



# **Using the Intel MIMO Channel Measurement Database**

## **User Guide**

---

Cliff Prettie, David Cheung, Jeng Lung, Ken Tang

April 5, 2004

# Table of Contents

---

<b>1 OVERVIEW .....</b>	<b>4</b>
<b>2 MEASUREMENT METHODOLOGY .....</b>	<b>5</b>
<b>2.1 DESCRIPTION OF ENVIRONMENT .....</b>	<b>5</b>
<b>2.2 DESCRIPTION OF MEASUREMENT EQUIPMENT .....</b>	<b>5</b>
<b>2.3 DESCRIPTION OF MEASUREMENT CAMPAIGN .....</b>	<b>7</b>
2.3.1 Conventions.....	7
2.3.2 AP and STA Locations.....	8
2.3.3 AP and STA Movement Setup.....	10
2.3.4 Polarization Setup.....	12
2.3.5 Frequency Span and Resolution.....	12
2.3.6 Measurement Environment and Remarks.....	13
<b>3 MEASUREMENT FILES .....</b>	<b>14</b>
<b>3.1 MEASUREMENT POST-PROCESSING: ISOLATING THE CHANNEL .....</b>	<b>14</b>
<b>3.2 RETRIEVING THE MEASUREMENT DATA SETS .....</b>	<b>14</b>
<b>3.3 DATA SET COORDINATE SYSTEM.....</b>	<b>15</b>
<b>3.4 USING THE DIFFERENT DATA SETS.....</b>	<b>18</b>
3.4.1 Individual Data Files.....	18
3.4.2 Concatenated Data Files.....	19
3.4.3 FFT Files.....	21
<b>4 SAMPLE ANALYSIS .....</b>	<b>23</b>
<b>4.1 WAVEFRONTS IN TIME .....</b>	<b>23</b>
<b>4.2 ANGULAR SPECTRA .....</b>	<b>24</b>
<b>5 RESOURCES .....</b>	<b>26</b>

## Table of Figures

---

FIGURE 1. INTEL CUBICLE ENVIRONMENT. ....	5
FIGURE 2. TYPICAL EQUIPMENT SETUP. ....	6
FIGURE 3. ANTENNA POSITIONERS. ....	6
FIGURE 4. STA AND AP ANTENNA POLARIZATION CONVENTION. ....	7
FIGURE 5. OFFICE LAYOUT AND MEASUREMENT LOCATIONS. ....	9
FIGURE 6. EXAMPLE ANTENNA POSITIONS. ....	11
FIGURE 7. EXAMPLE OF AP/STA LOCAL COORDINATE SYSTEM TO ABSOLUTE COORDINATE SYSTEM CONVERSION. ....	17
FIGURE 8. ANOTHER EXAMPLE OF LOCAL COORDINATE SYSTEM TO ABSOLUTE COORDINATE SYSTEM CONVERSION. ....	18
FIGURE 9. LOCAL COORDINATE ORIENTATION TO CONCATENATED FILE ORIENTATION FOR SEQUENCE #23. ....	21
FIGURE 10. TWO FRAMES, 0.32 NS OR 5 FRAMES APART, FROM THE MOVIE FOR SEQUENCE #7. ....	23
FIGURE 11. ANGULAR SPECTRUM FOR SEQUENCE #7. ....	24

# 1 Overview

---

Intel Labs began its channel measurement campaign in 2001, motivated by an interest to develop ultra-wideband (UWB) communication systems. At the time, no other public database was available to match the 2-8 GHz residential measurements that Intel researchers required to understand the characteristics of the UWB channel.

With a broadening interest in wireless systems, Intel Labs evolved its campaign to support multiple input multiple output (MIMO) systems. By the culmination of the campaign in 2003, the database had grown to over 730,000 MIMO channel measurements taken in the office environment.

These measurements have now been made public in the hopes that academia and industry will be able to use them to research and develop next-generation wireless systems. The increasing complexity of these systems and the importance of standardization make the cooperative development of channel models and the improved understanding of RF propagation an important part of this process.

This documentation describes the Intel MIMO channel measurement effort and how to use this data.

## 2 Measurement Methodology

---

### 2.1 Description of Environment

The measurements were taken in the Intel office cubicle environment. This environment is populated primarily by cubicles measuring 9'x8' and separated by 5.5' tall cloth partitions with metal frames. Each cubicle typically contains a 5' tall large metal filing cabinet and several smaller metal filing cabinets, one of which is usually mounted on the wall above the plastic/wood desk.

Drywall and metal studs are used for conference room construction. Structural columns running from floor to ceiling measure about 2.5'x2' and are spaced every 30'. A false ceiling of acoustic tile is approximately 10' from the floor, directly above which is a service area for heating, ventilation, and air-conditioning (HVAC) ducts and wiring. Floors and ceilings are concrete with rebar.

**Figure 1** shows the cubicle environment at Intel in which the measurements were taken.



**Figure 1.** Intel cubicle environment.

### 2.2 Description of Measurement Equipment

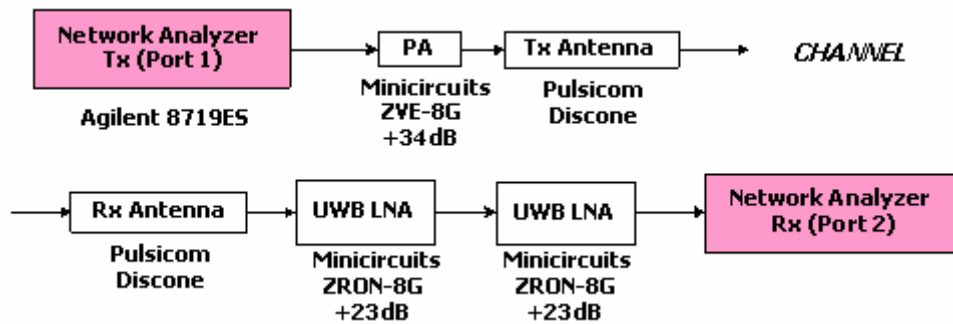
One robotic xy-positioner was attached to the ceiling to simulate a wireless access point (AP). Another was placed on a plastic cart to simulate a wireless user, or station (STA). Mounted on each xy-positioner was an antenna polarization positioner constructed primarily of plastic.

Using this system, we were able to move the AP antenna over a 6'x3' area and the STA antenna over a 1.5'x1.5' area, both with 1/100" precision. We were also capable of adjusting either antenna's polarization from 0° to 270° with 1° resolution.

Measurements were taken mainly with 0.5", 1.0", 1.5", 2.0", 4.0", and 6.0" spacing over either a square grid or a cross formation. As all measurements took place after office hours (at night or on weekends), the channel was static and the multiple single antenna measurements can be treated as a simultaneous measurement using an array of antennas. Tests of channel stationarity and consistency checks of our data have shown the average result repeatability to be within 12% over a 24-hour period.

The antenna used was a Pulsicom ultra-wideband (2-8 GHz) discone with azimuthal symmetry and a 3 dB elevation beamwidth at 5.20 GHz of 60°. The STA antenna feed was 4' above the ground, while the AP antenna feed was 7.5' high.

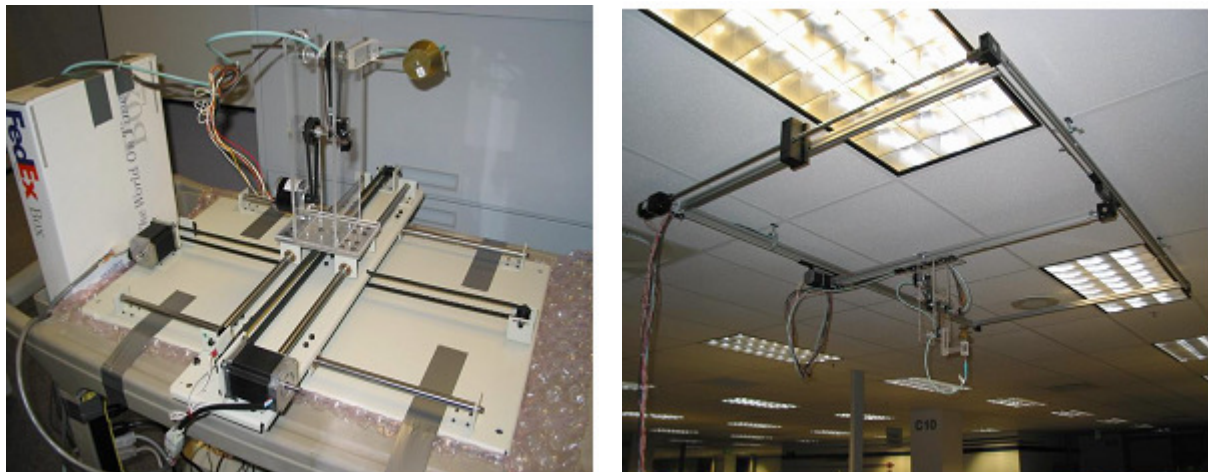
We took measurements using an Agilent 8719ES Vector Network Analyzer (VNA) with various frequency spans (2-8 GHz, 5-6 GHz, 5.15-5.40 GHz, etc.) and resolutions (typically 801 or 1601 frequency points). Two 2-8 GHz low-noise amplifiers with 23 dB gain each were consistently used. A 2-8 GHz power amplifier with 34 dB gain was used for longer range measurements and was shielded in a metal box to prevent RF leakage. This setup is shown in **Figure 2**.



**Figure 2. Typical equipment setup.**

The VNA and the antenna positioning equipment were controlled via software so that all measurements could be automated and run unattended.

The positioners and antenna assemblies are shown in **Figure 3**.



**Figure 3. Antenna positioners. Left: STA. Right: AP.**

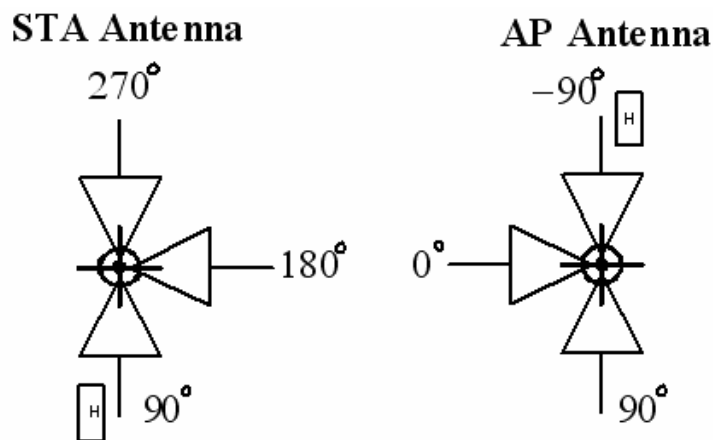
## 2.3 Description of Measurement Campaign

### 2.3.1 Conventions

All the measurements are described in detail in the *MIMO\_Measurement\_Summary.xls* file located at the University of Southern California's FTP site in the */MIMO/Documentation* directory. For each measured data set, the file notes the date of the measurement, position of the AP, position of the STA, number of measurements, AP and STA movement setup, polarization setup, frequency span and resolution, description of the measurement environment, and any remarks.

In all of our measurements, the STA was used as the transmit unit (TX) while the AP was used as the receive unit (RX). The STA positioner was built by Arrick Robotics while the AP positioner frame was built by Macron and integrated with motors and drivers from Applied Motion. In all of our documents, the terms STA, TX, and Arrick will be used interchangeably, as will the terms AP, RX, and Macron. Note that because the channel is reciprocal, it does not matter whether AP or STA was transmitter or receiver.

**Figure 4** shows the antenna polarization convention for the desktop-level Arrick/STA/TX and the ceiling-mounted Macron/AP/RX.



**Figure 4. STA and AP antenna polarization convention.**

The figure above shows the antenna positions as seen from the perspective of someone standing rightside up viewing the antenna with the polarization rig behind the antenna. The antenna feed point is the center of rotation. The home switches of the antenna, which allow the antenna to be placed in a known orientation at the start of measurements and which are denoted by the rectangles marked with an "H", are set to two different positions. The 90-degree position is referenced such that the antenna is vertical (disk on top) in the orientation for which the rig was designed. Nominal range of the STA antenna is +90 to +360 degrees. Nominal range of the AP antenna is -90 to +180 degrees.

### 2.3.2 AP and STA Locations

The positions of AP and STA are indicated by both a label and a set of coordinates, both of which refer to the floor plan files *MeasurementPositions.jpg* and *MeasurementPositions\_AP2.jpg* located at USC's FTP site in the */MIMO/Documentation* directory. The coordinates are in meters relative to the bottom-left corner of the floor plan (the x-axis increasing horizontally from left-to-right and the y-axis increasing vertically from bottom-to-top) and the label corresponds to labels printed on the floor plan. In the measurement campaign, there were 2 fixed AP location (A1 & A2) and 41 STA locations (S1 to S41).

**Figure 5** shows the office layout and measurement locations. The AP was fixed, at different times, in the sites marked A1 and A2 while the STA was moved around the office to the various sites marked with the prefix S. The purple lines represent walls while the thick blue lines indicate windows. Note that STA locations S5, S10, and S13 are all in a conference room with drywall and a closed wooden door.

At each intersection of the lines labeled A through F and 8 through 11 is a 2.5'x2' floor-to-ceiling structural column.





Figure 5. Office layout and measurement locations. A\* is the AP location. Each S\* is a different STA location. Top: Measurement positions for A1. Bottom: Measurement positions for A2.

### 2.3.3 AP and STA Movement Setup

The AP and STA movement setup (specified in the column titled “Description: Mechanics” in the spreadsheet) describes the mechanical motion of the positioners and the type of measurement conducted. Mechanical motion can be categorized as grid setups and cross setups. Special types of measurements include interlace, coherence, and Doppler.

An example description of a grid setup is:

**37x37 STA (0.5" step, 1.5' square travel), 4 AP (4" step, 4" square travel)**

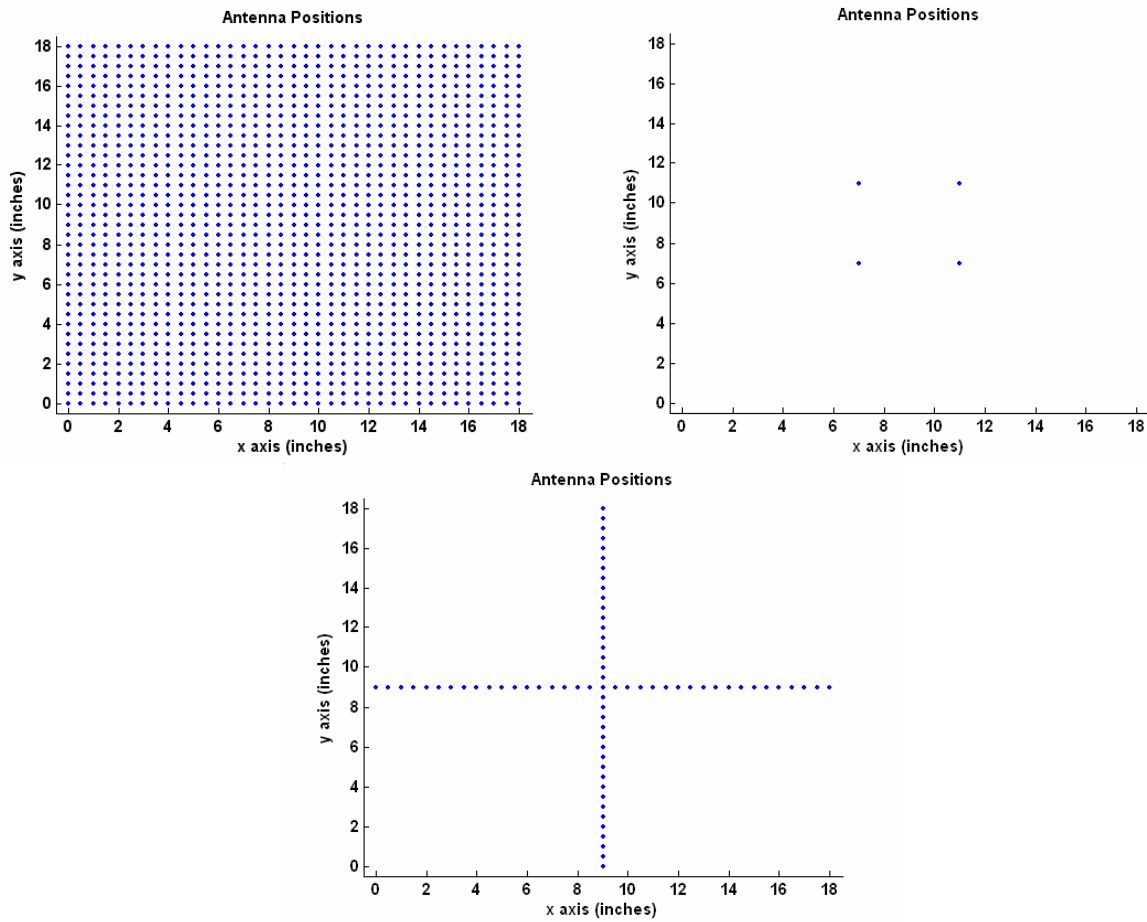
In this example, there were 1369 ( $37 \times 37$ ) different STA antenna positions in a square grid pattern 1.5' across with 0.5" between each position. On the AP side, there were 4 antenna positions, one each at the vertices of a 4" square. Thus we measured a total of 5476 ( $37 \times 37 \times 4$ ) different channels between the AP and STA for this particular setup.

An example of a cross setup is:

**Cross: 1 STA, 37+37 AP (0.5" step)**

In this case the cross was performed at the AP and there was only one antenna position at the STA. The cross was made up of two perpendicular lines running down the center of the positioner, 37 positions by 37 positions. Thus there were a total of 74 ( $37 + 37$ ) channels between AP and STA in this measurement.

**Figure 6** depicts these antenna positions.



**Figure 6. Example antenna positions. Top-left: 37x37, 0.5" spacing, 1.5' across. Top-right: 2x2, 4" spacing, 4" across. Bottom: cross, 37+37, 0.5" spacing, 1.5' across.**

The phrase “**interlace test**” indicates that a set of measurements was repeated in the same location, separated in time by roughly 12 hours, in a test to measure the repeatability of the measurements and the stationarity of the environment. An analysis of the interlace tests of sequences #53 / #54 and #55 / #56 showed that the two sets of measurements spaced in time do indeed match (a mean difference of less than 12%), indicating a stationary environment.

In the coherence measurements the AP and STA antennas did not move at all. Instead, two people walked around the AP and STA setups while measurements were being taken. A single frequency, or a small set of frequencies, was measured repeatedly over a short period of time.

For the Doppler test measurements the antennas were moved during a single measurement to see the Doppler effect. Like the coherence measurements, the data points were sampled at a single or small set of frequencies repeatedly over time.

We conducted both the “**coherence**” and “**Doppler**” tests to measure the channel coherence time. The labels “**coherence**” and “**Doppler**” are only used to differentiate the setups where the antennas were stationary or were moving.

### 2.3.4 Polarization Setup

In most of the measurements, both the AP and STA antennas were oriented vertically, as noted in the measurement summary file by the letters “VV.” In some cases there are measurements described with “VV HV HH.” This label indicates that there were three measurements for each antenna position, one for each of three different antenna polarization combinations.

The first letter of each pair of letters indicates the polarization of the STA antenna. The second letter indicates the polarization of the AP antenna. Thus the letters “HV” indicate that a measurement was taken with the STA antenna oriented horizontally and the AP antenna oriented vertically. “HH” indicates that a measurement was taken with both AP and STA antennas oriented horizontally.

Note that because the discone develops a squint down along the cone, away from the disk, at higher frequencies, we chose the standard “VV” orientation such that the STA antenna was at 270° and the AP antennas was at 90°. Thus with a “VV” orientation the antennas “point” at each other at higher frequencies. Our characterization of the Pulsicom discone antennas can be found on USC’s FTP site ([ftp://click.usc.edu/Antennas/Pulsicom\\_Characterization.pdf](ftp://click.usc.edu/Antennas/Pulsicom_Characterization.pdf)).

In some data sets the polarization setup is indicated by “TX Pol 90:4:270.” Using our antenna convention, this indicates that the AP antenna was held in the normal position (vertical) while the STA antenna was rotated 180 degrees (from “upside-down” vertical at 90° to horizontal at 180° to “rightside-up” vertical at 270°) in steps of 4 degrees.

The polarization measurements were done to investigate the effect of different antenna orientations on performance. For more information, see the PowerPoint presentation on time variability and polarization results located on USC’s FTP site (<ftp://click.usc.edu/MIMO/Presentations/11-03-0523-00-htsg-propagation-results-802.11-modeling-mimo-channels.ppt>).

### 2.3.5 Frequency Span and Resolution

The channel measurement summary notes the frequency span and resolution for each data set. For example, “2-8 GHz (1601 pts)” indicates measurements spanning 2 to 8 GHz with 1601 frequency points (wideband, 3.75 MHz spacing). “5.15-5.40 GHz (801pts)” indicates measurements spanning 5.15 to 5.40 GHz with 801 points (802.11a sub-carrier spacing of 312.5 kHz). When two frequency bands are listed (e.g., “2-3 GHz (1601 pts) / 5-6 GHz (1601 pts)”), we performed each measurement in the set in both bands.

In a few cases the data set shows the following:

**Coherence measurement, 1601pt, 800.5 ms sweep time, 5.16 GHz**

For coherence measurements, the same frequency is measured repeatedly over a short period of time. In this case, the channel between AP and STA is measured 1601 times at 5.16 GHz for a total time of 800.5 ms (one measurement is taken every 0.5 ms).

### 2.3.6 Measurement Environment and Remarks

The measurement environment column describes the physical environment around the AP and STA. This description notes whether the AP and STA have line-of-sight (LOS) or not (NLOS), the distance between the AP and STA, the elevation of the AP, and whether the STA is in a conference room or is around any other objects that may affect propagation (walls and windows, metal cabinets, etc.).

For example, “**NLOS, AP 1.12 m, 9.29m separation**” indicates that for this particular measurement, there was no line-of-sight between the AP and STA and that the two were separated by approximately 9.29 meters. This description also indicates that the AP antenna was 1.12 meters above the ground instead of the typical height of 2.29 meters (7.5’). This group of measurements was done to investigate the effect of AP elevation on MIMO capacity. For more information, see the PowerPoint presentation on elevation results located at USC’s FTP site ([ftp://click.usc.edu/MIMO/Presentations/11-03-xxx-00-000n-Elevation\\_TGn.ppt](ftp://click.usc.edu/MIMO/Presentations/11-03-xxx-00-000n-Elevation_TGn.ppt)).

The remarks section is useful since it points out data sets where the measurements are in doubt or are bad. The following are examples of two data sets that are in doubt and one data set that should not be used for any analysis:

**STA may have slipped!**  
**Using New Antenna, AP not stable**  
**BAD DATA: incorrect polarization!**

Note that the measurement summary file is color-coded to visually differentiate good and bad data sets (bad data sets appear in red).

## 3 Measurement Files

---

### 3.1 Measurement Post-Processing: Isolating the Channel

All available measurement data has been post-processed to isolate the wireless channel. The frequency response of all characterizable components in the system, including amplifiers, cables, and antennas, has been removed from the measurements. Unfortunately the measurements cannot be used to determine absolute delay (time-of-flight) because of a phase-wrapping issue with the antenna characterization. Delays are still valid in a relative sense, however, as is made apparent by the “Wavefronts in Time” analysis described in section 4.1.

Removing the effect of the antennas is a complex problem that we address very simply. While the Pulsicom antennas used in our measurements are azimuthally symmetric, they are by no means symmetric in elevation (again, our characterization of the Pulsicom discone antennas can be found on USC’s FTP site). Since it is difficult to accurately extract elevation angle-of-arrival from our planar measurements, we assume that energy typically arrives from the line-of-sight direction. Thus the post-processed measurements have been compensated for the gain of the antennas at the elevation angle corresponding to the LOS path. It is apparent from the angular spectra analysis in section 4.2 that energy arrives from other directions. However the LOS path is often the strongest component in the office environment; we thus believe that this compensation is a reasonable method to remove the effect of the antennas.

### 3.2 Retrieving the Measurement Data Sets

All of the good MIMO measurement data sets are located at the University of Southern California’s FTP site, accessible via anonymous login. The MIMO measurement files are located at:

<i>/MIMO/Data/ZipFiles</i>	individual data files, compressed by data set
<i>/MIMO/Data/ConcatFiles</i>	concatenated files
<i>/MIMO/Data/FFTfiles</i>	2-D FFT of the concatenated files

The *ZipFiles* directory contains zip compressed files of the original individual MIMO measurement data files. Each zip file corresponds to a specific data set, identified by a sequence number that can be indexed in the *MIMO\_Measurement\_Summary.xls* file, and contains all the individual measurement files in that sequence. For example, sequence #7 consists of 5,476 separate measurements, all of which can be found in file *07.zip*. Each individual measurement file is stored in a .mat format which can be loaded directly into Matlab.

The *ConcatFiles* and *FFTfiles* directories contain the same MIMO measurement data after additional processing. The *ConcatFiles* directory contains the concatenated versions of the measurement files. A single .mat file in this directory contains an entire array of measurements. This format is particularly useful for MIMO analysis since it eliminates the need to load

individual measurement files and stores the measurements in a uniform manner, consistent with our coordinate system (described in detail in the next section).

The *FFTfiles* directory contains the Fourier transformed versions of the concatenated files. Each .mat file in the *FFTfiles* directory is a 2-D Fourier transform of the corresponding concatenated file in the *ConcatFiles* directory. These FFT files are useful for angular spectra analysis, presented in section 4.2.

USC's website at <http://impulse.usc.edu> has additional measurement data. The website contains the Intel UWB Channel Measurement Database and allows query and retrieval of the residential and primarily SISO channel measurements collected by Intel Labs. There is an online pdf document detailing instructions on using the Intel UWB Channel Measurement Database.

### 3.3 Data Set Coordinate System

Before using the measurement data, take a look at sheet 2 of the *MIMO\_Measurement\_Summary.xls* file. It lists the AP and STA movements with the start, increment, and stop locations. More importantly, it lists the absolute coordinates for the AP and STA.

We used three different coordinate systems in our measurements: absolute, AP, and STA. The absolute coordinate system corresponds to the office layout shown in **Figure 5**. The origin is located at the bottom-left corner of the floorplan. The x-axis increases toward the right of the floorplan; the y-axis increases toward the top. AP and STA each has its own local coordinate system relative to the home position of its antenna. (the home position is the position the antenna is placed at the start of every measurement run to ensure repeatability and reduced positioning error.) The home positions of the AP and STA are listed in absolute coordinates in the "AP Position" and "STA Position" columns on sheet 1 of the *MIMO\_Measurement\_Summary.xls* file. However, the individual measurement filenames reference the local coordinate system used by the AP and STA. In this local coordinate system, the home position corresponds to x=0 and y=0. In all of our measurements, the AP and STA movements are strictly limited to the first quadrant (positive x, positive y) of their respective local coordinate system.

In sequence #65, the local AP and STA movements are listed below:

<b>RxX start</b>	<b>= 6096</b>	Receiver/AP local x-coordinate starting point
<b>RxX end</b>	<b>= 7620</b>	Receiver/AP local x-coordinate ending point
<b>RxX inc</b>	<b>= 1524</b>	Receiver/AP local x-coordinate step size
<b>RxY start</b>	<b>= 3048</b>	Receiver/AP local y-coordinate starting point
<b>RxY end</b>	<b>= 4572</b>	Receiver/AP local y-coordinate ending point
<b>RxY inc</b>	<b>= 1524</b>	Receiver/AP local y-coordinate step size
<b>TxX start</b>	<b>= 0</b>	Transmitter/STA local x-coordinate starting point
<b>TxX end</b>	<b>= 1524</b>	Transmitter/STA local x-coordinate ending point
<b>TxX inc</b>	<b>= 508</b>	Transmitter/STA local x-coordinate step size
<b>TxY start</b>	<b>= 0</b>	Transmitter/STA local y-coordinate starting point



<b>TxY end</b>	<b>= 1524</b>	Transmitter/STA local y-coordinate ending point
<b>TxY inc</b>	<b>= 508</b>	Transmitter/STA local y-coordinate step size

The numbers are listed in units of 10\*millimeters (6096 is thus 0.6096 meters). We chose to use this unit to avoid decimal points in the filenames. Converting these numbers to inches (1 inch = 0.0254 meter), we see that the AP is moving in 6" steps while the STA is moving in 2" steps. Further calculation will show that there are 2x2 (a total of 4) AP measurement locations and 4x4 (a total of 16) STA measurement locations, which matches the measurement description on sheet 1 for this sequence.

Sheet 2 of the *MIMO\_Measurement\_Summary.xls* file also contains the information to translate the local AP and STA coordinate systems to the global absolute coordinate system. There are four columns that describe the translation:

<b>RxX AbC</b>	Receiver/AP x-coordinate translation equation to absolute coordinates
<b>RxY AbC</b>	Receiver/AP y-coordinate translation equation to absolute coordinates
<b>TxX AbC</b>	Transmitter/STA x-coordinate translation equation to absolute coordinates
<b>TxY AbC</b>	Transmitter/STA y-coordinate translation equation to absolute coordinates

There are four notations used:

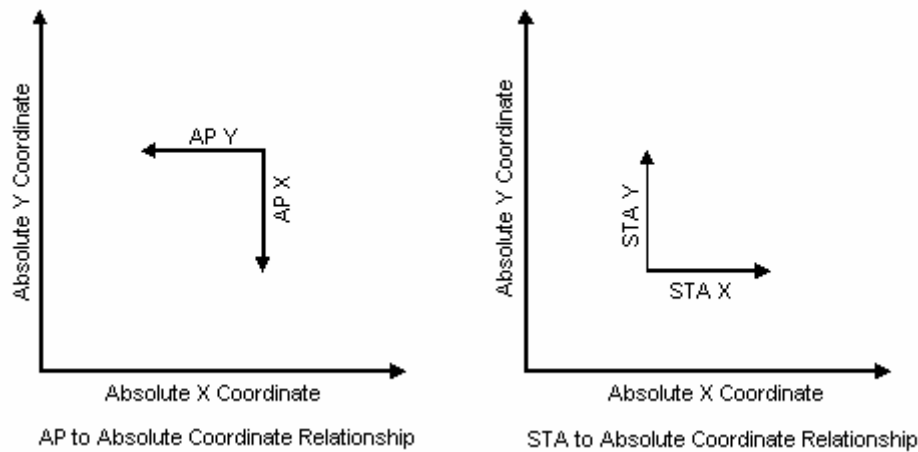
<b>Mx</b>	absolute x-coordinate
<b>My</b>	absolute y-coordinate
<b>mx</b>	local x-coordinate
<b>my</b>	local y-coordinate

For example, a sequence may have the following:

<b>RxX AbC = Mx-my</b>	For Receiver/AP, increasing absolute x-coordinates correspond to decreasing local (AP) y-coordinates.
<b>RxY AbC = My-mx</b>	For Receiver/AP, increasing absolute y-coordinates correspond to decreasing local (AP) x-coordinates.
<b>TxX AbC = Mx+mx</b>	For Transmitter/STA, increasing absolute x-coordinates correspond to increasing local (STA) x-coordinates.
<b>TxY AbC = My+my</b>	For Transmitter/STA, increasing absolute y-coordinates correspond to increasing local (STA) y-coordinates.

Graphically, this conversion is represented in **Figure 7**.



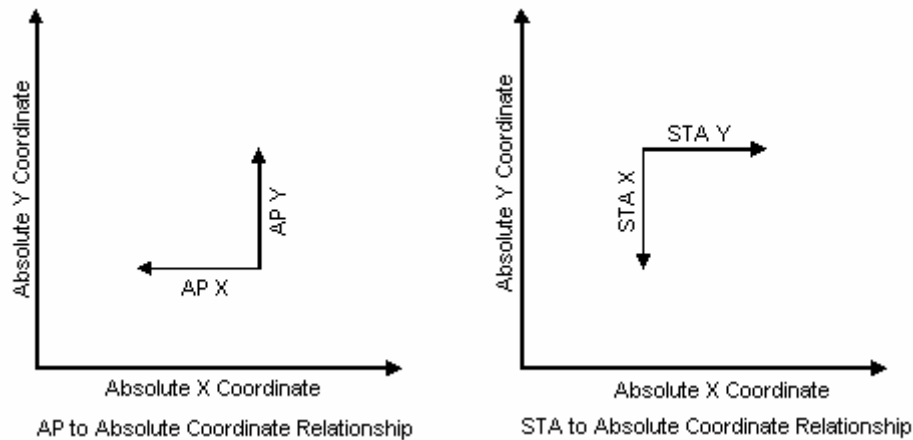


**Figure 7. Example of AP/STA local coordinate system to absolute coordinate system conversion.**  
**Left: first quadrant of AP coordinate system in relationship to first quadrant of absolute coordinate system. Right: first quadrant of STA coordinate system in relationship to first quadrant of absolute coordinate system.**

In another example:

<b>RxX AbC = Mx-mx</b>	For Receiver/AP, increasing absolute x-coordinates correspond to decreasing local (AP) x-coordinates.
<b>RxY AbC = My+my</b>	For Receiver/AP, increasing absolute y-coordinates correspond to increasing local (AP) y-coordinates.
<b>TxX AbC = Mx+mx</b>	For Transmitter/STA, increasing absolute x-coordinates correspond to increasing local (STA) x-coordinates.
<b>TxY AbC = My-my</b>	For Transmitter/STA, increasing absolute y-coordinates correspond to decreasing local (STA) y-coordinates.

Graphically, this conversion is represented in **Figure 8**.



**Figure 8. Another example of local coordinate system to absolute coordinate system conversion.**  
**Left: first quadrant of AP coordinate system in relationship to first quadrant of absolute coordinate system. Right: first quadrant of STA coordinate system in relationship to first quadrant of absolute coordinate system.**

## 3.4 Using the Different Data Sets

### 3.4.1 Individual Data Files

The individual data files are all stored in the */MIMO/Data/ZipFiles* directory at USC's FTP site. They are grouped by zipped files, the filenames of which indicate the sequence number of the data. For example, the file *15.zip* contains all 256 data files for sequence #15. The filename format for these individual files is as follows:

**[A],[B]\_[C],[D]\_[E],[F]\_[G]\_[H]\_[I].mat**

- A** Transmit x-location in 10\*millimeters (STA local coordinate)
- B** Transmit y-location in 10\*millimeters (STA local coordinate)
- C** Receive x-location in 10\*millimeters (AP local coordinate)
- D** Receive y-location in 10\*millimeters (AP local coordinate)
- E** Transmit antenna polarization in degrees
- F** Receive antenna polarization in degrees
- G** Starting frequency in 10\*GHz, rounded
- H** Stopping frequency in 10\*GHz, rounded
- I** Sequence number

Below are some sample filenames from sequence #15:

<b>1000,1000_1000,1000_270,090_52_54_15.mat</b>	(first file)
<b>1000,1000_1000,2016_270,090_52_54_15.mat</b>	(second file)
...	
<b>4048,4048_4048,4048_270,090_52_54_15.mat</b>	(last file)

For the first file, the filename indicates that the transmitter/STA is at x=100mm and y=100mm, receiver/AP is at x=100mm and y=100mm, transmit/STA antenna is vertically polarized (see **Figure 4** for antenna polarization conventions), receive/AP antenna is vertically polarized, frequency band is 5.15 GHz to 5.40 GHz (refer to the measurement summary spreadsheet for the exact frequency band), and this measurement was for sequence #15. The filename of the last file indicates that the transmitter/STA is at x=404.8mm and y=404.8mm, receiver/AP is at x=404.8mm and y=404.8mm, and the other parameters remained the same.

Here is a sample filename from sequence #163:

**2286,2286\_2540,2286\_270,090\_20\_30\_163.mat**

In this case, the filename indicates that the transmitter/STA is at x=228.6mm and y=228.6mm, receiver/AP is at x=254.0mm and y=228.6mm, transmit/STA antenna is vertically polarized, receive/AP antenna is vertically polarized, and frequency band is 2 to 3 GHz.

Each of these .mat files can be loaded into Matlab directly using the load 'filename' command. The load command will retrieve two variables, data\_dB and data\_phase, from the .mat file. The data\_dB variable contains the magnitude information in decibels and the data\_phase variable contains the phase information in radians. For example, the Matlab command

**load '1000,1000\_1000,1000\_270,090\_52\_54\_15.mat'**

will load the two variables data\_dB and data\_phase into Matlab. The dimension of both variables is 801-by-1 corresponding to the 801 frequency points listed in the MIMO measurement summary file for sequence #15 (5.15 to 5.40 GHz, 312.5 kHz spacing).

These individual data files are useful for analyzing a small subset of a particular sequence or for taking a sampling over all measurements (as for path loss and delay spread analysis) but for analysis requiring the entire data set (e.g. generating wave front propagation movies), the concatenated files are more useful.

### 3.4.2 Concatenated Data Files

The concatenated data files are all stored in the */MIMO/Data/ConcatFiles* directory at USC's FTP site. This directory contains the concatenated files along with the Matlab scripts that were used to generate these files from the individual data files. These concatenated files were generated to provide easy access to a set of measurements during analysis so only selected sequences have these files. However, the provided Matlab scripts that generated these files can be modified to concatenate other sequences.

The filename format for the concatenated data files is as follows:

**[A]\_[B]-[C]\_[D],[E]\_[F][G],[H].mat**

**A**      Sequence number

- B** Starting frequency in GHz
- C** Stopping frequency in GHz
- D** Transmit antenna polarization in degrees
- E** Receive antenna polarization in degrees
- F** Indicates whether the subsequent coordinate is for the TX or RX
- G** The x-location in 10\*millimeters (local coordinate)
- H** The y-location in 10\*millimeters (local coordinate)

Below are the concatenated files for sequence #23 along with the Matlab script:

```
seq23_2-8_270,090_tx0000,0000_mimo.mat
seq23_2-8_270,090_tx0000,1016_mimo.mat
seq23_2-8_270,090_tx1016,0000_mimo.mat
seq23_2-8_270,090_tx1016,1016_mimo.mat
seq23_5.15-5.40_270,090_tx0000,0000_mimo.mat
seq23_5.15-5.40_270,090_tx0000,1016_mimo.mat
seq23_5.15-5.40_270,090_tx1016,0000_mimo.mat
seq23_5.15-5.40_270,090_tx1016,1016_mimo.mat
seq23_concat_data.m
```

The filename for the first data file indicates data for sequence #23, frequency band 2 to 8 GHz, transmit/STA antenna vertically polarized, receive/AP antenna vertically polarized, and transmit/STA antenna located at x=0mm and y=0mm (data is from the “perspective” of the receiver/AP, since that is the side with the antenna array). The last data filename indicates data for sequence #23, frequency band 5.15 to 5.40 GHz, transmit/STA antenna vertically polarized, receive/AP antenna vertically polarized, and transmit/STA antenna located at x=101.6mm and y=101.6mm (data is from the perspective of the receiver/AP).

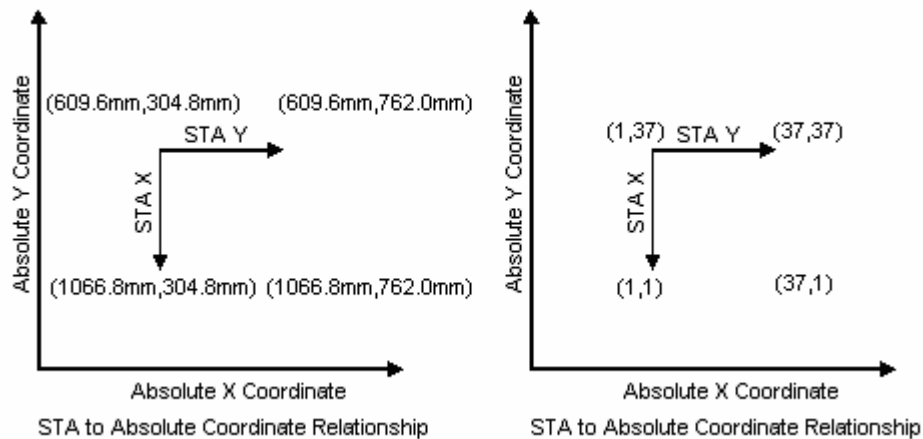
The MIMO measurement summary description for sequence #23 shows that there are 2-by-2 STA/TX positions and 37-by-37 AP/RX positions over two different frequency bands: 2-8 GHz (1601 sample points) and 5.15-5.40 GHz (801 sample points). Hence there are four concatenated files from the AP/RX perspective for each of the frequency bands. Each concatenated file contains measurements for the 37-by-37 AP/RX locations for each STA/TX location.

These files load directly into Matlab. The command **load 'seq23\_2-8\_270,090\_tx0000,0000\_mimo.mat'** yields two variables `data3D_dB` and `data3D_phase` which correspond to a 2-D array of individual `data_dB` and `data_phase` data. They both have the dimension of 37-by-37-by-1601. Each 37-by-37 slice of the array represents a separate frequency, each point on the 37-by-37 grid is one antenna position. Units of the array are thus (meter, meter, Hz) and the array represents (x-position, y-position, frequency).

Similarly, the command **load 'seq23\_5.15-5.40\_270,090\_tx1016,1016\_mimo.mat'** will yield the same two variables but with dimensions of 37-by-37-by-801. This result corresponds to the measurement summary description, which indicates 1601 sample points for the 2-8 GHz frequency band and 801 sample points for the 5.15-5.40 GHz frequency band.

These files are concatenated such that the ordering of the arrays corresponds to the absolute coordinate system. For example, `data3D_dB(1,1)` is the measurement made in the lower-left

corner of the array (in the absolute coordinate system), `data3D_dB(37,37)` is the measurement made in the upper-right corner, `data3D_dB(1,37)` the upper-left, and `data3D_dB(37,1)` the lower-right. The mapping from individual data files to the 2-D array varies with each sequence depending on how the STA and AP were situated, as explained in section 3.3. **Figure 9** shows an example of this mapping for sequence #23.



**Figure 9. Local coordinate orientation to concatenated file orientation for sequence #23.**  
**Left: local coordinate orientation of STA/TX (numbers in parentheses are local x,y coordinates).**  
**Right: concatenated file's array indexing (numbers in parentheses are Matlab array indices).**

The script file `seq23_concat_data.m` is used to generate these concatenated files and can be used as a guide to concatenate other sequences. It is also useful to see how the local coordinate orientation is translated to the absolute coordinate orientation.

### 3.4.3 FFT Files

The `/MIMO/Data/FFTfiles` directory at USC's FTP site stores all of the 2-D FFT data used for angular spectra analysis. As before, not all of the concatenated files were converted into this format. However, the Matlab script used to generate these files (`as_savefft_volts.m`) is provided for reference on the FTP site. This script file is easily modified to generate other FFT files.

The filename format for the FFT files is basically the concatenated data filename with a `_fft` extension at the end indicating that the file has been Fourier transformed. Below are some FFT files for sequence #23:

```
seq23_5.15-5.40_270,090_tx0000,0000_fft.mat
seq23_5.15-5.40_270,090_tx0000,1016_fft.mat
seq23_5.15-5.40_270,090_tx1016,0000_fft.mat
seq23_5.15-5.40_270,090_tx1016,1016_fft.mat
```

Loading any of the files above in Matlab will yield the variable `as3D` with a size of 37-by-37-by-801. Each 37-by-37 slice of the array represents a separate frequency. Units of the array are

(radians/meter, radians/meter, Hz) and the array represents (x-direction wavenumber, y-direction wavenumber, frequency). The values stored in the array are complex voltage.

The analysis section in the 2003 MPRG paper, located at [ftp://click.usc.edu/MIMO/Papers/Angular\\_Spectra\\_Results\\_for\\_Office\\_Environment.pdf](ftp://click.usc.edu/MIMO/Papers/Angular_Spectra_Results_for_Office_Environment.pdf), gives a detailed explanation of angular spectra and wavenumbers.

The following is a comparison of the units used for the three types of measurement data using sequence #23 as an example:

### **Individual Data File**

*Matlab Command:*

```
load '0000,0000_10033,3048_270,090_52_54_23.mat'
```

*Result:*

data\_dB in decibels with size of 801-by-1  
phase\_dB in radians with size of 801-by-1  
data\_dB and phase\_dB are measured at a single location over 801 frequency points.

### **Concatenated Data File**

*Matlab Command:*

```
load 'seq23_5.15-5.40_270,090_tx0000,0000_mimo.mat'
```

*Result:*

data3D\_dB in decibels with size of 37-by-37-by-801  
phase3D\_dB in radians with size of 37-by-37-by-801  
data3D\_dB and phase3D\_dB are a 37-by-37 2-D distance grid over 801 frequency points.

### **2D-FFT of Concatenated Data File**

*Matlab Command:*

```
load 'seq23_5.15-5.40_270,090_tx0000,0000_fft.mat'
```

*Result:*

as3D in voltage with size of 37-by-37-by-801  
as3D is a 37-by-37 2-D wavenumber grid over 801 frequency points.

## 4 Sample Analysis

---

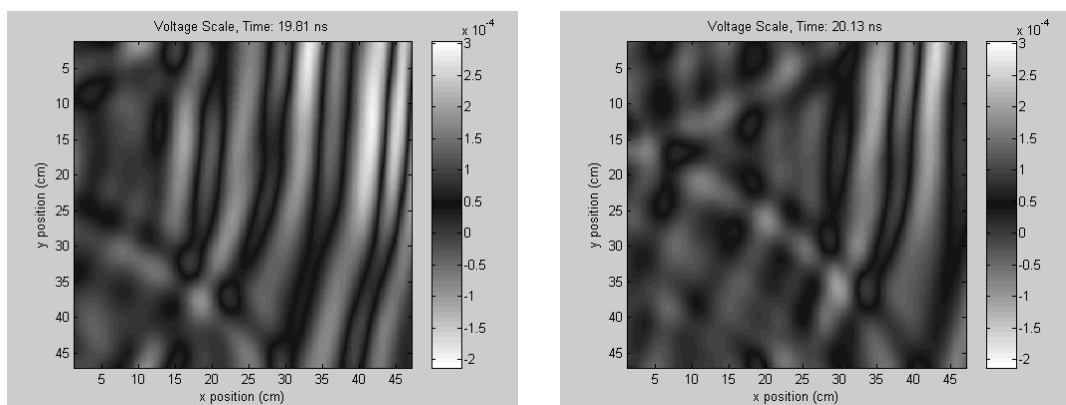
Here are some sample analyses of the MIMO measurement data. For additional examples of analysis and additional detail, please see section 5. That section contains links to various papers and presentations that analyzed the MIMO measurements.

We have performed all of our analysis in Matlab. The relevant scripts are all located in the */MIMO/MatlabScripts/* directory at USC's FTP site.

### 4.1 Wavefronts in Time

For each measurement location, the VNA provides the channel transfer function at each position on the  $n$ -by- $n$  array. The inverse Fourier transform of the network analyzer measurements over the array produces an array of impulse responses. Displays of the impulse response over the spatial array at a fixed moment in time show the position and shape of waves as they pass over the array. Snapshots in time can be sequenced together to form a movie that illustrates the motion of the waves, angles of arrival, and diffractive scattering. Kunisch demonstrated in his paper "Measurement Results and Modeling Aspects for the UWB Radio Channel" that plotting the impulse response over the two-dimensional array at a sequence of times allows us to generate a movie that depicts the propagation of RF energy over the array.

**Figure 10** below shows two frames of such a movie, generated from 2-8 GHz data for sequence #7, STA perspective, and 3 m from the AP. These frames are five frames or 0.32 ns apart (time resolution is increased with interpolation) and show three distinct wavefronts passing over the array: the main line-of-sight (LOS) path and reflections off two nearby metal cabinets.



**Figure 10. Two frames, 0.32 ns or 5 frames apart, from the movie for sequence #7.**

To generate a wavefront movie, select a concatenated data file and process it with the following three Matlab script files sequentially:

create\_time.m

Input: 2-D MIMO concatenated data array

Output: 2-D inverse Fourier transform of the MIMO data array

create\_time\_shift.m

Input: 2-D inverse Fourier transform of the MIMO data array

Output: Time shifted impulse response array (peak shifted to 20 ns)

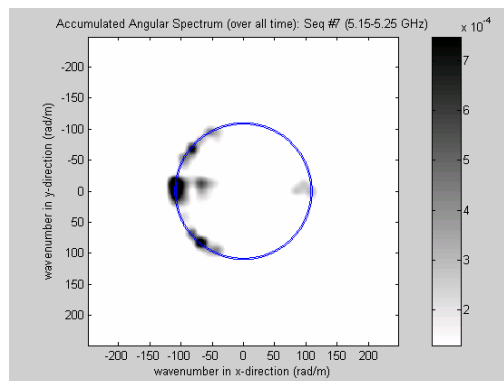
make\_movie.m

Input: Time shifted impulse response array

Output: AVI movie depicting wavefront propagation over array in time

## 4.2 Angular Spectra

While the above time domain approach provides an excellent tool to observe wavefront propagation, it is difficult to quantify the direction from which energy arrives using it. For this analysis we turn to the angular spectrum. By taking the 2-D Fourier transform across an array of n-by-n transfer functions at a single frequency, we generate the angular spectrum at that frequency and can thus quantify the angles of arrival.



**Figure 11. Angular spectrum for sequence #7, showing the three primary angles of arrival plus backscatter. Scale is linear power\*m<sup>4</sup>.**

**Figure 11** shows the angular spectrum for sequence #7 accumulated over all time and over a frequency band of 5.15-5.25 GHz. Here we can see the three clusters that correspond to the LOS path and two cabinet bounces, in addition to a small amount of backscatter. Note that this plot has been oriented such that the perspective is that of the office layout as seen from above.

In this plot, the x and y axes are x- and y- components of the wavenumber in radians/meter, where the wavenumber  $k$  is

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}.$$

As described by Helmholtz equation, the physics of electromagnetic wave propagation requires that

$$k_x^2 + k_y^2 + k_z^2 = k^2.$$

If we assume that energy is incident upon the antenna array with 0° elevation ( $k_z = 0$ ), the angular spectrum will show energy along a circle of radius  $k$ . This circle is drawn for reference



in **Figure 11**. Any energy within the perimeter of this circle is incident upon the array with a non-zero elevation angle. Generally, only measurement and processing artifact appears outside the circle.

We have generated movies to display the dependence of the angular spectrum on measurement frequency. These movies allow us to detect scattering clusters and ascertain their spectral permanence. An inverse Fourier transform of the angular spectrum across frequency yields the angular spectrum as a function of time delay. These results can be used in the analysis of multi-antenna Rake receivers and tapped delay line channel models.

We used the following Matlab script to generate the angular spectra movie.

[anspc2d\\_v4.m](#)

Input: FFT of a 2-D concatenated data file

Output: AVI movie of angular spectra progressing in frequency domain

The USC website provides an interactive demo of this angular spectrum analysis. Additional analysis, including path loss and delay spread calculation for the residential measurements, can also be found on the website.

The Matlab routines used for all of the demos are located on USC's FTP site. The 2003 MPRG and the 2003 WNCG papers listed in the next section have a more in-depth analysis of angular spectra and clustering phenomenon.

## 5 Resources

---

### Intel Channel Measurement Database Web Page

<http://impulse.usc.edu>

### Intel Channel Measurement Database FTP Site

<ftp://click.usc.edu> (anonymous login)

### FTP Directory Structure

<ftp://click.usc.edu>

```
├ Antennas
├ MIMO
│   ├── Data
│   │   ├── ZipFiles
│   │   ├── ConcatFiles
│   │   └── FFTfiles
│   ├── Documentation
│   ├── MatlabScripts
│   ├── Papers
│   └── Presentations
│       ├── 2003_1024_WNCG
│       └── Movies
├ UWB
│   ├── Data
│   │   ├── UWB_SQLDB_Files
│   │   └── MatFiles
│   ├── Demos
│   │   ├── Pathloss
│   │   └── DelaySpread
│   ├── Documentation
│   └── Papers
└ MatlabLibrary
```

## Description of Directories

**Antennas:** characterization report of Pulsicom discone antenna

**MIMO:** all files related to MIMO channel measurements

**Data:** MIMO channel measurement data in various formats

**Documentation:** detailed summary of measurements, map of measurement locations, this user guide

**MatlabScripts:** Matlab scripts for MIMO analysis (wavefronts in time and angular spectrum)

**Papers:** papers describing measurements and analysis performed by Intel Labs

**Presentations:** presentations for IEEE 802.11n meeting on channel models (Ricean K-factor, elevation and polarization effects, coherence time) and for 2003 WNCG symposium at UT-Austin, various movies showing RF propagation

**UWB:** all files related to UWB channel measurements

**Data:** database files and associated documentation, channel measurement data

**Demos:** Matlab scripts for analysis of pathloss and delay spread

**Documentation:** instructions on how to use the UWB channel measurement data (similar to this file but for the UWB measurements and less detailed)

**Papers:** a comparison of the 2.4 GHz ISM band and the 5 GHz U-NII band from a residential pathloss perspective

**MatlabLibrary:** general Matlab scripts, many used for UWB analysis