LINE-OF-SIGHT CHANNEL SIMULATION - A NEW APPROACH

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ABSTRACT

This paper describes the first phase of a multiphase project to develop a line-of-sight microwave channel simulator. The paper describes the simulator concept, the development of a proof-of-concept prototype of the simulator, and the work to be accomplished during later phases of the project. Examples of the spectral output of the simulator showing simulated frequency selective fading effects are provided as well as a description of the unique hardware implementation approach used. The usefulness of the simulator as a test device for the performance evaluation of digital radios is also discussed.

INTRODUCTION

The need for channel simulation becomes apparent when one considers the complexity of analytically evaluating digital radio performance or the difficulty and expense of field testing digital radios. For digital radios designed for military use, one must consider the radio performance not only in a channel that is subject to frequency selective fading but also one which may be corrupted by intentional jamming. Digital radio performance is dependent upon factors such as the radio parameters as well as the channel fading characteristics. Although many papers may be found in the literature that report a specific radio's performance during fading conditions, it is difficult to generalize on these results so that the performance of some other radio operating under some other fading conditions can be predicted. It would be time consuming and prohibitively expensive to exhaustively field test a large variety of different radio configurations, i.e., different modulations, different types of adaptive equalizers, different types of space diversity combiners or switching algorithms, etc. Therefore, the use of a channel simulator is a logical approach for the performance evaluation of digital radios.

The concept of channel simulation has been investigated by many people for at least twenty years. Many systems have been designed and constructed during this period of time to simulate HF, LOS, or troposcatter channels. In recent years much interest has been generated in the LOS microwave channel model proposed by Rummler (refs. 1-7). Other researchers have developed hardware implementations of Rummler's model both at IF (refs. 8-12)

and at rf (refs. 13, 14). A summary of this simulation research may be found in reference 15.

The mathematical model of the channel transfer function we have used differs slightly from that used by Rummler. However, the hardware implementation of the model is thought to be unique. This paper describes the results of the first phase - the proof-of-concept phase - of a multi-phase project for the design, construction, testing, and application of a device for simulating multipath in the 4.0 to 8.5 GHz frequency range. The device is not one in which the parameters are varied dynamically in order to simulate the random fluctuations of a real-world LOS microwave channel. It is a static device rather than a dynamic one which provides a random variation of device parameters. One of the key differences between the LOS channel simulator developed at the ITS and most of those discussed in the literature is that here the simulation is implemented at rf rather than at IF (intermediate frequency). Simulation at IF has the disadvantage that some of the critical components of the signal path through the radio are omitted. These critical components include the phase locked loop (PLL) and automatic gain control (AGC). The simulator is based on a two-path propagation model and is implemented using delay lines constructed from semirigid coaxial cable. Details of the simulator are provided in the following sections and in Hartman and Pratt (ref. 16).

SIMULATOR CONCEPTS AND PROGRAM OBJECTIVES

The objective of this project is to develop a hardware/software system capable of providing a realistic simulation of a frequency-selective fading LOS microwave channel. At the early stages of the project the following two-path model of the channel transfer function was chosen:

$$H(\omega) = a(1 + be^{j\omega\tau}) \quad (1)$$

Here "a" represents flat fading, "b" represents the amplitude of the indirect path relative to the direct path, "τ" represents the relative delays between the two paths, and "ω" represents the carrier frequency in the band of interest.

Figure 1 is a functional block diagram for implementing the two-path model given by eq. 1. The relative delay (τ) between the direct and

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indirect paths is provided by switching in various lengths of semirigid coax lines in the switched delay sections. The programmable attenuator in the indirect path represents the parameter "b". The other programmable attenuator represents the parameter "a", i.e., the flat fading parameter. The manual attenuator at the input to the simulator reduces the signal level of the transmitter under test to levels that are compatible with the receiver section of the radio being tested.

One concern throughout this project has been to design the system such that changes in relative delay between the two paths would not change the relative signal level between the two paths and vice versa. That is, relative phase and relative amplitude of the two paths must be independently controlled. Great care was taken in the design and implementation of the system to ensure that this was accomplished. For this reason a signal leveler is needed in the indirect path so that the signal level does not change when additional delay is placed in the indirect path by switching in additional delay sections.

The purpose of the attenuator and line stretcher in the direct path is to make the delay and the attenuation of the indirect and direct paths equal when there is zero relative delay in the indirect path.

Figure 2 provides more detail of the block in Figure 1 labeled "switched delay sections." There are eight such sections, each having different lengths of semi-rigid coaxial cable. This cable has delay characteristics which effectively simulate delays typical of LOS microwave channels. The maximum range of delay reported in the literature for measurements on typical communications links is on the order of 18 ns. In the simulator that has been developed, delays of 19.125 ns are achievable. The first delay section has a nominal delay of 0.075 ns. Each successive delay section has twice the delay of the previous one. Thus, the eighth (last) delay section has a delay of approximately 9.6 ns.

The line stretcher shown in Figure 2 is used to adjust the amount of delay in each section and to place nulls at the proper location in the spectrum regardless of the operating center frequency. The purpose of the attenuator is to ensure that attenuation through the delay section is approximately the same regardless of whether the delay path or the nondelay path is switched in. This helps reduce the requirements on the load-leveler circuitry previously described. These attenuators are only placed in the two longest delay sections, because the amount of attenuation inserted is less than 1/2 dB for the short delay sections.

The design objectives for the simulator are provided in Table 1. All of these design objectives have been met by the proof-of-concept implementation described in this paper. For any specific radio test, one might expect to operate the simulator by placing nulls anywhere within ± 100 MHz of the radio's operating frequency. Although typical digital LOS microwave radio bandwidths are of

the order of 14 MHz to 30 MHz, it is important to be able to create nulls outside the radio's bandwidth in order to simulate a sloped response across the band.

There were a number of uncertainties at the start of this project regarding the general simulation concept and implementation approach described above. These uncertainties included:

- 1) the ability to implement the device at rf without reflections that would degrade the performance of the device,
- 2) the control of the relative amplitude and phase of the two paths,
- 3) whether the simulator could be easily adjusted or calibrated for different operating frequencies,
- 4) the repeatability and stability of the simulator transfer function.

All of these uncertainties have been resolved. It has been demonstrated that the simulator as constructed can be adjusted for phase and amplitude differences, is usable over a wide range of frequencies, is stable and repeatable, and is amenable to computer control.

Because of the initial uncertainties and questions about simulator design and implementation, the project was broken into the following phases:

- I) development of proof-of-concept prototype hardware,
- II) automation of the simulator control and building a second channel for testing of space diversity radios,
- III) exercising the simulator with a DRAMA (Digital Radio and Multiplexer Acquisition) radio, and
- IV) development of a jamming system applique unit.

As of April 1985, Phase I has been completed. Work on Phases II and III is in progress. Phase IV is more applicable to the performance evaluation of the next generation (mid-1990's) digital microwave radios for the Defense Communications System (DCS). Before any Phase IV effort can, or should, be initiated, the results of previous EW (electronic warfare) threat-definition studies should be reviewed.

The following sections will describe the work that has been accomplished to date under Phase I and the current and future work under Phases II and III.

IMPLEMENTATION OF DESIGN PHILOSOPHY

Each switched delay section (see Figure 2) consists of an input switch, a nondelay path (1 cable), a delay path (2 cables plus a line stretcher), and an output switch. The last two switched delay sections also include a fixed attenuator in the nondelay path.

The salient coax cable requirements include a small size so that long lengths could be coiled to fit in a small space; stability with bending, coiling, and fabrication; easily coiled and fabricated; rigid enough that cable flexing during operation will not cause changes in delay time or phase changes; usable to at least 12 GHz; and temperature stability in laboratory environments.

The cable used in the multipath simulator meets all of these requirements. It is 0.141 in. (0.36 cm) diameter, solid copper shielded coax. It has a 69.5% propagation velocity factor, or 8.202 inches (20.8 cm) per nanosecond, and 33 inches (83.8 cm) per dB attenuation at 8 GHz.

A 1-inch diameter was determined to be the shortest bend diameter that would not distort the transmission characteristics of the cable, and a 4-inch length is the shortest cable that can be fabricated with a 180° bend on a 1-inch diameter. These 4-inch cables were used between sections and to connect the input switch to the line stretcher as shown in Figure 2.

In most sections, the delays of the nondelay cables were made equal to the delay of a four-inch coupling cable plus a line stretcher set at midpoint. Thus the delay cable from the line stretcher to the output switch is equal to the true delay of the section. In the shortest sections, the time delay required was shorter than a 4-inch cable, so the delay cable was made four inches long and the length of the nondelay cable was increased by four inches minus the delay value of the section. The total delay of the nondelay path for all sections in the indirect path is equal to the delay of the direct path.

Each section was fabricated according to calculated cable lengths. They were then tested for actual delay by measuring the frequency difference between 10 nulls and calculating the delay time. Any section with more than ± 25 ps error was trimmed to this tolerance. The line stretcher range is ± 83 ps. The cable lengths used in the eight delay sections are tabulated in Table 2.

A 1-dB pad was added to the nondelay portion of section 7 and a 2-dB pad was added to the nondelay portion of section 8 to keep the attenuation of the delay vs. nondelay paths equal within 1/2 dB at 8 GHz. Sections 1 through 6 did not require attenuators as the difference in attenuation with the shorter delays was less than 1/2 dB.

The direct path was made equal in delay to the indirect path when all 8 delay sections were in the nondelay mode, and attenuation was added to match the attenuation of the indirect path at 8 GHz. In this mode the simulator has no multipath and all frequencies from 4.0 to 8.5 GHz are passed in phase through the simulator.

The output of the 8th delay section is fed to a voltage-controlled attenuator that is controlled by comparing the indirect signal with a reference value. This provides automatic signal leveling at any reference value desired, and

removes all amplitude variations caused by the switching of delay sections. The reference control can give small scale resolution of 0.01 dB.

Larger scale control is provided by a 1-dB and a 10-dB step attenuator. The step attenuator was included to avoid any phase shift vs. attenuation of the voltage controlled attenuator. However, the off-the-shelf attenuator initially used changed phase with attenuation changes and was not remotely programmable. This attenuator is being replaced with a programmable "phase free" unit.

All components (switches, line stretchers, attenuators, cables and connectors, etc.) were carefully selected to insure good VSWR.

The 60-dB notch which was obtained requires amplitude balance of 0.01 dB and phase balance of a fraction of a degree. This achievement resulted from the well-balanced, low-VSWR system. The 60-dB notch is better than the objective (40 dB) specified in Table 1.

Figure 3 is a photograph of the simulator front panel showing the attenuator reference controls, the manual delay control switches, the adjustable delay lines, the manual step attenuator, and the input and output ports.

MEASUREMENTS AND CALIBRATION

The procedure for setting the line stretcher in the direct path (to ensure that the delay is the same in the direct path as in the indirect path with all switches off) is explained as follows. First, set the frequency synthesizer to the desired frequency, for example $f_o = 8.1$ GHz. With switch 1 on and all others off, set the line stretcher in switched delay section 1 to obtain the minimum output signal. As a check, adjust the attenuation to obtain the minimum output signal and readjust the line stretcher if necessary. Similarly, adjust the line stretchers for switch sections 2 and 3 to obtain minimum output signal. With switches 1, 2, and 3 all on, observe the position of the notch. If it is not at f_o , say it is at $f_o + D$ (where D is the frequency offset), adjust the line stretcher in the direct line so that the notch moves to $f_o + 1.5 D$. That is, set the frequency to $f_o + 1.5 D$ and adjust the line stretcher in the direct line to obtain a minimum. Return to the start of the procedure and repeat, until the position of the notch with 1 (or 2 or 3) on is the same as the position with 1, 2, and 3 all on. At this point the direct path and the nondelay portion of the indirect path have the same delay. The position of the caliper for the direct path should be noted. The setting was found to be stable at least for a period of several days. It was also observed that the caliper could be changed and then repositioned to give repeatability.

The procedure for setting the line stretchers in each switched delay section to ensure that nulls are placed within the band of interest is under investigation at this time. For the purpose of the Phase I proof-of-concept development efforts, the

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line stretchers in the switched delay sections were set manually. As part of the Phase II effort the calibration of the simulator will be automated. The overall setup or calibration time for the simulator is of the order of one-half hour.

Figure 4 shows the results of measurements using a spectrum analyzer set at $f = 8.0$ GHz, 20 MHz/div horizontal scale and 10⁰ dB/div vertical scale. Figures 4(a), 4(b), and 4(c) show the resulting spectrum respectively for switched delay sections 1, 5, and 8 switched into the indirect path. Figure 4(d) shows the spectrum when all switched delay sections are switched in. Figure 4(e) shows the results when all switches are off. The variations in the trace are due to the measurement equipment and not the simulator, as was verified by making measurements with the simulator removed. Figure 4(f) shows an overlay of four traces each with the same delay, but with attenuation of 0, 1, 3, and 8 dB in the delay component. Table 3 shows the levels of the peaks and notches for each of these attenuations.

One can verify that notches in the spectrum occur as expected by examining Figure 4(d). With all switches on, there is a total delay in the indirect path of:

$$\sum_{i=0}^{i=7} (0.075)2^i = 19.125 \text{ ns.} \quad (2)$$

The spacing between nulls is $1/\tau$. With τ equal to 19.125 ns the null spacing should be approximately 52 MHz. This is roughly apparent in Figure 4(d) where the scale is 20 MHz per division. This was verified more accurately in the laboratory using a precision signal generator and a power meter.

Achievable notch depth was also verified accurately in laboratory measurements. Notch depths of 60 dB were measured.

Measurements of attenuation as a function of frequency were only partially completed due to problems with the measurement equipment. As noted in the discussion of Figure 4(e), a ripple effect is apparent in the back-to-back mode, and is attributed to the spectrum analyzer-tracking filter combination. Within the accuracy limitations, the preliminary results indicate that the attenuation as a function of frequency behaves as expected for center frequencies ranging from 6 to 9 GHz.

FUTURE WORK

The following modifications and additions to the simulator are planned for Phase II:

- 1) automate the control, data collection and calibration of the simulator, and
- 2) develop a second simulator channel for testing space diversity radios.

One task under Phase II is to place the simulator under computer control. The purpose of the

computer is to provide fast settings in order to measure receiver characteristics in practical times. The primary functions of the computer are to:

- 1) control the amount of relative delay between the direct and indirect paths by switching the various switched delay sections,
- 2) control the relative signal level of the two paths by switching in various amounts of attenuation in the indirect path (this will be setup such that both minimum and nonminimum phase conditions can be simulated, i.e., either the direct or indirect path may have the strongest signal level),
- 3) control of the notch location,
- 4) control of the attenuator which simulates flat fading,
- 5) data acquisition and storage of bit-error-rate or synchronous errored second information,
- 6) data analysis,
- 7) automatic calibration of the system, and
- 8) ultimately control noise and jamming levels for system evaluation.

The data analysis function will consist of processing the error information that is collected and stored during the performance evaluation of a digital radio. It is expected that "m-curves" and/or other methods of analyzing and displaying the data will be developed. Each test of a digital radio may consist of as many as 25,600 data points ($2^8 = 256$ possible combinations of the switched delay sections times 10 relative signal level settings times 10 settings for the flat-fading signal level). Obviously, a computer is needed to process and analyze this amount of data.

The automatic calibration function is depicted in Figure 5. One of the functions of the computer is to switch between the radio test mode and the calibration mode. In the radio test mode as previously described a BER test set is used to generate a digital signal and to detect errors after the signal has passed through the transmitter portion of the radio, the channel simulator, and the radio receiver. In the calibration mode, the computer is used to control a synthesized signal generator. The signal is swept across the frequency band of interest for a particular channel simulator configuration of delay and attenuation settings. The output of the simulator is sent to a wideband power meter and then to the computer. In this test configuration the null locations and depths can be accurately measured for each simulator configuration. The objective of calibrating the simulator entirely in an automatic mode depends upon the ability to control all components of the simulator with the computer. The automatic control and calibration concept will be evaluated during Phase II.

MODEL VERIFICATION AND PARAMETER STATISTICS

In parallel with the development of the simulator, the Institute for Telecommunication Sciences (ITS) is conducting a data analysis program that will provide statistical distributions of the channel model parameters (a , b , and τ in eq. 1).

Although the expected range of these parameters is known, their statistical distribution needs further investigation. These distributions are needed for two reasons:

- 1) the control of a dual channel simulator for testing either space or frequency diversity radios requires that the statistics of the diversity channel relative to the first channel be well understood, and
- 2) calculation of outage time requires knowledge of the statistical distribution of the model parameters.

The data base that is being analyzed to obtain the requisite statistics consists of channel probe data collected on a long communications link in Southern California. The statistical distributions that will be obtained from this data-analysis program include delay, multipath power, multipath phase, delay versus power, rate of change in relative multipath power, rate of change in multipath delay, rate of change in multipath phase, and rate of development and collapse of multipath. Note that the last four items listed are relevant to the question of whether the static simulation of the fading channel is always valid or whether a capability for simulating the dynamics of the channel should eventually be added to the present simulator.

This data-analysis project will also provide

- 1) a minimal phase/nonminimal phase distribution,
- 2) information for the eventual computer control of a dual-channel simulator used in testing space diversity radios, and
- 3) statistics on a third component of fading.

The last mentioned item is needed to help answer the question as to the validity of a 2-ray path model (such as eq. 1), or whether a 3-ray path model is required. Publication of the results of this data-analysis program is expected in the near future.

CONCLUSIONS AND RECOMMENDATIONS

A simulator based on a two-path model was constructed and tested in the proof-of-concept phase of a program for constructing a computer-controlled device. The testing showed that the devices as constructed provided better performance than was originally anticipated.

The highlights of the testing were (1) the ability to control the relative delays between the direct and indirect path so that notches could be positioned to within 1 MHz, (2) the control of the relative amplitudes between the two paths to within the difference required to produce notch depths of at least 40 dB, (3) the repeatability and stability of the device calibration, and (4) the incorporation of design features which will allow rapid computer control of measurements.

Based upon the success of the proof-of-concept phase of the project, it is recommended that the

simulator be used for performance specification for future military LOS microwave radios, digital radio acceptance testing, and performance comparison of digital radios.

One possible approach to digital radio performance specification and acceptance testing is:

- 1) to specify an "m-curve" above which a system is considered unacceptable, and
- 2) to use the LOS channel simulator described in this paper to measure a radio's signature relative to the minimally acceptable "m-curve".

The use of m-curves for digital radio performance specification, acceptance testing and performance comparison is but one possible approach to the problem. Other methods are possible. Regardless of the technique used, the microwave LOS channel simulator developed under this project will be a useful tool for digital radio performance evaluation.

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Table 1. Design Criteria

Parameter	Affected by	Target Criteria
Operating frequency range	Individual and assembled component specifications	4.0 to 8.5 GHz
Ability to control fade notch location	Delay line and line stretcher characteristics	± 1.0 MHz accuracy
Fade notch depth control	Control of relative attenuation	Notches of 40 dB
Number of delay sections	Desired overall range and resolution	8 switch sections of length $2^i d$ where $i = 0, 1, 2, \dots, 7$
Smallest increment of delay	Ability to cut delay lines	$d = 0.075 \text{ ns} \pm \epsilon + LS$ where ϵ is a small error and LS is the range/2 of the line stretchers

Table 2. Summary of Indirect Path Cable Lengths and Delays

Section	Delay Cable (inches)	Nondelay Cable (inches)	Delay Time (ns)	
			Calculated	Measured
1	4.000	15.609	0.075	0.07594
2	4.000	14.994	0.150	0.1487
3	4.000	13.732	0.300	0.2946
4	4.921	11.797	0.600	0.5947
5	9.843	11.797	1.200	1.1749
6	19.686	11.797	2.400	2.3755
7	39.371	11.797	4.800	4.8001
8	78.742	11.797	9.600	9.5938

Table 3. Peak and Notch Level in dB Above the Direct Ray (0 dB) for Different Levels of the Delayed Component, b, Corresponding to Figure 4(f)

b	Peak	Notch (dB)	Difference (dB)
0	6	$-\infty$	$-\infty$
1	5.5	-19.3	24.8
3	4.6	-10.7	15.3
8	2.9	-4.4	7.3

Figure 1. LOS Channel Simulator Functional Block Diagram

Figure 2. Physical Implementation of a Switched Delay Section

Figure 3. Front View of Simulator

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Figure 4. Simulator Output as Displayed on the Spectrum Analyzer

Figure 5. Calibration and Radio Test Functional Block Diagram