

# A Measurement Study of User-Induced Propagation Effects for UHF Frequency Bands

Yan Shi, Eric Johnson, John Wensowitch, and Joseph Camp  
Department of Electrical Engineering, Southern Methodist University

**Abstract**— Understanding user-induced effects on signal reception across multiple frequency bands is of great scientific and military importance to the wireless industry. Various on-body locations and directional heading of the user are believed to impact the performance of mobile devices, but there has been little work across multiple frequency bands to quantify these user-induced effects. In this work, we perform a measurement study to explore user effects on radio wave propagation with varying line-of-sight conditions and environments across multiple frequency bands, including white space (500 and 800 MHz), cellular (1800 MHz), and WiFi (2400 MHz) frequency bands. To do so, we first conduct a baseline experiment that characterizes the propagation channel in this environment. We show that the propagation differences for ground-to-ground communication (common in Ad Hoc and WiFi scenarios) and tower-to-ground communication (common in cellular scenarios) are frequency dependent. Then, we measure signal quality as a function of the on-body location of the receiver, directional heading of the user with respect to the transmitter, vegetation type, frequency band, and propagation distance. Our assessment reveals that the user directionality with respect to the transmitter can reduce received signal strength up to 20 dB and reduce throughput by 20.9% at most. We also find that the body can act like an antenna, increasing reception by 4.4 dB and throughput by 14.4% over a reference node at the same distance. Since our study spans many critical (UHF) frequency bands, we believe these results will have far-reaching impact on a broad range of network types.

**Index Terms**—Propagation, On-Body Locations, Directional Heading, UHF, Path Loss, Shadowing, Ad Hoc, WiFi, Cellular

## I. INTRODUCTION

Wave propagation knowledge of user-induced effects has recently been of increasing interest for military communications, cellular network deployments, and device antenna design [1] – [6]. The receiver directionality and on-body location caused by human behavior can strongly affect the reception of electromagnetic waves. When there is a change in user behavior, antenna elevation, or scatter distributions, the channel quality can vary, resulting in fluctuations in signal reception within the same environment. Depending on the magnitude of the variation, the received signal strength (RSS) can drastically change the user experience, especially on the outer edges of the propagation range. According to [1], some early measurements of mobile phone network performance relating to orientation and position were conducted by Lehne. Myllymaki [2] proposed a method for evaluating the user-induced load on a cellular antenna on different hand grip positions. Khan [3] investigated the impacts of body shapes on the radio propagation, but his work ignored multiband and shadowing effects. Independently, Huang [4] and Chetcuti [5] performed similar techniques simulating the effects of human movements on signal reception of mobile receiver, but

both lacked adequate experimental support. In this work, we experimentally investigate the human body induced effects on path loss analysis and shadowing parameters over multiple frequency bands and diverse propagation environments. Our measurement study has impact on future WiFi and cellular deployments for potential crowdsourcing applications and Ad Hoc networks such as when designing military networks.

Theoretical studies for characterization and modeling of radio wave propagation have been conducted for a number of years [7] – [8], and measurement-driven designs have also been conducted under different practical scenarios. Measurement results for near-ground propagation were presented by Joshi [9]. By using narrowband and wideband channels at 300 and 1900 MHz, Joshi characterized the effects of antenna height on signal reception. Meng [10] developed an experiment to study near ground radio wave propagation at 240 and 700 MHz on an island in Singapore. However, most of these works focus on a particular environment type at a particular frequency band without varying the on-body location and directional heading of the user. To the best of our knowledge, this work is the first to quantitatively analyze these user-induced propagation effects over a wide range of UHF frequency bands at transmitter distances similar to typical WiFi and cellular base stations.



Fig. 1. Long Term Measurements Locations.

In this work, we first study the effects of transmitter elevation on radio wave propagation in two practical channels: ground-to-ground communication (Ad Hoc and WiFi scenarios) and tower-to-ground communication (cellular scenarios), characterized by antenna height and transmission power. We investigate signal attenuation caused by the environment as a function of frequency, distance, and antenna height. Then, the dominant propagation parameters (path loss exponent and shadowing standard deviation) are extracted and analyzed. In

order to achieve a representative sample of the environment, experiments are performed on up to 10 randomly-selected NLOS paths for each frequency band in both the ground-to-ground scenarios and tower-to-ground scenarios.

Second, we implement a measurement-driven framework to collect and analyze aggregated data sets to study the effects of different user-induced behaviors on signal reception. This framework is applied at multiple frequency bands (500, 800, 1800 and 2400 MHz) at several geographical locations near a campus (SMU-in-Taos) in Northern New Mexico over a month-long measurement campaign, shown by an aerial map in Fig. 1. We measure the RSS under diverse conditions characterized by on-body location of the receiver, directional heading of the user with respect to the transmitter, vegetation type, frequency band, and propagation distance, quantitatively revealing the user-induced effects on signal reception from relatively distant transmitters. Directional heading refers to the two-dimensional representation of user location in relation to the transmitter. The signal quality received by a mobile device is observed to also depend on the antenna directionality (facing directly towards or turning away from the radiation source) and on-body locations (in the hand or in the front pants pocket).

We perform measurements in a Line-of-Sight (LOS) setting with a single user focusing on the effects of diverse mobile phone positioning on the body and the direction the user with respect to the transmitter. Fig. 2(a) shows our setup with the receivers in the hand and pocket when squarely facing the transmitter, while the backpack is on the opposite side of the transmitter. By conducting measurements in a LOS path and comparing three different on-body locations, including holding the receiver in the hand, placing in a backpack, and putting in the pants pocket, our results indicate that users facing the transmitter can receive up to 20 dB greater signal quality versus reverse-facing users at the same location. However, these user-induced effects are more pronounced at shorter distances. Moreover, we find that a forward-facing user can act like an antenna that receives up to 4.4 dB over a reference node mounted on a tripod at the same distance.

Considering many real applications are Non-Line-of-Sight (NLOS), we further explore the effects of directional heading by conducting NLOS experiments with four simultaneous users at each of the cardinal directions at varying distances. These radial experiments are performed in two NLOS environments: a densely treed environment and a brush environment. While we still observe a dominant effect of directional heading in all directions (up to 20 dB), our results show that received signal quality is severely susceptible to environmental impacts and largely depends on frequency. We find that the forward versus reverse facing directionality loss is more pronounced in the tree environment (6-8 dB) as opposed to the brush environment (3-7 dB).

Finally, motivated by recent LTE standardization that allows user devices to feed back Key Performance Indicators to cellular towers, we consider the impact of the aforementioned user-induced effects on crowdsourcing wireless channel characteristics. Our assessment reveals that the directional heading of facing towards the transmitter results in higher path loss exponents than turning away in channel propagation, and user

directionality can have more than triple the shadowing effect in a given environment.

The rest of the paper is organized as follows. In Section II, we introduce the experimental setup and calibration measurements. In Section III, the baseline propagation in our experimental environment is investigated. We experimentally evaluate the results of single-user, linear LOS measurements in Section IV and multiple-users, NLOS measurements in Section V. Then, the user-induced effects on channel propagation is studied in Section VI. Finally, we conclude in Section VII.

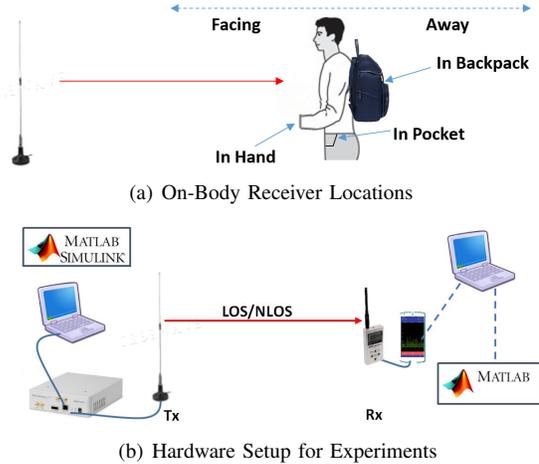


Fig. 2. Measurement Scenario for both LOS and NLOS Environments.

## II. BACKGROUND AND EXPERIMENTAL SETUP

In this section, we discuss relevant path loss models which will be used in characterizing the propagation channel over multiple frequency bands. In addition, we describe the experimental setup and ambient noise experiments we performed before beginning the measurements on user-induced effects.

### A. Background: Path Loss Models

Multipath propagation effects can be modeled through fast-fading that typically follows a Rician or Rayleigh distribution [11] with even slight movements by the receiver or scatters potentially causing significant variations in RSS [12]. Complex environmental factors, such as dense and deciduous forest groups, foliage vibration, and capricious weather conditions, can largely affect the signal reception [13]. Such uncertainty caused by location dynamics or multiple paths is usually denoted as shadow-fading. The propagation channel from the transmitter (TX) to receiver (RX) can be described by the widely-used log-distance path loss model in addition to a shadow-fading component [12] [14], given by:

$$P_{RX} = P_{TX} - PL_{d_0} - 10\lambda \log_{10}\left(\frac{d}{d_0}\right) + X_s \quad (1)$$

Here,  $PL_{d_0}$  is the path loss at a reference distance  $d_0$ ,  $P_{RX}$  is the received signal strength, and  $P_{TX}$  is the transmission power. The term  $10\lambda \log_{10}\left(\frac{d}{d_0}\right)$  corresponds to the log-distance path loss model, where  $d$  denotes the transmitter-receiver separation distance. Lastly,  $X_s$  is the shadow-fading parameter

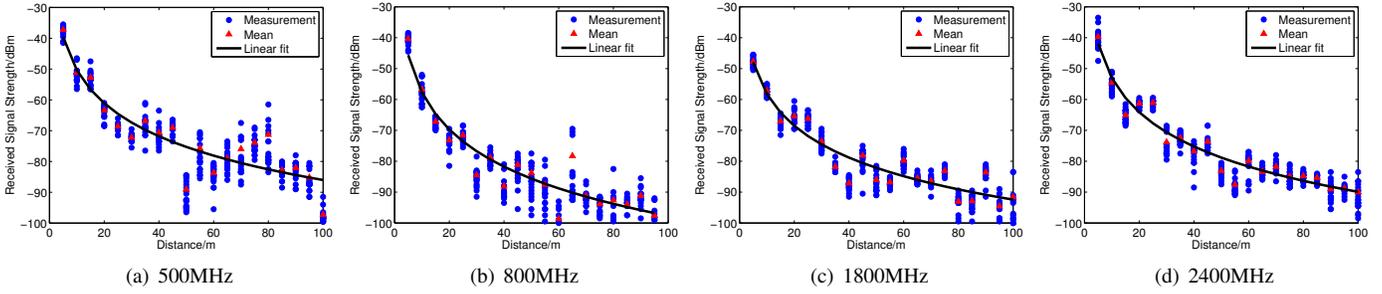


Fig. 3. Received Signal Strength vs Distance on Four Frequency Bands.

that is typically zero-mean, normally-distributed with standard deviation  $\sigma$ . Linear regression fitting is implemented to estimate the path loss exponent  $\lambda$  and the standard deviation  $\sigma$ .

### B. Hardware Setup and Experimental Calibration

The experiments are carried out using the Universal Software Radio Peripheral (USRP) N210 as the transmitter controlled by a Simulink diagram running on a laptop to generate continuous waves at 500, 800, 1800, and 2400 MHz. The transmitter USRP is equipped with a SBX daughterboard that covers a frequency range from 400 to 4400 MHz and provides a bandwidth of 40 MHz. The continuous waves are produced by feeding a tone of zero frequency directly to an amplitude modulator. An omni-directional, multi-band antenna with a gain of 4 dBi is implemented at the transmitter at various heights according to the scenarios described. A Nuts About Nets Handheld RF Explorer is working as a spectrum analyzer (SA) to capture received signal strengths (dBm) during in-field experiments per user. The handheld SA operates in the frequency range of 15 to 2700 MHz with an NA-773 dual band extendable whip antenna used at the receiver. Using the on-board memory of a Samsung S5 via a USB interface, the data sets are collected in real-time with the Nuts About Nets Touchstone-Pro mobile application. For each experiment, we collect a minimum of 80 samples and later export them in a comma-separated format for post-processing. During measurements, any unnecessary user movement is restricted in order to suppress human movement as much as possible. Fig. 2(b) depicts the hardware setup for our experiments.

In-lab calibration of USRP RF transmission power on four frequency bands is performed by directly connecting the Rohde & Schwarz FSH8 SA to the transmitter USRP using two SMA connectors and a coaxial 50  $\Omega$  cable. Besides, in order to calibrate the frequency based gain caused by the multi-band antenna and fairly characterize the large-scale coverage distances over all frequency bands, we use a close-in free space reference distance as to perform linear fitting for path loss (dB) as a function of distance (m) [11]. The path loss at the free space reference distance  $d_0$  is given by:

$$PL_{d_0} = 20 \log_{10} \left( \frac{4\pi d_0}{\theta} \right) \quad (2)$$

Here,  $\theta$  is the carrier wavelength. We first measure the RSS at a fixed distance of 1 m with the calibrated transmission power and then calculate the relative path loss (PL) for each

measurement position. The path loss scatters can be plotted by adding the relative PL on the reference PL obtained from Equation (2). Table I gives an example of the PL calibration at a measurement position of 20 m. Before exploring user-induced effects, we also explore the ambient noise over four frequency bands in our selected measurement environments while disabling our USRP transmitter. It is observed that the noise floor for is generally less than -98 dBm under test.

TABLE I  
PATH LOSS CALIBRATION BASED ON 1 M REFERENCE DISTANCE

Frequency	500 MHz	800 MHz	1800 MHz	2400 MHz
RSS at 1 m	-31.3 dBm	-46.4 dBm	-41.3 dBm	-40.8 dBm
RSS at 20 m	-58.7 dBm	-68.7 dBm	-72.0 dBm	-73.4 dBm
Relative PL	27.4 dB	22.3 dB	35.7 dB	32.6 dB
Reference PL	26.42 dB	30.50 dB	37.55 dB	40.05 dB
PL at 10 m	53.82 dB	52.80 dB	73.25 dB	72.65 dB

### III. BASELINE IN-FOREST PROPAGATION PREDICTION

In this section, we set up a baseline experimental framework that predicts the propagation in our experimental environment while controlling for the user behaviors.

#### A. Baseline Experiment Setup

In this baseline setup, the experiments are performed in two practical channels: a ground-to-ground scenario and a tower-to-ground scenario, which enable the study of the effects of transmitter elevation on signal reception, and of controlled user behaviors at diverse user positions. The user always faces the transmitter and the on-body location of the receiver is the hand. The transmitter is located to a height of 1 m above ground in the ground-to-ground setup, while the transmitter antenna is fixed at 10 meters above the receiver antenna to imitate the tower-to-ground cellular networks. The user holds the handheld spectrum analyzer (SA) in-hand facing the transmitter and takes at least 80 measurements of the received signal strength at each measurement position while moving within a radius of ten times the wavelength to average out fast fading effect throughout our experiments [11]. We then characterize the channel with measurement data and path loss model to study the propagation for our experiments.

For reference purpose, we first conduct measurements in a LOS path where no obvious objects might interfere with the transmission. Results show that 800 MHz LOS path has the least path loss exponent of 1.87, which is slightly less than free space. This is accounted for by the existence of neighbor

scatters that produce strong signal reflections in that frequency band. However, other frequency bands, such as 1800MHz, show relatively larger path loss exponents.

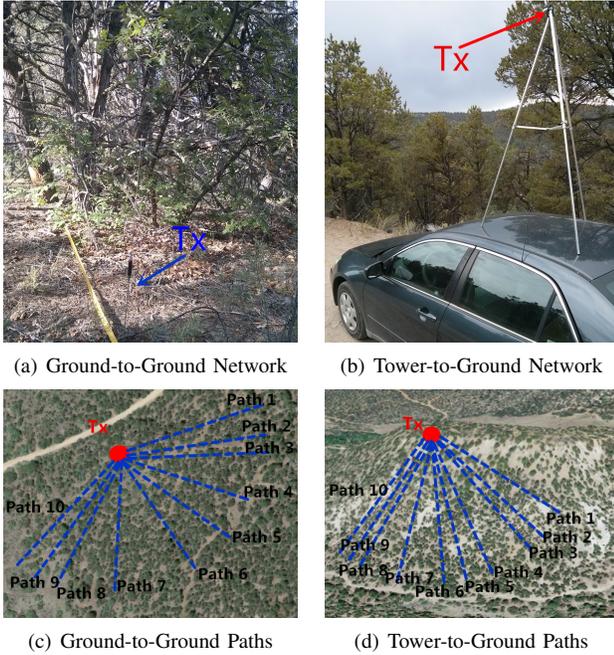


Fig. 4. Forest Propagation Measurements.

### B. Ground-to-Ground Propagation Measurements

The ground-to-ground setup mimics the communication scenarios similar to WiFi networks and Ad Hoc networks, as shown in Fig. 4(a), where there is no direct LOS. We evaluate the propagation by performing measurements in ten random selected NLOS paths with dense foliage coverage, with the overhead image shown in Fig. 4(c). The USRP transmission power is calibrated to 12 dBm for all four frequency bands. In order to get a general understanding of the propagation channel, the path loss exponent and shadowing standard deviation are extracted for all paths.

Fig. 3 presents the multiple bands propagation results of *Path 3* in the ground-to-ground scenario, with the measurement data and resulting fitted curves depicted as the solid black lines. The transmitter-receiver separation distance ranges from 5 to 100 meters with 5 meter granularity, and measurement positions are identical across all frequency bands measured. Table II gives the estimated path loss exponent  $\lambda$  and shadowing standard deviation  $\sigma$  for each frequency band. The signal reception based on the measurement position at different frequency bands seem to follow the same pattern: the received signal strength decreases as the distance increases. However, the peak patterns for all four frequency bands based on RSS and distance are not consistent for the chosen geographic paths and user positions. For example, 500 MHz has a peak value of -62 dBm at the distance of 80 m and 800 MHz has a peak value of -67 dBm at 65 m, while no comparable peak values can be found at higher frequency bands; this reveals that the channel quality is closely frequency dependent. On

the other hand, the environment is another factor that greatly affects the wave propagation. The fact that a low frequency does not strictly obtain better propagation is also explained by the complex obstructions that increase the attenuation and absorption intermittently blocking signals based on frequency. Next, We extend our evaluation to ten geographic paths and use a free space reference distance to perform linear fitting for spectral path loss analysis.

TABLE II  
ESTIMATED LOG-DISTANCE PATH LOSS MODEL PARAMETERS

Parameters	500 MHz	800 MHz	1800 MHz	2400 MHz
SA bandwidth (MHz)	40	40	40	40
Sampling Interval (s)	1.13	1.13	1.16	1.19
$\lambda$	3.36	3.99	3.42	3.68
$\sigma$ (dB)	2.98	3.39	2.30	2.27
Route	Fig. 3(a)	Fig. 3(b)	Fig. 3(c)	Fig. 3(d)

Fig. 5 shows the path loss scatters for the ground-to-ground propagation on four frequency bands generalizing all measurement areas. The path loss exponents and shadowing standard deviation are given for the reference LOS path (LOS), the best path (NLOS,B), the worst path (NLOS,W), and average path (NLOS,A). The so-called best path has the least path loss exponent, which is mostly preferred by future cellular system. The worst path is the one that has the highest path loss component. The average path is defined to average on the propagation parameters of all independent measurement paths in order to describe the overall channel quality in selected experimental area. In addition to measurement data collection, all path loss characterizations are based on a free space reference distance of 1 meter, as previously described in Table I. It is obvious that for all frequency bands, NLOS paths lead to higher path loss exponents than LOS paths by an increase ranging from 0.46 to 1.34. Compared with free space, the pass loss can be as high as 23 dB at the distance of 50 meters and 38 dB at the distance of 100 meters. Interestingly, in terms of averages, the LOS path for 800 MHz has the least path loss exponent of 1.87, while the 800 MHz NLOS path has the largest path loss reaching 3.88, comparable with 2400 MHz that has a path loss exponent of 3.81. If considering the best path alone, all four frequencies have similar path loss exponent of nearly 3.3. On the other hand, the largest path loss exponent happens to result from 800 MHz, indicating the worst path. Our evaluation also reveals that higher frequency bands (1800 and 2400 MHz) have smaller fluctuation in shadowing than lower frequency bands (500 and 800 MHz), with 2400 MHz actually presenting the least shadowing standard deviation of 1.99 dB.

### C. Tower-to-Ground Propagation Measurements

Tower-to-ground propagation is characterized by the fact that the transmitter usually has a higher elevation and transmission power than the receiver, with typically omni-directional radiation from rooftop to ground. Several experimental contexts have been found near an institutional campus, characterized by a terrain of steep cliffs with a depth ranging from 5 to 15 meters. Similar to the ground-to-ground communication, the tower-to-ground also implements the same basic measurement setup, but has a transmitter elevation height of

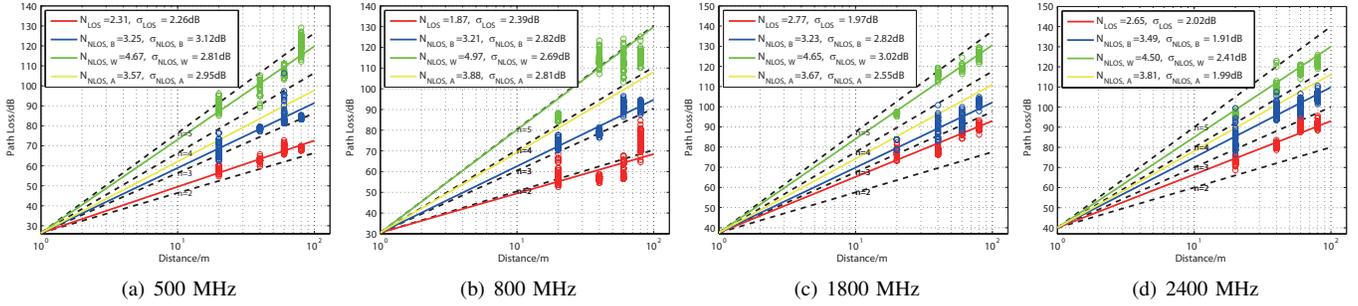


Fig. 5. Ground-to-Ground Path Loss Model above 1 m Reference on Four Frequency Bands.

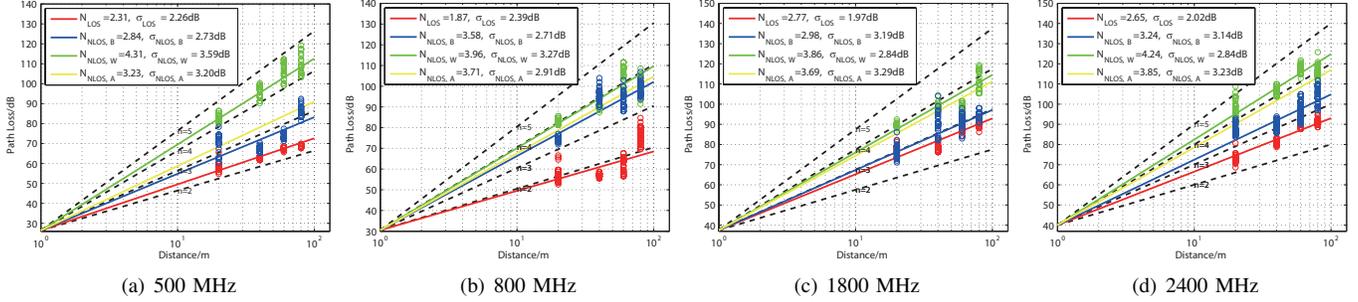


Fig. 6. Tower-to-Ground Path Loss Model above 1 m Reference on Four Frequency Bands.

around 10 meters by fixing the antenna on a tripod on the roof of a car and polling by the edge of cliff face, as shown in Fig. 4(b). By conducting measurements under the cliff with spatial measurement positions in ten different radiation paths, the vertical difference forms a cellular alike communication scenario. During our experiments, the transmitter power is aligned to 19 dBm (the highest transmission power available) for all four frequency bands. Independently, we also evaluate up to ten paths radiated by a fixed transmitter position with respect to the tower-to-ground setup, as shown in Fig. 4(d), and characterize these channels with path loss calibration.

The path loss scatter diagrams are given in Fig. 6 to summarize the tower-to-ground channel path loss distributions at multiple bands. Compared with the ground-to-ground scenario, 500 and 800 MHz propagation channels are observed to be more favored in tower-to-ground setup due to their slightly smaller path loss exponents. One reason for the reduced path loss is the existence of the relatively fewer objects blocking the propagation path in the view from tower to ground. It is interesting to observe that at 500 MHz the tower-to-ground path has the least path loss exponent of 2.84, compared with 2.31 in the LOS path. Furthermore, we detect an increase in shadowing standard deviation, ranging from 0.5 to 1 dB at 1800 and 2400 MHz, due to the large fluctuations of tree branches and foliage under the influence of wind. Considering that a typical forest environment usually contains rich scatters, and any slight movement in the transmitter antenna location will greatly affect the propagation channels, it is very likely that significant fluctuations can be present in tower-to-ground networks. *Finding: The Tower-to-ground scenario results in much higher shadowing standard deviations than the ground-*

*to-ground scenario.*

#### IV. SINGLE-USER LINEAR LOS EXPERIMENT

In this section, we describe the linear LOS experiment to explore the user-induced effect of a single user on wave propagation. Specifically, we conduct measurements in a selected LOS path and investigate the effects of on-body positioning and directional heading of the receiver with respect to the transmitter, as shown in Fig. 7. The transmitter and receiver have an unobstructed path between them only affected by various on-body locations, as depicted in Fig. 2(a), as a function of whether the user is forward facing or reverse, propagation distance, and frequency band under test.



Fig. 7. Spatial Depiction of Linear LOS Measurements.

During our experiments, the transmitter power is set at 19 dBm for all four frequency bands, and the height is fixed at 2 m above the ground to maintain better radiation. We simultaneously measure the signal receptions at three different on-body locations, including the receiver in the hand, backpack, and pocket, at a transmitter-receiver separation distance ranging from 20 to 200 meters with 20 meter linear granularity. Except the three on-body receivers, an extra receiver

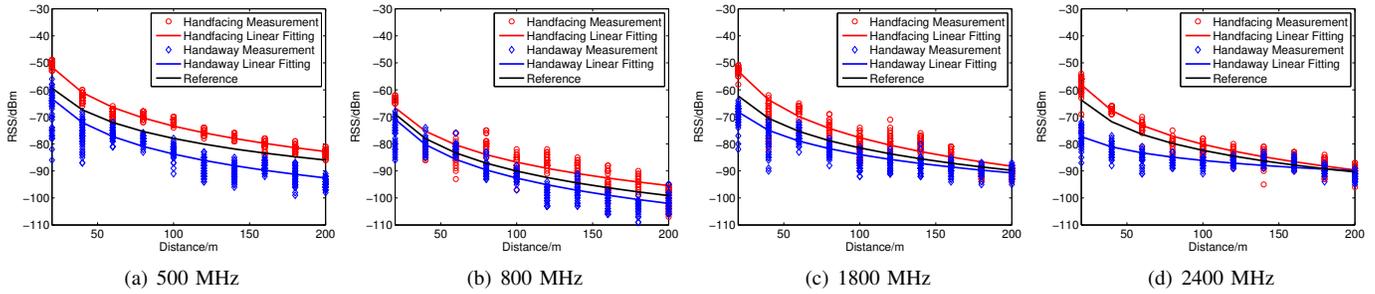


Fig. 8. Hand Facing Towards/Turning Away the Transmitter in Linear LOS Measurements.

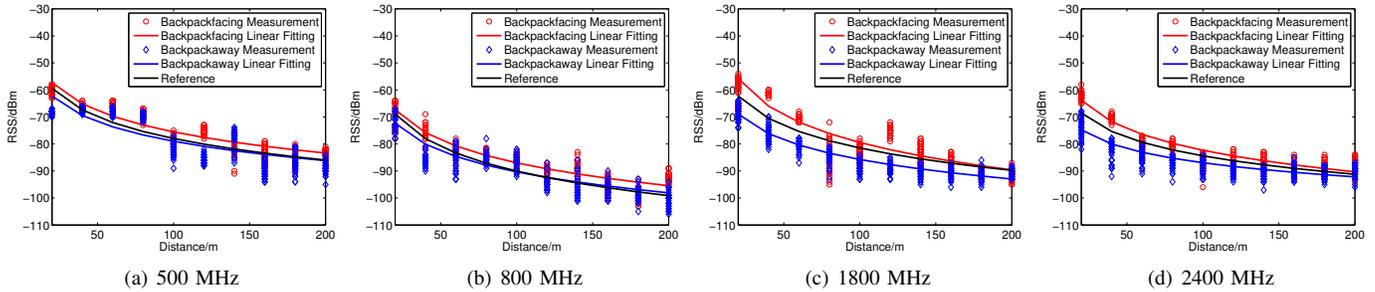


Fig. 9. Backpack Facing Towards/Turning Away the Transmitter in Linear LOS Measurements.

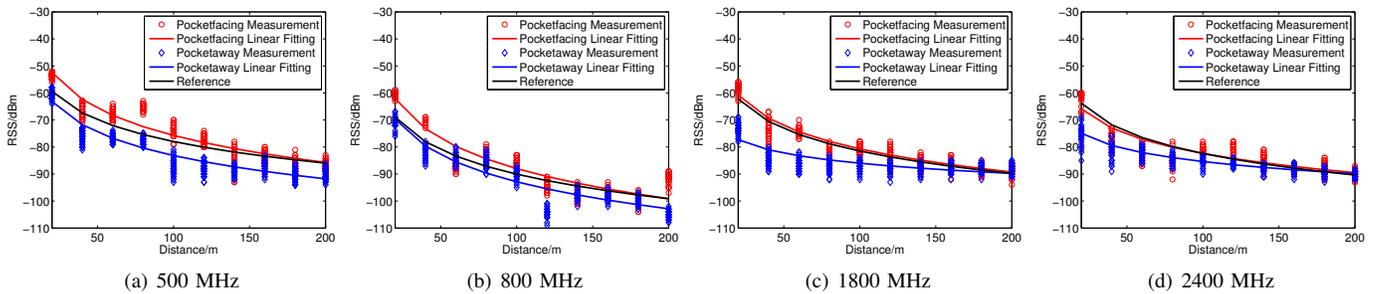


Fig. 10. Pocket Facing Towards/Turning Away the Transmitter in Linear LOS Measurements.

is vertically mounted on a tripod at a height of 1 meter as reference (with a clear LOS path to the transmitter). Each on-body location is used for two directional heading scenarios at each distance: facing directly towards the transmitter and turning away from the transmitter.

TABLE III  
ESTIMATED USER-INDUCED LOSS AFTER LINEAR FITTING

Location	User-Induced Loss (dB)	500 MHz	800 MHz	1800 MHz	2400 MHz
Hand	Min	9.32	2.56	2.47	0.27
	Max	13.42	7.02	15.10	19.15
	Mean	10.73	5.48	6.81	6.77
	St Dev	0.81	0.93	4.12	6.01
Backpack	Min	2.81	0.65	3.36	0.35
	Max	4.96	2.96	11.11	8.55
	Mean	3.55	1.44	5.71	3.17
	St Dev	0.68	0.73	3.10	2.89
Pocket	Min	6.02	3.79	0.50	0.38
	Max	10.71	8.04	16.46	9.04
	Mean	7.63	5.25	5.99	3.36
	St Dev	1.49	1.21	5.08	3.75

Fig. 8, Fig. 9 and Fig. 10 show the measurement results with the reference reception after linear fitting as a function of distance, frequency and receiver directional heading for each of the three on-body locations: hand, backpack, and

pocket.<sup>1</sup> Throughout this work, we use the term user-induced loss (dB) to denote the RSS difference between the direction facing respect to the transmitter and turned away from the transmitter. We expect that when facing towards the transmitter that the RSS is stronger than facing away in all cases.

Table III provides the quantitative evaluation on user-induced loss for each of the three on-body locations. For the location of the receiver held in the hand, we observe that the user-induced loss ranges from 9.32 to 13.42 dB and from 2.47 to 15.10 dB at 500 and 1800 MHz, respectively. The highest user-induced loss occurs at the shortest distance. As distance increases there is only a slight decrease at 500 MHz, however, at 1800 MHz, user-induced loss drops to almost zero. One reason might be the large path loss experienced at higher frequencies that causing clipping beyond the sensitivity level of the receiver as compared to the shorter distances where the forward and reverse heading are both in the receivable received signal quality region. This is also supported by the fact that relatively higher values of standard deviation (St Dev)

<sup>1</sup>It should be noted that the backpack facing term refers to the scenario where the backpack (receiver) is actually facing the transmitter, not the user.

with regard to user-induced loss occur at higher frequencies. Hence, the full range of user-induced loss can be measured at shorter distances (20 to 120 meters) as opposed to more distant distances (140 to 200 meters).

Although similar patterns can be found at the other two locations, it is interesting to note that the location inside the backpack shows the least loss out of the three locations, ranging from 3 to 11 dB; while the location of receiver held in the hand has the largest difference, ranging from 9 to 17 dB. When the user is facing the transmitter, this results in higher received signal strength than the reference node in all cases except Fig. 10(c)(d), indicating that the user can act as an antenna and cause higher signal reception. *Findings: The effects of user behaviors tend to be more critical on received signal strength at relatively close distances. The location in the hand presents the largest user-induced loss out of all three locations. Users can act like an antenna and cause signal reception of up to 4.4 dB more than the reference node.*

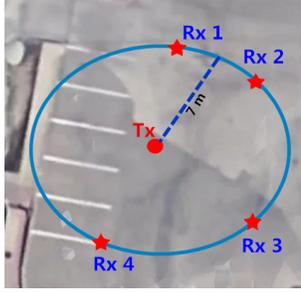
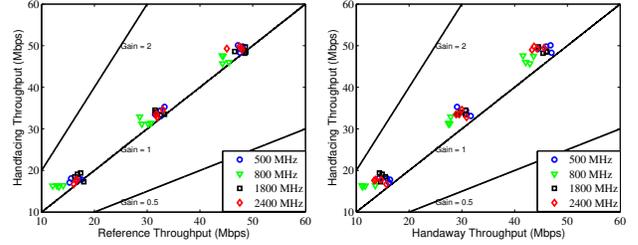


Fig. 11. Overhead Image of Throughput Performance Measurement.

In order to further justify that the user can act as an antenna, we perform extensive experiments to compare the throughput performance among three receiver setups: in the hand facing towards the transmitter (handfacing), in the hand turning away from the transmitter (handaway), and a reference location (same elevation without human interference). In our experiments, one USRP board operates as the transmitter with a fixed position, while another USRP board operates as a receiver, located at four positions randomly selected on a circle with a radius of 7 m. At each position, We evaluate the throughput performance of each of the three receiver setups. We place the two USRP boards in an outdoor area, as shown in Fig. 11. We implement an OFDM scheme with 600 subcarriers, similar to LTE devices. This transmission scheme requires a 10-MHz bandwidth with a sampling rate of 15.36 MHz. To adjust the transmission rate, we choose between three different modulation schemes: QPSK, 16QAM, and 64QAM. We send training OFDM symbols to synchronize the reception of all OFDM symbols in our implementation. The throughput for handfacing, handaway and reference location are shown in Fig. 12 for the three modulation schemes. Our evaluation reveals that with the same transmission power, the location of the in-hand facing receiver can achieve an average of 13% (ranging from 11.0% to 14.4%) improvement in terms of throughput than the reference node, and an average of 19% (ranging from 18.1% to 20.9%) improvement than the in-hand receiver that is facing away from the transmitter.



(a) Handfacing vs Reference

(b) Handfacing vs Handaway

Fig. 12. Comparison of Throughput among Three Receiver Setups.

## V. MULTIPLE USERS RADIAL NLOS EXPERIMENT

In this section, we discuss the radial NLOS experiment that investigates the effects of cardinal direction forming a radial pattern, as opposite to the single path in linear LOS experiment, and directional heading of the user with respect to the transmitter on signal reception. We conduct the radial experiments with four simultaneous users of resemble size taking samples at each of the cardinal directions in two distinct propagation scenarios: a densely treed environment and a brush environment, as shown in Fig. 13. During the time of measurements, the shrubbery is found to have mature and full leaves in brush environment, while in densely treed environment, the pine trees are observed to have sparse foliage but possess a larger trunk with much greater height. Compared with LOS experiments, we perform radial NLOS experiments on one on-body location (in the hand) in order to focus on the investigation of the spatial effects. The path between the transmitter and the receiver is affected by diverse cardinal directions, whether the user is facing directly towards or turning away from the transmitter, propagation distance and frequency band under test.



(a) Radial Tree Area

(b) Radial Brush Area

Fig. 13. Spatial Depiction of Radial NLOS Measurements.

In each area, measurements are performed along the four cardinal directions to explore the areal effects at distances ranging from 20 to 80 meters outward, with 20 meter granularity. The transmitter is centered radially at a same distance of 2 meters above ground level. Along each directional heading, each individual user is required to follow the uniform pattern to conduct measurements under both directional headings.

Fig. 14 and Fig. 15 show the quantitative evaluation on user-induced loss extracted from the measurement data sets as a function of distance, frequency and cardinal direction for the tree and brush environment, respectively. A positive value of user-induced loss denotes that user location facing towards the transmitter has a higher value of received signal strength than the reverse heading, while a negative value means the opposite.

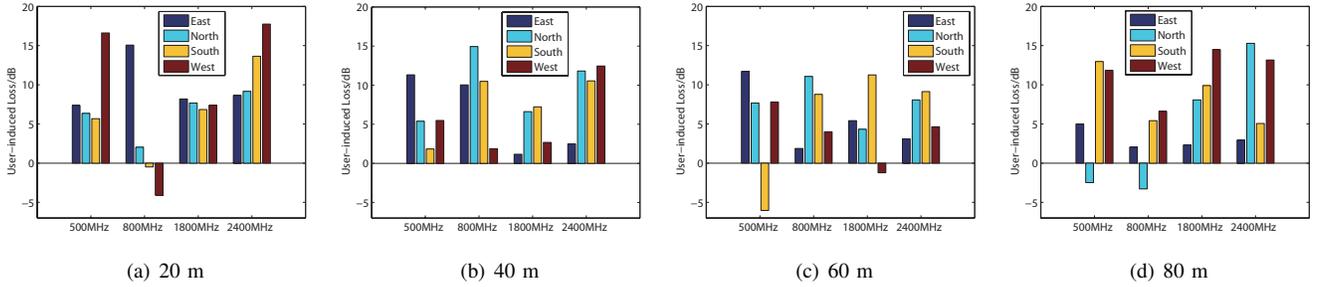


Fig. 14. Estimated User-Induced Loss in Tree Area.

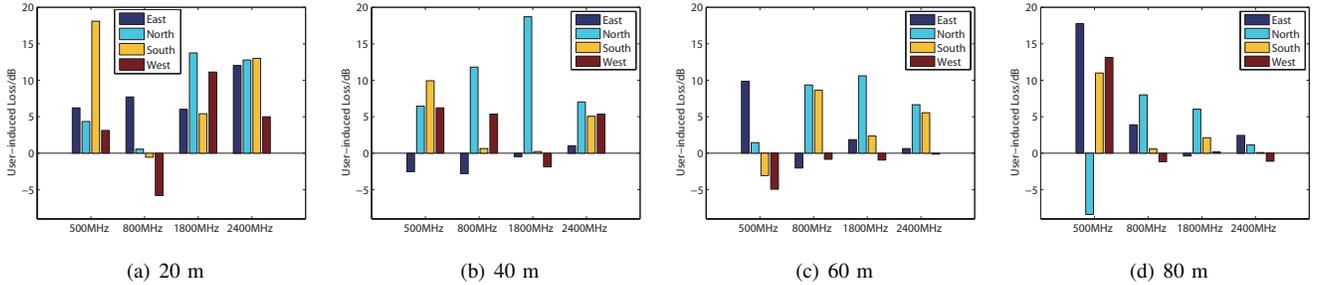


Fig. 15. Estimated User-Induced Loss in Brush Area.

We expect that positive values are more likely to occur in our experiments. Both areas reveal that, given a certain distance and vegetation type, analysis along the four cardinal directions does not follow an identical pattern affecting the results of user-induced loss. For instance, by looking at Fig. 14(a), at 800 MHz a high positive loss of 17 dB is detected in the east, compared with the unexpected -4 dB in the west; which results in a signal reception difference of 21 dB. However, at 1800 MHz band, all cardinal directions suffer a uniform user-induced loss of approximately 8 dB. Similar results can be found in the other figures, with received signal strength differences in various cardinal direction pairs ranging from 1 db (1800 MHz, Fig. 14(a)) to 25 dB (500 MHz, Fig. 15(d)). As a result, we conclude that the distinct propagation channels in different cardinal directions indeed impact the measurement results in complex forest environments. *Finding: Received signal quality is severely susceptible to environmental impacts.*

Furthermore, we find that the treed environment actually presents less outcomes of negative user-induced loss than brush environment, which is likely due to the less dense foliage distribution and sparse undergrowth in the pine tree area. Besides, higher frequency bands are observed to present more results of positive user-induced loss than lower frequency bands, which demonstrates that the higher frequency signals tend to be easily absorbed within the environment. Our evaluation reveals that the average user-induced losses are 4.05, 5.53, 5.60 and 7.01 dB for 500, 800, 1800 and 2400 MHz, respectively. *Finding: Users can affect received signal strength up to 20 dB, and the user-induced losses varies with frequency.*

Fig. 16 shows the averaged user-induced loss based on the aggregate user effects aligned in all cardinal directions and frequency bands. It is interesting to observe that the averaged user-induced loss decreases to 5.7 and 2.9 dB at 60 m for tree and brush area, respectively, and then obtains a slight increase at 80 m. The tree area presents apparently higher

user-induced loss than brush area by average, which agree well with our previous conclusion that RSS is severely susceptible to environmental impacts. It is assumed that the relatively sparse vegetation distribution in tree area provides a better propagation environment than brush area. Combined with the results from LOS experiment, our evaluation reveals that users can affect received signal strength by an average of 5.6 dB.

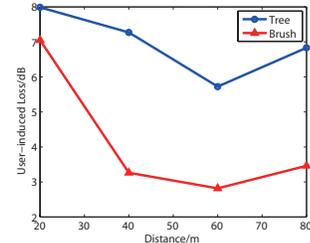


Fig. 16. Averaged User-Induced Loss Based on Aggregate User Effects.

## VI. USER DIRECTIONALITY-AWARE PROPAGATION PREDICTION

In this section, we consider the user-induced impact of cellular providers crowdsourcing and inferring wireless channel characteristics from users via LTE Key Performance Indicators. To do so, we experimentally quantify the role of directional heading of the user with respect to the transmitter on propagation parameters derived from previous discussed linear LOS and radial NLOS experiments. The path loss exponent and shadowing standard deviation are extracted by analyzing the measurement data sets in terms of three aspects for each band: when the user is facing towards the transmitter, when the user is turning away from the transmitter, and mixed directionality when data sets in both directional headings are jointly considered. In radial NLOS experiments, we examine the aggregate user effects aligned in all cardinal directions to remove the spatial differences.

TABLE IV  
ESTIMATED PROPAGATION PARAMETERS WITH USER-INDUCED EFFECTS

Scenario	500 MHz						800 MHz						1800 MHz						2400 MHz					
	Facing		Away		Mix		Facing		Away		Mix		Facing		Away		Mix		Facing		Away		Mix	
Parameters	$\lambda$	$\sigma$																						
Linear LOS	2.78	3.26	2.58	3.37	2.69	4.54	3.15	3.02	2.45	3.00	2.79	8.78	3.11	2.37	2.97	2.19	3.05	2.76	3.51	2.75	2.15	2.85	2.83	9.84
Tree NLOS	3.80	3.27	3.66	3.19	3.74	3.89	3.63	3.06	2.79	3.73	3.18	7.06	3.52	3.53	3.87	3.38	3.68	6.49	3.79	2.87	2.84	2.96	3.31	8.77
Brush NLOS	3.74	3.08	4.67	2.85	4.22	8.18	4.39	3.15	3.98	2.44	4.20	6.33	3.67	3.78	2.21	2.61	2.91	9.07	3.87	3.24	2.59	3.16	3.24	9.21

Table IV provides the results of propagation parameters as a function of directional heading and mixed directionality across the frequency bands. In the LOS setting, the path loss exponent ranges from 2.78 to 3.51 and from 2.58 to 2.97 in the directional headings of facing towards the transmitter and turning away from the transmitter, respectively. We conclude that facing the transmitter results in higher values of path loss exponent than away. However, this can be misleading because the starting point of the received signal of user facing forwards is much higher than the starting point of the received signal of away. Hence, the path loss exponents derived from measurements with regard to reverse heading are often clipped at the largest distance. Furthermore, the forward facing path loss exponent is not always less than that of reverse heading (see NLOS settings). For instance, the higher path loss exponents have occurred in the direction of turning away at 1800 MHz in tree area and 500 MHz in brush area. This is likely due to the large impact introduced by the complex NLOS environments that cause higher fluctuation as compared LOS environments containing fewer objectives that can interfere with the radiowave transmission. With regard to the values of shadowing standard deviations, it turns out that the received signal suffers very close fluctuations for both directions in LOS setting, while in NLOS settings, the difference between the deviation of facing directly toward the transmitter and that of turning away varies, ranging from 0.08 to 1.17 dB. While mixed directionality produces a path loss exponent that lies between the two directional headings (*i.e.*, perhaps leading to the conclusion that the user directionality impact is nominal), an extremely large increase in shadowing standard variance has been observed. *Finding: User directionality can more than triple the shadowing effect in a given environment.*

## VII. CONCLUSION

In this work, we performed a measurement study of user-induced effects on wireless reception across multiple frequency bands under various conditions characterized by on-body location of the receiver, directional heading, propagation distance, vegetation type, and elevation. We first established a baseline knowledge of the propagation channels by comparing the ground-to-ground and tower-to-ground scenarios. The induced propagation channels were characterized by the propagation parameters using a path loss model. We found that the shadowing standard deviations are elevated in the tower-to-ground setup, especially for higher frequency bands.

We also performed experiments under LOS and NLOS settings to explore the signal attenuation and give quantitative analysis on user-induced effects. In the linear LOS experiments, we reported that the location of held in the hand having the greatest user-induced loss out of all locations and the user can act like an antenna that receives up to 4.4 dB

more over a reference node. In radial NLOS experiments, we observed that RSS is severely susceptible to environmental impacts and the user directionality can affect received signal strength up to 20 dB. Our evaluation on user directionality-aware propagation showed that user directionality can more than triple the shadowing effect. Lastly, we estimated that the impact of user effects will only increase with the growth of higher frequency bands such as those with millimeter wavelengths. These measurement results have impact on the next generation network design of WiFi, cellular, and Ad Hoc networks of all types.

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