On the Robustness of Ultra-Wide Bandwidth Signals in Dense Multipath Environments

Moe Z. Win, *Member, IEEE* and Robert A. Scholtz, *Fellow, IEEE*

***Abstract*—The results of an ultra-wide bandwidth (UWB) signal propagation experiment, using bandwidth in excess of 1 GHz, performed in a typical modern office building are presented. Robustness of the UWB signal in multipath is quantified through cumulative distribution functions of the signal quality in various locations of the building. The results show that an UWB signal does not suffer multipath fading.**

***Index Terms*— Multipath, propagation measurements, ultra-wideband radio.**

I. INTRODUCTION

RECENT work in the area of ultra-wide bandwidth (UWB) communications has indicated that it may be attractive for multiple access communications [1]. Accurate performance prediction of such systems in a realistic environment necessitates knowledge of UWB propagation channels.

Many propagation measurements have been made over the years on indoor channels with much "narrower bandwidths." A comprehensive reference on the indoor propagation channels (a total of 281 references) can be found in the tutorial survey paper by Hashemi [2]. Some of the work by Rappaport [3]–[5] and a few other papers [6]–[8] are listed here as selected references. However, these measurements are inadequate for UWB transmission systems, and characterization of UWB signal propagation channels has not been available previously in the literature.

This letter describes a UWB signal propagation experiment performed in a typical modern office building, and quantifies the robustness of the UWB signals in multipath.

II. THE UWB PROPAGATION MEASUREMENT

The measurement technique employed here is to probe the channel periodically with a sub-nanosecond pulse and to record the response of the channel using a digital sampling oscilloscope (DSO). Path resolution is possible down to about 1 ns of differential delay, corresponding to about 1-ft differential path length, without special processing. The repetition rate of the pulses is 2×10^6 pulses per second, implying that multipath spreads up to 0.5 μs can be observed unambiguously.

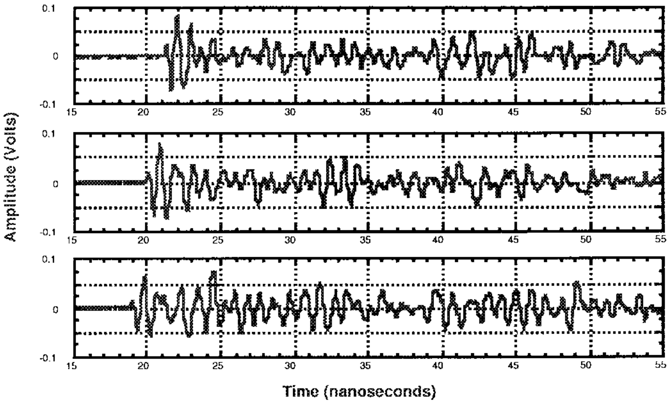

Fig. 1. Averaged multipath profiles in a 40-ns window measured in an office, along a horizontal line of the grid at three different positions 1 ft apart. The transmitter is approximately 6 m from the receiver, representing typical UWB signal transmission for the "high SNR" environment.

Propagation measurements were made in 14 different rooms and hallways on one floor of a modern laboratory/office building. In each office, multipath measurements over a 300-ns-wide window were made at 49 different locations. They are arranged spatially in a level 7×7 square grid with 6-in spacing covering 3 ft $\times$ 3 ft. A total of 741 different multipath profile measurements were made at various locations (12 different rooms with 49 locations/room, 2×49 locations in the lab, 21 locations in the shield room, and 34 locations around the hallways).

Fig. 1 shows the typical multipath profiles measured along a horizontal line of the grid at three different positions 1-ft apart. This represents typical UWB signal transmission for the "high signal-to-noise ratio (SNR)" environment. Notice that the direct path response (leading edge of the responses) suggests that the location of the receiver for the lower trace is closer to the transmitter than that of the upper trace. Similar results are given in Figs. 2 and 3 representing typical UWB signal transmissions for the "low SNR" and "extremely low SNR" environments. Note that the first arriving path is not always the strongest path.

III. ROBUSTNESS IN MULTIPATH

Robustness of the UWB signals in multipath can be assessed by measuring the received energy in various locations of the building relative to the received energy at a reference

---

Manuscript received August 14, 1997. The associate editor coordinating the review of this letter and approving it for publication was Prof. A. Haimovich. This work was supported in part by the Joint Services Electronics Program under Contract F49620-94-0022, and in part by the Integrated Media Systems Center, a National Science Foundation Engineering Research Center, with additional support from the Annenberg Center for Communication at the University of Southern California, and by the California Trade and Commerce Agency.

The authors are with Communication Sciences Institute, Department of Electrical Engineering-Systems, University of Southern California, Los Angeles, CA 90089-2565 USA (e-mail: win@milly.usc.edu).

Publisher Item Identifier S 1089-7798(98)01916-4.

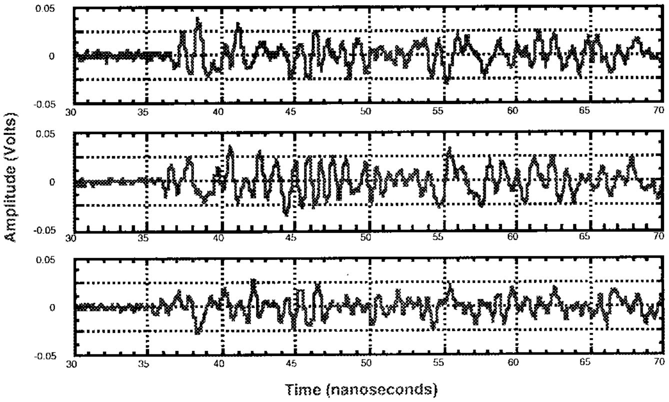

Fig. 2. Averaged multipath profiles representing typical UWB signal transmission for the "low SNR" environment. The transmitter is approximately 10 m away from the receiver.

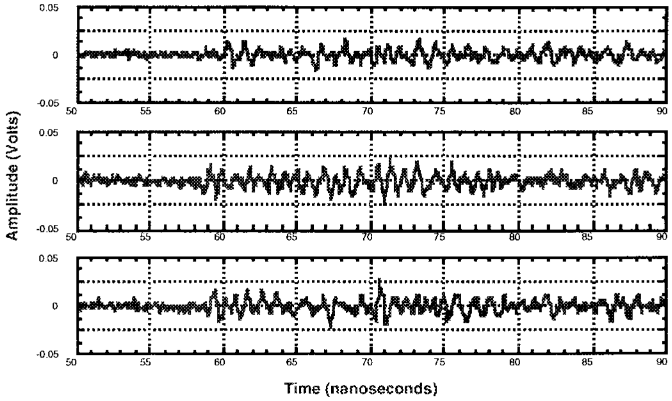

Fig. 3. Averaged multipath profiles representing typical UWB signal transmission for the "extremely low SNR" environment. The transmitter is approximately 17 m away from the receiver.

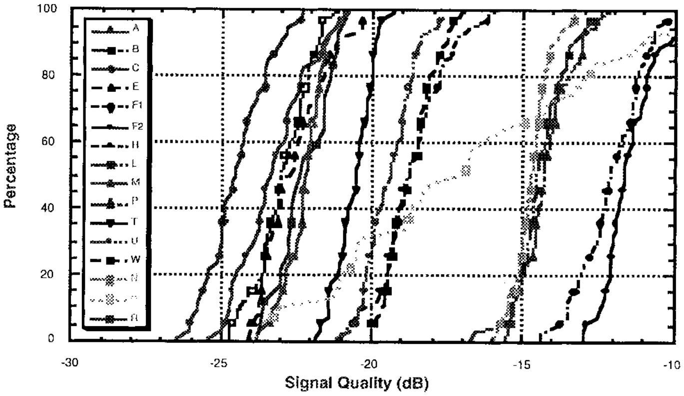

Fig. 4. The cumulative distribution functions of the signal quality based on 49 spatial sample points (except 21 spatial points for room R, and 34 spatial points for hallways) in each room. A total of 741 measurements were used in this plot.

TABLE I

SIGNAL QUALITY STATISTICS

Office	≈ distance (meters)	Minimum (dB)	Maximum (dB)	$\hat{\mu}$ (dB)	Median (dB)	$\hat{\sigma}$ (dB)	# of Samples
F2	5.5	-12.9970	-9.64586	-11.5241	-11.6813	0.8161	49
N	5.5	-16.0060	-13.2949	-14.7260	-14.7690	0.5892	49
P	6.0	-15.5253	-12.2185	-14.2373	-14.2820	0.8091	49
L	8.0	-16.6966	-12.4310	-14.4500	-14.5538	0.8342	49
W	8.5	-20.0157	-17.0351	-18.7358	-18.7425	0.7622	49
F1	9.5	-14.4064	-9.79770	-12.0986	-12.1407	1.0563	49
H	10.0	-21.0415	-16.1628	-18.7141	-18.8142	1.1240	49
U	10.0	-21.1719	-17.6232	-19.4275	-19.4092	0.8024	49
T	10.5	-21.9113	-19.2986	-20.6100	-20.5419	0.5960	49
R	10.5	-23.7221	-20.8867	-22.2675	-22.3851	0.8686	21
M	13.5	-23.8258	-20.9277	-22.2568	-22.2064	0.6439	49
E	13.5	-24.1454	-20.2000	-22.5973	-22.7824	1.0332	49
A	16.0	-25.4171	-20.7822	-23.2826	-23.3541	1.1512	49
B	17.0	-24.7191	-21.2006	-22.9837	-22.9987	0.8860	49
C	17.5	-26.4448	-22.3120	-24.4842	-24.5777	1.0028	49
Hallways		-23.8342	-6.72469	-16.9317	-17.3286	4.5289	34

point. Mathematically, the *signal quality* at measurement grid location (i,j) can be defined as

$$Q_{i,j} = 10\log_{10} E_{i,j} - 10\log_{10} E_{\text{ref}} \quad [\text{dB}]. \tag{1}$$

The received energy $E_{i,j}$ at location (i,j) is given by

$$E_{i,j} = \int_0^T |r_{i,j}(t)|^2 \, dt \tag{2}$$

where $r_{i,j}(t)$ is the measured multipath profile at location (i,j) in the grid and T is the observation time. The reference energy E_{ref} is chosen to be the energy in the LOS path measured by the receiver located 1 m away from the transmitter.

The signal quality $Q_{i,j}$ is calculated for measurements made at 741 different locations (14 different rooms with 49 locations/room, 21 locations in the shield room, and 34 locations in the hallways).

Table I shows the estimates of the mean and the variance of the signal strength in each room based on the samples taken in that area. The cumulative distribution functions of the signal quality for measurements made in these locations are shown in Fig. 4. These data indicate that the signal energy per received multipath waveform varies by at most 5 dB as the receiver position varies over the measurement grid within a room. This is considerably less than the fading margin in narrow-band systems, and indicates the potential of UWB radios for robust indoor operation at low transmitted power levels.

IV. CONCLUSION

Extensive UWB propagation measurements were made in 14 different rooms and hallways of a modern office building. Robustness of the UWB signal in multipaths is quantified through cumulative distribution functions of the signal quality in various locations of the building. The results show that the UWB signal does not suffer multipath fading. Therefore, very little fading margin is required to guarantee reliable communications.

ACKNOWLEDGMENT

The authors wish to thank M. A. Barnes, A. Petroff, and L. Fullerton of Time Domain Systems, and P. Withington of Pulson Communications for several helpful discussions concerning the technology, capabilities, and signal processing of impulse signals.

REFERENCES

[1] M. Z. Win and R. A. Scholtz, “Comparisons of analog and digital impulse radio for multiple-access communications,” in *Proc. IEEE Int. Conf. on Communications*, Montreal, PQ, Canada, June 1997, pp. 91–95.

[2] H. Hashemi, “The indoor radio propagation channel,” *Proc. IEEE*, vol. 81, pp. 943–968, July 1993.

[3] J. B. Andersen, T. S. Rappaport, and S. Yoshida, “Propagation measurements and models for wireless communications channels,” *IEEE Commun. Mag.*, vol. 33, pp. 42–49, Jan. 1995.

[4] T. S. Rappaport, “Characterization of UHF multipath radio channels in factory buildings,” *IEEE Trans. Antennas Propagat.*, vol. 37, pp. 1058–1069, Aug. 1989.

[5] T. S. Rappaport, S. Y. Seidel, and K. Takamizawa, “Statistical channel impulse response models for factory an open plan building radio communication system design,” *IEEE Trans. Commun.*, vol. 39, pp. 794–807, May 1991.

[6] D. M. J. Devasirvatham, “Multipath time delay jitter measured at 850 MHz in the portable radio environment,” *IEEE J. Select. Areas Commun.*, vol. SAC-5, pp. 855–861, June 1987.

[7] A. A. Saleh and R. A. Valenzuela, “A statistical model for indoor multipath propagation,” *IEEE J. Select. Areas Commun.*, vol. SAC-5, pp. 128–137, Feb. 1987.

[8] R. J. Bultitude, S. A. Mahmoud, and W. A. Sullivan, “A comparison of indoor radio propagation characteristics at 910 MHz and 1.75 GHz,” *IEEE J. Select. Areas Commun.*, vol. 7, pp. 20–30, Jan. 1989.