Wireless Channel Modeling Using a Miniaturized City and MM-Wave Transceivers

Farshid Aryanfar* and Kamal Sarabandi
faryanfa@umich.edu, saraband@eecs.umich.edu
Radiation Laboratory, EECS Department, University of Michigan
Address: RADLAB, 1301 Beal Ave., Ann Arbor, MI 48109, USA

Abstract

A scaled propagation measurement system (SPMS) is developed as an alternative to the time consuming and expensive measurements for wireless channel characterization. This system allows accurate measurements of well-defined channels in a laboratory environment. Confining the desired range of frequency to systems operating at UHF to L-Band (0.5-2GHz), dimensions of the scatterers and terrain features can be reduced by a factor of 50-200 for the SPMS that operates at around 100GHz. The system includes a probe positioner, scaled model of city, miniaturized millimeter wave transceivers probes, and a network analyzer. SPMS is capable of measuring path loss as well as power delay profile (PDP) for any desired environment. It can be used to verify available channel models or collect data for developing new models. The system has a dynamic range around 85 dB and a nominal spurious level of -40dBc.

I. Introduction

Successful implementation of novel mobile wireless networks with advanced modulation schemes and sophisticated signal processing algorithms depend heavily on the reliability of the association. Assessment of system performance under different scenarios environmental conditions is a crucial step before implementing such wireless systems. In this process the electromagnetic behavior of the wave propagation in channel and its influence on the characteristics of the signal at the receiver must be investigated. Over the past two decades significant efforts have been devoted towards the development of simulation tools for propagation modeling and channel characterization [1]. In general, these methods can be categorized into two groups: 1) Empirical and statistical methods that are based on measurements, and 2) Site specific and physics-based methods that are developed upon theoretical and numerical simulations of wave propagation for specific scenarios.

Reliable statistical models need a large set of measured data to extract the required parameters representing the channel characteristics. Also the accuracy of theoretical models need be evaluated using a complete set of signal and ground-truth data. Measurements in urban or suburban areas are both time consuming and expensive. To remedy this problem we considered developing a scale model that allows accurate measurements of well-defined channels in a laboratory environment. A millimeter wave scaled propagation measurement system (SPMS) is designed for this purpose. Figure 1 shows the main components of the University of Michigan W-band SPMS. The system includes a probe positioner, scaled model of the city, RF probes, and a network analyzer. In the following sections brief descriptions of individual components of the SMPS are provided.

II. System description and specification

SMPS makes use of a vector network analyzer (VNA) for signal processing and data acquisition. Therefore the setup for path loss and power delay profile measurements is the same as a standard S_{21} measurement. The network analyzer features allow coherent, broadband and time domain measurement. As the operating frequency of the VNA is different from the required SMPS frequency, up- and down-converter have been designed to convert the L-band signal to W-band and back to L-band. In order to move the probe with the required accuracy (fraction of wavelength, $\lambda \cong 3\text{mm}$) a computer-controlled xy-table has been designed and built.

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III. Millimeter wave Transceiver probes

As mentioned earlier the VNA signal is up/down converted to/from W-band from/to L-band by the transmitter and receiver probes. Figure 2 shows the block diagrams of the transmitter and receiver probes. It can be seen the IF signal (F_{IF}), which is the output signal from port 1 of the VNA, and the local signal (F_{LO}) are mixed by a subharmonic mixer at the transmitter and generates $mF_{LO} \pm nF_{IF}$. The desired harmonic, which is the result of mixing the 4th harmonic of LO signal and the IF signal ($4F_{LO}$-F_{IF}), is selected by the RF filter, and then it is amplified and transmitted. At the receiver, the RF signal captured by the antenna is amplified by the RF amplifier then mixed with the local signal. The desired IF signal ($4F_{LO}$-F_{RF}) is selected by IF filter and carried to the port 2 of the VNA for amplitude and phase measurements.

In order to achieve the maximum dynamic range of the VNA, the IF bandwidth has to be set at its minimum value (10Hz for HP8720D). SPMS uses a common source as the local oscillator of the transmitter and receiver. This prevents any frequency variation during the up- and down-conversion, as long as the local signal variation is negligible during one cycle of this process. This allows for reduction of the VNA's IF bandwidth to its minimum value. The common local oscillator is a dielectric resonator oscillator that has a frequency stability of 6kHz/^{o}C and phase noise of -86dBc/Hz at 10kHz offset from the center frequency that provides the required condition.

The transceiver circuit has been fabricated on 10mil (~250μm) thick quartz wafer. As the width of a 50Ω microstrip line on available substrates becomes comparable with the wavelength at W-band frequencies and also to be compatible with the test setup, the circuit has been designed and fabricated using CPW lines. The fabrication processes were performed in the University of Michigan's clean room, using wet etching technique on 3 micrometer electroplated gold on the quartz wafer. The skin depth for the RF, LO, and IF frequencies are 0.26, 0.52, and 1.5μm respectively. The gold thickness is marginally sufficient for the IF signal but as the minimum feature size in the circuit layout is about 10μm the thickness of the plated gold is limited to 3μm. Fortunately insufficient metal thickness does not degrade the circuit performance because the IF signal path on the circuit is just 2.5mm which is smaller than $0.01\lambda_g$ at the IF frequency. Therefore the associated metallic loss is negligible. The simulation results in the following sections have been performed using ADS Momentum for the passive elements and harmonic balance simulator for the subharmonic mixer. The measurement has been realized using probe station (for on wafer measurements), HP-8510C network analyzer, HP-W85104A mm-wave test setup, HP-8562A spectrum analyzer, and HP-11970W waveguide harmonic mixer.

III.a. Up- and down-converter

In order to convert the network analyze signal from L-band to W-band, sub-harmonic mixer is intended to generate $F_{RF} = 4F_{LO}$-F_{IF}. As the local frequency is chosen 23.7GHz its 4th harmonic is 94.8GHz, and this will result in RF operational frequency range of 90.8 to 92.8GHz for an IF signal sweeping from 2 to 4GHz. A flip chip back-to-back diode with junction capacitance of 60fF and series resistance 5.5Ω per diode is used as nonlinear component in the sub-harmonic mixer. As shown in Figure 2, IF filter isolates the IF and RF signal for improving the subharmonic mixer efficiency. The RF filter is used to select desired mixed harmonics of the IF and LO signal ($4F_{LO}$-F_{IF}) generated by the subharmonic mixer. It also prevents IF signal leakage to the RF port to improve the conversion loss of the subharmonic mixer. However in the transmitter probe in addition to RF-IF isolation this filter should reject the strong and undesired LO harmonics to prevent saturation of the RF amplifier. The layout of the RF probe is shown in Figure 3. Figures 4 and 5 show RF power and spurious level at the output of subharmonic mixer respectively. As shown the average of maximum spurious level is -40dBc which is enough for measuring fading depth values as low as 40dB. The S-parameter of the RF amplifier is shown in Figure 6. This amplifier has a gain of 27dB which compensates the up- and down-converter conversion losses and therefore increases the measurement dynamic range.

III.b. Packaging

Packaging for the W-band probes is very important for different reasons: 1) Size limitation to minimize the interaction between the transceivers and the measurement environment, 2) Effect of package on the circuit as well as accuracy in the antenna position which is less than 0.5mm long. Although the mm-wave probes dimensions are only $11mm^2$, the reduction in package size is limited by the connector size. Figure 7 shows the packaged probe.

IV. XY Table

A computer-controlled xy-table that places the receiver probe to any arbitrary position within a 1.5×1.5 meter area has been designed and built. This system includes a motion control card, two step motors, power amplifiers, encoder and drivers. The computer issues commands to the motion control card, which in turn triggers the power amplifier to drive the motor. An optical encoder attached to each motor sends the position and velocity data back to the computer. The computer uses this information to control the probe movement. The system placement is accurate within 0.25mm, which is acceptable accuracy for measurement at 92GHz ($\lambda_0 \cong 3.26$mm).

V. Miniaturized city

Using a 3D printer a scaled model of the desired city environment is built. Figure 8 shows the CAD model of a scaled building and actual printed building. The exact material properties, size and geometry of the buildings in the scaled city are known and will be used to define required parameters in wave propagation simulators. Therefore the error caused by the uncertainties in the physical parameters of the environment is avoided.

VI. Dielectric measurement

The premise of using the scaled model measurement system is that the building positions, sizes and properties are all known. Hence the material used to make these blocks must be characterized. In this study, different techniques at different frequencies are used to characterize the real and imaginary parts of the dielectric constant of the scaled buildings. The first method is based on capacitor measurements at L-band and below. The second method uses transmission and reflection measurements in a WR-90 X-band waveguide. The third dielectric measurement is done using reflectivity measurement from a metal-backed dielectric slab at W-band. The lower frequency dielectric measurements are mainly done to verify the measured results at W-band. The measurement results for two different materials are shown in Table I.

Table I. Measured effective dielectric constant

Frequency Band	L	X	W
Sample 1	2.70-j0.05	2.40-j0.04	2.34-j0.03
Sample 2	3.05-j0.15	2.70-j0.07	2.48-j0.06

VII. Conclusion

A scaled propagation measurement system (SPMS) with a high dynamic range around 85 dB and average spurious level -40dBc has been designed and built. This system can be used as an alternative to the outdoor measurements for wireless channel characterization. SPMS is capable of measuring coverage as well as PDP therefore it can be used to verify available channel models or collect data for developing new models. The high accuracy of computerized probe positioner in this system allows for measuring fast and slow fading. The miniaturized mm-wave transceiver probes with monopole antennas have been designed and fabricated for this system. The average of total up and down conversion loss for the SPMS is 10dB.

References

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[2]. F. Aryanfar and K. Sarabandi, "Evaluation of a Wave Propagation Simulator Using a 95 GHz Transceiver System", *IEEE Antennas and Propagation Int. Symposium* , Columbus, Jun. 22-27, 2003, pp. 900-902.

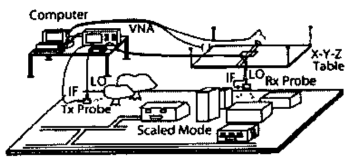

Figure 1. SPMS blocks

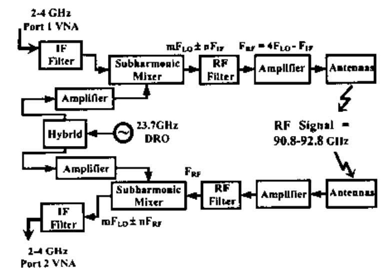

Figure 2. Transceiver block

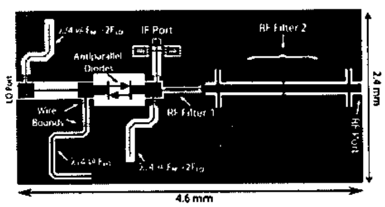

Figure 3. RF probe layout

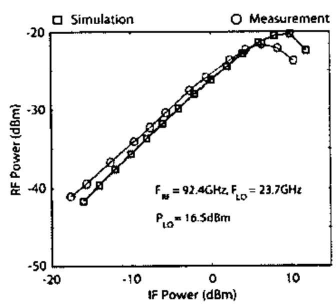

Figure 4. RF power at mixer output

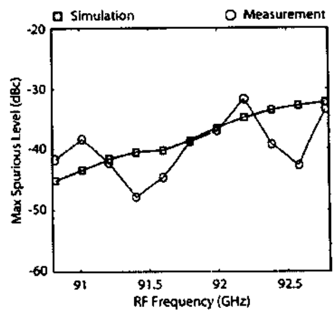

Figure 5. RF signal spurious

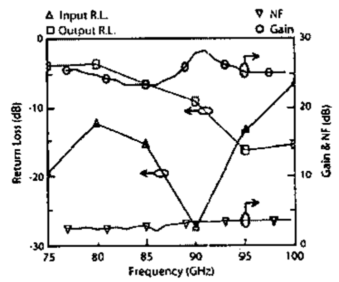

Figure 6. RF amplifier specifications

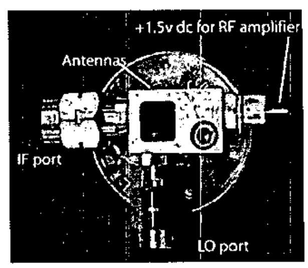

Figure 7. Packaged probe against a Quarter

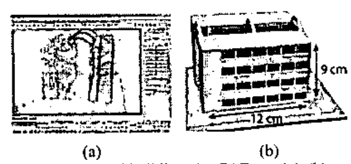

Figure 8. Scaled building; (a) CAD model, (b) printed building