDP measurement is initiated.
3. The PDP as visible on the oscilloscope screen is recorded into the laptop in a file format via a GPIB interface. The calibration process involves mapping of Spectrum Analyzer (SA) output voltage values (corresponding to power received into SA) to the receiver excess attenuation. The significance of the process is explained in detail in Sections 3.3.2.3 and 3.3.2.4. The attenuation offered by the external variable attenuator is increased in steps of 10dB and similar measurements are recorded until the entire linear range of receiver operation has been measured.
4. All the steps outlined above are repeated for both horizontal and vertical polarization configurations. In addition, vertical propagation measurements with both 90-degree waveguide-twists connected back-to-back to the receiver antenna are also performed. This facilitates comparison of received power statistics from the simple vertical polarization scenario (without waveguide twists) and the special vertical polarization

scenario (with waveguide twists) and thereby allows calculation of cumulative losses introduced by the waveguide twists during propagation measurements. Note that since both 90-degree twists are connected back-to-back, the receiving antenna is still vertically polarized. The cumulative waveguide is calculated as 4.43dB.

The steps 1 - 3 outlined above are repeated for the 60GHz configurations while exactly maintaining all the test equipment (generators, spectrum analyzer and oscilloscope) settings.

3.3.2.2 38GHz and 60GHz Frequency Diversity Measurements

The Sliding Correlator Channel Sounder was designed and developed for operation at 37.8GHz and 59.4GHz. However, as a part of the frequency diversity propagation measurements, the channel sounder is operated at as many as 24 carrier frequencies in the 38GHz and 60GHz frequency bands. It is therefore extremely important to verify and accurately characterize the functioning of the channel sounder at each of these carrier frequencies. Section 3.3.2.1 presents steps involved in characterizing the channel sounder at two specific carrier frequencies of 37.8GHz and 59.4GHz. This section outlines steps for characterizing the performance of channel sounder at all carrier frequencies by recording free-space calibration measurements.

As mentioned in Chapter 2, frequency diversity measurements involve extensive propagation measurements at twelve carrier frequencies (separated by 100MHz), centered at 37.8GHz and 59.4GHz each. The set of transmission frequencies for each frequency band are presented in Table 3.1 along with other pertinent equipment settings for the Channel Sounder. In the table, ‘IF Frequency’ is the frequency generated by the HP synthesized sweeper. The ‘Tx Frequency’ is the frequency transmitted by the antennas and ‘Detection Frequency’ if the spectrum analyzer detection frequency for envelope detection. With appropriate parameter settings, steps outlined in Section 3.3.2.1 are repeated to record individual free-space calibration measurements for each of the 24 carrier frequencies.

Table 3.1 Transmission Frequencies and Equipment Settings

38GHz	IF Signal Power - 16dBm Tx PN frequency - 100MHz Rx PN frequency - 99.99MHz Calibration Distance - 4 meters Oscilloscope Sampling - 100Ksps	
Tx Frequency	**IF Frequency**	**Detection Frequency**
37.2 GHz	5.3142857143	4.8 GHz
37.3 GHz	5.3285714286	4.9 GHz
37.4 GHz	5.3428571429	5.0 GHz
37.5 GHz	5.3571428571	5.1 GHz
37.6 GHz	5.3714285714	5.2 GHz
37.7 GHz	5.3857142857	5.3 GHz
37.8 GHz	5.4000000000	5.4 GHz
37.9 GHz	5.4142857143	5.5 GHz
38.0 GHz	5.4285714286	5.6 GHz
38.1 GHz	5.4428571429	5.7 GHz
38.2 GHz	5.4571428571	5.8 GHz
38.3 GHz	5.4714285714	5.9 GHz

60GHz	IF Signal Power - 16dBm Tx PN frequency - 100MHz Rx PN frequency - 99.99MHz Calibration Distance - 4 meters Oscilloscope Sampling - 100Ksps	
Tx Frequency	**IF Frequency**	**Detection Frequency**
58.8 GHz	5.3454545455	4.8 GHz
58.9 GHz	5.3545454545	4.9 GHz
59.0 GHz	5.3636363636	5.0 GHz
59.1 GHz	5.3727272727	5.1 GHz
59.2 GHz	5.3818181818	5.2 GHz
59.3 GHz	5.3909090909	5.3 GHz
59.4 GHz	5.4000000000	5.4 GHz
59.5 GHz	5.4090909091	5.5 GHz
59.6 GHz	5.4181818182	5.6 GHz
59.7 GHz	5.4272727273	5.7 GHz
59.8 GHz	5.4363636364	5.8 GHz
59.9 GHz	5.4454545455	5.9 GHz

3.3.2.3 Calibration Data

For the FS calibration configuration, if $P_{T,dBm}$ represents the total power transmitted into the transmitting antenna, G_T represents transmitter antenna gain, G_R represents total receiver system gain up to the Spectrum Analyzer (inclusive of Rx antenna gain), $PLoss_{ref}$ represents free-space path loss for four meters and EA represents the 'Excess Attenuation' (external attenuation) introduced into the system at the receiver, then the received signal power into the SA, $P_{R,dBm}$ can be expressed by Equation 3.12.

$$P_{R,dBm} = P_{T,dBm} + G_T + G_R - PLoss_{ref} - EA \qquad \textbf{Equation 3.12}$$

In Section 3.3.2.2, it was explained that EA is increased in steps of 10dB during successive calibration measurements to facilitate a linear mapping between received Spectrum Analyzer (SA) Output Voltage values and corresponding EA values.

With reference to Figure 3.1, in the receiver subsystem, the Spectrum Analyzer (SA) performs envelope detection and feeds the received signal power to the oscilloscope. However, the fact that the output of the spectrum analyzer is a voltage signal rather than dBm-valued power necessitates extensive data processing for determining a linear mapping between voltage samples V, and dBm value of power. The linear relationship between the received signal power and corresponding voltage output values can be expressed by Equation 3.13, where α and β are system constants [Gre01].

$$P_{R,dBm} = aV + b \qquad \textbf{Equation 3.13}$$

Combining Equations 3.12 and 3.13 gives Equation 3.14, where ξ is expressed by Equation 3.15.

$$aV + x = -EA \qquad \textbf{Equation 3.14}$$

$$x = b - P_{T,dBm} - G_T - G_R + PLoss_{ref} \qquad \textbf{Equation 3.15}$$

Equation 3.14 shows that for a given system, the received voltage at the output of the zero-span SA is a linear function of the excess attenuation introduced into the system. If we can calculate α and ξ, then we have the ability to estimate the excess attenuation from the voltage level measured during an experiment and further calculate the path loss values using equation 3.22.

To calibrate the system, we need a collection of (EA, V) data points - excess attenuation and the corresponding voltage at the spectrum analyzer. The desired data is recorded for each system configuration by following the steps outlined in Sections 3.3.2.1 and 3.3.2.2. An example of calibration points (EA, V) is show in Table 3.2.

Table 3.2 An example of Calibration data points

Attenuation EA (dB)	SA Voltage V (volts)
20	3.37
30	3.23
40	2.76
50	2.56
60	1.92
70	1.41

The calibration constants can be calculated by performing linear regression on the data set of (EA, V). To solve for α and ξ, we use following equations based on min. mean-squared error.

These equations provide a "best fit" for the calibration constants [Gre01].

$$a = \frac{(S_{10})^2 - NS_{20}}{NS_{11} - S_{10}S_{01}} \qquad \textbf{Equation 3.16}$$

$$x = \frac{-aS_{01} - S_{10}}{N} \qquad \textbf{Equation 3.17}$$

where,

$$S_{mn} = \sum_{i=1}^{N} (EA_i)^m (V_i)^n \qquad \textbf{Equation 3.18}$$

It is important that the regression must be performed across the linear range of calibration data. From the calibration data presented in Table 3.2, it can be seen that the system has two regions of non-linear operation.

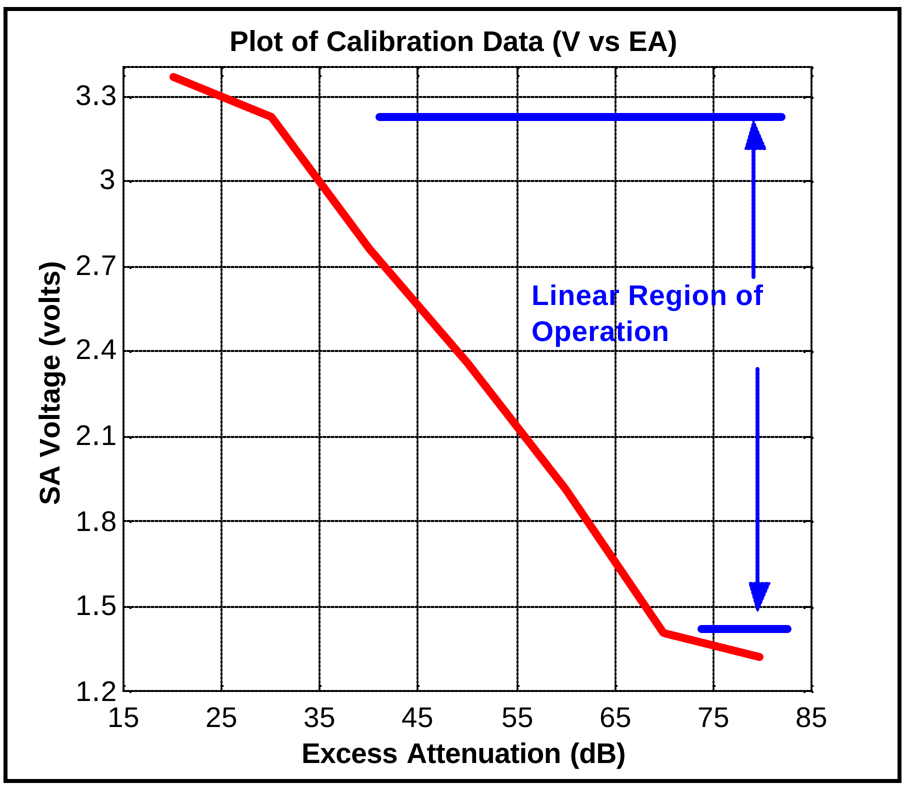

Figure 3.9 A sample calibration plot depicting linear and non-linear regions.

The first non-linearity occurs for low excess attenuation values due to saturation of receiver amplifiers and mixers. The second non-linearity occurs for weak signal levels (high excess attenuation) that are now comparable in power to the system's thermal noise. Figure 3.9 shows calibration data points and two non-linear regions. The lowest and highest linear attenuation points are 30dB, and 70dB, respectively. The difference between these limits is the dynamic range of the receiver. For the system under consideration, the dynamic range is 40dB.

3.3.2.4 Link Budget Analysis

After completing all requisite calibration measurements and calculating calibration constants for each configuration, wireless free-space propagation measurements in a pico-cell scenario are performed. The following section presents the end-to-end link budget and explains the relevance of calibration constants in calculation of path loss statistics.

The link budget for the wireless measurement system is given by

$$P_{R,dBm} = P_{T,dBm} + G_T - PLoss_D + G_R - A_{dB} \qquad \textbf{Equation 3.19}$$

where, $PLoss_D$ represents the free-space Path Loss over a distance of D meters and A_{dB} is the step attenuator setting of the receiver subsystem that is usually set to zero during measurements. The free-space path loss can be expressed in terms of reference path loss as follows

$$PLoss_D = PLoss_{ref} + PLoss_{D\_relative\_to\_ref} \qquad \textbf{Equation 3.20}$$

Combining Equations 3.19 and 3.20 gives

$$P_{R,dBm} = P_{T,dBm} + G_T + G_R - PLoss_{ref} - PLoss_{D\_relative\_to\_ref} - A_{dB} \qquad \textbf{Equation 3.21}$$

Comparison and re-arranging of Equations 3.12, 3.14 and 3.21 gives

$$PLoss_{D\_relative\_to\_ref} = -aV - x - A_{dB} \qquad \textbf{Equation 3.22}$$

Equation 3.22 allows us to convert any voltage data to equivalent path loss data. Thus, relative path loss (relative to reference distance) statistics can be calculated using calibration constants and Spectrum Analyzer Output Voltage samples. Note that it is mandatory to maintain all the system equipment settings throughout the measurement campaign so as to be able to calculate path loss statistics directly from the voltage samples.