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Stanford July 2008 Radio Channel Measurement Campaign

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1 Introduction

This measurement campaign covers two different types of scenarios: (i) Outdoor-to-Indoor MIMO measurements with focus on MIMO interference described in Section 2, and (ii) distributed array measurements, both outdoor-to-indoor and indoor-to-indoor described in Section 3. The data from this measurement campaign is publicly available and can be obtained under the terms in the next section.

The equipment used for both measurements is summarized in Section 4. Finally, the documentation of the individual measurement routes as well as the photograph documentation are provided in the Appendix.

We gratefully acknowledge the support of Beceem Communications Inc., USA, who provided us with a cubicle-style office environment, and helpful support before and during the measurement campaign.

1.1 Terms of use for receiving and using this data

AGREEMENT FOR RECEIVING AND USING DATA

These terms refer to the use of Measurement Data collected by the Smart Antenna Research Group (Collection lead - Dr. Nicolai Czink), Stanford University, in July 2008.

1. DEFINITIONS

- a. "Data" shall mean "Measurement Data" collected by the Smart Antenna Research Group at Stanford University.
- b. "Data Owner" (DO) shall mean Smart Antenna Research Group - Contact: Dr. Nicolai Czink (nicolai.czink@stanford.edu) - at Stanford University
- c. "Data Recipient" (DR) shall mean any individual or institution receiving the Data.

2. AGREEMENT

All prospective DRs wishing to receive and use the Data shall confirm their agreement to these terms to the DO in writing / e-mail.

3. PERMITTED USE

The permitted use of the Data is limited to scientific research purposes. If the results obtained from this data are used in any publications, the source of the data (i.e. Smart Antennas Research Group, Stanford University) has to be acknowledged in the publication.

4. RESTRICTIONS

The DR may not transfer the Data without prior permission from the DO. Commercial exploitation of the data is prohibited.

5. NO WARRANTY

The data is only offered "as is" without any kind of support for its usage, and without any claim to be correct and/or complete.

2 Outdoor-to-indoor measurement campaign

The background of the outdoor-to-indoor (O2I) measurements is to quantify the spatial properties of interference.

Two different outdoor base-station positions were measured, and at each position, the BS was pointed into three different directions to emulate receivers in the center of the cell, and at its edges. For every combination of BS position and direction, we measured five indoor routes. These *routes were maintained with meticulous precision* with the receiver trolley using the distance trigger wheel to trigger the measurements at the same locations. In this way we can interpret the data for one receiver route and two different base station positions as cooperative downlink, or as downlink channel and interference channel.

2.1 Scenarios

Figure 1 shows the map of the outdoor scenario with two transmitter positions and the corresponding transmitter directions. Indoors, we measured along five routes *for each Tx location and rotation* as indicated in Figure 2. There was a glass wall along Route 3, supported by a metallic structure. The cubicles consisted of metal frames with clothing, the offices at the edges were separated by glass walls. The top corner of the rectangle marking the office location in the outdoor transmitter map corresponds to the top-right corner of the route map.

Using the distance trigger wheel, one MIMO block was recorded every 1.6 cm (0.13λ).

2.2 Measurement setup

Outdoors, we used high-gain dual-polarized transmit antennas (see Section 4.2.3) and fixed them to the platform of a scissor lift (see Section 4.6). We did measurements with different Tx antenna spacings: The “Narrow spacing” was 40.6 cm (3.3λ), while the “Wide spacing” was 66 cm (5.4λ).

The antennas were connected to the Tx equipment on the street by long low-loss RF cables (for the cable parameters, see Section 4.3). The cables were first fixed on the platform for strain relief, and then connected to the transmitter switch. The port numbering and specific cables used are given in Table 1. A gas generator (see Section 4.5) provided the electric power supply for both sounder and scissor lift. Figure 3 shows the Tx setup.

Indoors, we mounted the following receive antennas on the receiver trolley: (i) two Discone antennas used as reference, (ii) a planar inverted-F antenna (PIFA) array on a PC Card, (iii) a WiMAX customer premises equipment (CPE) antenna array, (vi) a ceramic antenna array on a USB stick. The mounted configuration is shown in Figure 4, the port configuration is summarized in Table 1. A detailed description of the antennas is found in Section 4.2.

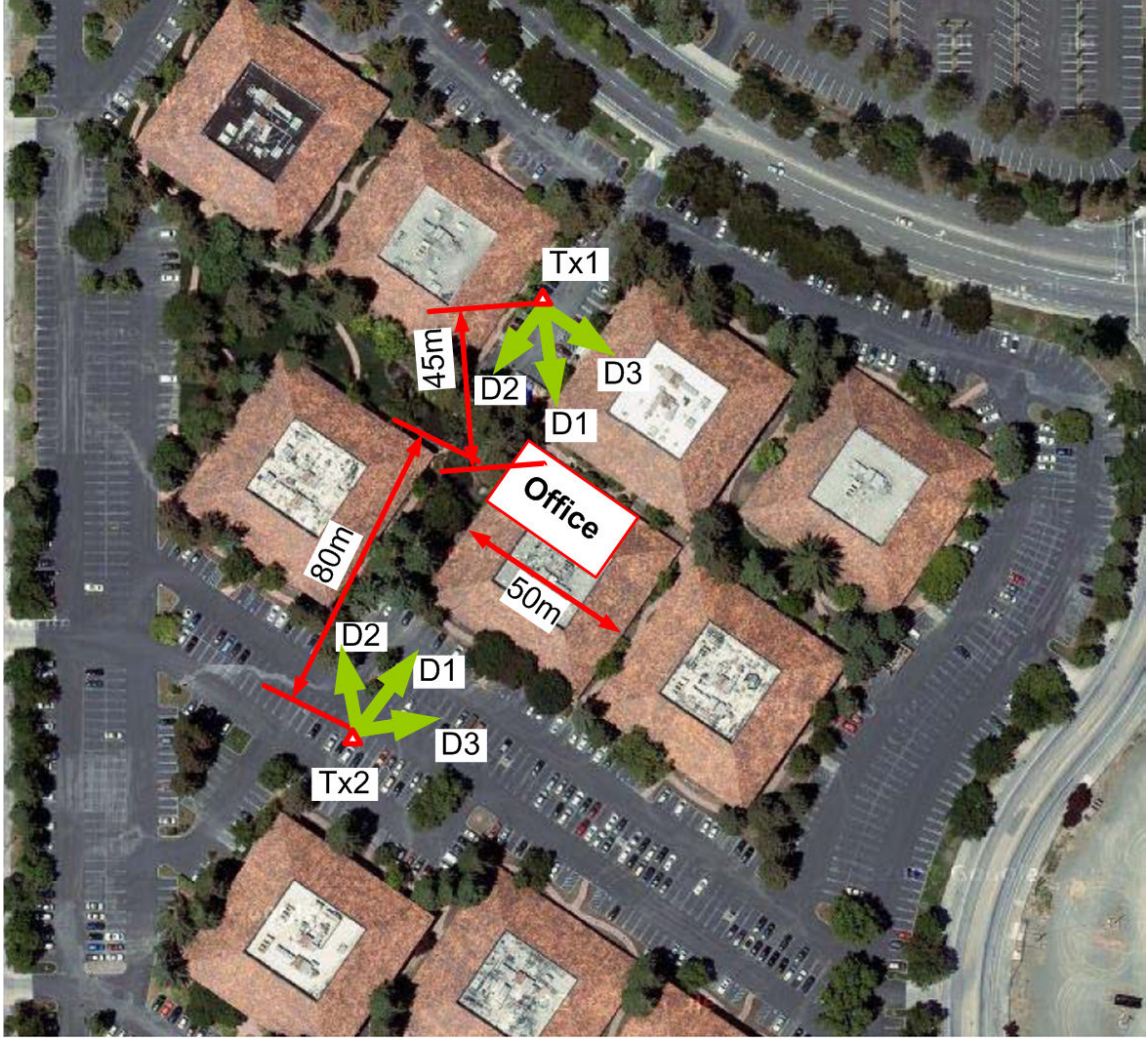


Figure 1: Outdoor measurement map (Picture: © Google Maps)



Figure 2: Outdoor measurement plan



(a)



(b)

Figure 3: Outdoor transmitter setup: (a) Tx sounder equipment, generator, and antennas on retracted lift, (b) Fully deployed configuration

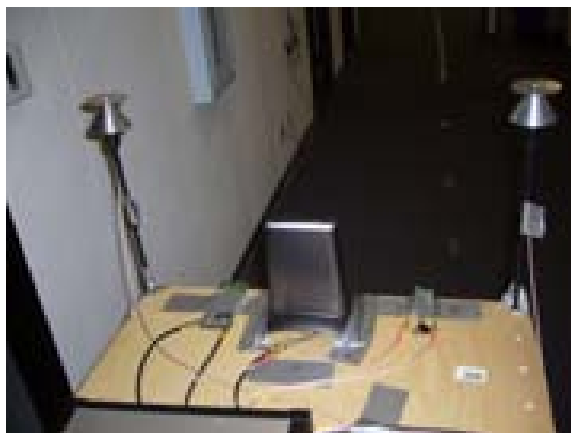


Figure 4: Receive arrays used for the O2I moving measurements (see also Sec. 4.2.1)

Tx switch		
Antenna 1, vert.	Port 1	Cable 1
Antenna 1, hor.	Port 2	Cable 2
Antenna 2, vert.	Port 3	Cable 5
Antenna 2, hor.	Port 4	Cable 7
Rx switch		
Discone antennas	Ports 1-2	
PIFA	Ports 3-4	
CPE	Ports 5-6	
Ceramic array	Ports 7-8	

Table 1: Antenna / port configuration

2.3 Measurement practice

The indoor routes were first marked by duct tape on the floor. Although we tried hard to exactly keep the routes, there was still a distance error of around 2% in the length of the measurements. In few measurements we had troubles with the distance wheel as documented in the individual notes of each measured route. In the case of RF interference (from WiFi and/or microwave ovens) the measurement route was repeated.

However, some routes always showed a certain level of bursty interference. This interference must be eliminated in the post processing. There are two simple ways to eliminate this interference:

- (i) If one is interested in using the measured frequencies as samples, the easiest way is to cut the middle band where WiFi is present
- (ii) When the full bandwidth is required, one can disregard samples with interference. Interference resulted in a significantly higher noise floor in the measured impulse response. This higher noise floor can be detected and the respective snapshot should be disregarded.

During a measurement run, all helping people were at designated places (e.g. at corners to help with the cable). These positions were kept the same for all measurements of the same route.

2.4 Sounding parameters

The channel sounder was configured to sample the channel every 1.6 cm along the travelled route. The exact sounding parameters are provided in Table 2.

Parameter	Value
Spacing between blocks	1.6 cm = 0.13λ
Number of snapshots per block	16
Training sequence length	$3.2\ \mu\text{s}$
Number of channels ($N_{\text{Tx}} \times N_{\text{Rx}}$)	32
Switch gap	$9.6\ \mu\text{s}$
MIMO channel sample time	$307.2\ \mu\text{s}$
Block sample time	4.9 ms

Table 2: Outdoor-to-indoor sounder parameters

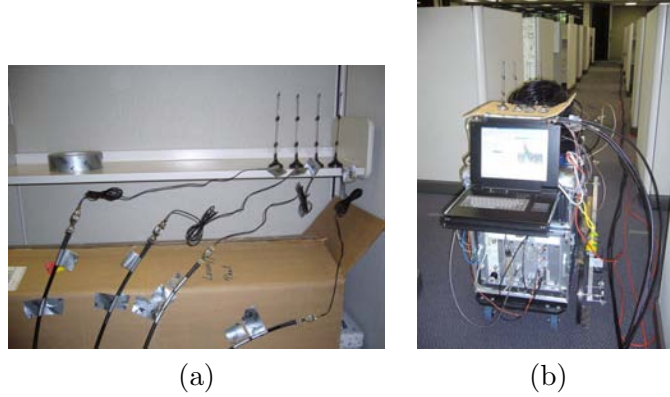


Figure 5: Distributed Rx array measurements: (a) Rx array fixed in the cubicle, (b) moving Rx array on the sounder

3 Distributed antenna measurements

These measurements shall provide input for a number of new ideas. They are grouped into: (i) O2I distributed array measurements, (ii) O2I cooperative relay measurements, (iii) indoor randomly distributed networks, (iv) indoor clustered nodes measurements including interference scenarios, (v) indoor localization measurements, (vi) indoor measurements for spatial focusing.

3.1 Scenarios

3.1.1 Outdoor-to-indoor distributed array measurement

First, we measured the effect of array separation between two 4-element linear uniform Rx arrays. The question is whether one can spatially distinguish between the MIMO channels of the two arrays by signal processing at the Tx.

The setup of the experiment is shown in the route description on page 28. We used the WiFi antennas (see Section 4.2.2) to build the two Rx arrays as shown in Figure 5. One Rx array was fixed in a cubicle, while the other was placed on the receiver and moved towards the fixed Rx array. Both arrays were connected using the long RF cables to ensure similar system parameters. The Tx antenna array (high-gain BS antennas outdoors on a scissor lift, see Section 4.2.3) was placed at Tx1D1 (see Fig. 1) and directed facing the office building.

We did four measurement runs of the same environment using the distance measuring wheel to also check the similarity of the channels in different measurement runs.

3.1.2 Outdoor base station to indoor distributed array measurements

These measurements shall shed light on the following questions: (i) What is the performance of relaying schemes, when there are multiple possible relays? (ii) What is the performance of collaborative schemes for nodes with strongly varying path loss? (iii) What is a good channel model for a system of strongly distributed nodes that are moving locally?

To account for the additional path loss at the receiver caused by the low-loss RF cables, the Tx antennas (high-gain BS antennas outdoors on a scissor lift, see Section 4.2.3) was placed at Tx1D1 (see Fig. 1) and always directed facing the office building (no other directions). We investigated only the closest Tx position because of the high path loss.

The measurement setup is shown in the measurement description on pages 29 and 30.

Indoors, four receive antennas (again, WiFi antennas, see Section 4.2.2) were distributed along the window facing the Tx (simulating “relays”), while the other four antennas were distributed farther back in the office (simulating the destination nodes). The position of the four receivers in the back of the office was changed in a second measurement run while the relays at the window remained fixed.

The locations of the nodes was well documented such that pure indoor measurements were done later with the nodes on the same locations.

3.1.3 Indoor randomly distributed networks

The straight-forward extension to the previous experiment was to measure the distributed indoor channels. As Rx locations, we used the locations of the receivers that were previously distributed in the room (not the ones at the window). For the Tx, we used the four antennas at the windows (relays) as transmitters, and distributed four more transmitters in the office.

We did four different kinds of measurements: (i) Stationary measurements, where fading was generated by walking people carrying metal structures (see description on page 31). (ii) Time-variant measurements, where all 8 receive antennas were moved randomly within a 2 m radius (see page 32). (iii) Time-variant measurements, where all 8 transmit antennas were moved randomly within a 2 m radius (see page 33). (iv) Time-variant measurements, where 4 transmit antennas and 4 receive antennas were moved randomly within a 2 m radius (see page 34).

3.1.4 Indoor clustered nodes measurements

To investigate the properties of intra-cluster and inter-cluster communication, as well as inter-cluster interference, we did two different kinds of clustered-nodes measurements: (i) 2 Tx clusters communicating to 2 Rx clusters (see 35-36), (ii) 2 clusters containing both 4 Rx and 4 Tx antennas, each (see 37-38).

Again, we conducted stationary measurements where fading was introduced by moving people carrying metallic items, and time-variant measurements where some antennas were moved locally within the same cubicle.

3.1.5 Indoor measurements for spatial focusing

In [1] the authors could show by simulation that by using the local array response, focusing can be significantly improved. We tried to make measurements to check whether this concept also works with reduced bandwidth in radio environments.

The idea (see also page 39) was the following: To be able to measure the local responses, one would need transceivers. Since we only had transmitters and receivers, we paired a transmitter with a receiver (now called “virtual transceiver”) and put them very close to each other. To measure the local response, we split the virtual transceivers into two clusters of linear arrays. Cluster 1 had an antenna spacing of 20.3 cm, where cluster 2 had an antenna spacing of 53.3 cm.

These measurements can be interpreted in two ways, either by using cluster 1 as focusing array and cluster 2 as control array, or vice versa.

3.1.6 Indoor localization measurements

The idea of localization using unknown random sources [2] shall be investigated. The algorithm to be tested estimates the distance between different receiving antennas by using second-order or higher-order correlations of the received signal.

This approach works best, when the transmit antennas are at the boundaries of the environment, hence, we distributed our transmit antennas at the edges of the office building. The receive antennas were distributed in the office at different locations (see page 40). During the measurements, different fading realizations were generated by moving people.

3.2 Measurement setup

For the *outdoor-to-indoor measurements*, we used the outdoor base station position and direction Tx1D1 (see Fig. 1) with the high-gain dual-polarized base-station antennas (see Section 4.2.3). As distributed antennas, we used only the 7 dBi (black) WiFi antennas having antenna numbers 1-8 (see Section 4.2.2).

For all *indoor measurements*, we used both the 7dBi (black) WiFi antennas (numbers 1-8) and the 10dBi (white) WiFi antennas (numbers 11-18).

The SMA connectors on the receiver switch were spaced too closely such that we could not connect all long RF cables directly. For this reason, we used 1 m extension cables on

the ports 2, 4, 6, and 8. This must be especially taken into account when processing the localization measurements. This fact is also reflected in the scenario documentation sheets by the plus sign (+) after the cable number.

The sounding parameters varied between the measurements to optimally capture the environment. They are also specified in the scenario documentation pages.

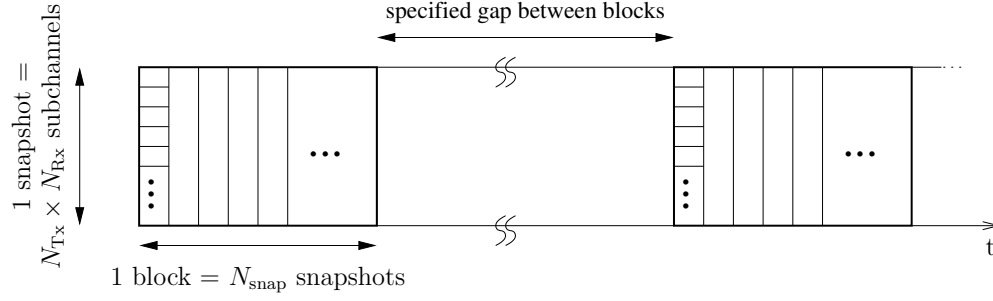


Figure 6: Measurement principle of the RUSK Stanford channel sounder

4 Equipment

4.1 RUSK Stanford Channel Sounder

The RUSK Stanford radio channel sounder [3] is capable of measuring up to 8×8 MIMO channels at a center frequency of 2.45 GHz. The bandwidth is scalable up to 240 MHz maximum around the center frequency.

The sounder utilizes the switched-array principle, i.e. only one link between a specific Rx element and Tx element is measured at a time (using only one transmitter and one receiver chain), while switches at the transmitter and receiver select the link to be measured. The time for measuring one complete MIMO matrix thus depends on the number of Tx and Rx antennas used, and on the length of the channel sounding sequence.

Figure 6 demonstrates this principle. The sounder measures all subchannels (Rx/Tx combination), i.e. a full frequency-dependent MIMO channel matrix, which is called one “snapshot”. Multiple snapshots are combined in blocks as specified in the sounding parameters. Between the blocks, a time gap can be specified to allow for bursty sounding.

In our measurements we use block sizes of 8-32 snapshots over which we average to increase the effective SNR of the measurement. The sounding parameters are summarized in the individual sections describing the measurements.

4.2 Antennas

The antennas used in the measurements are summarized in the next paragraphs. Note that we unfortunately do not have antenna calibration data from an anechoic chamber for directional evaluation. The focus of these measurements were rather to quantify the radio channel including different kinds of antennas.

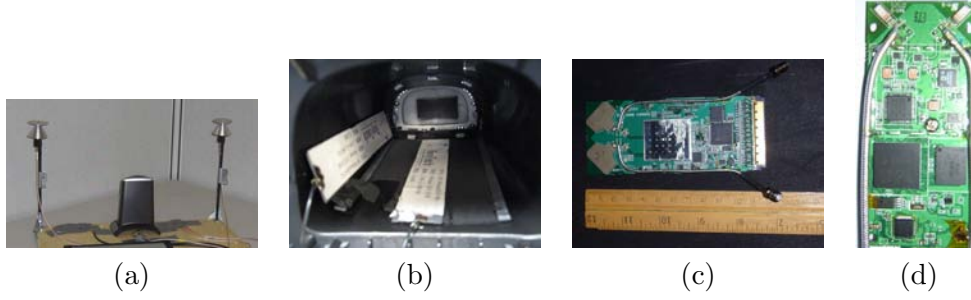


Figure 7: Antennas used for the O2I mobile measurements: (a) Discones and CPE mounted on the wooden board, (b) inside-view of the CPE antennas: two patches with orthogonally oriented main lobes, (c) broadband WiMAX PC-card antenna array, (d) narrowband WiMAX antenna array with ceramic elements

4.2.1 Antennas for the O2I moving measurements

We used four different arrays of WiMAX antennas for the O2I measurements at the receiver (see Figure 7): (i) two Discone antennas spaced approx. 60cm, (ii) a WiMAX customer premises equipment (CPE) array, (iii) a broadband WiMAX PC-card antenna array, and (iv) a WiMAX narrowband ceramic antenna on a USB dongle.

We observed the largest SNR at the Discone antennas due to their large gains. Even though the Discone array had quite a large antenna separation, the antenna correlation was quite high because of the omni-directional nature and the high gain. The WiMAX CPE antennas had both good antenna gain and low antenna correlation due to its layout. Both the PC-card antenna and the USB antenna have largely uncorrelated antennas but their gain is lower due to their small form factor.

4.2.2 WiFi antennas

For the distributed antenna measurements, we used two different kinds of standard vertically-polarized WiFi antennas matched at 2.45 GHz as shown in Figure 8. Their gain is 7dBi and 10dBi, respectively, specified in the range of 2.4-2.83 GHz with an omni-directional radiation pattern in the azimuth plane (according to the data sheets).

The antennas had a 1.83m (7 ft) pigtail having a male *reverse-polarity* SMA connector, so we used converter plugs to connect our standard female SMA cables to them.

4.2.3 Base station antennas

At the base station, we used two ProShape Dual 90 (J23016D00-90N) dual-polarized patch antennas. They were mounted to the scissor lift. Figure 9 shows a picture of the antenna,

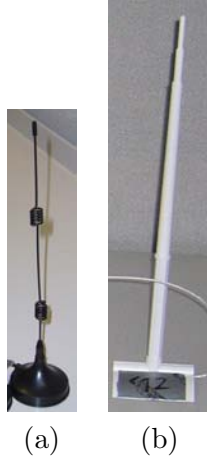


Figure 8: WiFi antennas used: (a) 7dBi gain (antenna numbers 1-8), (b) 10dBi gain (antenna numbers 11-18)

while Figure 10 shows the antenna pattern of the vertical normalization (normalized to the maximum gain). The patterns of the horizontal polarization match the vertical ones quite well.

The gain in the direction of the main lobe is 15.5 dB, which decays quite rapidly in elevation. For this reason, the antenna was tilted 7 degrees, to ensure that the office is in the elevation direction of the main lobe. This tilt angle was found optimal by simple trigonometric calculations.

4.3 Low-loss RF cables (100 ft)

We used LMR-400 low-loss RF cables with SMA connectors on both ends. The cables showed an average loss of 6.1 dB. The parameters of the cables (measured with an HP vector network analyzer) are summarized in Table 3.

4.4 Distance trigger wheel

The distance trigger wheel is self-made. We connected a rotary sensor S5S-500 manufactured by US digital to a distance-measure wheel with a circumference of 1 m. The rotary sensor provides 500 pulses per rotation (i.e. 1 pulse every 0.002 m) at a maximum of 100 rotations per minute, equal to a movement speed of 1.6 m/s.

In order to scale the distance for a trigger event, we developed a divider logic based on a ripple counter (see Fig. 11), which provides the interface between the wheel sensor and the trigger input of the sounder. Only one output of the wheel sensor is used, i.e. forward and



Figure 9: Picture of BTS antenna

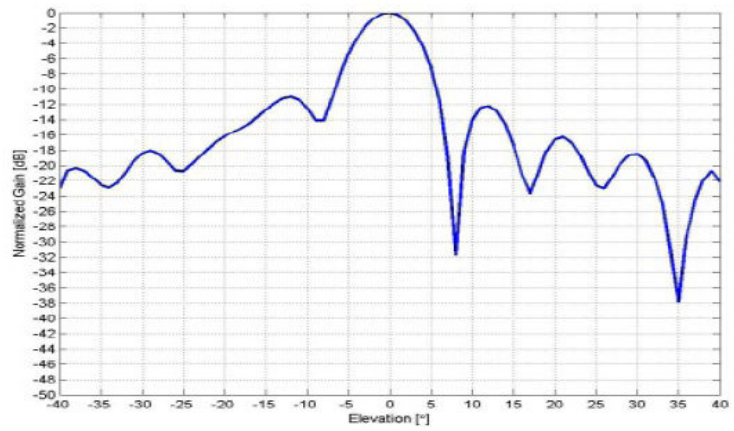
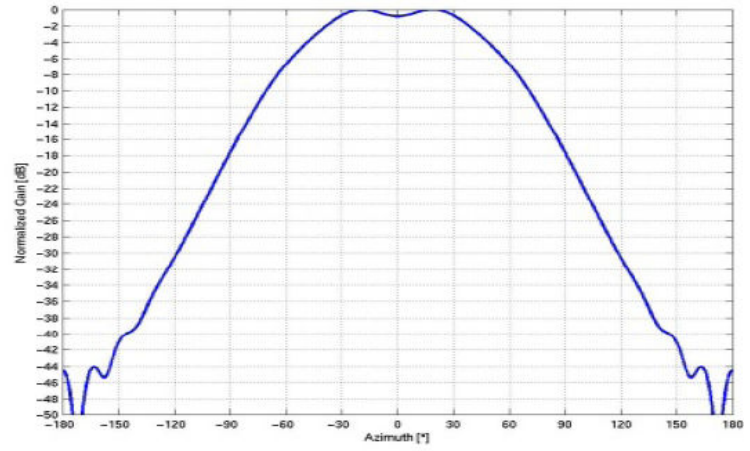


Figure 10: Antenna pattern of the BTS antenna (vertical polarization)

Cable No.	Cable Loss					Cable delay
	2.3 GHz	2.4 GHz	2.5 GHz	2.6 GHz	2.7 GHz	
1	6.3 dB	6.4 dB	6.6 dB	6.7 dB	6.9 dB	115.90 ns
2	6.2 dB	6.4 dB	6.5 dB	6.7 dB	6.8 dB	115.72 ns
3	6.2 dB	6.4 dB	6.5 dB	6.6 dB	6.8 dB	115.42 ns
4	6.2 dB	6.4 dB	6.5 dB	6.7 dB	6.8 dB	115.67 ns
5	6.2 dB	6.3 dB	6.5 dB	6.6 dB	6.8 dB	115.57 ns
6	6.1 dB	6.2 dB	6.4 dB	6.6 dB	6.7 dB	115.38 ns
7	6.2 dB	6.4 dB	6.5 dB	6.7 dB	6.8 dB	115.85 ns
8	6.2 dB	6.4 dB	6.5 dB	6.7 dB	6.8 dB	115.64 ns
9	6.1 dB	6.3 dB	6.5 dB	6.6 dB	6.7 dB	115.54 ns
10	6.1 dB	6.3 dB	6.4 dB	6.6 dB	6.8 dB	115.46 ns
11	6.1 dB	6.3 dB	6.5 dB	6.6 dB	6.8 dB	115.59 ns
12	6.1 dB	6.3 dB	6.4 dB	6.7 dB	6.7 dB	115.43 ns
13	6.1 dB	6.2 dB	6.4 dB	6.5 dB	6.7 dB	115.26 ns
14	6.2 dB	6.3 dB	6.5 dB	6.6 dB	6.7 dB	115.59 ns
15	6.1 dB	6.3 dB	6.4 dB	6.6 dB	6.7 dB	115.52 ns
16	6.1 dB	6.3 dB	6.5 dB	6.6 dB	6.8 dB	115.47 ns

Table 3: Long RF cables: parameters

backward movements are both possible, although only forward movements are encouraged because of the mechanical mounting of the measuring wheel.

The divider was set to measure snapshots every 1.6 cm. Before each measurement, the counter was reset to provide a common starting point.

4.5 Power generator

We used a McCulloch 1800 W Digital Inverter Generator running on gasoline to power the outdoor Tx equipment and the scissor lift. The generator was CARB compliant.

4.6 Scissor lift

We rented a Genie GS-2032 scissor lift (see Figure 12) from Hertz Equipment Rentals. The base station antennas were mounted onto the carriage of the lift, where the long RF cables were used to connect the antenna elements.

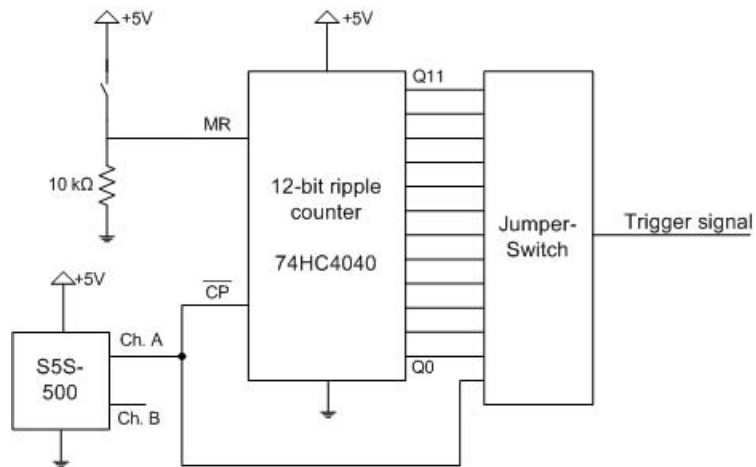


Figure 11: Circuit diagram of the wheel counter divider logic



Figure 12: Scissor lift used

A Outdoor-to-indoor documentation sheets

The next pages contain the outdoor-to-indoor documentation sheets for the individual measurements. The red arrow indicates the measured route on which the trolley was moved. Green dots in the floor plan mark the position of involved people during the measurement (additionally to the person pushing the measurement trolley).

Route 1

Narrow Tx antenna spacing ($40.6\text{ cm} = 3.3\lambda$):

File Tx1D1: 02Im_Tx1_D1_close_R1_001

Comments Tx1D1: Good.

File Tx1D2: 02Im_Tx1_D2_close_R1_003

Comments Tx1D2: First two runs impaired by interference. Third run quite ok, but still some interference in the last part.

File Tx1D3: 02Im_Tx1_D3_close_R1_001

Comments Tx1D3: Good.

File Tx2D1: 02Im_Tx2_D1_close_R1_001

Comments Tx2D1: Good.

File Tx2D2: 02Im_Tx2_D2_close_R1_001

Comments Tx2D2: Some interference at the beginning. Invalid AGC value in Snap #20416

File Tx2D3: 02Im_Tx2_D3_close_R1_001

Comments Tx2D3: Some interference at the beginning. Invalid AGC value in Snaps #1199, #1418, #1419. Maybe troubles with the wheel



Rx map

Wide Tx antenna spacing ($66\text{ cm} = 5.4\lambda$):

File Tx1D1:

Comments Tx1D1:

File Tx1D2:

Comments Tx1D2:

File Tx1D3: 02Im_Tx1_D3_far_R1_001

Comments Tx1D3: Two runs for consistency. In first run: Invalid AGC value in Snap #6612. Little interference



Tx map

Route 2

Narrow Tx antenna spacing ($40.6\text{ cm} = 3.3\lambda$):

File Tx1D1: 02Im_Tx1_D1_close_R2_001

Comments Tx1D1: Good.

File Tx1D2: 02Im_Tx1_D2_close_R2_001

Comments Tx1D2: Good.

File Tx1D3: 02Im_Tx1_D3_close_R2_001

Comments Tx1D3: Good, but small stop in the middle for the power cord.

File Tx2D1: 02Im_Tx2_D1_close_R2_001

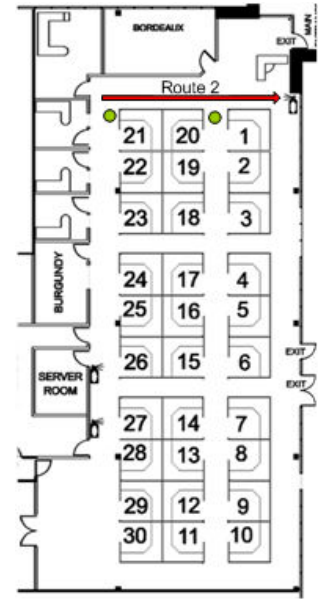
Comments Tx2D1: Good.

File Tx2D2: 02Im_Tx2_D2_close_R2_001

Comments Tx2D2: Good, but single invalid AGC value in snap #39

File Tx2D3: 02Im_Tx2_D3_close_R2_002

Comments Tx2D3: In first tun, wheel had problems. In second run, maybe problems with the wheel.



Rx map

Wide Tx antenna spacing ($66\text{ cm} = 5.4\lambda$):

File Tx1D1:

Comments Tx1D1:

File Tx1D2:

Comments Tx1D2:

File Tx1D3: 02Im_Tx1_D3_far_R2_001

Comments Tx1D3: Good.



Tx map

Route 3

Narrow Tx antenna spacing ($40.6\text{ cm} = 3.3\lambda$):

File Tx1D1: 02Im_Tx1_D1_close_R3_002

Comments Tx1D1: Interference in first run. Little interference at the end of the second run.

File Tx1D2: 02Im_Tx1_D2_close_R3_001

Comments Tx1D2: Interference in the last part of the measurements.

File Tx1D3: 02Im_Tx1_D3_close_R3_001

Comments Tx1D3: Occasional interference in specific channels, at the very end much interference.

File Tx2D1: 02Im_Tx2_D1_close_R3_001

Comments Tx2D1: Interference at the end of the route, plus one person moving in the channel.

File Tx2D2: 02Im_Tx2_D2_close_R3_002

Comments Tx2D2: First run: Strong interference. Second run: Interference from the middle of the route to the end.

File Tx2D3: 02Im_Tx2_D3_close_R3_002

Comments Tx2D3: Interference at the end, wheel slipped a little

Wide Tx antenna spacing ($66\text{ cm} = 5.4\lambda$):

File Tx1D1: 02Im_Tx1_D1_far_R3_002

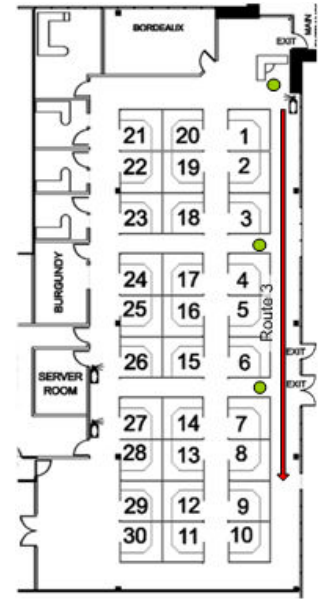
Comments Tx1D1: First run: Occasional interference, but strong interference at the end. Second run: occasional interference. Another boom lift was standing outside, opposite cubicle 3.

File Tx1D2: 02Im_Tx1_D2_far_R3_001

Comments Tx1D2: First run: Occasional interference, but strong interference at the end. Second run: strong interference. Another boom lift was standing outside, opposite cubicle 1.

File Tx1D3: 02Im_Tx1_D3_far_R3_001

Comments Tx1D3: Some interference at the end. Some difference in the distance wheel.



Rx map



Tx map

Route 4

Narrow Tx antenna spacing ($40.6\text{ cm} = 3.3\lambda$):

File Tx1D1: 02Im_Tx1_D1_close_R4_001
Comments Tx1D1: Some interference in the beginning.

File Tx1D2: 02Im_Tx1_D2_close_R4_001
Comments Tx1D2: Some interference in the beginning.

File Tx1D3: 02Im_Tx1_D3_close_R4_001
Comments Tx1D3: Some interference in the beginning.

File Tx2D1: 02Im_Tx2_D1_close_R4_002
Comments Tx2D1: Both routes: low SNR in the beginning

File Tx2D2: 02Im_Tx2_D2_close_R4_001
Comments Tx2D2: Some interference in the beginning.

File Tx2D3: 02Im_Tx2_D3_close_R4_001
Comments Tx2D3: Some interference and low SNR in the beginning.



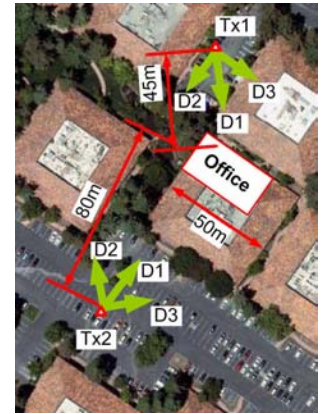
Rx map

Wide Tx antenna spacing ($66\text{ cm} = 5.4\lambda$):

File Tx1D1:
Comments Tx1D1:

File Tx1D2:
Comments Tx1D2:

File Tx1D3: 02Im_Tx1_D3_far_R4_001
Comments Tx1D3: Some interference in the beginning.

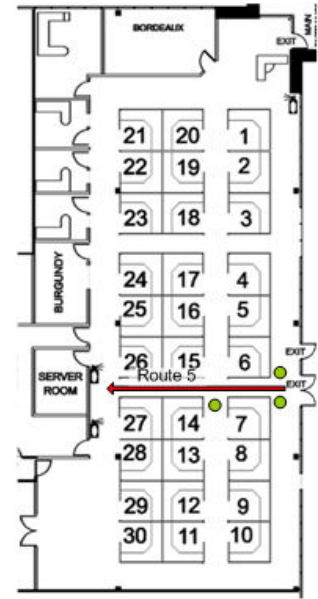


Tx map

Route 5

Narrow Tx antenna spacing ($40.6\text{ cm} = 3.3\lambda$):

- File Tx1D1:** 02Im_Tx1_D1_close_R5_001
Comments Tx1D1: Minor interference, but quite good.
- File Tx1D2:** 02Im_Tx1_D2_close_R5_001
Comments Tx1D2: Some interference (especially at the Discone antennas)
- File Tx1D3:** 02Im_Tx1_D3_close_R5_001
Comments Tx1D3: Minor interference.
- File Tx2D1:** 02Im_Tx2_D1_close_R5_001
Comments Tx2D1: Low SNR, some interference.
- File Tx2D2:** 02Im_Tx2_D2_close_R5_001
Comments Tx2D2: Low SNR, some interference.
- File Tx2D3:** 02Im_Tx2_D3_close_R5_001
Comments Tx2D3: Very bad SNR, partly impaired by interference.



Rx map

Wide Tx antenna spacing ($66\text{ cm} = 5.4\lambda$):

- File Tx1D1:**
Comments Tx1D1:
- File Tx1D2:**
Comments Tx1D2:
- File Tx1D3:** 02Im_Tx1_D3_far_R5_001
Comments Tx1D3: Good.



Tx map

B Distributed measurements

The next pages contain the documentation sheets for the distributed measurements. Whenever the outdoor transmitter was used, the transmitter position 1, direction 1 (Tx1D1) was used (see Fig. 1). The photograph numbers in the notes refer to the last four digits of the filenames in Appendix C.

O2I Moving

Description: Moving 4 receive antennas towards the other 4 receive antennas. Tx is outdoors

Photograph numbers: 0725 – 0736

Filename: 02Idist_Tx1_D1_close_R4_{001-004}

Rx ports: Stationary: 1,3,5,7; Moving: 2,4,6,8

Rx antenna numbers: Stationary: 1,2,3,4; Moving: 5,6,7,8;

Rx cables: Stationary: 8,3,4,6; Moving: 9+,10+,11+,12+;

Tx ports: 1,2,3,4

Tx antenna numbers: BTS: 1V,1H,2V,2H

Tx cables: 1,2,5,7

Measurement parameters:

Snap/block: 16

External trigger (wheel)



Floorplan

Comments:

Four runs, no interference. In the fourth run, cable 4 (Rx port 5) accidentally got caught in one of the cubicle corners and was strongly bent.

Antenna spacing: $\lambda/2$

System calibrated with one long RF cable plus cables to the switches.

O2I Relay 1

Description: 4 Antennas at the window (Relay), 4 antennas randomly distributed. Fading by people moving in the room.

Photograph numbers: 0737 – 0746

Filename: 02Idist_Tx1_D1_close_relay_001

Rx ports: Window: 1,3,5,7; Random: 2,4,6,8

Rx antenna numbers: Window: 1,2,3,4; Random: 5,6,7,8

Rx cables: Window: 8,3,4,6; Random: 9+,10+,11+,12+

Tx ports: 1,2,3,4

Tx antenna numbers: BTS: 1V,1H,2V,2H

Tx cables: 1,2,5,7

Measurement parameters:

Snap/block: 32
Gap between blocks: 250 ms
Number of blocks: 120
Total time: 32s

Comments:

Relay Rx2 had very bad SNR.
System calibrated with one long RF cable plus cables to the switches.



Floorplan

O2I Relay 2

Description: 4 Antennas at the window (Relay), 4 antennas randomly distributed. Fading by people moving in the room.

Photograph numbers: 0748 – 0750

Filename: 02Idist_Tx1_D1_close_relay_002

Rx ports: Window: 1,3,5,7; Random: 2,4,6,8

Rx antenna numbers: Window: 1,2,3,4; Random: 5,6,7,8

Rx cables: Window: 8,3,4,6; Random: 9+,10+,11+,12+

Tx ports: 1,2,3,4

Tx antenna numbers: BTS: 1V,1H,2V,2H

Tx cables: 1,2,5,7

Measurement parameters:

Snap/block: 32
Gap between blocks: 250 ms
Number of blocks: 120
Total time: 32s

Comments:

Relay Rx2 had very bad SNR.
System calibrated with one long RF cable plus cables to the switches.



Floorplan

I2I stationary

Description: 4 transmitters at the window positions (see O2I Relay measurements), 4 transmitters randomly distributed. 8 receivers at the positions from the O2I Relay measurements.

Photograph numbers: 0756 – 0771

Filename: I2Idist_relay_fixed_{001-002}

Rx ports: 1-8

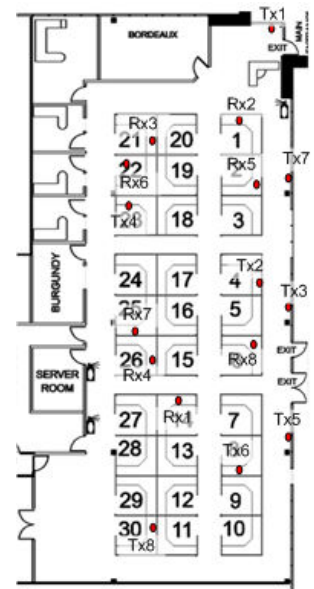
Rx antenna numbers: 18,5,17,6,15,7,16,8

Rx cables: 16,9+,14,10+,15,11+,7,12+

Tx ports: 1-8

Tx antenna numbers: 1,11,2,13,3,12,4,14

Tx cables: 8,1,3,5,4,2,6,13



Floorplan

Measurement parameters:

Snap/block: 32

Gap between blocks: 250 ms

Number of blocks: 120

Total time: 32s

Comments:

System calibrated with two long RF cables plus cables to the switches.

I2I moving receivers

Description: Same scenario as stationary measurements, but Rx were moved randomly (within the same cubicle) during the measurement

Photograph numbers: 0756 – 0771

Filename: I2Idist_relay_movingRx_{001-002}

Rx ports: 1-8

Rx antenna numbers: 18,5,17,6,15,7,16,8

Rx cables: 16,9+,14,10+,15,11+,7,12+

Tx ports: 1-8

Tx antenna numbers: 1,11,2,13,3,12,4,14

Tx cables: 8,1,3,5,4,2,6,13

Measurement parameters:

Snap/block: 8

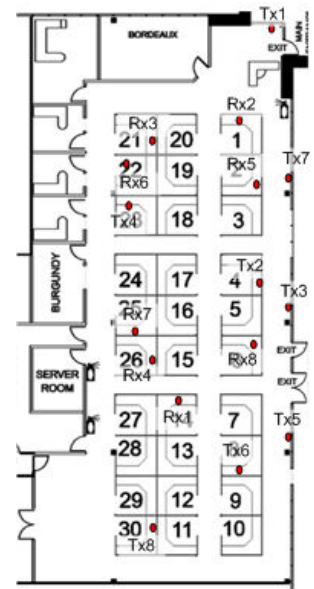
Gap between blocks: 9.83 ms

Number of blocks: 1200

Total time: 19.7s

Comments:

System calibrated with two long RF cables plus cables to the switches.



Floorplan

I2I moving transmitters

Description: Same scenario as stationary measurements, but Tx were moved randomly (within the same cubicle) during the measurement

Photograph numbers: Video: 0774

Filename: I2Idist_relay_movingTx_{001-002}

Rx ports: 1-8

Rx antenna numbers: 18,5,17,6,15,7,16,8

Rx cables: 16,9+,14,10+,15,11+,7,12+

Tx ports: 1-8

Tx antenna numbers: 1,11,2,13,3,12,4,14

Tx cables: 8,1,3,5,4,2,6,13

Measurement parameters:

Snap/block: 8

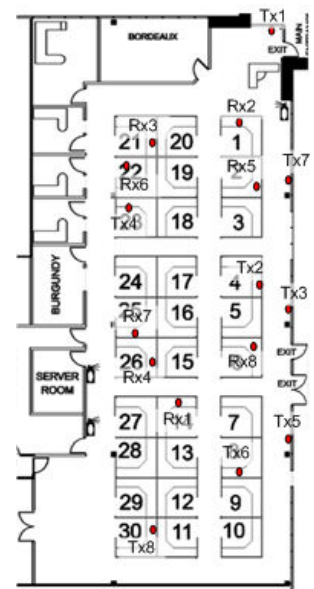
Gap between blocks: 9.83 ms

Number of blocks: 1200

Total time: 19.7s

Comments:

System calibrated with two long RF cables plus cables to the switches.



Floorplan

I2I moving Rx & Tx

Description: Same scenario as stationary measurements, but the (white) antennas on the following ports were moved randomly (within the same cubicle) during the measurement: Tx2, Tx4, Tx6, Tx7, Rx1, Rx3, Rx5, Rx7

Photograph numbers: Video: 0774

Filename: I2Idist_relay_movingRxTx_{001-002}

Rx ports: 1-8

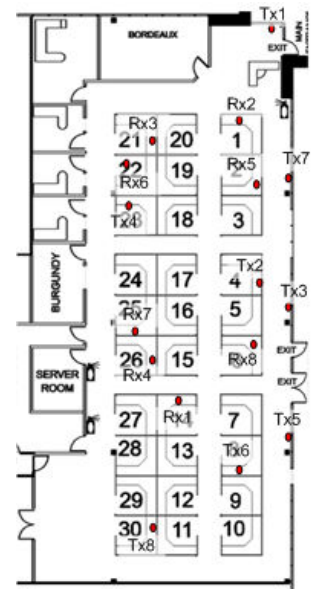
Rx antenna numbers: 18,5,17,6,15,7,16,8

Rx cables: 16,9+,14,10+,15,11+,7,12+

Tx ports: 1-8

Tx antenna numbers: 1,11,2,13,3,12,4,14

Tx cables: 8,1,3,5,4,2,6,13



Floorplan

Measurement parameters:

Snap/block: 8

Gap between blocks: 9.83 ms

Number of blocks: 1200

Total time: 19.7s

Comments:

System calibrated with two long RF cables plus cables to the switches.

I2I clustering stationary (4 clusters)

Description: Distributed channel between 2 Tx and 2 Rx clusters (interference considerations). Fading by moving people.

Photograph numbers: Clusters: Tx1: 0775-0776, Tx2: 0783, Rx1: 0777-0780; Rx2: 0781-0782

Filename: I2Idist_4clusters_{001-002}

Rx ports: 1-8

Rx antenna numbers: 18,5,17,6,15,7,16,8

Rx cables: 16,9+,14,10+,15,11+,7,12+

Tx ports: 1-8

Tx antenna numbers: 1,11,2,13,3,12,4,14

Tx cables: 8,1,3,5,4,2,6,13

Measurement parameters:

Snap/block: 32

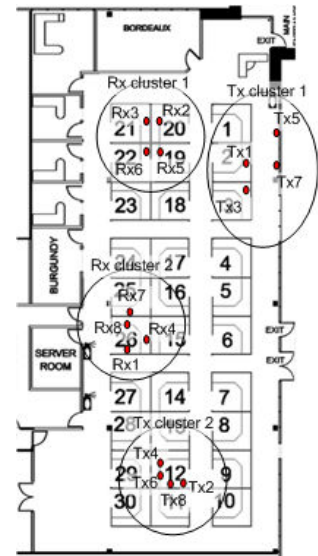
Gap between blocks: 250 ms

Number of blocks: 120

Total time: 32s

Comments:

System calibrated with two long RF cables plus cables to the switches.



Floorplan

I2I clustering moving (4 clusters)

Description: Distributed channel between 2 Tx and 2 Rx clusters (interference considerations). Fading by moving antennas locally.

Photograph numbers: Clusters: Tx1: 0775-0776, Tx2: 0783, Rx1: 0777-0780; Rx2: 0781-0782

Filename: I2Idist_4clusters_moving_{001-002}

Rx ports: 1-8

Rx antenna numbers: 18,5,17,6,15,7,16,8

Rx cables: 16,9+,14,10+,15,11+,7,12+

Tx ports: 1-8

Tx antenna numbers: 1,11,2,13,3,12,4,14

Tx cables: 8,1,3,5,4,2,6,13

Measurement parameters:

Snap/block: 8

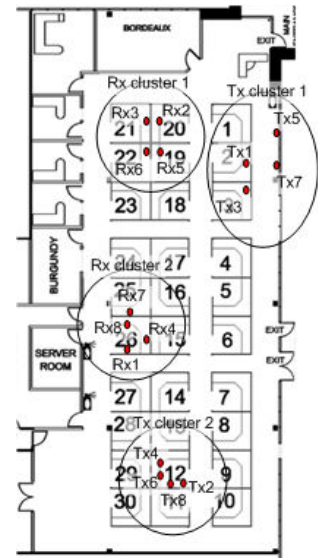
Gap between blocks: 9.83 ms

Number of blocks: 1200

Total time: 19.7s

Comments:

System calibrated with two long RF cables plus cables to the switches.



Floorplan

I2I clustering stationary (2 clusters)

Description: Distributed channel between 2 Tx and 2 Rx clusters, each having 4 antennas (interference considerations). Fading by moving people.

Photograph numbers: Cluster 1: 0790-0792; Cluster 2: 0784-0789

Filename: I2Idist_2clusters_{001-002}

Rx ports: 1-8

Rx antenna numbers: 18,5,17,6,15,7,16,8

Rx cables: 16,9+,14,10+,15,11+,7,12+

Tx ports: 1-8

Tx antenna numbers: 1,11,2,13,3,12,4,14

Tx cables: 8,1,3,5,4,2,6,13



Floorplan

Measurement parameters:

Snap/block: 32

Gap between blocks: 250 ms

Number of blocks: 120

Total time: 32s

Comments:

System calibrated with two long RF cables plus cables to the switches.

I2I clustering moving (2 clusters)

Description: Distributed channel between two clusters, each having 4 Tx and 4 Rx antennas. Measuring inter/intra cluster properties. Fading by moving antennas locally.

Photograph numbers: Cluster 1: 0790-0792; Cluster 2: 0784-0789

Filename: I2Idist_2clusters_moving_{001-002}

Rx ports: 1-8

Rx antenna numbers: 18,5,17,6,15,7,16,8

Rx cables: 16,9+,14,10+,15,11+,7,12+

Tx ports: 1-8

Tx antenna numbers: 1,11,2,13,3,12,4,14

Tx cables: 8,1,3,5,4,2,6,13



Floorplan

Measurement parameters:

Snap/block: 8

Gap between blocks: 9.83 ms

Number of blocks: 1200

Total time: 19.7s

Comments:

System calibrated with two long RF cables plus cables to the switches. First run: some interference in the middle part of the run

I2I focusing measurements

Description: Time-reversal plus prefilter focusing experiment
Photograph numbers: Cluster 1: 0794-0795; Cluster 2: 0796-0797

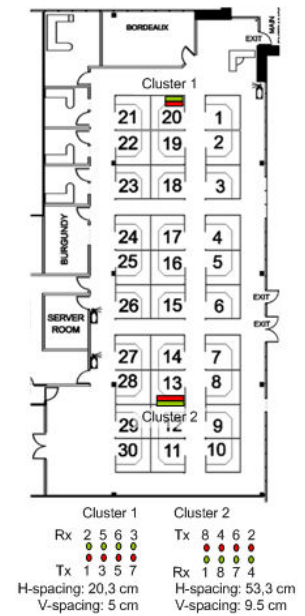
Filename: I2Idist_focusing_{002-003}
Rx ports: 1-8
Rx antenna numbers: 18,5,8,15,6,7,16,17
Rx cables: 16,9+,14,10+,15,11+,7,12+
Tx ports: 1-8
Tx antenna numbers: 1,11,2,13,3,12,4,14
Tx cables: 8,1,3,5,4,2,6,13

Measurement parameters:

Snap/block: 32
Gap between blocks: 250 ms
Number of blocks: 120
Total time: 32s

Comments:

System calibrated with two long RF cables plus cables to the switches.



Floorplan

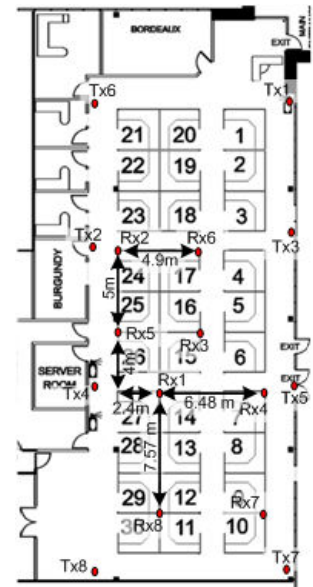
I2I localization measurements

Description: Passive indoor localization test
Photograph numbers: 0799 – 0802

Filename: I2Idist_localization_{001-002}
Rx ports: 1-8
Rx antenna numbers: 18,5,8,15,6,7,16,17
Rx cables: 16,9+,14,10+,15,11+,7,12+
Tx ports: 1-8
Tx antenna numbers: 1,11,2,13,3,12,4,14
Tx cables: 8,1,3,5,4,2,6,13

Measurement parameters:

Snap/block: 8
Gap between blocks: 100.76 ms
Number of blocks: 1200
Total time: 129s



Floorplan

Comments:

System calibrated with two long RF cables plus cables to the switches. First run: Antenna 4 horizontal

C Photographs



P1020635

Equipment calibration using one long RF cable



P1020636

Tx position Tx1D1



P1020637

Tx position Tx1D1 closeup



P1020638

Tx position Tx1D1, from behind the Tx looking towards the office building



P1020639

Tx position Tx1D1, from behind the Tx looking towards the office building



P1020640

Tx position Tx1D1, from behind the Tx looking towards the office building, zoom of the antennas



P1020641

Tx position Tx1D1,
from behind the Tx
looking towards the
office building



P1020642

Tx position Tx1D1,
view from the office
building



P1020719

Tx1D1 from the top



P1020720

Tx1D1, but looking
towards Tx1D2



P1020721

Tx1D1, but looking
towards Tx1D3



P1020722

Tx1D1 from the top



P1020723

Tx1D1 from the top



P1020663

Tx equipment at
Tx1D1 being lifted



P1020669

Tx equipment at Tx1D1 with large antenna spacing



P1020666

Tx equipment at Tx1D1: Changing the Tx mounting to large spacing



P1020673

Tx equipment - Tx1D1



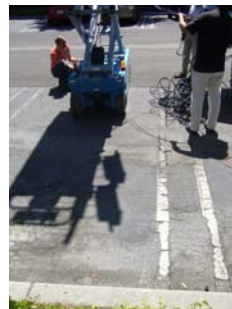
P1020674

Tx equipment - rotated to Tx1D2



P1020675

Tx equipment - Tx1D2 from the back



P1020676

Tx equipment - rotated to Tx1D2



P1020677

Tx equipment -
Tx1D2 from the
back



P1020684

Tx equipment
Tx1D2 photograph
from halfway be-
tween the office and
the equipment



P1020685

Tx equipment:
Sounder, antennas
on the lift, power
generator



P1020706

Tx1D3 (view from
direction of the main
lobe)



P1020707

Tx1D3 (zoom on an-
tennas)



P1020708

Tx1D3 equipment
setup



P1020686

Tx equipment
Tx2D1 (setting up)



P1020687

Tx equipment
Tx2D1 (setting up)



P1020688

Tx equipment
Tx2D1 (setting up)



P1020689

View from the Tx2
towards the office
building



P1020690

Tx equipment
Tx2D1 (setting up)



P1020691

Tx equipment
Tx2D1 (setting up)



P1020692

Tx equipment
Tx2D1



P1020693

Tx equipment
Tx2D1 (zoom of the
antennas)



P1020694

Tx equipment
Tx2D1 from the
back facing the office



P1020695

Tx equipment
Tx2D1 from the
back facing the office



P1020697

Tx2D2 from the top



P1020698

Tx2D2 from the top



P1020699

Tx2D2 from the top



P1020700

Tx2D2 setup



P1020701

Tx2D2 setup



P1020702

Tx2D2 (view from
halfway towards the
office)



P1020705

Tx2D3 view from behind looking towards the office



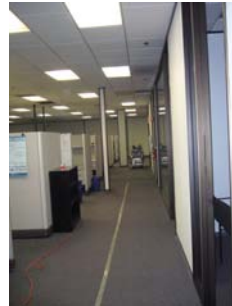
P1020703

Tx2D3



P1020683

Rx equipment on Route 1



P1020643

Rx route 1 duct-taped to the floor



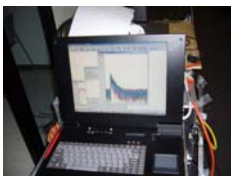
P1020644

Rx equipment with route-keeping support



P1020645

Rx equipment with antenna configuration for the O2I measurements



P1020646

Rx equipment control screen



P1020647

Intersection of Route 1 & Route 2



P1020648

Intersection of Route
1 & Route 2



P1020649

Intersection of Route
2 & Route 4



P1020650

End of Route 2



P1020651

Intersection of Route
2 & Route 3



P1020652

Route 3



P1020653

Rx equipment on be-
ginning of Route 3



Rx equipment in the middle of Route 3

P1020654



Rx equipment at the end of Route 3

P1020655



Rx equipment on Route 3

P1020670



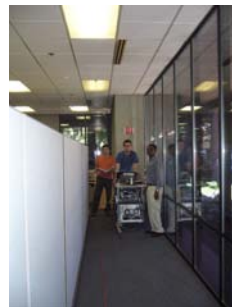
Rx equipment at the end of Route 3

P1020671



Rx equipment on Route 3

P1020672



Rx equipment on Route 3

P1020681



Rx equipment at the beginning of Route 4

P1020656



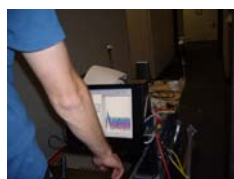
Route 4, from the middle to the end

P1020657



Route 4 with Rx equipment at the end

P1020658



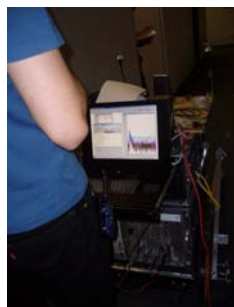
Rx equipment at the beginning of Route 5

P1020661



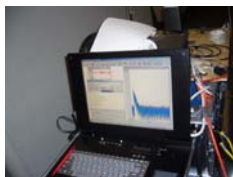
Rx equipment in the middle of Route 5

P1020662



Rx equipment showing the effect of interference

P1020659



P1020660

Rx equipment showing no interference



P1020678

Other boom lift doing constructions on the house



P1020679

Other boom lift doing constructions on the house



P1020680

Other boom lift doing constructions on the house



P1020682

Documentation while setting up the equipment for the next run



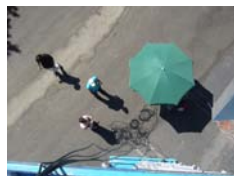
P1020717

Antenna setup of the O2I measurements (front view)



P1020718

Antenna setup of the O2I measurements (top view)



P1020724

view from above: the equipment was always kept in the shadow to avoid heat problems



P1020729

O2I distributed
array measurement:
both Rx arrays



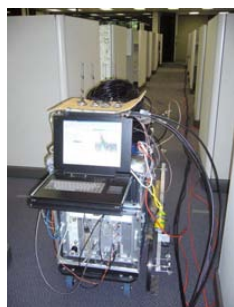
P1020730

O2I distributed
array measurement:
mobile Rx array on
sounder



P1020731

O2I distributed
array measurement:
mobile Rx array on
sounder



P1020732

O2I distributed
array measurement:
mobile Rx array on
sounder



P1020733

O2I distributed
array measurement:
mobile Rx array on
sounder



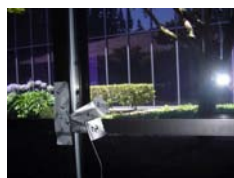
P1020735

O2I distributed
array measurement:
sounder display
showing different
delays



P1020736

O2I distributed
array measurements:
fixed Rx array



P1020739

O2I relay measure-
ments: Antenna 2



P1020742

O2I relay measurements: Antenna 3



P1020738

O2I relay measurements: Antenna 4 and other "relay" antennas mounted on the wall



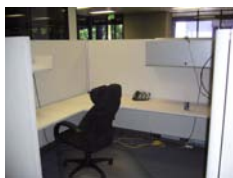
P1020746

O2I relay measurements: Antenna 5



P1020744

O2I relay measurements: Antenna 6



P1020745

O2I relay measurements: Antenna 7



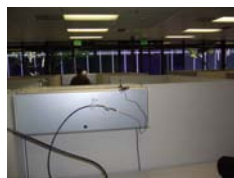
P1020743

O2I relay measurements: Antenna 8



P1020748

O2I relay measurements (second run): Antenna 5



P1020749

O2I relay measurements (second run): Antenna 6



P1020747

O2I relay measurements (second run): Antenna 7



P1020750

O2I relay measurements (second run): Antenna 8



I2I distributed: Antenna 5

P1020756



I2I distributed: Antenna 6

P1020767



I2I distributed: Antenna 7

P1020770



I2I distributed: Antenna 8

P1020762



I2I distributed: Antenna 11

P1020760



I2I distributed: Antenna 12

P1020763



I2I distributed: Antenna 13

P1020769



I2I distributed: Antenna 14

P1020766



I2I distributed: Antenna 15

P1020757



I2I distributed: Antenna 16

P1020768



P1020771

I2I distributed: Antenna 17



P1020764

I2I distributed: Antenna 18



P1020765

I2I distributed: Antenna 18



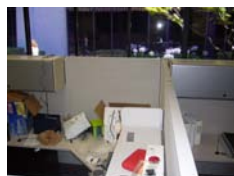
P1020773

Long RF cables running through the whole office



P1020774

Moving the antennas within the cubicle



P1020776

I2I 4-cluster measurements: Antennas 1-2



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I2I 4-cluster measurements: Antennas 3-4



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I2I 4-cluster measurements: Antennas 5,15



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I2I 4-cluster measurements: Antennas 6,8,18



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I2I 4-cluster measurements: Antenna 7



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I2I 4-cluster measurements: Antennas 16



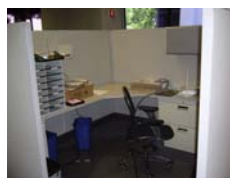
P1020780

I2I 4-cluster measurements: Antennas 17



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I2I 4-cluster measurements: Antennas 11,12,13,14



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I2I 2-cluster measurements: Antennas 5,17 (Cubicle 1)



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I2I 2-cluster measurements: Antenna 1 (Cubicle 2)



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I2I 2-cluster measurements: Antenna 2 (Cubicle 3)



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I2I 2-cluster measurements: Antennas 6,8,13,14 (Cubicle 12)



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I2I 2-cluster measurements: Antennas 11,12,16,18 (Cubicle 13)



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I2I 2-cluster measurements: Antennas 11,12,16,18 (Cubicle 13)



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I2I 2-cluster measurements: Antennas 11,12,16,18 (Cubicle 13)



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I2I 2-cluster measurements: Antennas 7,3,4 (Cubicle 19)



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I2I 2-cluster measurements: Antenna 15 (Cubicle 20)



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I2I focusing measurements: Cluster 1



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I2I focusing measurements: Cluster 1



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I2I focusing measurements: Cluster 2



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I2I focusing measurements: Cluster 2



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I2I localization measurements



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I2I localization measurements

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References

- [1] L. Borcea, T. Callaghan, J. Garnier, and G. Papanicolaou, “A universal filter for enhanced imaging with small arrays,,” *to be submitted*, 2008. [Online]. Available: <ftp://math.stanford.edu/pub/papers/papanicolaou/kernel.pdf>
- [2] J. Garnier and G. Papanicolaou, “Passive sensor imaging using cross correlations of noisy signals in a scattering medium,” *SIAM Journal on Imaging Sciences*, *submitted*, 2008. [Online]. Available: <ftp://math.stanford.edu/pub/papers/papanicolaou/cross.pdf>
- [3] “RUSK MEDAV channel sounders,” 2008. [Online]. Available: <http://www.channelsounder.de>