Exhibits for the Experimental License Applications of Prof. Mary Ann Ingram of Georgia Institute of Technology

This document provides the exhibits as part of an application to the FCC for an experimental license to enable Dr. Mary Ann Ingram, an Associate Professor in the School of Electrical and Computer Engineering at Georgia Institute of Technology, to conduct experimental research in wireless communications. Her general research goals are to investigate new combinations of multi-antenna architectures and signal processing algorithms to mitigate or exploit multipath propagation for spectrally efficient wireless communications. Since the modeling of wireless channels, especially for multiple-input, multiple-output (MIMO) channels, is a subject of current intense research, channel sounding and over-the-air communications trials are critically important to her research program as well as to the development of future wireless communications technologies and standards.

The proposed emissions are in the 5.8 and 2.45 GHz unlicensed bands and are either CW or 802.11b waveforms. In the case of CW waveforms, the proposed power levels are within the FCC Part 15 regulations for the "Field Disturbance Sensors" category of emitters. In the case of 802.11b waveforms, the proposed power levels are within the the FCC Part 15 regulations for "Spread Spectrum Transmitters". For each experiment, the type of waveform and the field strength or power level is indicated in a bold face font. The proposed power levels are high enough to capture the small-scale fading effects of multipath channels with the receivers that Prof. Ingram has. Adhering to the regulations of the "Any" category of emitters in these bands would require such low transmitted powers as to prohibit accurate measurements with her current equipment.

This document describes 5 experiments, one at 5.8GHz and four at 2.4 GHz. Of these, the one at 5.8 GHz, an indoor experiment to be described first, is the one for which she respectfully requests the soonest possible approval.

Exhibit 1. Adaptive MIMO Element Locations for the 5.8 GHz Band

Multiple-input multiple-output (MIMO) wireless channels have been demonstrated recently to provide unprecedented spectral efficiencies in indoor environments by transmitting data streams in parallel. In this experiment, we wish to adapt the element *locations* at both ends of an indoor link to further enhance its spectral efficiency. Most studies about wireless MIMO channels assume that the element locations for a given link are fixed, and the objective is to determine the excitations on the transmit antennas and the methods of combining on the receive antennas to optimize the performance of the link (or links). Studies based on computer simulation promise improvements in Shannon capacity (bits/second/Hz) of as much as 20% relative to the capacity averaged over all possible MIMO channel realizations and almost 100% relative to the worst case MIMO channel realization. Because our setup has computer-controlled virtual arrays at both ends of the link, we have the ability to vary all of the element locations to maximize the MIMO capacity of the link. We would like to demonstrate the maximum improvements available over real channels and develop efficient algorithms for realizing these improvements.

Spatial diversity can be achieved by combining multiple antenna elements, as in maximal ratio combining. Generally, there is a trade-off between diversity and the number of independent, parallel streams. Adaptive movement of elements is another form of spatial diversity; it has the advantage over combining that it does not imply a reduction in the number of parallel streams.

To perform this experiment, we propose to identify the MIMO channel matrix response **at a single frequency (CW)** in the 5.8 GHz unlicensed band for a given set of antenna element positions. A computer program will calculate the theoretical capacity for the channel matrix and then calculate the next set of antenna element positions. Next, the MIMO channel matrix response for the new element locations will be measured. This process will be repeated until further element location changes do not improve the capacity.

The virtual array method uses just one transmit antenna and one receive antenna. Each antenna is moved to a number of discrete locations corresponding to the locations of elements in an array. The single real antenna can be thought of as “sampling” space. The measurement technique works as long as the channel is static while the antennas are marched through their programmed positions. For this reason, we propose to perform the measurements between the hours of 12am and 6 am to minimize human traffic in the building.

The Measurement System

As illustrated in Figure 1, our MIMO-channel measurement system is composed of two parts: (1) the HP85301B antenna pattern measurement system, used to measure the channel frequency response, and (2) the actuator positioning system, which emulates an arrays at both ends of the link by moving the antennas to arbitrary pre-programmed locations. The actuator controller moves the antennas to a pair of specified positions, and then the channel is measured. This procedure is repeated until all the desired antenna positions have been sampled. The measurements will be conducted in the Georgia Tech Residential Laboratory (GTRL) on 10th street and the GCATT Building at 250 14th street, both in Atlanta, GA.

The details of the components are listed in Table 1. The last column of the table lists the maximum rated outputs of the components; these are not the values we are proposing to use in the experiment. Rather, we propose to apply 20 dBm to the antenna. Because the antenna gain at 5.8GHz is 2.6dBi, the EIRP will be **22.6 dBm (0.779V/m @ 3m)**. Because the virtual array approach requires that the channel be static during the course of the measurements, all the experiments will be conducted after midnight (12:00 am – 8:00 am).

At this power level, a person would have to put their body within 17 mm of the source for at least 6 minutes to exceed the ANSI threshold for harmful exposure.

Each trial of the experiment is expected to take about 30 minutes. We plan to perform trials in many different locations on the 5th Floor of the GCATT building and the GTRL.

Actuator Positioning System

Driven by three brushless motors, the actuators can translate the antenna through a volume of approximately 50cm × 50cm × 7cm. The 7cm in the Z-direction ensures that the angles of paths arriving at nearly all elevations can be identified. For convenience, a mobile platform is also prepared to move both actuator systems to various locations. The design of actuator and mobile platform systems are demonstrated in Figure 2 and 3, respectively. The antennas are mounted on plastic telescoping masts such that the receive antenna can be positioned at heights ranging from 4 to 5 feet from the floor and the transmit antenna can be positioned at heights ranging from 4.5 to 5.5 feet from the floor.

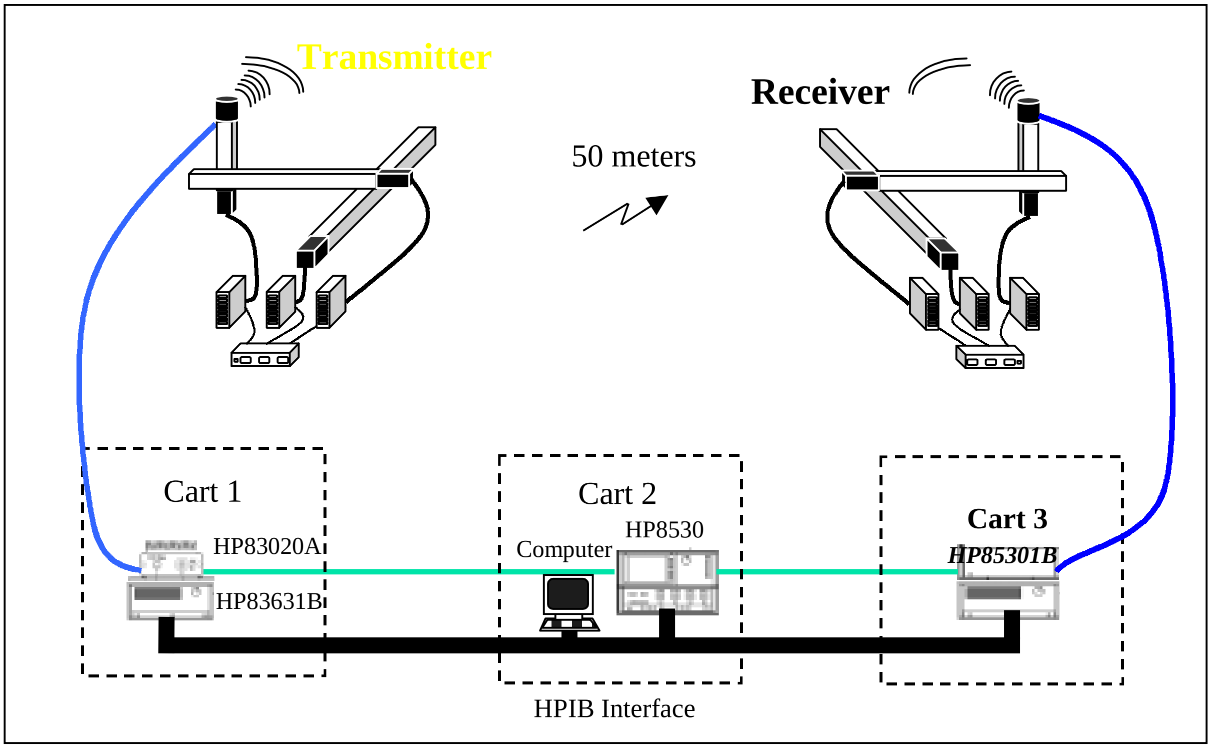

Figure 1. MIMO channel measurement system.

Table 1. HP85301B measurement system specifications

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Component	Equipment	Functions & Specs
Transmit source	HP83631B synthesized sweeper	Frequency range : 0.045 – 26.5GHz Max. output power : < 20 GHz, +13 dBm : 20-26.5 GHz, +10 dBm Resolution : 1 Hz
Amplifier	HP87422 power supply and HP83020 power amplifier	Frequency range : 2 –26.5 GHz Gain : 30 dB Max. output power : 30 dBm
LO source	HP83621B synthesized sweeper	Frequency range : 0.045 – 20GHz Max. output power : +13 dBm Resolution : 1 Hz
RF downconverter	HP85320A/B Mixers	Downconvert RF signal to IF band Sensitivity : -113 dBm Dynamic range : 89 dB
	HP85309A LO/IF distribution unit	1. Receive LO source and provide it to the mixers 2. Receive IF signals and send it to the microwave receiver
Microwave receiver	HP 8530A microwave receiver (HP85101C Display/Processor + HP85102R IF/Detector)	1. Synchronize and control the RF transmitter and the RF receiver 2. Receive and display the IF signal 3. Send the data to computer
Antenna (for Tx & Rx)	EM 6865 omni-directional wideband antenna	Type : Biconical Frequency range : 2-18 GHz Polarization : Vertical Gain : 2.6 dB at 5.5GHz 3.5 dB at 17.0 GHz Max. power : 5W VSWR : <2:1 Output impedance: : 50Ω Interface : Type “N” female Weight : 1 lbs

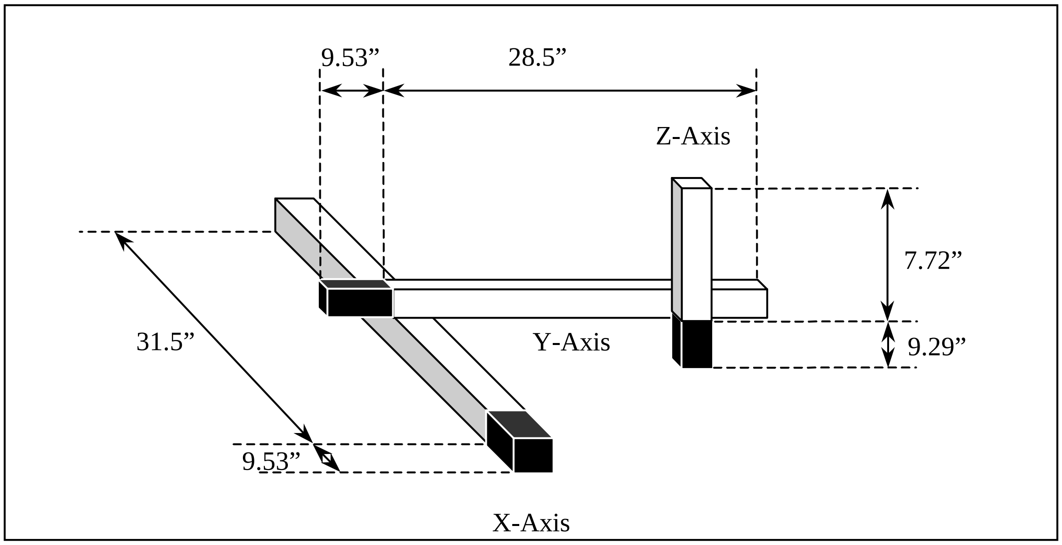

Figure 2. Three-dimensional actuator positioning system.

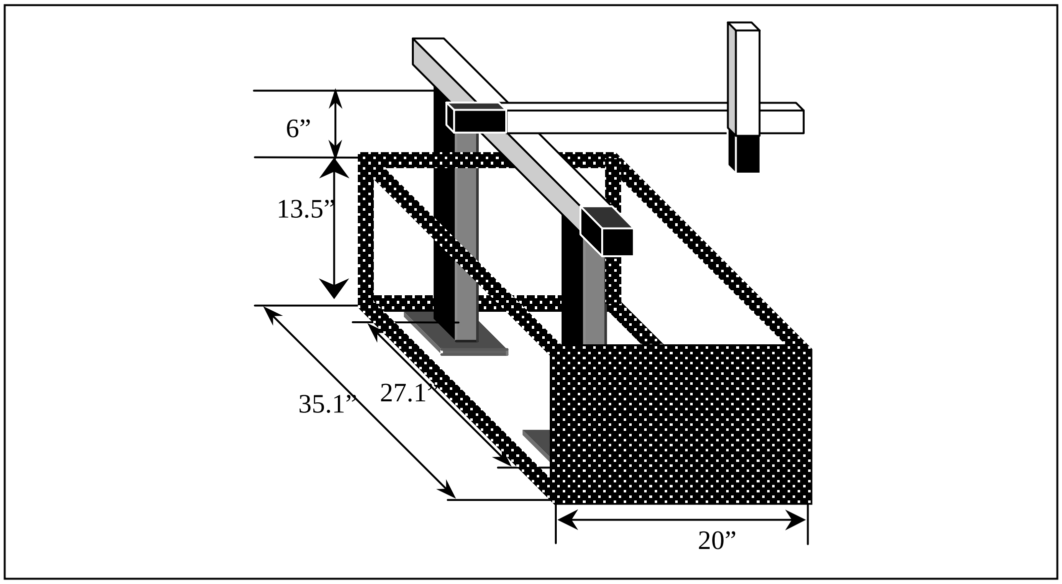

Figure 3. Mobile platform.

2. Experiments in the 2.45 GHz Band

We wish to conduct three experiments in the 2.45 GHz unlicensed band. The first two have to do with RF modulated backscatter and the third one has to do with multibeam beamformers.

Exhibit 2.1 Channel Sounding for RF Modulated Backscatter

RF modulated backscatter (RFMB) has traditionally been used only for very low cost and low data rate transmitters with either no batteries or batteries that must have extremely long lifetimes. RFMB is used for so-called "long-range" (<20m) RF tags. Applications include labels for large shipping containers, electronic shelf labels, and automated vehicle tolling. The purpose of the proposed experiment is to develop models for the large- and small-scale multipath fading in the RFMB channel. Such models will facilitate improved communication system design.

RFMB operation is illustrated in Figure 4 and explained as follows. An off-board source (the interrogator) transmits an interrogation waveform, which can be a CW wave or a frequency-hopped waveform. The interrogation waveform propagates to the RF tag that uses RFMB and reflects off of the tag antenna. A simple diode switch across the terminals of the antenna modulates the *impedance* of the antenna, thereby changing the reflection coefficient of the antenna with time. When the switch is in one state, the antenna reflects and when the switch is in another state, the antenna absorbs. The reflection or backscattered signal from the RF tag is therefore pulsed, creating an on-off keyed modulated signal. This is how an RF tag can transmit digital data without a power amplifier. Of course, the unmodulated wave from the interrogator reflects off of other objects in the environment, but the reflection from the tag is only the reflection that is pulsed. If the diode switching function is simply a periodic square wave, then the backscattered signal is amplitude modulated by a periodic square wave. The interrogator receiver can detect the presence of the backscattered signal by tuning a narrow filter to the frequency which is the carrier frequency plus the pulse repetition frequency, i.e. the first sideband.

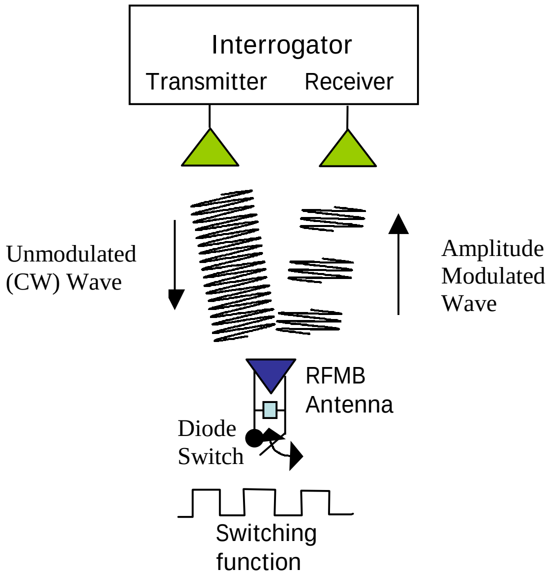

Figure 4. Illustration of RF Modulated Backscatter (RFMB)

We wish to transmit CW interrogation waveforms for the purpose of channel sounding, specifically, to measure the fading characteristics of the RFMB signal. Because of the two-way nature of this link (the interrogation waveform propagating to the tag and then reflecting back to the interrogator), we expect the two-way fading to be the product of typical one-way fades. As the product of two faded channel gains the RFMB channel gain can have very deep fades, and we want to capture those fades to get an accurate estimate of the fading distribution. This is the main reason why we are requesting a transmit power that exceeds the "ANY" category in the Part 15 regulations.

The measurement setup is shown in Fig. 5. For our reflection antenna, we will use the nearly omnidirectional antenna on the electronic shelf tag (EST) from NCR's DecisioNet^{TM} system. The EST is modified to allow the antenna to be switched continuously by an HP33120A function generator at a rate of 25 KHz with a 50 % duty cycle. The EST will be attached to the side of a T-shaped fixture made of plastic. The **unmodulated (CW)** RF carrier (i.e. the interrogator signal) will be transmitted by a patch antenna (ANP-C-116) in the suspended ceiling, indicated by Antenna 1 in Fig. 7. The patch antenna has right hand circular polarization and a peak gain of 4 dBi. Antenna patterns are omnidirectional in azimuth and hemispherical in elevation as shown in Fig. 6, in which the contour scale is 5 dB per division. The peak power delivered to the transmit antenna will be 16 dBm, giving an EIRP of **20 dBm (0.577 V/m @ 3m).**

At this power level, a person would have to put their body within 13 mm of the source for at least 6 minutes to exceed the ANSI threshold for harmful exposure.

An active patch antenna, indicated by Antenna 2 in the figure, with a pattern similar to that of Antenna 1, will be used to receive the backscattered signal. The active antenna includes the low-noise amplifier (LNA) HP INA-10386. Its output signal will go to a modification of the DecisioNet ceiling base station (CBS), which includes amplifiers, a mixer, and an eighth-order filter and which produces I and Q outputs. The local oscillator (LO) for the mixer will be detuned by 1 KHz, in order to avoid signal cancellation and to get IF conversion, and the I output at 26 KHz will be monitored on an audio spectrum analyzer. A computer will controll all instruments through GPIB and RS-232C interfaces and collect data for analysis.

In the Form 442, we describe two "modulations" associated with this experiment, one for the "downlink" or interrogator transmitted signal and one for the "uplink" or backscattered signal. The downlink is the unmodulated segment of RFMB and the uplink is the modulated segment. The uplink signal is only a reflected signal, which is why it is described as having such a low EIRP and the "power applied to the terminals" is left as "not applicable" (N/A).

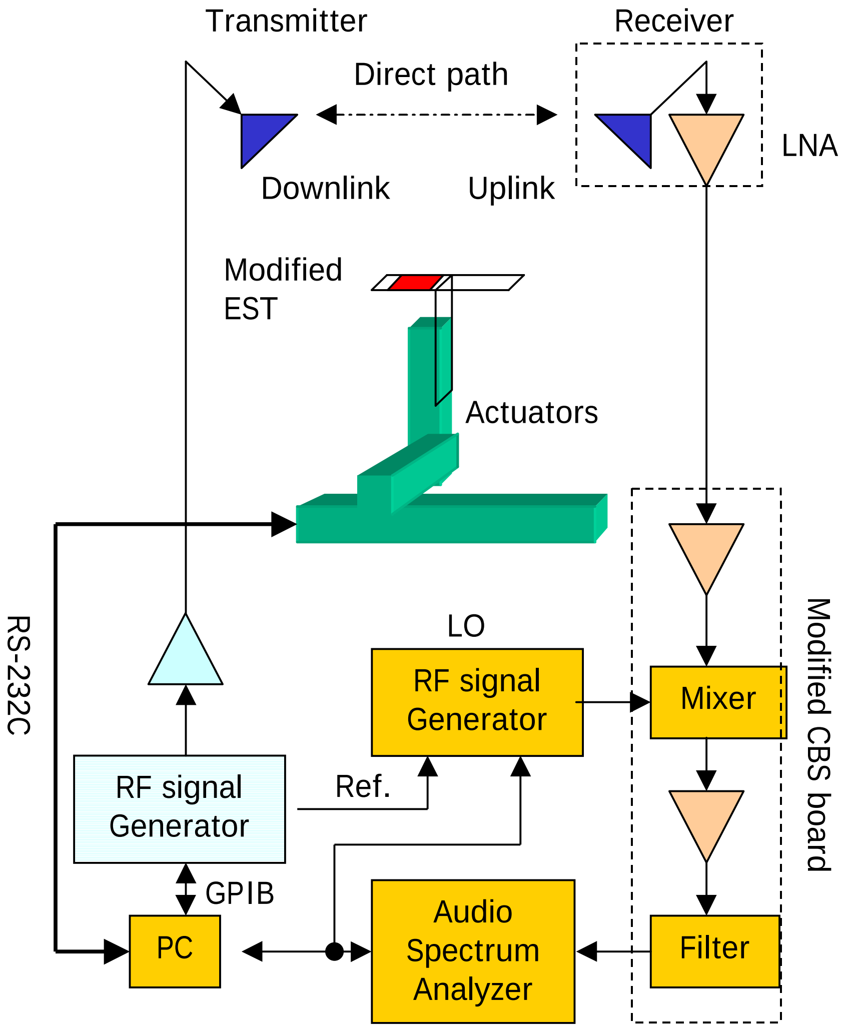

Figure 5. The setup for measuring the fading characteristics of the modulated backscatter link at 2.45 GHz

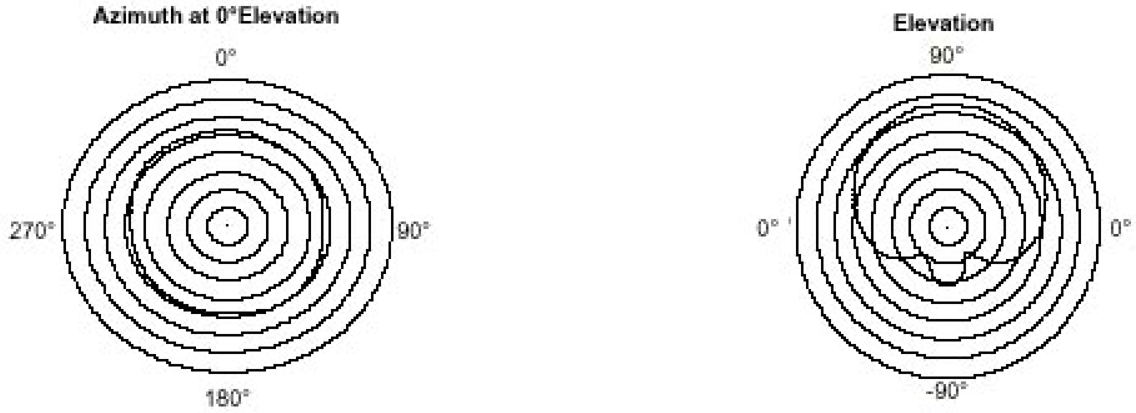

Figure 6. Representative azimuth and elevation patterns for the patch antennas that will be used as the transmit and receive antennas (at the top of the diagram) in the previous figure. The EST is the reflection antenna on the RF tag, and is not used for active transmission.

Exhibit 2.2 RF Modulated Backscatter For An Agricultural Application

The purpose of this experiment is to determine the feasibility of using RFMB for interrogation of moisture sensors deployed on the ground in fields. An illustration of the intended application is shown in Figure 7. Studies have shown that significant amounts of water, as well as other substances such as fertilizer and pesticide, are applied only where they are needed and in the amounts that are needed.

We want to test the strength of the RFMB backscattered signal when the tag antenna is on or very near the ground. To this end, we propose to make a RFMB signal strength measurement on a grassy knoll on the Georgia Tech campus. The interrogator transmit and receive antennas will be mounted on masts similar to those in Figure 4 at a height of 15 feet, which is the height of a typical pivot-type of farm sprinkler. The tag will be on the ground, with a horizontal distance from the interrogator antenna up to about 10 m. The tag on the ground will emulate the transceiver on a ground sensor. The tag antenna will be a patch with a gain of 4 dBi. The interrogator antennas will also be patches with 4 dBi of gain. We propose to transmit a **CW signal** from the interrogator transmitter, with 20 dBm of power delivered to the antenna, giving an EIRP of **24 dBm (0.915 V/m @ 3m).**

At this power level, a person would have to put their body within 2 cm of the source for at least 6 minutes to exceed the ANSI threshold for harmful exposure.

The experiment will be conducted for a variety of sensor locations on the ground. For each sensor location, the measurement is expected to take 20 minutes (to allow for numerous small shifts in the locations of the interrogator antennas to determine small-scale fading statistics). One outing in the field could take a few hours, and we expect that we might have to make a couple of outings to refine our measurements.

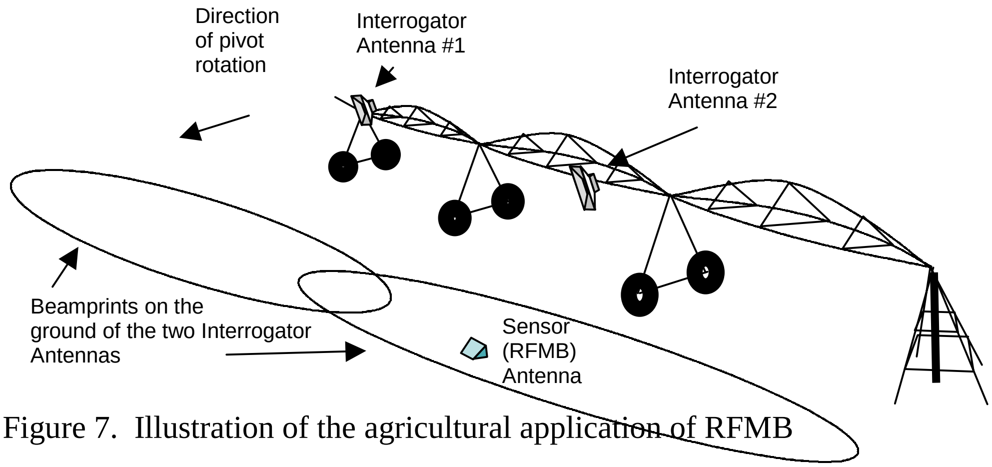

Figure 7. Illustration of the agricultural application of RFMB

Exhibit 2.3. Beam Pattern Measurement

We are building a multibeam beamformer to enhance the performance of indoor wireless local area networks. Simulations of such a beamformer used on a receiver in an indoor environment show an 11dB improvement in signal-to-interference ratio compared to an omnidirectional antenna, because the sidelobes attenuate the interference. .After our beamformer is built, we would like to measure the beam patterns. We have determined that we can achieve sufficient precision in the measurement if we use a highly directive antenna (a 20 dB horn) and mount both the horn and the unit under test (the multibeam beamformer), respectively, on two masts approximately 4 meters high, on the roof of the GCATT Bldg (the building is 5 stories high). We wish to transmit an unmodulated wave at 2.45 GHz through a 20 dB horn, as shown in Figure 8. The purpose of the horn is to minimize the degradation in pattern measurement from multipath. We will place absorber on the roof where we expect the largest multipath to reflect from the roof surface. The transmitted signal will be generated from an RF signal generator. The power received through the beamformer will be measured on an audio spectrum analyzer. The power applied to the horn antenna will be no more than 0dBm. The horn has 20dBi of gain, so the EIRP **is 20dBm (0.577 V/m @ 3m).**

At this power level, a person would have to put their body within 13 mm of the source for at least 6 minutes to exceed the ANSI threshold for harmful exposure.

The beamformer will be on the receiver, which will be rotated using an automated turntable. We propose to do the measurement during regular business hours. The estimated time required to measure all six beams of the beamformer is 30 minutes. We wish to repeat this measurement several times, not all on the same day, for a number of different beamformers.

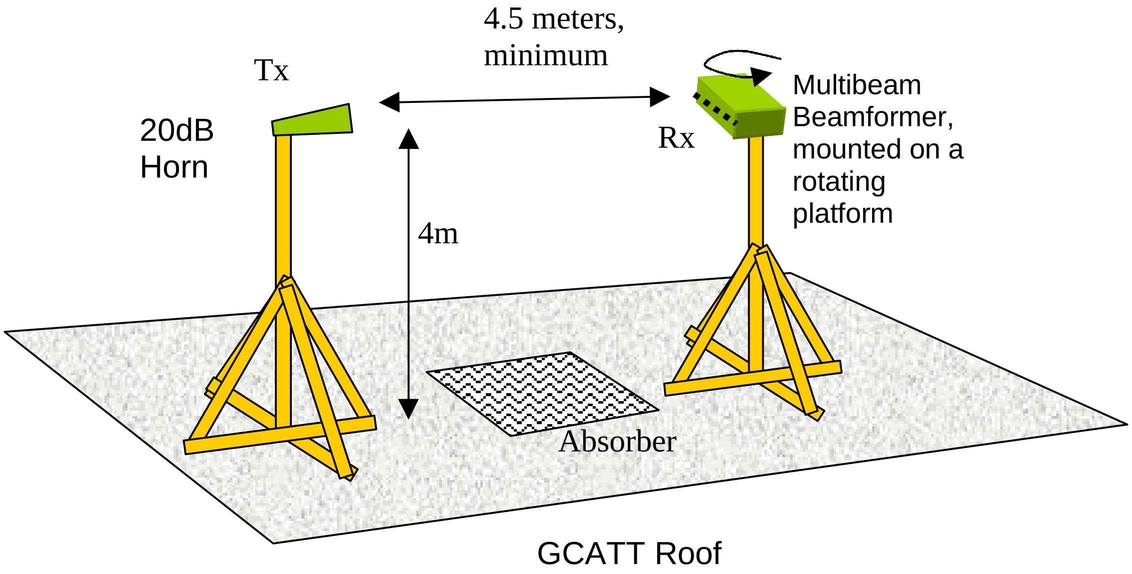

Figure 8. Beam pattern measurement setup.