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## ABSTRACT

### NUMERICAL SIMULATION OF CLIPPING DISTORTION IN LIGHTWAVE CATV SYSTEMS

by

**Luay Al-Nadi**

Clipping induced distortion is an essential limit for modulation depth and number of channels in subcarrier multiplexed lightwave video transmission systems. Two different types of laser clipping are compared (single-clipping vs. double-clipping). In this work, the distortion limits imposed by clipping effects, in both directly (single-clipping) and externally (double-clipping) modulated systems, are examined. Numerical simulations were performed to test the efficiency of Saleh's Model. A comparison of results with clipping induced distortion in directly modulated lightwave systems (single-clipping) and clipping induced distortion in externally modulated lightwave systems (double-clipping) is presented, it is shown through numerical simulation that the total non-linear distortion (NLD) summed over the complete frequency band is 3 dB higher for two levels symmetrical clipping (external modulators) than for one level clipping (direct-modulators).

**NUMERICAL SIMULATION OF CLIPPING DISTORTION IN  
LIGHTWAVE CATV SYSTEMS**

**by  
Luay Al-Nadi**

**A Thesis  
Submitted to the Faculty of  
New Jersey Institute of Technology  
in Partial Fulfillment of the Requirements for the Degree of  
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**Department of Electrical and Computer Engineering**

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APPROVAL PAGE

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IN LIGHTWAVE CATV SYSTEMS

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To my beloved family

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# CHAPTER 1

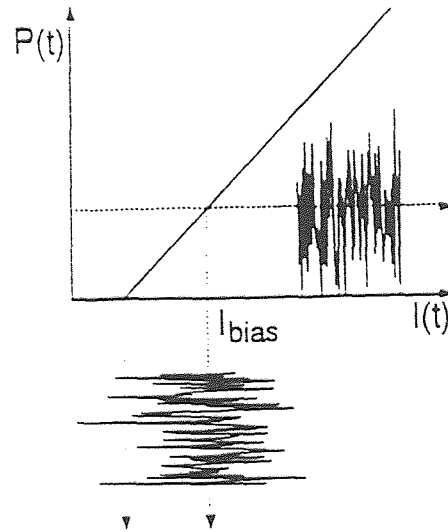
## INTRODUCTION

High bandwidth of lightwave transmission has led to its modern installation in CATV headend-to-hub links. Frequency-Division Subcarrier Multiplexing is a technique for transmitting more than 50 cable television signals over one optical fiber. The simplest multiplexing scheme for the CATV channels is passive subcarrier multiplexing (SCM) of the amplitude modulation vestigial-sideband (AM-VSB) channels directly onto the drive current of a semiconductor laser, and direct detection of the intensity modulated signal [1].

The channel carrying capacity of these lasers is large, but fundamentally limited by the fact that if the product of the number of channels ( $N$ ) and the rms modulation depth ( $\mu$ ) per channel exceeds the threshold current of the laser, infrequently the input current will drop below the laser threshold current, shutting the laser off. To maximize the capacity of a single laser and SNR due to noise, some amount of clipping distortion is usually allowed. A quantitative description of the induced clipping distortion for the U.S. NTSC CATV band (50.25 MHz to 450.25 MHz) is the subject of the numerical simulation [2].

There are four fundamental losses in an SCM system, (a) relative intensity noise (RIN) of the transmitting laser; (b) shot noise within the received photodiode; (c) thermal and electronic noise at the receiver and (d) nonlinear distortion (NLD) within the transmitting laser, caused by the curvature of the light-current ( $L/I$ ) characteristics. Nonlinear distortion (NLD) at the transmitter limits the fraction of laser power per

channel, since the optical power can not be negative, clipping can occur at the zero-power levels as shown in Figure 1.1. As in Figure 1.1 the laser's  $L/I$  curve is presumed to be linear to obtain the minimum possible nonlinear distortion (NLD) [3].



**Figure 1.1** Clipping of the input signal in laser diodes (single-clipping)

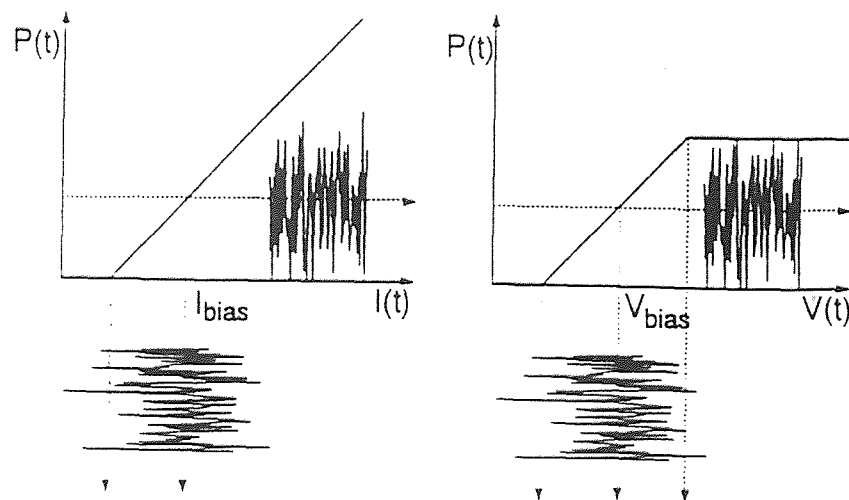
In Saleh's research, the nonlinear distortion (NLD) is determined by approximating the sum of multiple randomly phased subcarriers as a Gaussian probability density of the amplitude. The total nonlinear distortion is then accepted to be proportional to the power in the Gaussian tail that falls below zero [4]. The expression for the total nonlinear distortion (NLD) is:

$$NLD = \frac{1}{\sqrt{2\pi}} \frac{\mu^3}{1+6\mu^2} \exp\left(-\frac{1}{2\mu^2}\right)$$

Saleh calculates the distortion due to clipping as a function of the rms modulation depth,  $\mu$  ( $\mu = m\sqrt{N/2}$ , here  $N$  is the number of channels and  $m$  is the optical modulation depth per channel). He expected this distortion to be the minimum distortion emitted by the

laser under direct modulation (single-clipping). His theory predicts the total non-linear distortion (NLD) power falling within the channel bandwidth. He presented a model of clipping distortion for direct laser modulation (using a clipped Gaussian Statistics model to calculate the distortion power) [3]. The model was based on the assumption that all of the non-linear distortion power remains in the CATV band and is uniformly distributed over the channels [5].

Because of the complication found in the practice of implementing SCM with VSB-AM, it has been hoped that the case might be enhanced by replacing direct modulation (single-clipping) of the laser by external modulation (double-clipping, ideal external modulator can essentially introduce clipping near both the zero level and the peak level of the signal) [3]. In comparison, clipping distortion in an externally modulation (double-clipping) system is symmetrical at two levels, when using the Saleh model to such a system the non-linear distortion would be increased by 3 dB. Figure 1.2 shows this “ideal” light versus current (direct-modulators) and light versus voltage (external modulators) transmission curves.



**Figure 1.2** Clipping of the input signal in laser diodes, and external modulators

In this work, it will be shown that by numerical simulation the total non-linear distortion (NLD) summed over the complete frequency band is 3 dB higher for two levels symmetrical clipping (external modulators) than for one level clipping (direct-modulators).



## CHAPTER 2

### SPW DESIGN

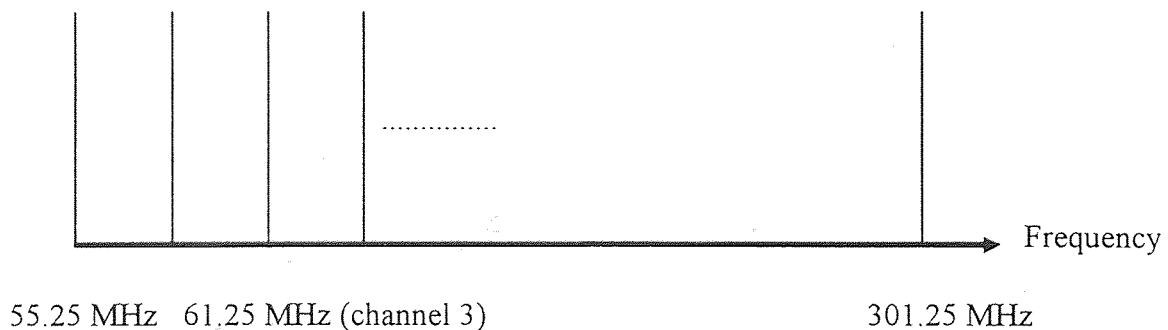
#### 2.1 Design

The frequency allocation plan is shown in Figure 2.1 and the design setup is shown in Figure 2.2a and Figure 2.2b. The design consists of a 42 channel ( $N = 42$ ) U.S. NTSC plan. Their frequency range between 55.25 MHz to 400.25 MHz with frequency spacing of 6 MHz. Table 1 lists the frequency for the 42 channels. The output of the channels is summed together, the summed signal can be written as:

$$s(t) = \sum_{i=1}^N A_i \cos(\omega_i t + \phi_i)$$

then a constant one is added to the summed signal. Since the optical power can not be negative, clipping is done by setting any negative value of the time signal to zero. A Fourier transform is performed over the clipped signal.

#### 42 AM carriers



**Figure 2.1** Frequency allocation plan

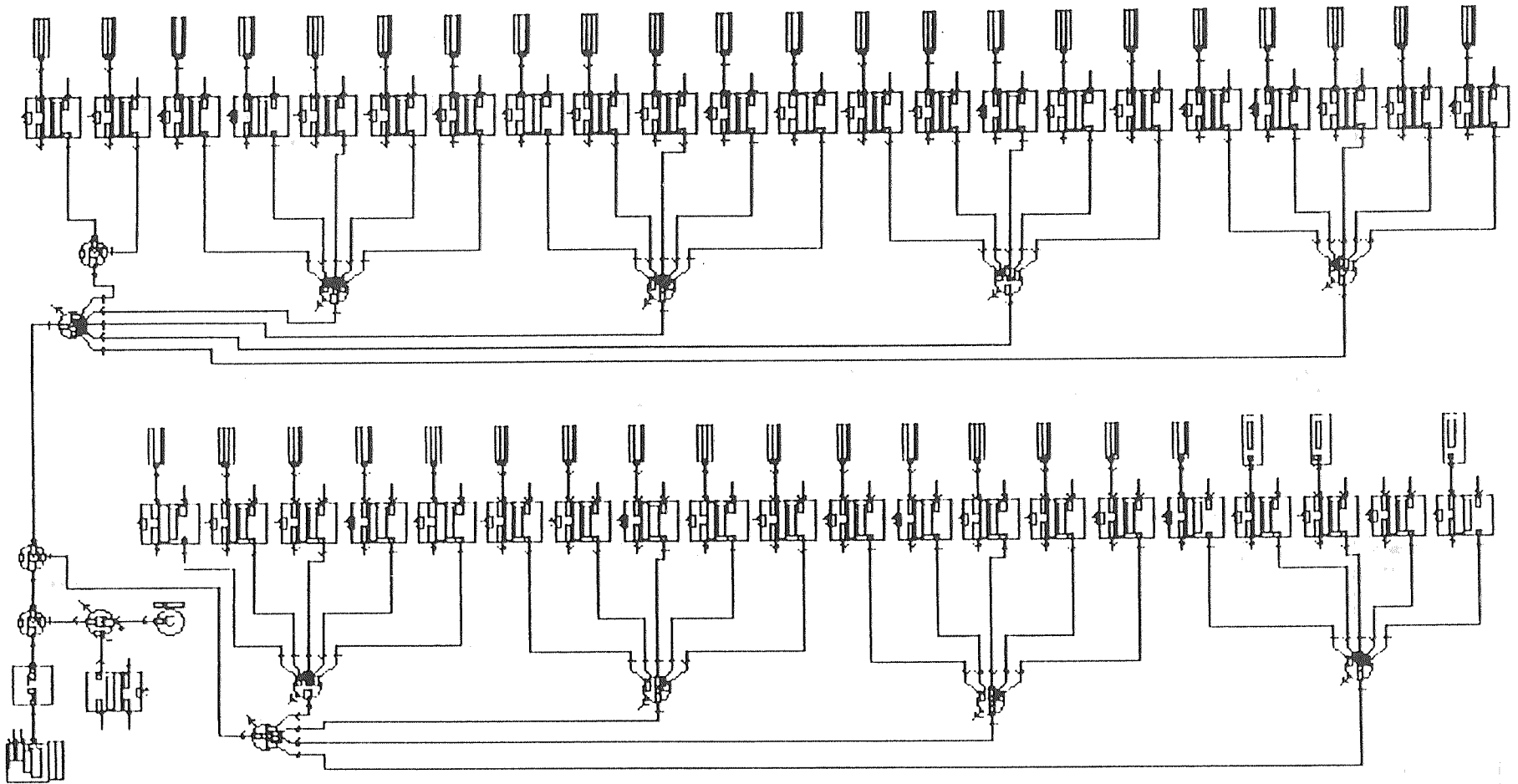


Figure 2.2a The design set-up

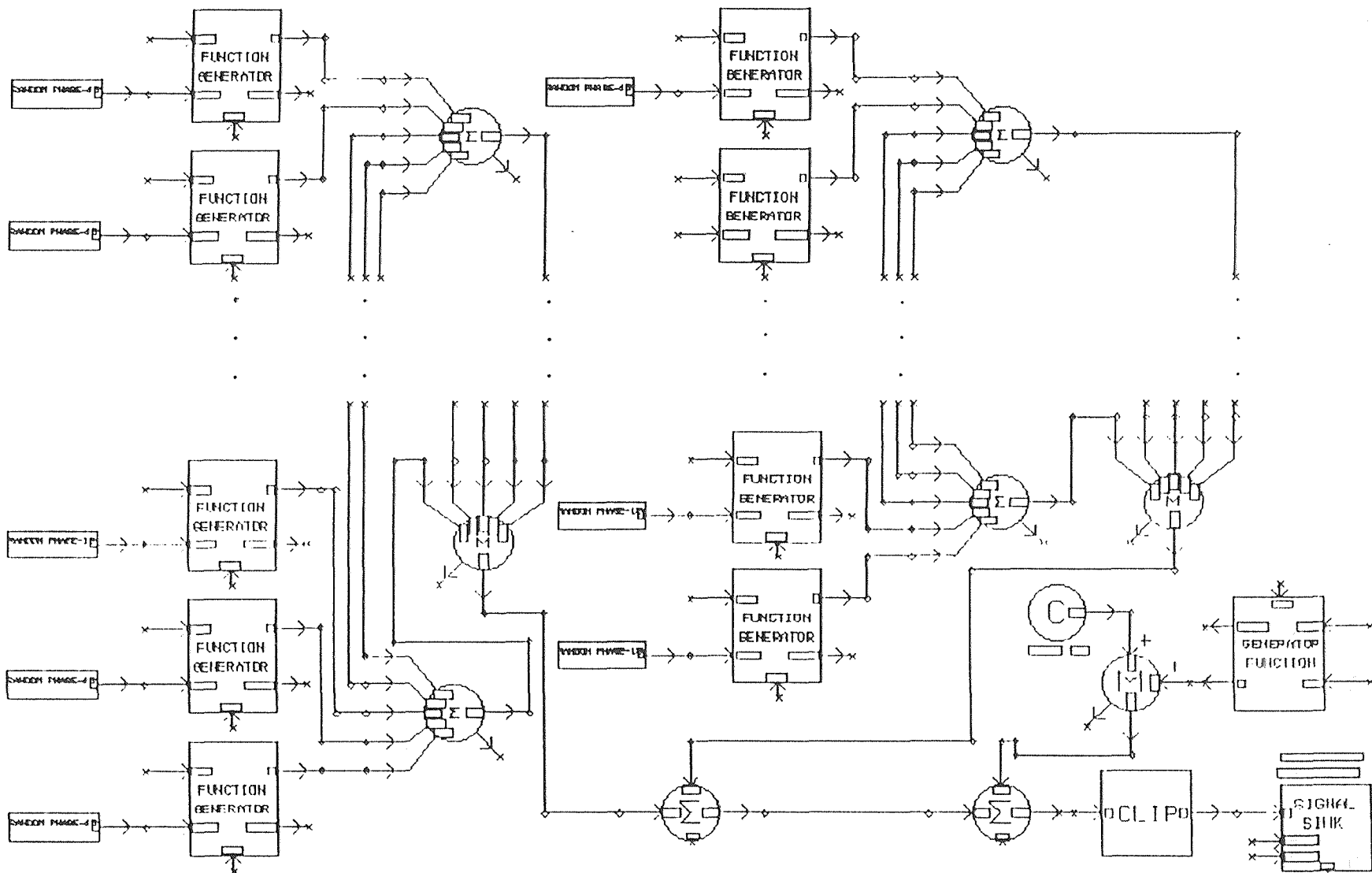


Figure 2.2b The design set-up (Zoom in)

The distortion at a particular channel is determined by turning off its tone and summing the power at all frequencies within the 6 MHz channel bandwidth centered on the carrier.

**Table 1** List of all 42 Frequencies

55.25 MHz	139.25 MHz	223.25 MHz
61.25 MHz	145.25 MHz	229.25 MHz
67.25 MHz	151.25 MHz	235.25 MHz
73.25 MHz	157.25 MHz	241.25 MHz
79.25 MHz	163.25 MHz	247.25 MHz
85.25 MHz	169.25 MHz	253.25 MHz
91.25 MHz	175.25 MHz	259.25 MHz
97.25 MHz	181.25 MHz	265.25 MHz
103.25 MHz	187.25 MHz	271.25 MHz
109.25 MHz	193.25 MHz	277.25 MHz
115.25 MHz	199.25 MHz	283.25 MHz
121.25 MHz	205.25 MHz	289.25 MHz
127.25 MHz	211.25 MHz	295.25 MHz
133.25 MHz	217.25 MHz	301.25 MHz

## 2.2 Signal Processing Worksystem (SPW) Blocks used in the Design

The SPW blocks used in the design can be seen in Figure 2.3. Figure 2.4 shows a partial area of the design with three nodes to show the output signal at each node. The system consists of 42 block generators. The frequency and phase of the output signal are controlled by the block parameters and the block input. The parameters specify the initial

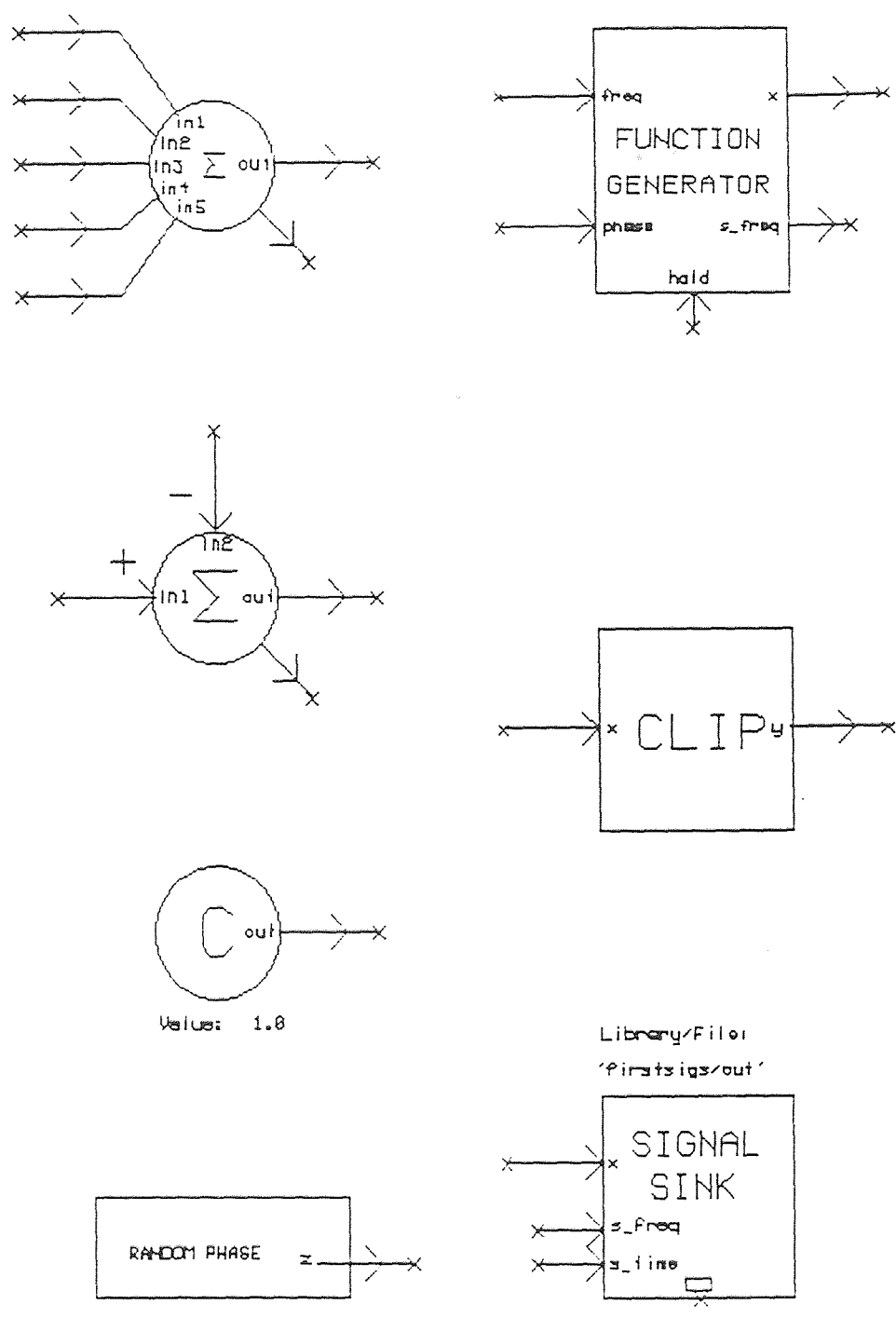


Figure 2.3 SPW blocks used in the design

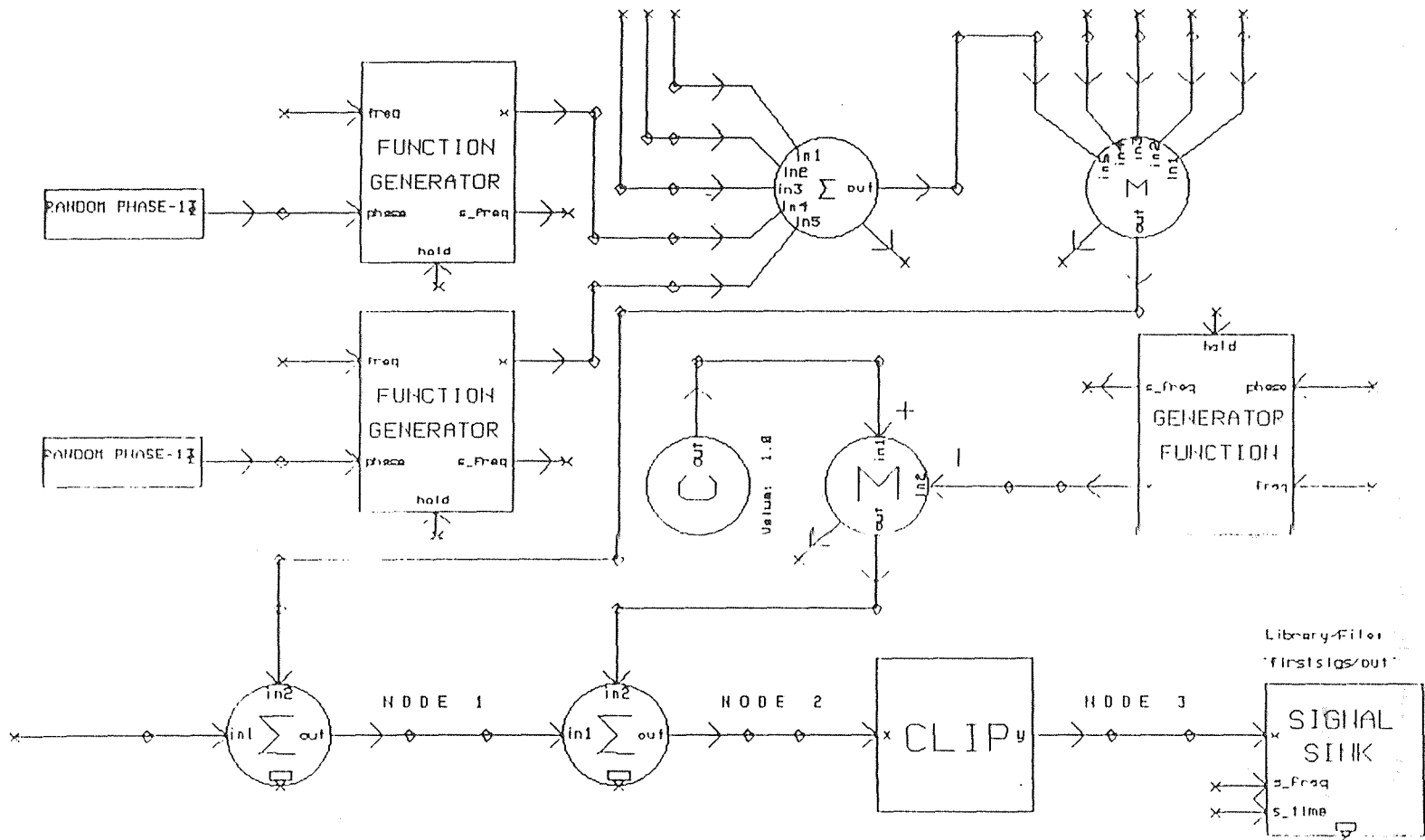


Figure 2.4 Selected node in the design

frequency and phase, and the inputs can be used to modify the frequency and phase during operation. The value on the “freq.” input is added to the parameter-set frequency to obtain the operation frequency. Similarly, the value in the “phase” input is added to the parameter-set phase to obtain the operation phase. Sampling frequency is also a main parameter and is fixed at 16 GHz for all operations. The amplitude of the periodic signal is varied according to the total rms modulation depth ( $\mu$ ) defined as

$$\mu = m\sqrt{N/2}$$

where,  $N$  is the number of channels (42), and  $m$  is the optical modulation depth per channel.  $\mu$  is greater than 0.3 and less than 1 predicted by Saleh, therefore  $m$  is chosen as  $0.0654654 < m < 0.21822179$ . The output of this block will be the generated signal. The output of the individual 42 blocks will be added together using an adder block to generate the summed signal. Figure 2.5 shows the summed signal for  $\mu = 0.35$  with seed # 87 and in Figure 2.6 the summed signal shown for  $\mu = 0.35$  with seed # 414881, both Figures obtained at node 1. Then a constant one is added to the summed signal, using a constant value block, the only parameter in this block is the constant value which is set to “1” and it is fixed during all operations at “1”. Figure 2.7 shows the signal at node 2 after a constant “1” is added,  $\mu = 0.35$  and seed # 87, Figure 2.8 shows the FFT (linear) for the same node (2) with  $\mu = 0.35$  and seed # 87 (when  $\mu = 0.35$ , the magnitude  $m = 0.076376$  but here it is half that value (0.038188) because the FFT splits the frequency to the negative side and the positive side). Also Figures 2.9 and 2.10 show the same signal at node 2 and its FFT (linear) for  $\mu = 0.35$  but different seed # (seed # 414881).

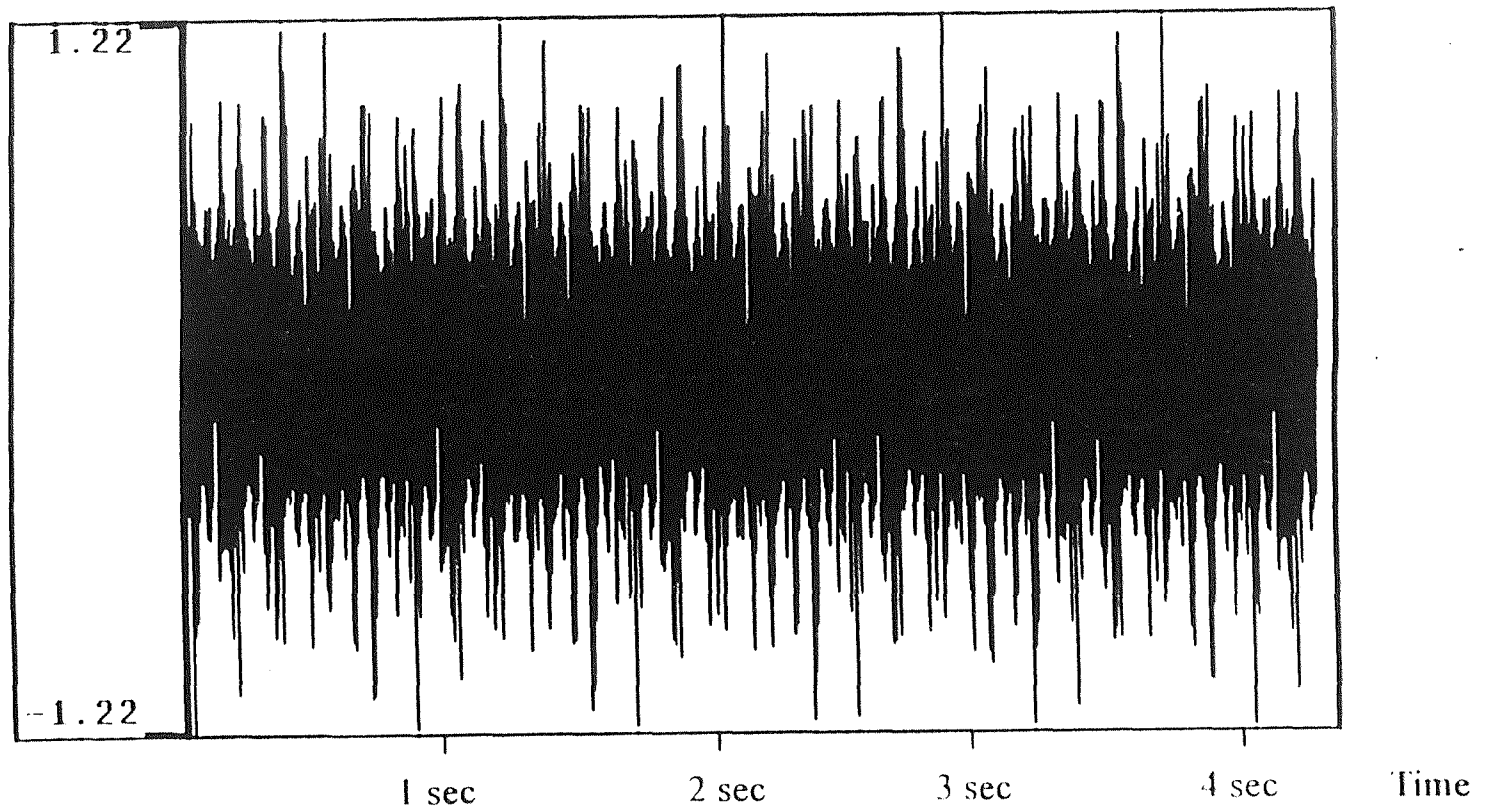


Figure 2.5 Signal at node 1 ( $\mu = 0.35$ , seed# 87)



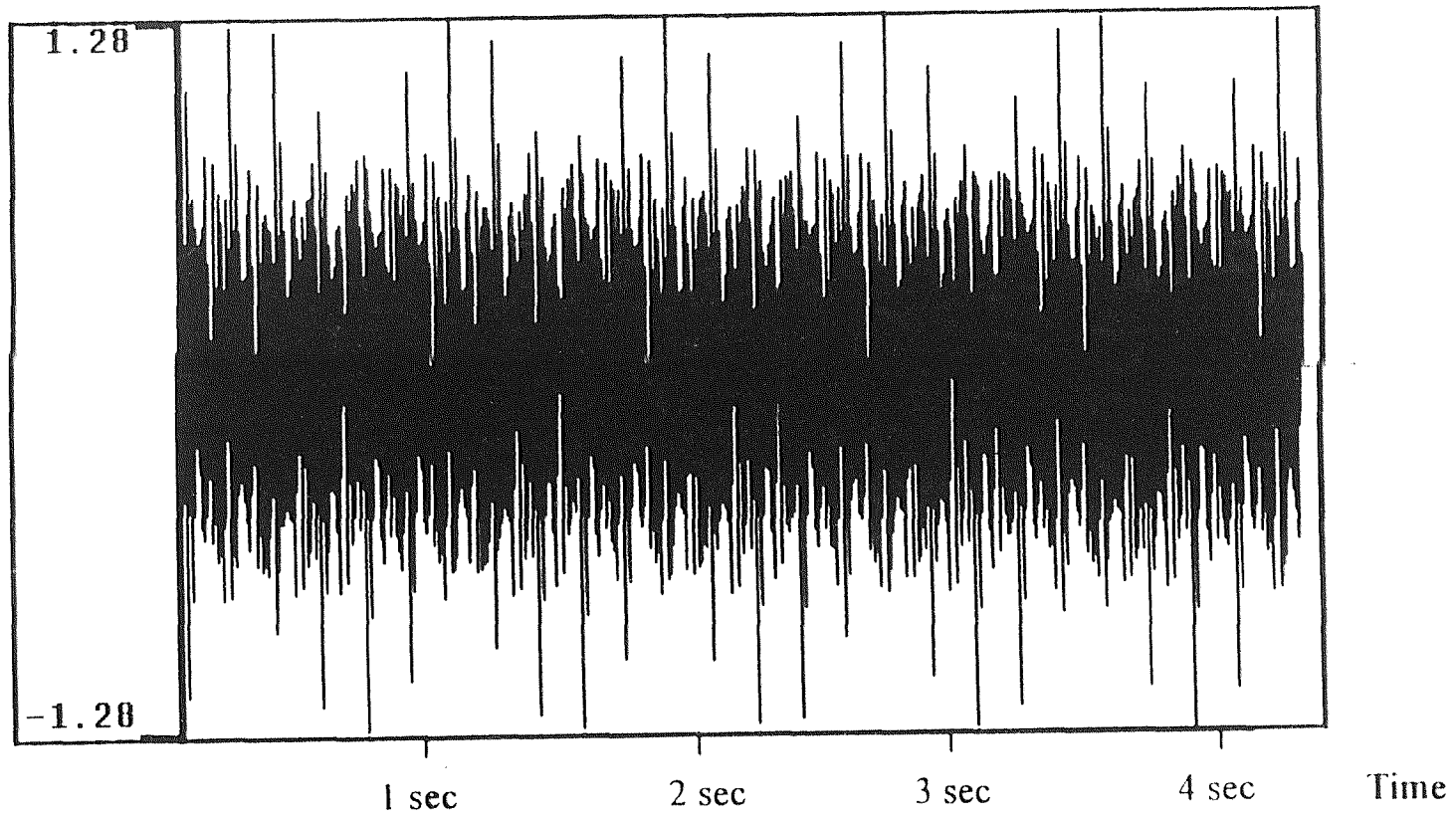


Figure 2.6 Signal at node 1 ( $\mu = 0.35$ , seed# 414881)

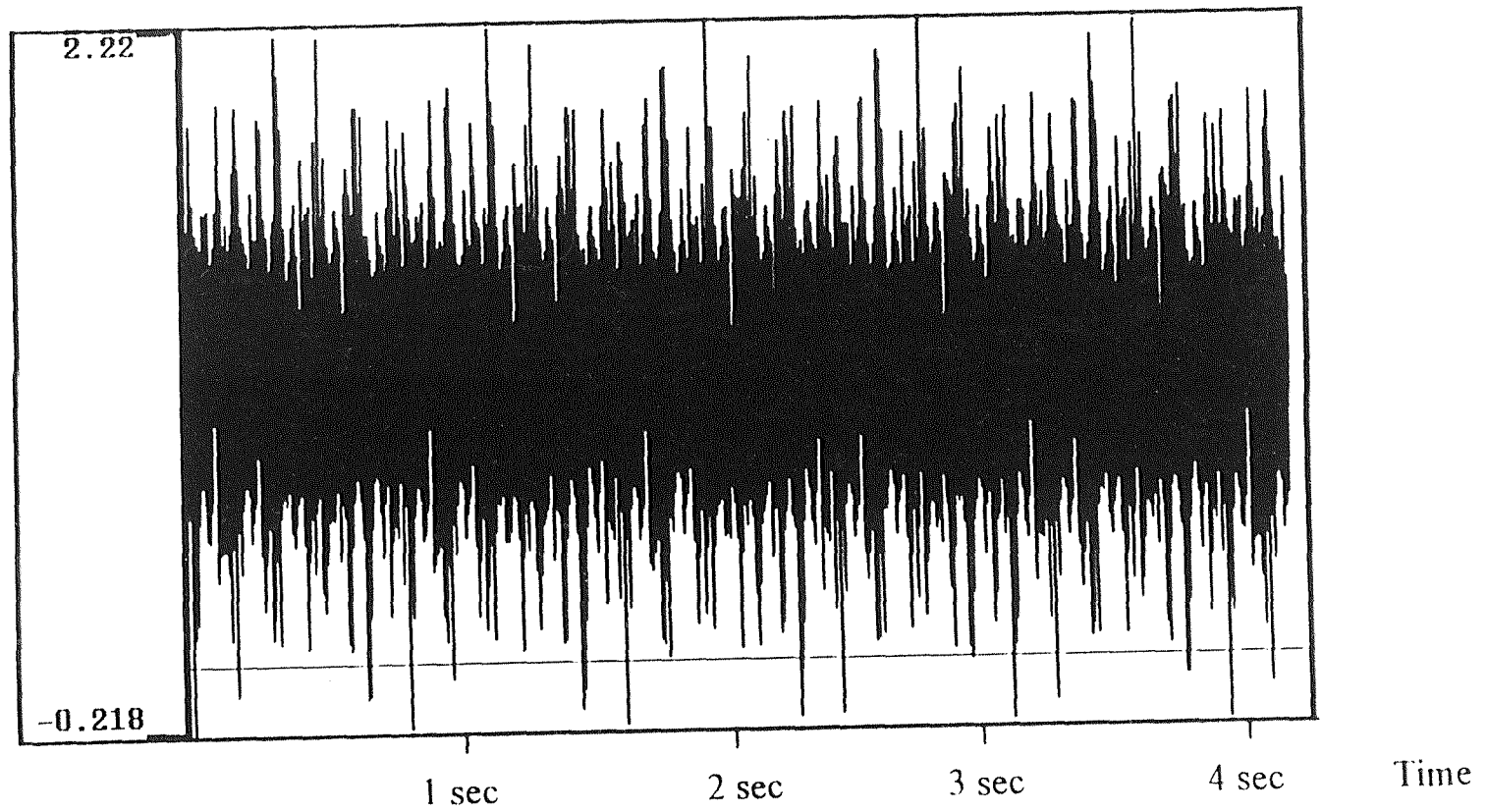


Figure 2.7 Signal at node 2 ( $\mu = 0.35$ , seed# 87)

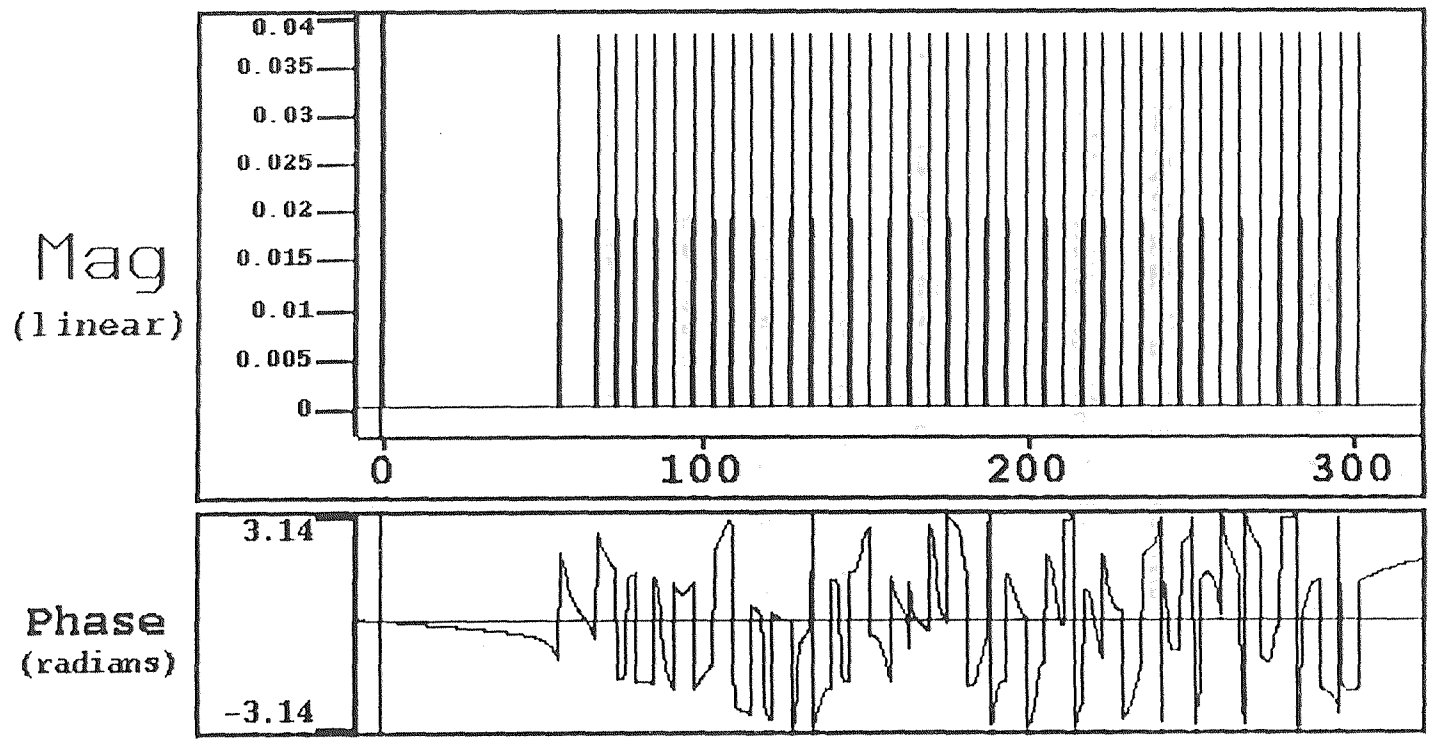


Figure 2.8 FFT at node 2 ( $\mu = 0.35$ , seed# 87)

The next step is clipping the summed signal  $X$ . The output signal is the same as the input, except that the output values are forced to remain within a specified range. The upper limit and lower limit are set as parameters. This signal will be shown in the next chapter. The block generates the output signal  $Y$  as shown in the following equation:

$$\begin{aligned}
 Y &= \text{upper limit} && \text{for } X \geq \text{upper limit;} \\
 Y &= X && \text{for lower limit} < X < \text{upper limit;} \\
 Y &= \text{lower limit} && \text{for } X \leq \text{lower limit.}
 \end{aligned}$$

The last block is the signal sink. This block stores signal data into a signal file. An editable parameter in the block symbol specifies the name of the file. The inputs of the block are the scalar data.

Since the results of the simulation are dependent on the phase of the carriers, the average is taken of a large number of runs, each with a different set of random phase. To generate a random phase for each run (select 42 random number) a custom-coded block was used. A custom-coded block is a signal processing block, the function of which is specified by a user-written program (Appendix A contains the C program). Once programmed and linked to the existing set of library blocks, a custom-coded block can be used like any other block.

The first step of the random phase custom-coded block is to create the symbol model, with one output and no input. Then to create the parameter screen model, all custom-coded blocks must be linked to a parameter screen model, certain parameters must be present in order for the block to work properly with the simulation, it depends on the type of output (scale).

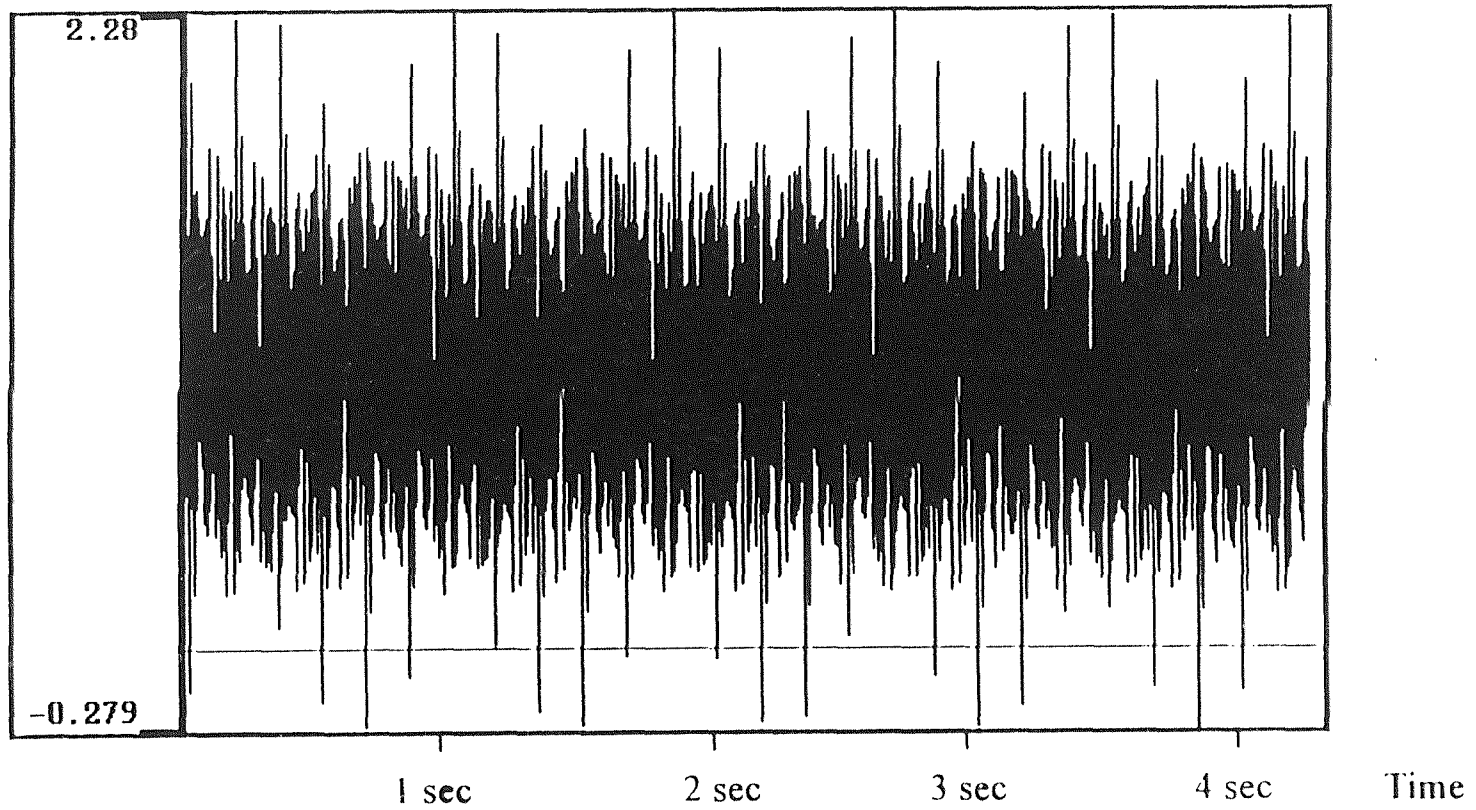


Figure 2.9 Signal at node 2 ( $\mu = 0.30$ , seed# 414881)

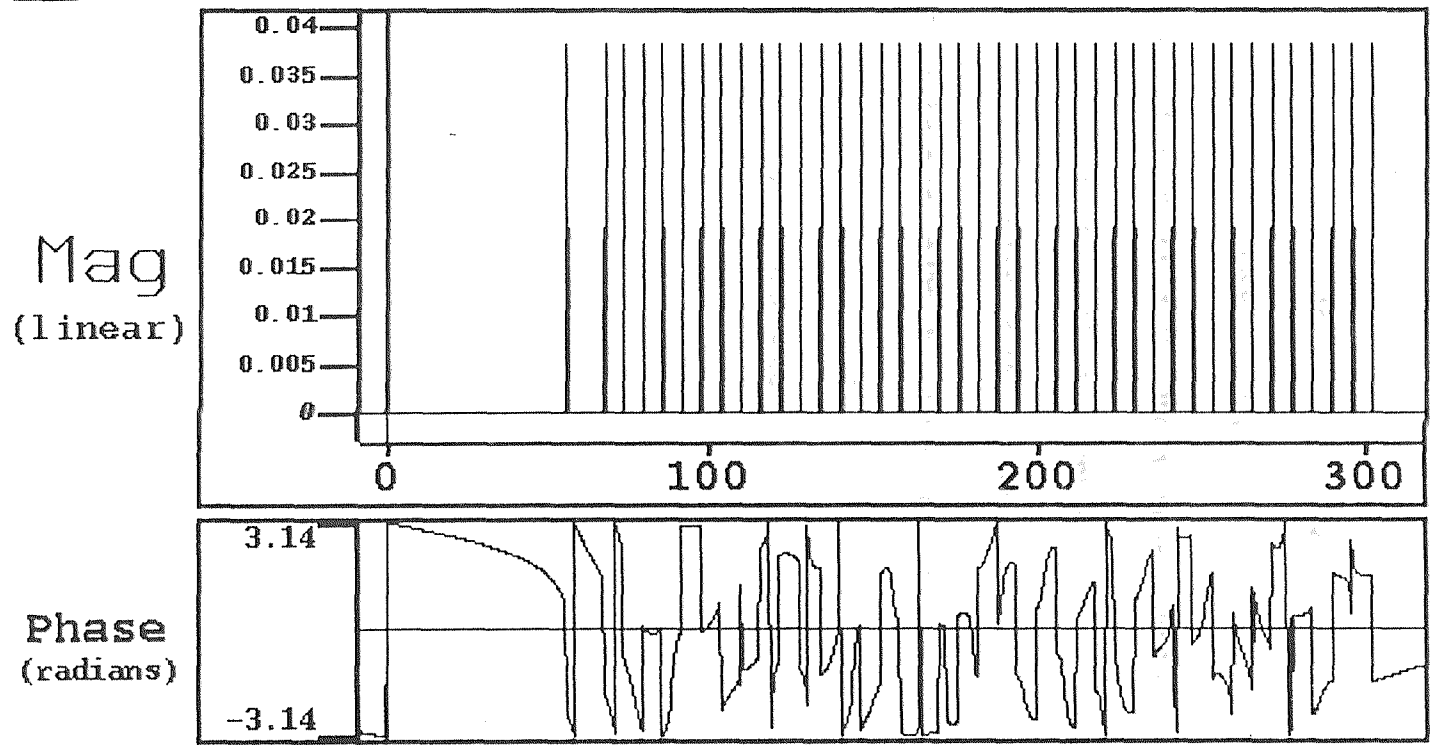


Figure 2.10 FFT at node 2 ( $\mu = 0.35$ , seed# 414881 )

Next, link the symbol model to the parameter screen model. The function “prepare block tool” will create two template files, random-phase.c and random phase.h, named after the block function, “random-phase”. The random-phase.c file contains the source code that implements the block function. The random-phase.h file code declares the variables used in the C program.

Finally, compile the block code and prepare the block for using. If the message “block compiled successfully” did not appear an error occurred in the process.

An additional step is done to test the random-phase custom-coded block by creating a small design consisting of random-phase custom coded block connected with a signal sink to test the output of the random-phase block. Once the block operates correctly, then its compiled code can be added to the SPW library and used with confidence for all future simulations. The random-phase custom-coded block was connected to the input of each block generator to obtain the operating random-phase.

## CHAPTER 3

### NUMERICAL SIMULATION

#### 3.1 Simulation Set-up

The clipping induced distortion for an ideal diode characteristic was calculated by a numerical simulation. In the design there are 42 carriers, each with a random-phase represented in the time domain. The time-domain modulation signal is put through a transfer function and subsequently transformed by means of a Fast Fourier Transform (FFT). The necessary number of sampling points is determined by the desired resolution in frequency and the bandwidth of the clipped signal spectrum. The sampling rate used is 16 GHz; lower sampling rate may not be fast enough to see all of the clipping events and this will not detect as much distortion [2]. So the sampling rate of 16 GHz allows the simulation to detect the great majority of clipping events with a frequency resolution of 0.25 MHz resulting in a number of points  $M=65536$  in the FFT [4]. Since the distortion output is strongly dependent on the particular phases of the tones, the average of the distortion for 33 runs, each with a new set of random-phase was calculated.

#### 3.2 Direct Modulation (Single-Clipping) Lightwave System

A crucial aspect for increasing the distribution capacity of SCM networks is to advance the optical loss budget. Active techniques at the transmitter to gain this include overmodulation of the laser to advance the optical signal [6]. Saleh calculated the distortion due to clipping as a function of the effective rms modulation depth and predicts it to be the minimum distortion emitted by lasers under direct modulation (single-



clipping) [4]. Figure 3.1 shows the total non-linear distortion (NLD) predicted by Saleh. His theory predicts the total non-linear distortion power (NLD) falling within the channel bandwidth. In Saleh's analysis, the non-linear distortion is calculated by :

$$NLD = \frac{1}{\sqrt{2\Pi}} \frac{\mu^3}{1+6\mu^2} \exp\left(-\frac{1}{2\mu^2}\right)$$

where  $\mu$  , the rms modulation depth is defined by:

$$\mu = m\sqrt{N/2}$$

where  $N$  is the number of channels and  $m$  is the optical modulation depth per channel.

Table 3.1 shows all the values of NLD for all possible  $\mu$  as it is predicted by Saleh.

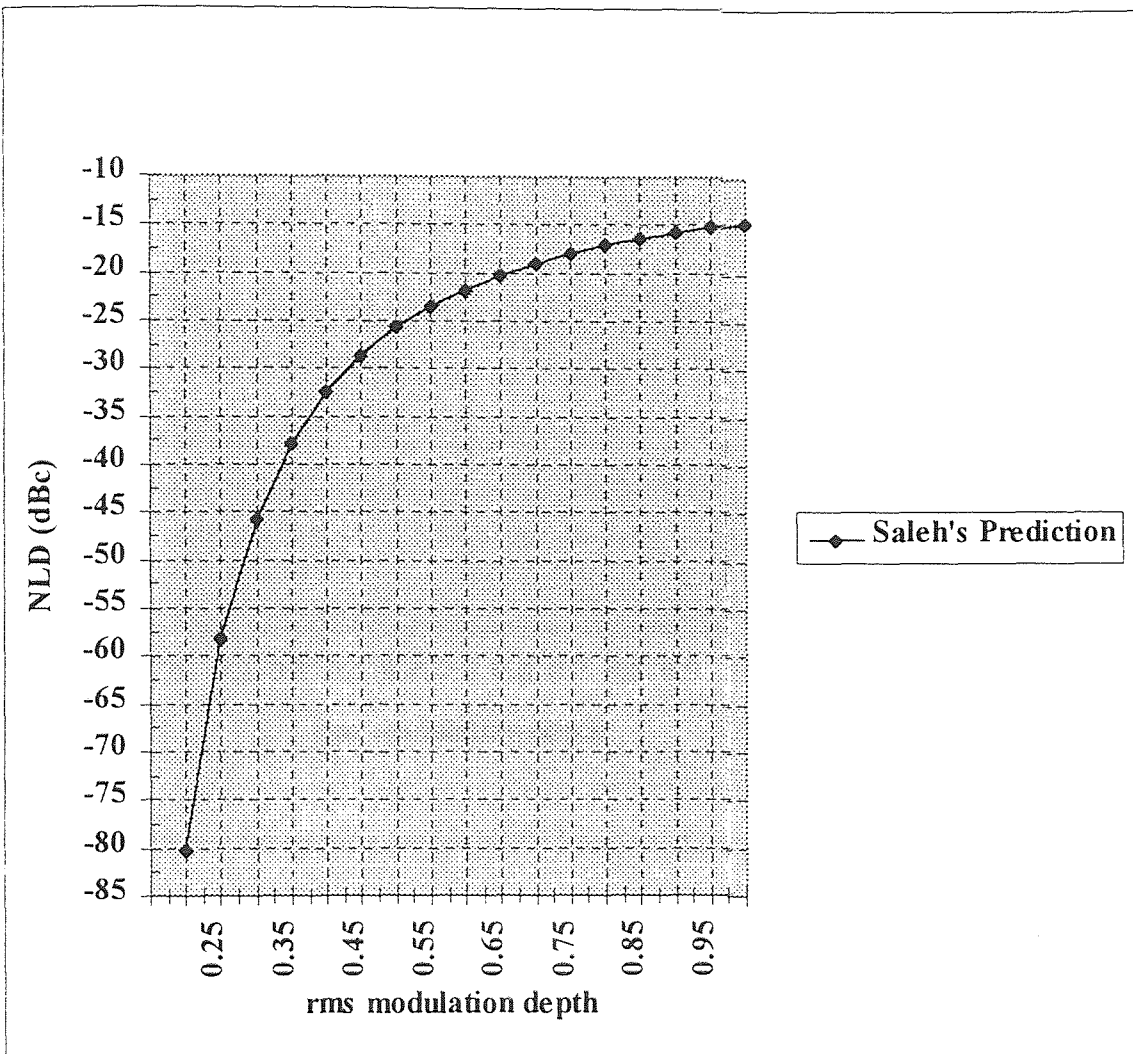
**Table 3.1** List of the NLD values as predicted by Saleh for  $\mu = 0.2 \sim 0.95$  :

$\mu=0.20$	NLD= -80.18	$\mu=0.50$	NLD= -25.69	$\mu=0.80$	NLD= -17.14
$\mu=0.25$	NLD= -58.18	$\mu=0.55$	NLD= -23.45	$\mu=0.85$	NLD= -16.39
$\mu=0.30$	NLD= -45.68	$\mu=0.60$	NLD= -21.68	$\mu=0.90$	NLD= -15.72
$\mu=0.35$	NLD= -37.79	$\mu=0.65$	NLD= -20.23	$\mu=0.95$	NLD= -15.14
$\mu=0.40$	NLD= -32.42	$\mu=0.70$	NLD= -19.02	$\mu=1.00$	NLD= -14.61
$\mu=0.45$	NLD= -28.57	$\mu=0.75$	NLD= -18.01		

The result of the numerical simulation for the non-linear distortion (NLD) direct modulating (single-clipping) is shown in Figure 3.2 and in Table 3.2 for Channel 3 (61.25MHz). The simulation distortion at a particular channel is determined by turning off the tone at that channel and summing the power that falls within its 6 MHz bandwidth. For Channel 3 the summed power was between 58.25 MHz and 64.25 MHz. Five different values of  $\mu$  were investigated ( $\mu=0.3; 0.35; 0.6; 0.7; 0.95$ ). At each value of  $\mu$ ,

33 runs were performed. At each run, 42 different values of Random-phases were selected randomly.

Each run was controlled by seed # at the beginning of the simulation. Different seed # was selected for all 33 runs to ensure that all runs had different sets of random-phase.



**Figure 3.1** NLD as a function of rms as predicted by Saleh for Channel 3

Figure 3.3 shows a block diagram of the five values of  $\mu$  ( $\mu = 0.30, \mu = 0.35, \mu = 0.60, \mu = 0.70, \mu = 0.95$ ) and their 33 runs with the seed # and the 42 different random-phase for all 33 runs (each run controlled by different seed #).

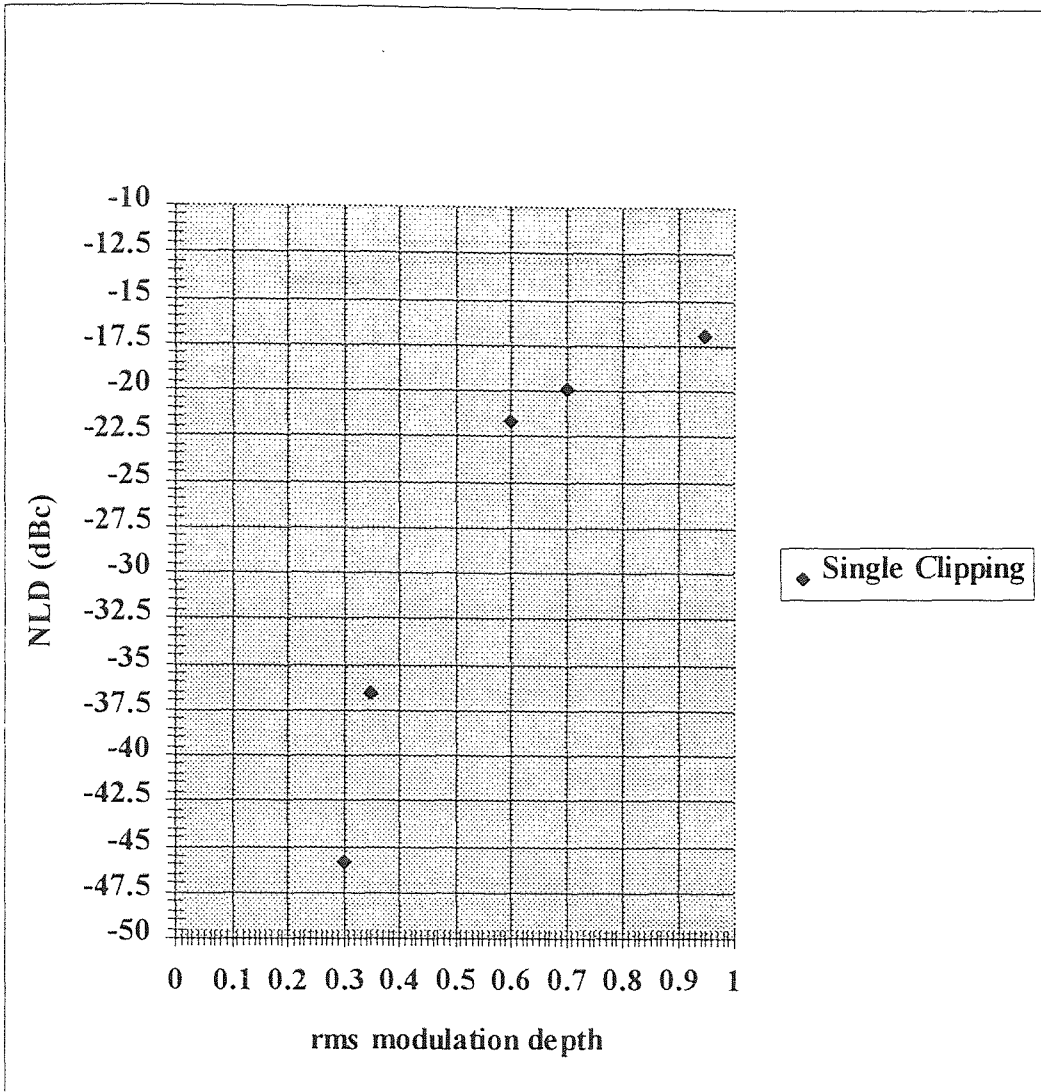
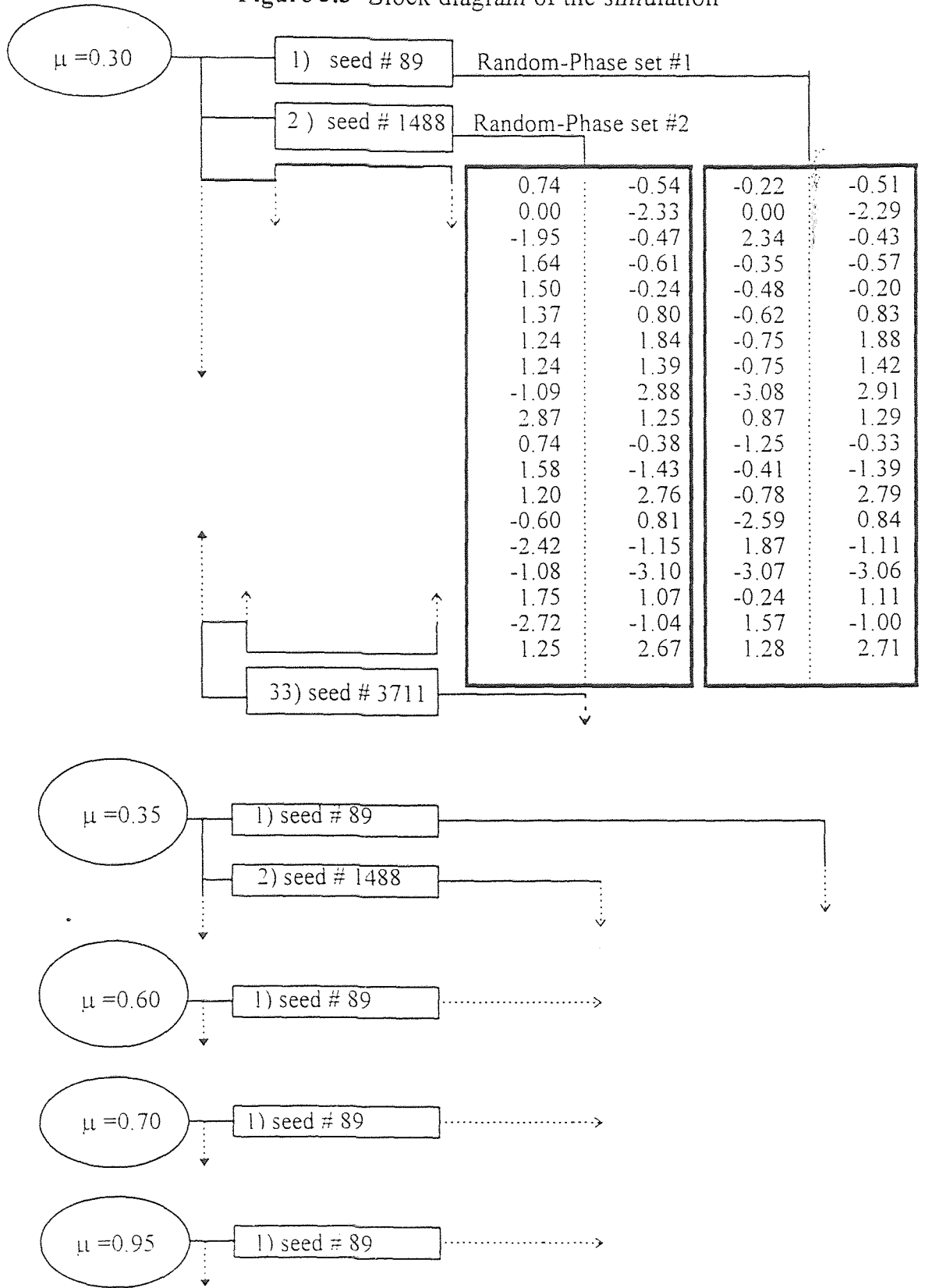


Figure 3.2 Numerical simulation for NLD direct modulation for Channel 3

Table 3.2 List of the NLD from the Numerical Simulation for direct modulating

$\mu=0.30$	NLD= -45.84 dB
$\mu=0.35$	NLD= -36.52 dB
$\mu=0.60$	NLD= -21.72 dB
$\mu=0.70$	NLD= -19.90 dB
$\mu=0.95$	NLD= -17.00 dB

Figure 3.3 Block diagram of the simulation



### Table 3.3 External Modulation (Double-Clipping) Lightwave System

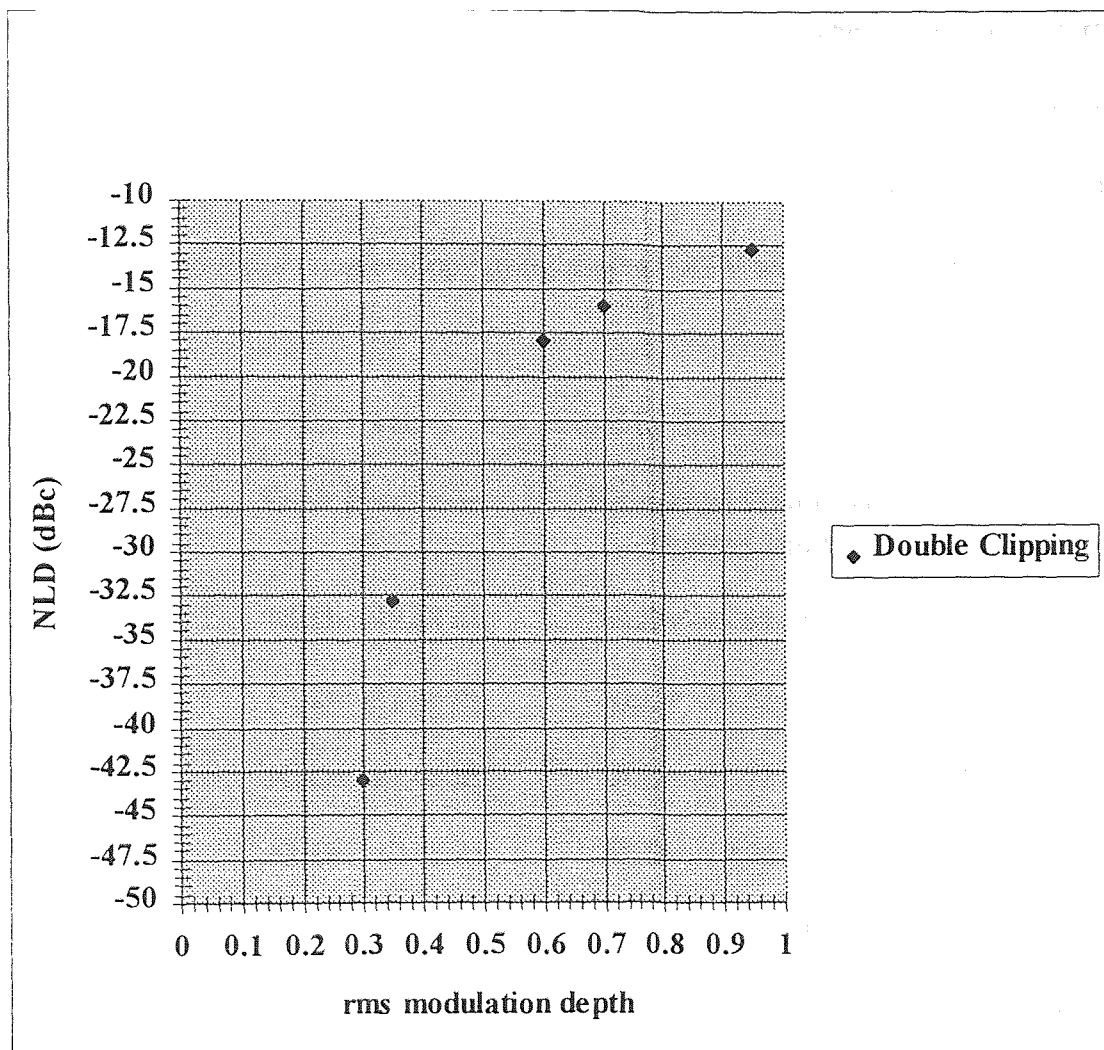
Another techniques that has received investigation currently is the use of improved light sources based on external modulation methods instead of direct laser modulation. This takes improvement of much lower relative intensity noise (RIN) values available from these solid-state sources, which can be important element in SCM systems. Beside, additional benefits include the absence of fiber dispersion limitation in comparison to direct modulated lasers, and important system benefit of improved tolerance to reflections and interferometric noise [6].

The results of the numerical simulation for the externally modulated (double-clipping) is shown in Figure 3.5 for Channel 3 (61.25 MHz) and in Table 3.3. The simulation distortion at a particular channel is determined by turning off the tone at that channel and summing the power that falls within its 6 MHz bandwidth. For Channel 3 the power was summed between the frequency 58.25 MHz and 64.25 MHz. Five different values of  $\mu$  were investigated ( $\mu=0.3; 0.35; 0.6; 0.7; 0.95$ ). At each value of  $\mu$ , 33 runs were performed. At each run, 42 different values of random-phases were selected randomly.

Each run was controlled by seed # at the beginning of the simulation. Different seed # was selected for all 33 runs to ensure that all runs had different sets of random-phase. (The 42 random-phase at run 1 with seed # 87 is a different form the 42 random-phase at run 2 with seed # 414881, etc...). Figure 3.3 shows a block diagram of the five values of  $\mu$  ( $\mu = 0.30, \mu = 0.35, \mu = 0.60, \mu = 0.70, \mu = 0.95$ ) and their 33 runs with the seed # and the 42 different random-phase for all 33 runs (each run controlled by different seed #).

**Table 3.3** List of the NLD from the numerical simulation for external modulating

$\mu=0.30$	NLD= -42.96 dB
$\mu=0.35$	NLD= -32.85 dB
$\mu=0.60$	NLD= -17.96 dB
$\mu=0.70$	NLD= -15.94 dB
$\mu=0.95$	NLD= -12.67 dB



**Figure 3.5** Numerical simulation for NLD externally modulating for Channel 3

## CHAPTER 4

### RESULTS AND DISCUSSIONS

#### 4.1 Results of the Numerical Simulation for Direct Modulation

The results of the numerical simulation for non-linear distortion single clipping for Channel 3 are shown with the Saleh limit in Figure 4.1. The data is the average of 33 runs of the simulation. As can be seen in Figure 4.1, the numerical simulation for Channel 3 (61.25 MHz) closely follows the curve of the Saleh limit. The numerical distortion of directly modulated (single-clipping) lightwave CATV falls within 1-2 dB of Saleh's theory for values of  $\mu$  between 0.30 ~ 0.95. Table 4.1 compares the numerical distortion of directly modulated (single-clipping) lightwave CATV with Saleh's prediction.

**Table 4.1** List of the NLD values as predicted by Saleh and the numerical simulation

$\mu$	Saleh Prediction	Numerical Simulated Direct Clipping
$\mu=0.30$	NLD= -45.68 dB	NLD= -45.84 dB
$\mu=0.35$	NLD= -37.79 dB	NLD= -36.52 dB
$\mu=0.60$	NLD= -21.68 dB	NLD= -21.72 dB
$\mu=0.70$	NLD= -19.02 dB	NLD= -19.90 dB
$\mu=0.95$	NLD= -15.14 dB	NLD= -17.00 dB

The simulation distortion at a particular channel is determined by turning off the tone at that channel and summing the power that falls within its 6 MHz bandwidth. For Channel 3 (61.25 MHz) the summed power was between 58.25 MHz and 64.25 Mhz.

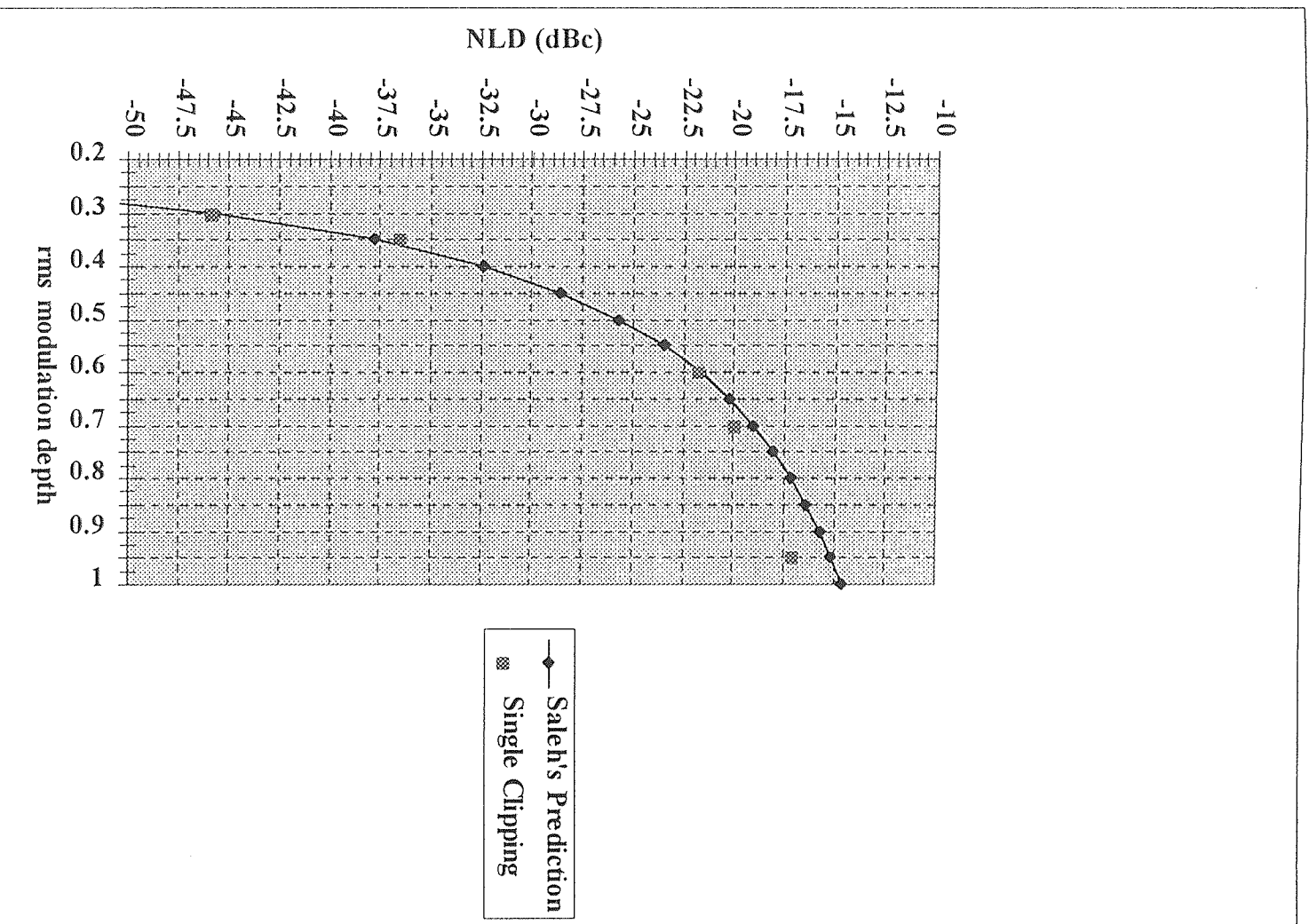


Figure 4.1 Saleh prediction vs. numerical simulation for Channel 3



Figure 4.2 shows the single-clipped signal for  $\mu = 0.30$  with seed # 87, and Figure 4.3 shows the power falling within the range 58.25 MHz ~ 64.25 MHz for the same signal. Figure 4.4 shows the single-clipped signal for  $\mu = 0.30$  with seed # 414881, and Figure 4.5 shows the power falling within the range 58.25 MHz ~ 64.25 MHz for  $\mu = 0.30$  with seed # 414881. The power in both Figures (4.3 - 4.5) is different due to the different random phase selection for each run. The same process was performed for  $\mu = 0.35, 0.60, 0.70,$  and  $0.95$ . Appendix B shows the power falling within the range 58.25 MHz and 64.25 MHz for the direct modulated (single-clipping) lightwave system for all values of  $\mu$ .

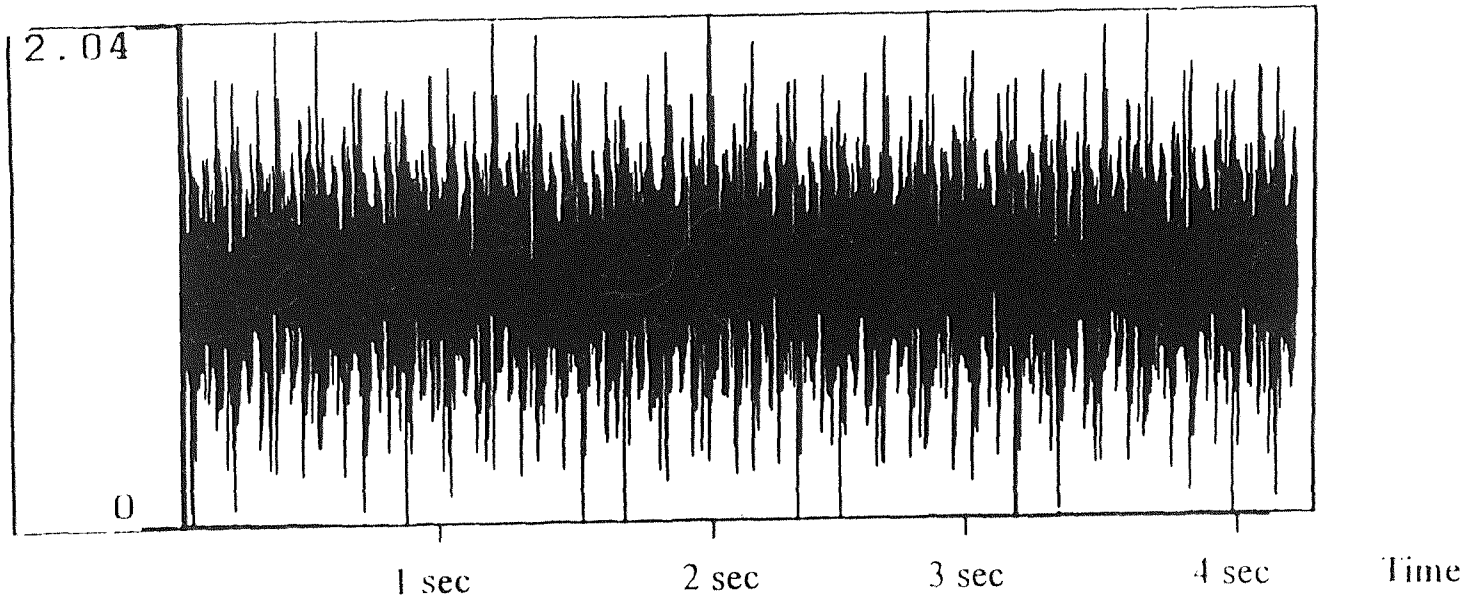


Figure 4.2 Signal at node 3 ( $\mu = 0.30$ , seed# 87)

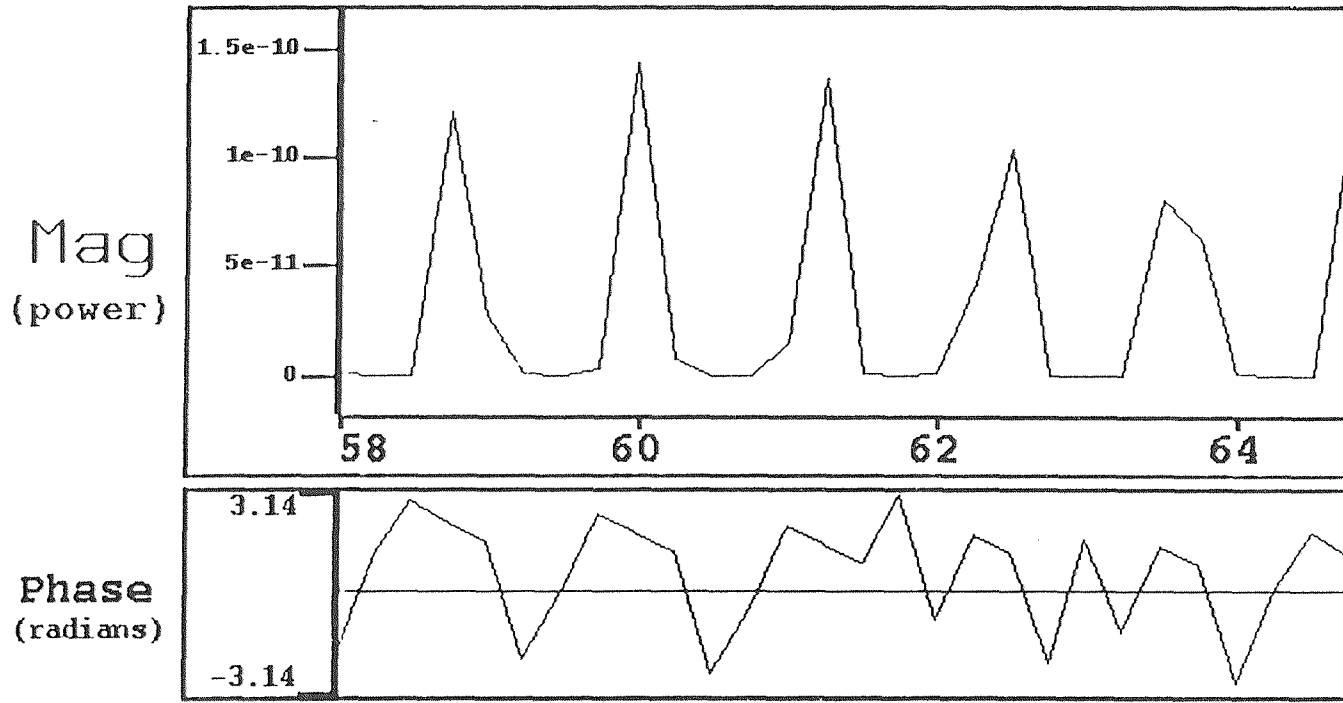


Figure 4.3 FFT at node 3 (  $\mu = 0.30$ , seed# 87 )

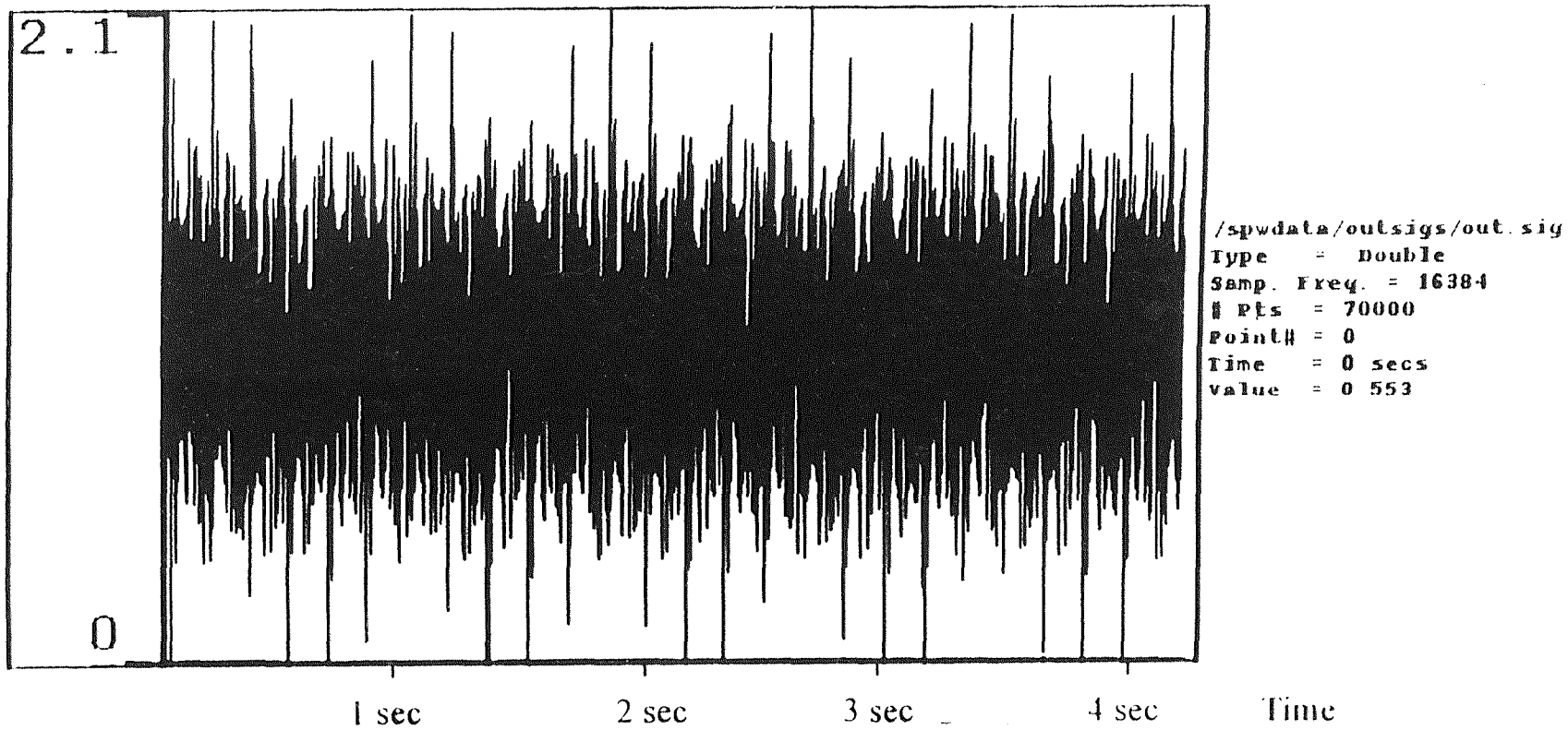


Figure 4.4 Signal at node 3 ( $\mu = 0.30$ , seed# 414887)

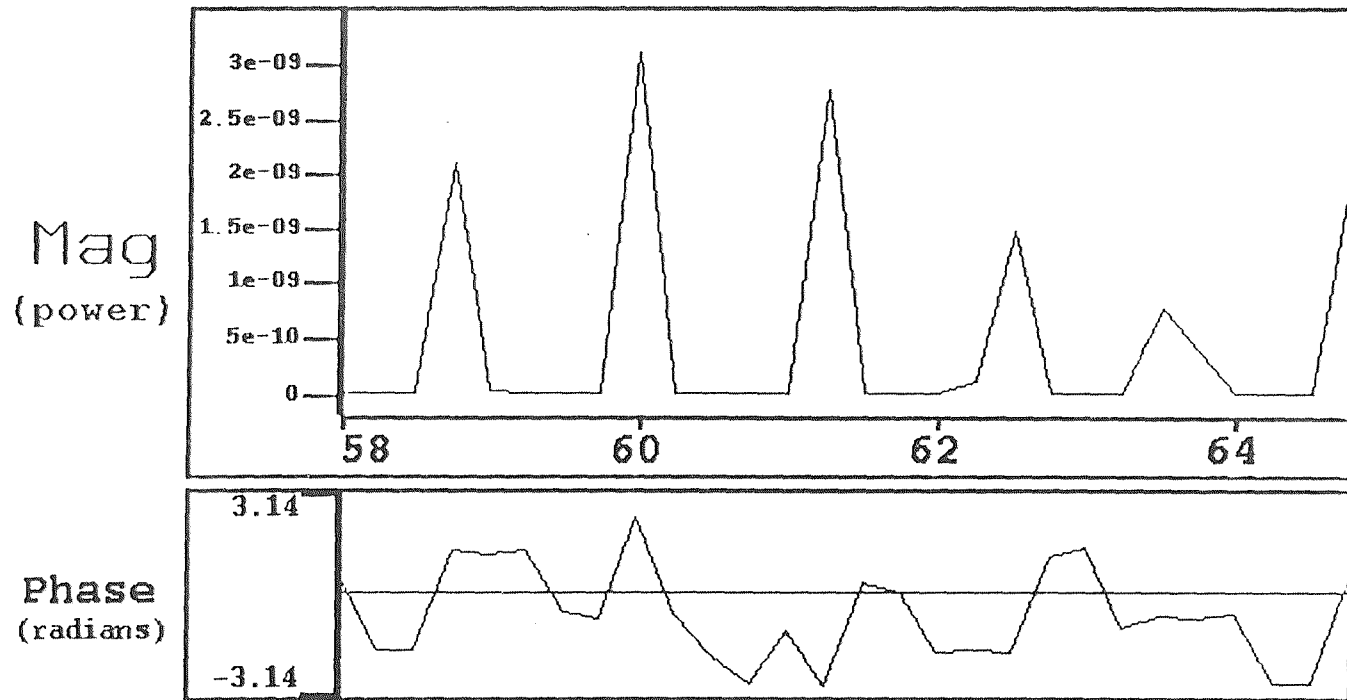


Figure 4.5 FFT at node 3 ( $\mu = 0.30$ , seed# 414887 )

#### 4.2 Results of Numerical Simulation for Direct Modulation vs. External Modulation

Applying Saleh's model to symmetrical clipping, yield a 3 dB increase in distortion power compared to single-level (laser) clipping. The results of the numerical simulation for direct modulation versus external modulation are plotted against rms modulation depth  $\mu$  ( $\mu = m\sqrt{N/2}$ ) in Figure 4.6. It is clear from this figure that the non-linear distortion (NLD) for the external modulator (double-clipping) is 3 dB higher than the direct modulator (single-clipping). Table 4.2 compares the numerical distortion of directly modulated (single-clipping) lightwave CATV with the numerical distortion of externally modulated (double-clipping) lightwave CATV.

**Table 4.2** List of NLD for directly and externally modulated lightwave systems

$\mu$	Externally Modulated	Directly Modulated
	double-clipping	single-clipping
$\mu = 0.30$	NLD= -42.96 dB	NLD= -45.84 dB
$\mu = 0.35$	NLD= -32.85 dB	NLD= -36.52 dB
$\mu = 0.60$	NLD= -17.96 dB	NLD= -21.72 dB
$\mu = 0.70$	NLD= -15.94 dB	NLD= -19.90 dB
$\mu = 0.95$	NLD= -12.67 dB	NLD= -17.00 dB

The simulation distortion of externally modulated (double-clipping) lightwave at a particular channel is determined by turning off the tone at that channel and summing the power that falls within its 6 MHz bandwidth. For Channel 3 (61.25 MHz) the summed

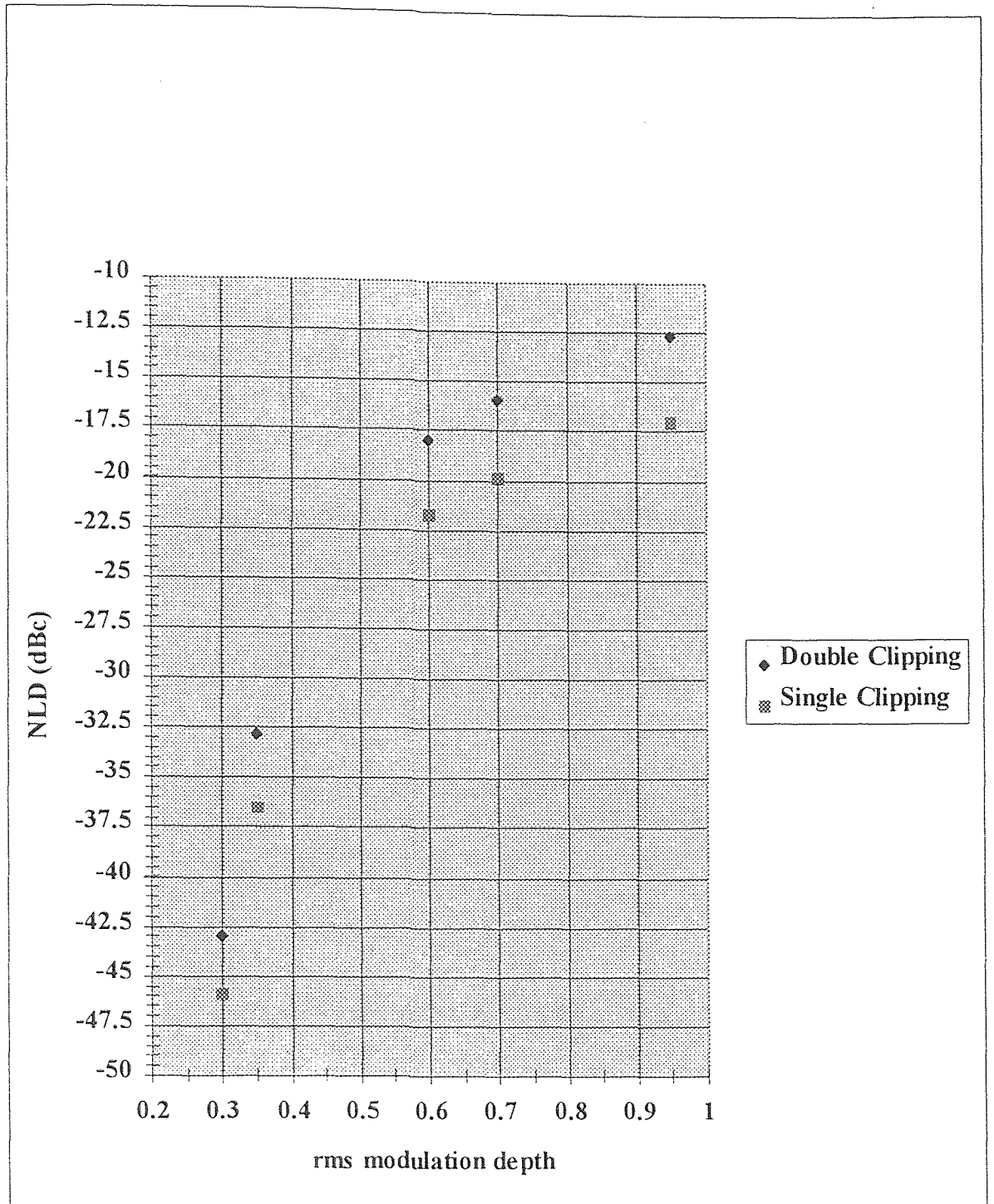


Figure 4.6 Numerical simulation for direct modulation vs. external modulation

power was between 58.25 MHz and 64.25 MHz. Figure 4.7 shows the double-clipped signal for  $\mu = 0.30$  with seed # 414, and Figure 4.8 shows the power falling within the range 58.25 MHz ~ 64.25 MHz for the same signal. Figure 4.9 shows the double-clipped signal for  $\mu = 0.30$  with seed # 414881, and Figure 4.10 shows the power falling within the range 58.25 MHz ~ 64.25 MHz for  $\mu = 0.30$  with seed # 414881. The power in both figures (4.8 - 4.10) is different due to the different random phase selection for each run. The same process was performed for  $\mu = 0.35, 0.60, 0.70,$  and  $0.95$ . Appendix B.2 shows the power falling within the range 58.25 MHz and 64.25 MHz for the direct modulated (single-clipping) lightwave system for all values of  $\mu$ .



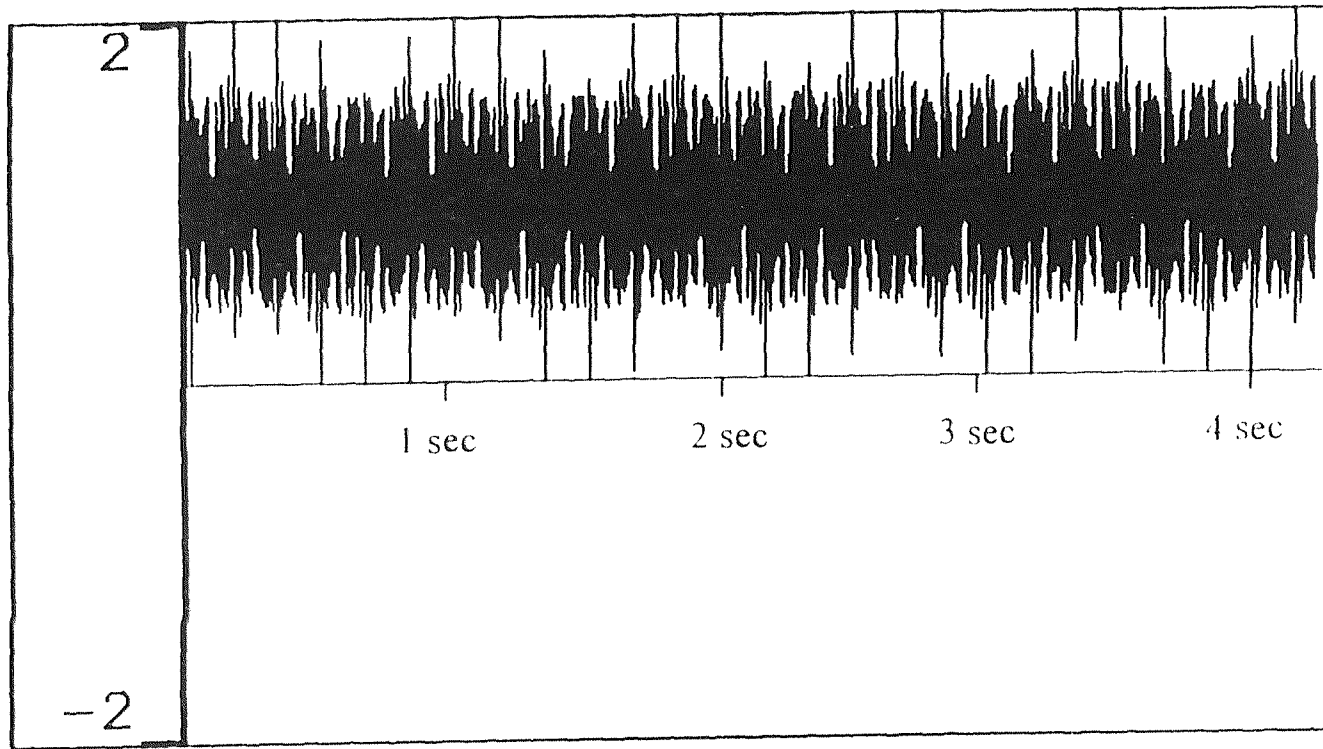


Figure 4.7 Signal at node 3 ( $\mu = 0.30$  , seed# 414)

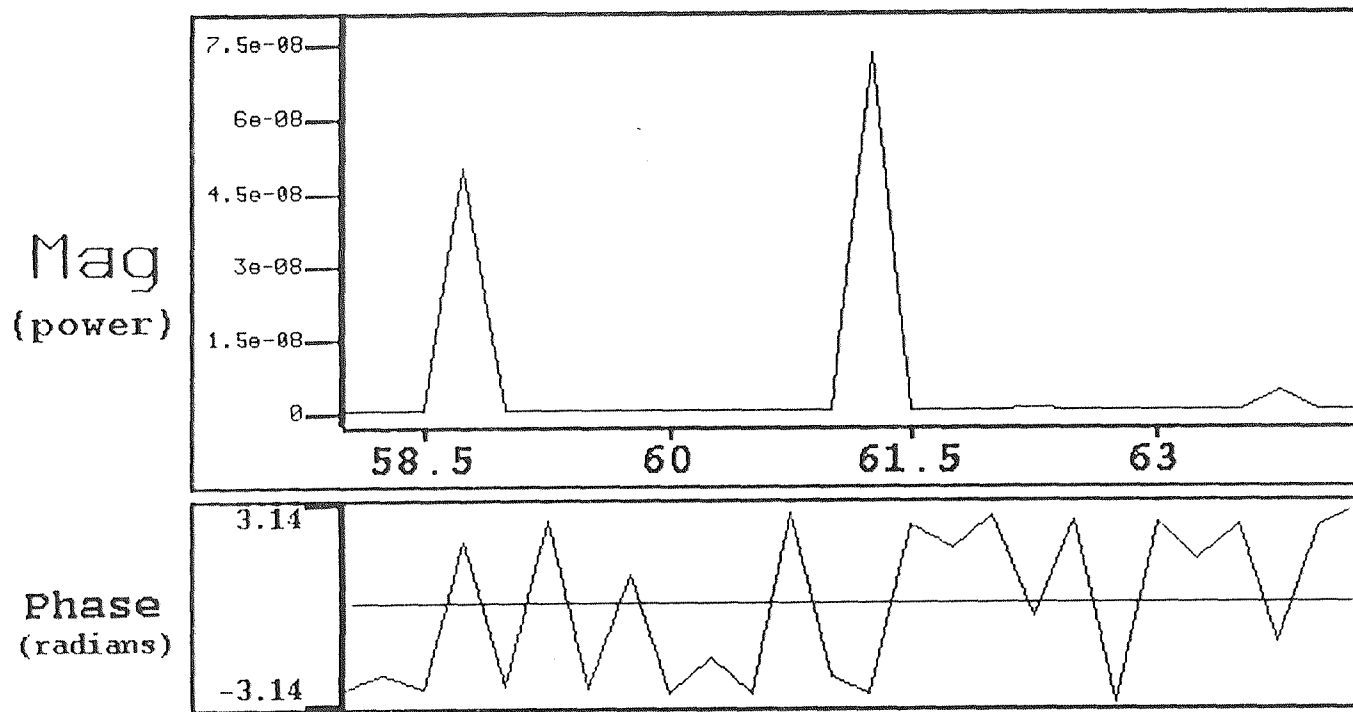


Figure 4.8 FFTat node 3 ( $\mu = 0.30$ , seed# 414)

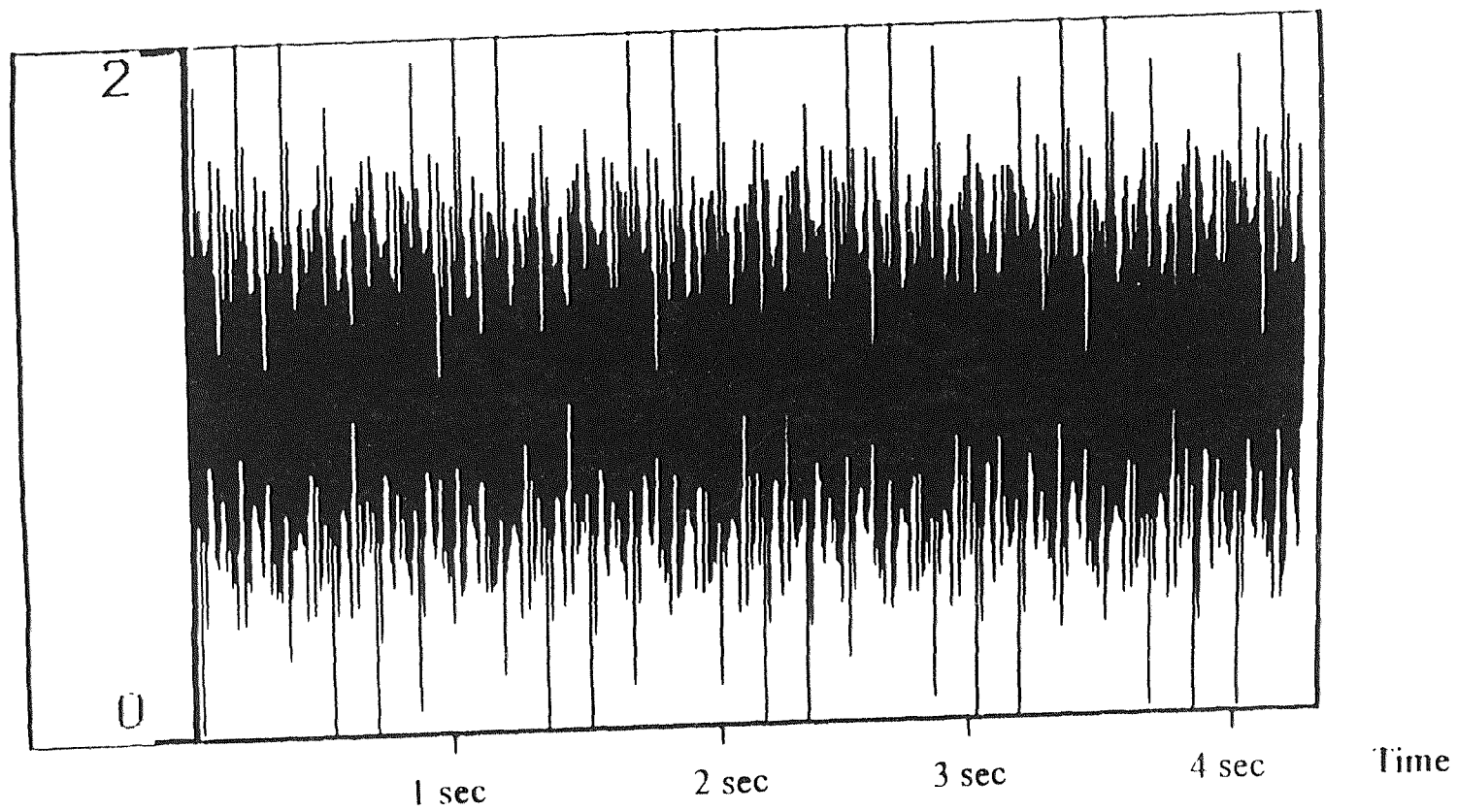


Figure 4.9 Signal at node 3 ( $\mu = 0.30$  , seed# 414881)

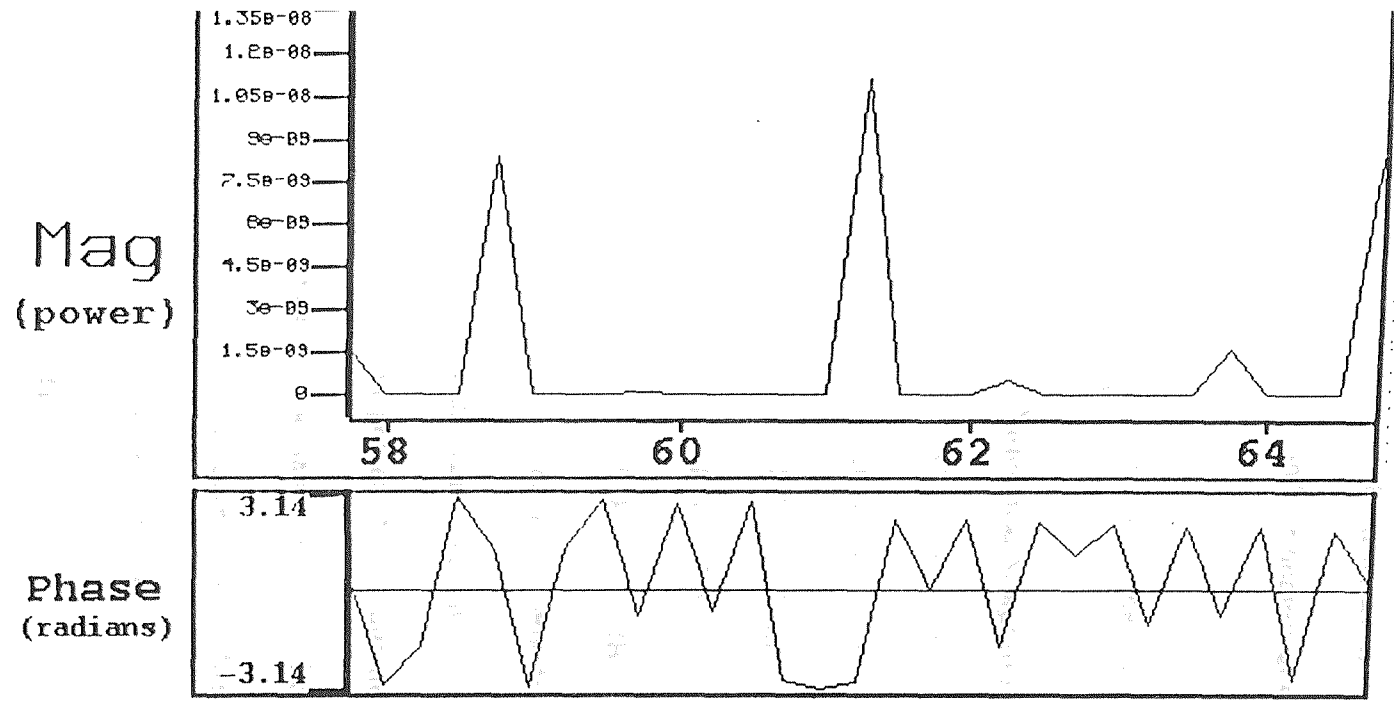


Figure 4.10 FFT at node 3 ( $\mu = 0.30$ , seed# 414881)

## CHAPTER 5

### CONCLUSIONS

The following observations based on the numerical simulations are reported here. The numerical simulation for Channel 3 (61.25 MHz) closely follows the curve of the Saleh limit. The numerical distortion of directly modulated (single-clipping) lightwave CATV falls within 1-2 dB of Saleh's theory for values of  $\mu$  between 0.30 ~ 0.95. Table 5.1 shows the difference between Saleh's prediction and the numerical simulation.

**Table 5.1** Difference between Saleh's prediction and numerical distortion of directly modulated (single-clipping) lightwave CATV system

$\mu$	<u>Saleh's Prediction</u>	<u>Numerical Simulation</u>	<u>Difference</u>
$\mu=0.30$	NLD= -45.68 dB	NLD= -45.84 dB	0.16 dB
$\mu=0.35$	NLD= -37.79 dB	NLD= -36.52 dB	-1.27 dB
$\mu=0.60$	NLD= -21.68 dB	NLD= -21.72 dB	0.04 dB
$\mu=0.70$	NLD= -19.02 dB	NLD= -19.90 dB	0.88 dB
$\mu=0.95$	NLD= -15.14 dB	NLD= -17.00 dB	1.86 dB

A comparison of the two different optical modulation methods (direct modulated vs. external modulated systems) shows that for the same frequency allocation and the same modulation per channel, the total distortion power (NLD) summed over the complete frequency band is 3 dB higher for external modulation (double-clipping) than for a laser diode (single-clipping). Table 5.2 shows the difference between direct modulated (single-clipping) and external modulated (double-clipping) systems.

**Table 5.2** Difference between directly modulated and externally modulated systems

$\mu$	Externally Modulated	Directly Modulated	Difference
$\mu=0.30$	NLD= -42.96 dB	NLD= -45.84 dB	2.88 dB
$\mu=0.35$	NLD= -32.85 dB	NLD= -36.52 dB	3.67 dB
$\mu=0.60$	NLD= -17.96 dB	NLD= -21.72 dB	3.76 dB
$\mu=0.70$	NLD= -15.94 dB	NLD= -19.90 dB	3.96 dB
$\mu=0.95$	NLD= -12.67 dB	NLD= -17.00 dB	4.33 dB

## **APPENDIX A**

### **RANDOM PHASE BLOCK**

#### **A.1 Signal Processing Worksystems (SPW) Random Numbers**

Certain blocks generate random numbers. Each of these blocks uses an internal algorithm to generate its random data. The sequence of data depends on a “noise seed” value, which is used to initialize the random sequence. If the same noise seed value is used in two simulation runs, the block produces the exact same sequence of data. Specifying a different initial value of the noise seed each time you simulate a system ensures that a particular random number sequence is not repeated.

Each block in the system changes the noise seed value so that the next block in the system starts with a different noise seed. This ensures that there is no correlation between the data from different block generators.

#### **A.2 SPW Custom-Coded Random-Phase Block**

In the design there are 42 random phase blocks connected to the 42 function generator blocks. All the random phase blocks used in the design are controlled by seed # from the simulator run control window. If a seed # X was applied in the simulator run control window the “spb-noiseseed” function will guarantee that all random phase blocks in that run will have different random phase numbers. Different selection for seed # every run gives a different set of random phase.

Two additional steps were performed to ensure that random phase output was selected in every run. From the user-written program, the C program, “spb\_noiseseed” is

incremented every time the program is executed, by adding a large constant to “spb\_noiseseed” ( $\text{spb\_noiseseed} = \text{spb\_noiseseed} + \{\text{large odd number}\}$ ). By creating 13 different random phase blocks in the design, named RANDOM-PHASE-1; RANDOM-PHASE-2; RANDOM-PHASE-3; etc..., every one is used 3 times except the last one RANDOM-PHASE-13 which is used 5 times in the design. All 13 used a different C program, example, RANDOM-PHASE-1 used C random function “drand48( )” to execute the function of the block, and RANDOM-PHASE-2 used C random function “rand( )”. All 13 used different odd, large numbers to increment the “spb\_noiseseed”. RANDOM-PHASE-1 block is copied 3 times in the design and it is connected to the first 3 Function Generators (55.25 ; 67.25 ; 73.25 MHz), RANDOM-PHASE-2 block is also copied 3 times in the design and it is connected to the next 3 Function Generators (79.25 ; 85.25 ; 91.25 MHz) etc.. .RANDOM-PHASE-13 is the only block used 5 times in the design, and it is connected to the last 5 Function Generators.

The C program for the RANDOM-PHASE blocks included these lines so that the program only executed 3 times, and it would not vary with time (t) during the operation of the simulation:

```
static int counter = 0;

static double temp = [3];

if ( counter < 3 ) {

“ output random-phase function “

temp[ counter ] = spb_output-> z;
```



```

counter++;

}else {

spb_output-> z = temp[ counter % 3 ];

counter++;

}

```

The last random phase block RANDOM-PHASE-13 was used 5 times in the design, and included different lines, so the output of the block would be executed 5 times only:

```

static double temp = [5];

if ( counter < 5 ) {

temp[ counter ] = spb_output-> z;

counter++;

spb_output-> z = temp[ counter % 5 ];

counter++;

```

The C program for RANDOM-PHASE-1 and RANDOM-PHASE-13 are included in this appendix. The output of RANDOM-PHASE-1 can be seen in figure A.1 and A.2 with seed # 87 and seed # 88777011, and the output of RANDOM-PHASE-13 can be seen in figure A.3 and A.4 with seed # 87 and seed # 88777011 ( the values for the phase are constant for the whole operation ). Table A.1 lists all random phases for one run with seed # 87, and table A.2 lists all random phases for a second run with seed # 88777011. From both tables we can see that each run generates different random phase numbers .

Program 1 For RANDOM-PHASE-1 :

```

#include "spw_platform.h"
#ifdef UNIX
#include "caedata/alnadilib/randomphase/blockcode/randomphaseu.c"
#else
#ifdef VAX_VMS
#include "[caedata.alnadilib.randomphase.blockcode]randomphaseu.c"
#endif
#endif
static char *REVISION = "2.50";

/*
 *
 *      Block Function: randomphase
 *      Library: alnadilib
 *      Date: Mon May 22 19:40:42 1995
 *
 */
In_randomphase_alnadilib (spb_parm, spb_output, spb_state)
STRUCT Pt_randomphase_alnadilib *spb_parm;
STRUCT Ot_randomphase_alnadilib *spb_output;
STRUCT St_randomphase_alnadilib *spb_state;
{
    return (SYS_OK);
}
Ro_randomphase_alnadilib (spb_parm, spb_output, spb_state)
STRUCT Pt_randomphase_alnadilib *spb_parm;
STRUCT Ot_randomphase_alnadilib *spb_output;
STRUCT St_randomphase_alnadilib *spb_state;
{
    int i;
    static int counter=0;
    static double temp[3];
    spb_noiseseed = spb_noiseseed + 11111;
    srand(spb_noiseseed );

    if (counter < 3){
        spb_output->z = 6.2832 *(((rand()%100000)/100000.0) - 0.5) ;
        temp[counter] = spb_output->z;
        counter++;
    } else{
        spb_output->z = temp[counter % 3];
        counter++;
    }
    return (SYS_OK);
}
Te_randomphase_alnadilib (spb_parm, spb_output, spb_state)
STRUCT Pt_randomphase_alnadilib *spb_parm;
STRUCT Ot_randomphase_alnadilib *spb_output;
STRUCT St_randomphase_alnadilib *spb_state;
{
    return (SYS_OK);
}

```

```

#include "FBCDEFS.h"
/*
 *
 *      Block Function: randomphase
 *      Library: alnadilib
 *      Date: Mon May 22 19:40:42 1995
 *
 */
/*
 *
 *          State Structure (User Defined)
 */
STRUCT St_randomphase_alnadilib {
    int instance;
    double z;
};

/*
 *
 *          Parameter Structure, Simulator Defined
 */
STRUCT Pt_randomphase_alnadilib {
    char * after_errs;
    double initial_value;
    long no_blk_errs;
    double overflow_val;
};

/*
 *
 *          Output Structure, Simulator Defined
 */
STRUCT Ot_randomphase_alnadilib {
    double z;
};

/*****
 */
/*
 *      The following #defines may be used to shorten
 *      references to members of the above structures.
 */
/*****
 */
#define P_after_errs (spb_parm->after_errs)
#define P_initial_value (spb_parm->initial_value)
#define P_no_blk_errs (spb_parm->no_blk_errs)
#define P_overflow_val (spb_parm->overflow_val)
#define O_z (spb_output->z)

```

Program 2 For RANDOM-PHASE-13 :

```

#include "spw_platform.h"
#ifdef UNIX
#include "caedata/alnadilib/randomphase13/blockcode/randomphase13u.c"
#else
#ifdef VAX_VMS
#include "[caedata.alnadilib.randomphase13.blockcode]randomphase13u.c"
#endif VAX_VMS
#endif UNIX
static char *REVISION = "2.50";

/*
 *
 *   Block Function: randomphase13
 *   Library: alnadilib
 *   Date: Mon Jun 12 11:05:46 1995
 *
 */

In_randomphase13_alnadilib (spb_parm, spb_output, spb_state)
STRUCT Pt_randomphase13_alnadilib *spb_parm;
STRUCT Ot_randomphase13_alnadilib *spb_output;
STRUCT St_randomphase13_alnadilib *spb_state;
{

    return (SYS_OK);
}

Ro_randomphase13_alnadilib (spb_parm, spb_output, spb_state)
STRUCT Pt_randomphase13_alnadilib *spb_parm;
STRUCT Ot_randomphase13_alnadilib *spb_output;
STRUCT St_randomphase13_alnadilib *spb_state;
{

    int i;
    double drand48();
    static int counter=0;
    static double temp[5];
    srand48(spb_noiseseed );
    spb_noiseseed = spb_noiseseed + 131313;

    if (counter < 5){
        spb_output->z = 6.2832* ( (drand48()) -0.50) ;
        temp[counter] = spb_output->z;
        counter++;
    } else{
        spb_output->z = temp[counter % 5];
        counter++;
    }

    return (SYS_OK);
}

Te_randomphase13_alnadilib (spb_parm, spb_output, spb_state)
STRUCT Pt_randomphase13_alnadilib *spb_parm;
STRUCT Ot_randomphase13_alnadilib *spb_output;
STRUCT St_randomphase13_alnadilib *spb_state;
{

    return (SYS_OK);
}

```

```

#include "FBCDEFS.h"

/*
 *
 *   Block Function: randomphase13
 *   Library: alnadilib
 *   Date: Mon Jun 12 11:05:46 1995
 *
 */

/*
 *
 *           State Structure (User Defined)
 *
 */
STRUCT St_randomphase13_alnadilib {
    int instance;
    double z;
};

/*
 *
 *           Parameter Structure, Simulator Defined
 *
 */
STRUCT Pt_randomphase13_alnadilib {
    char * after_errs;
    double initial_value;
    long no_blk_errs;
    double overflow_val;
};

/*
 *
 *           Output Structure, Simulator Defined
 *
 */
STRUCT Ot_randomphase13_alnadilib {
    double z;
};

/*****
 */
/*
 *   The following #defines may be used to shorten
 *   references to members of the above structures.
 */
/*****
 */
#define P_after_errs (spb_parm->after_errs)
#define P_initial_value (spb_parm->initial_value)
#define P_no_blk_errs (spb_parm->no_blk_errs)
#define P_overflow_val (spb_parm->overflow_val)
#define O_z (spb_output->z)

```

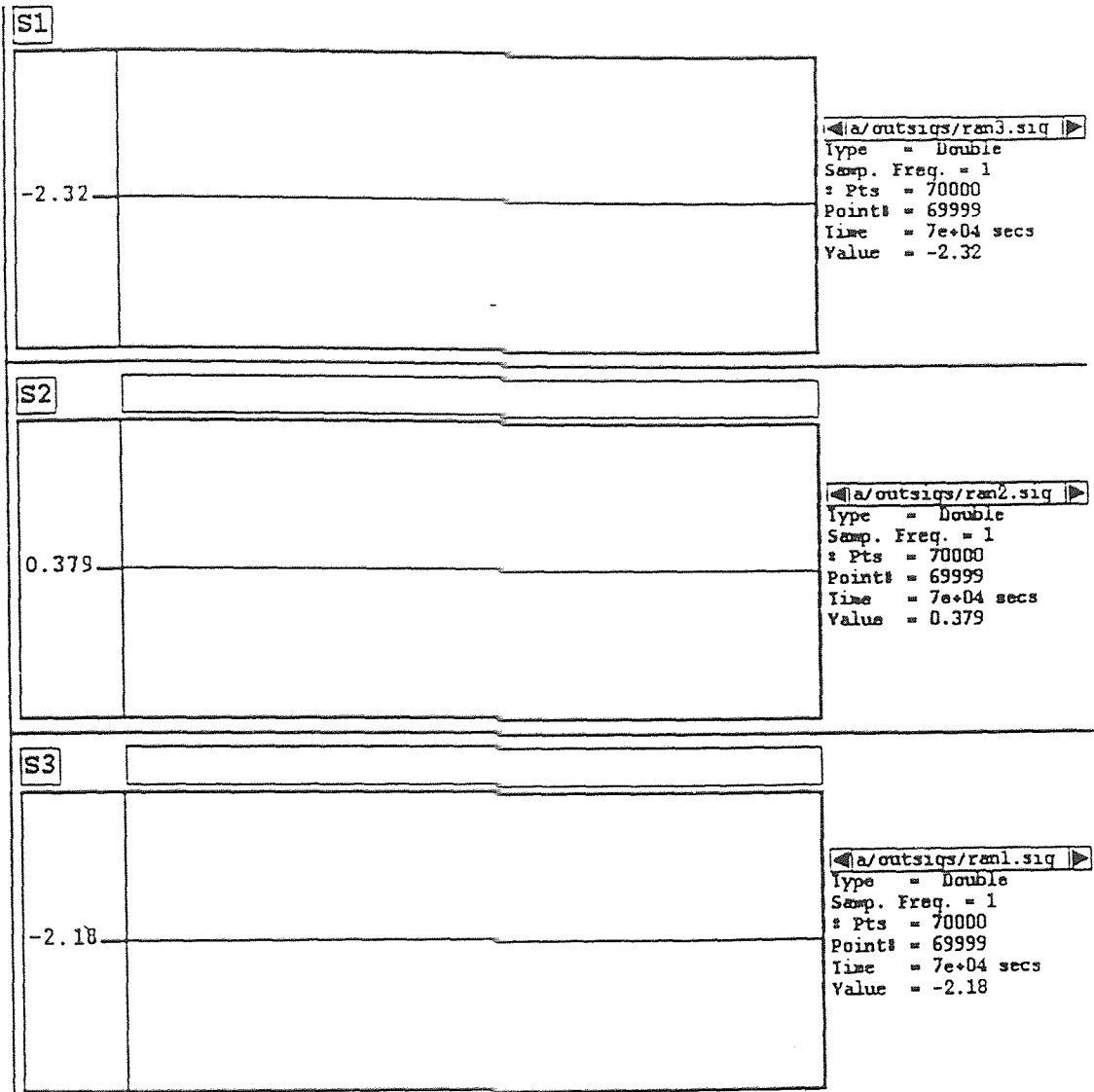


Figure A.1 Out of block Random-Phase-1 when seed# = 87

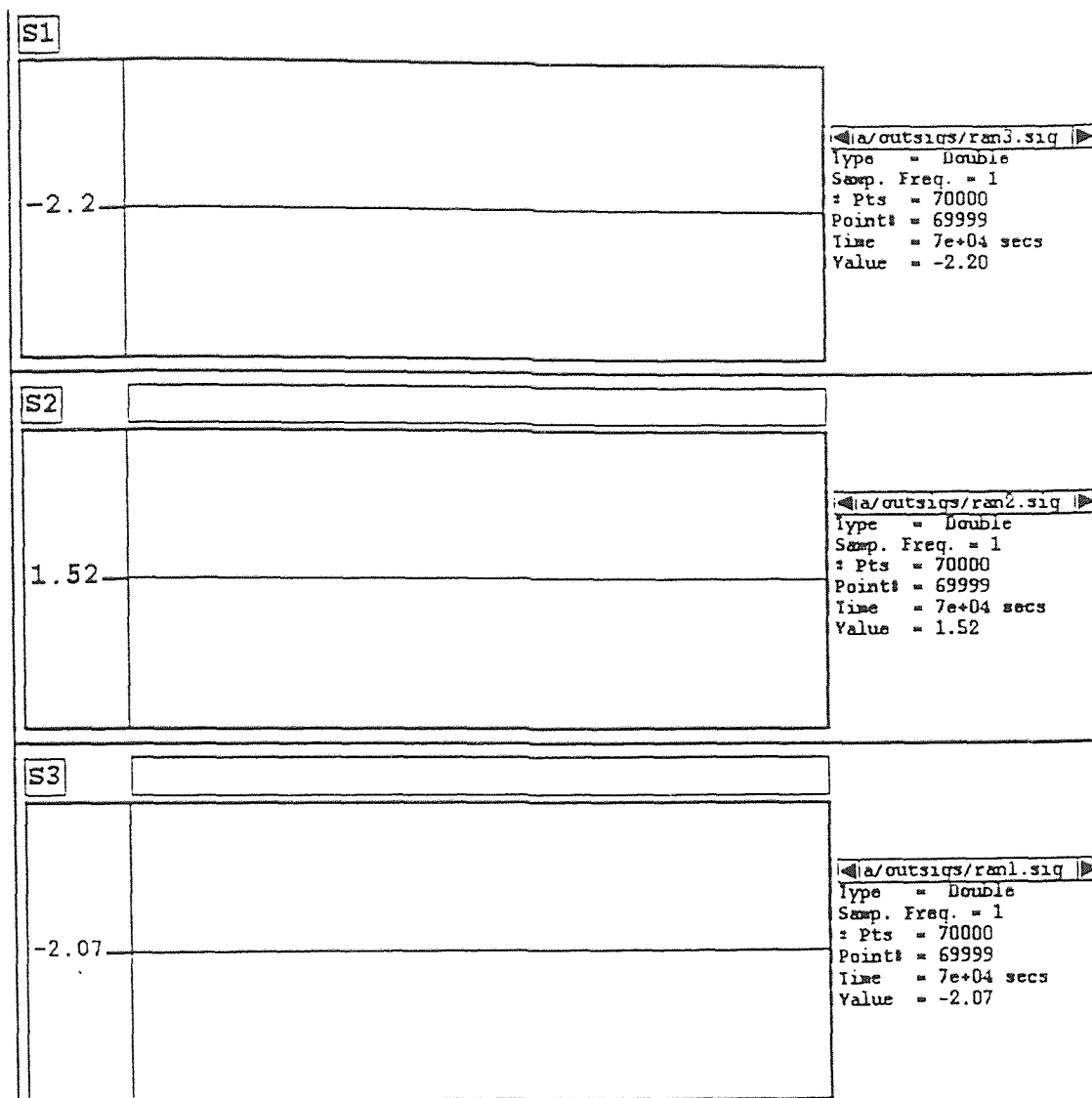


Figure A.2 Out of block Random-Phase-1 when seed# = 88777011

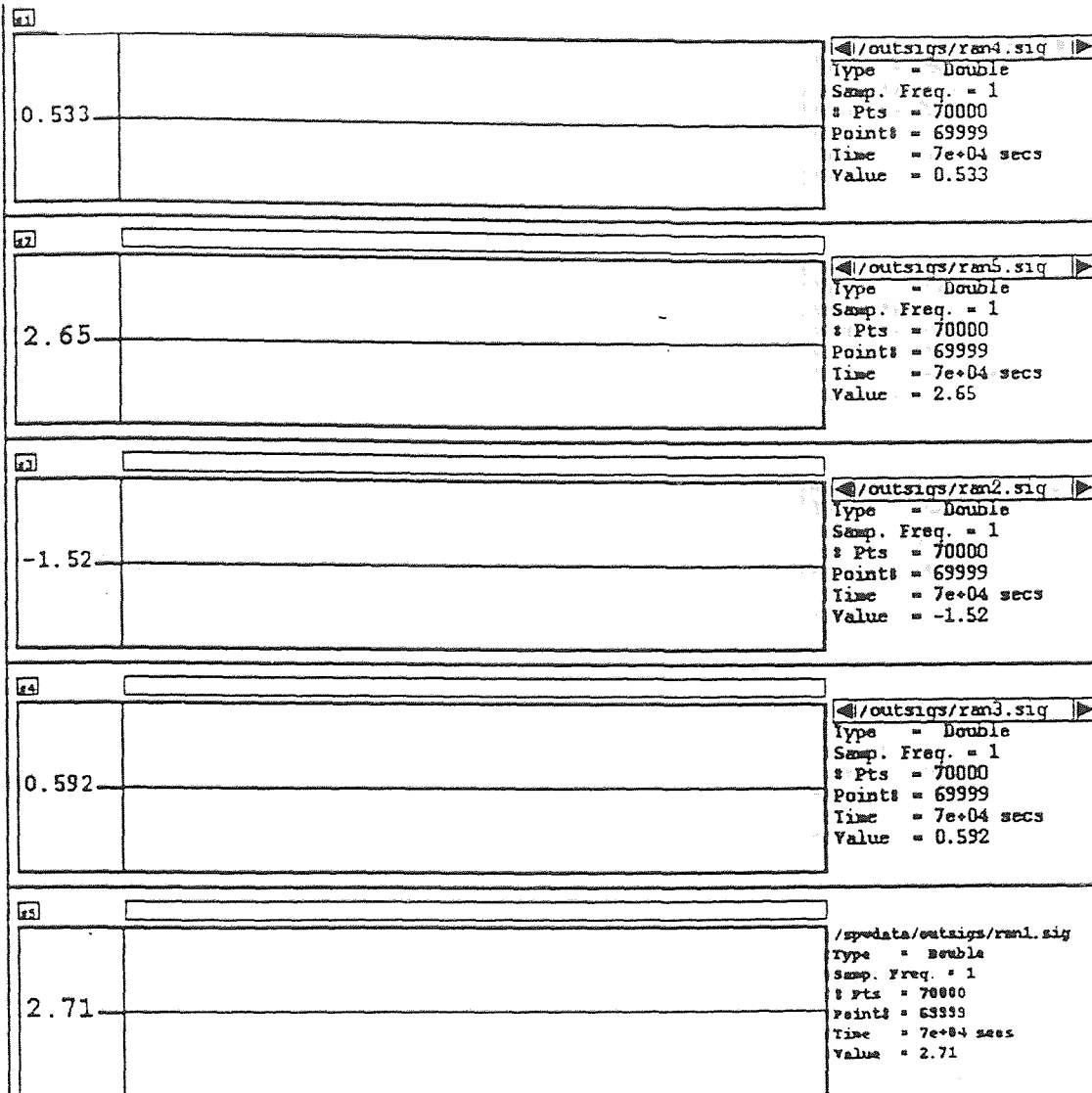


Figure A.3 Out of block Random-Phase-13 when seed# = 87



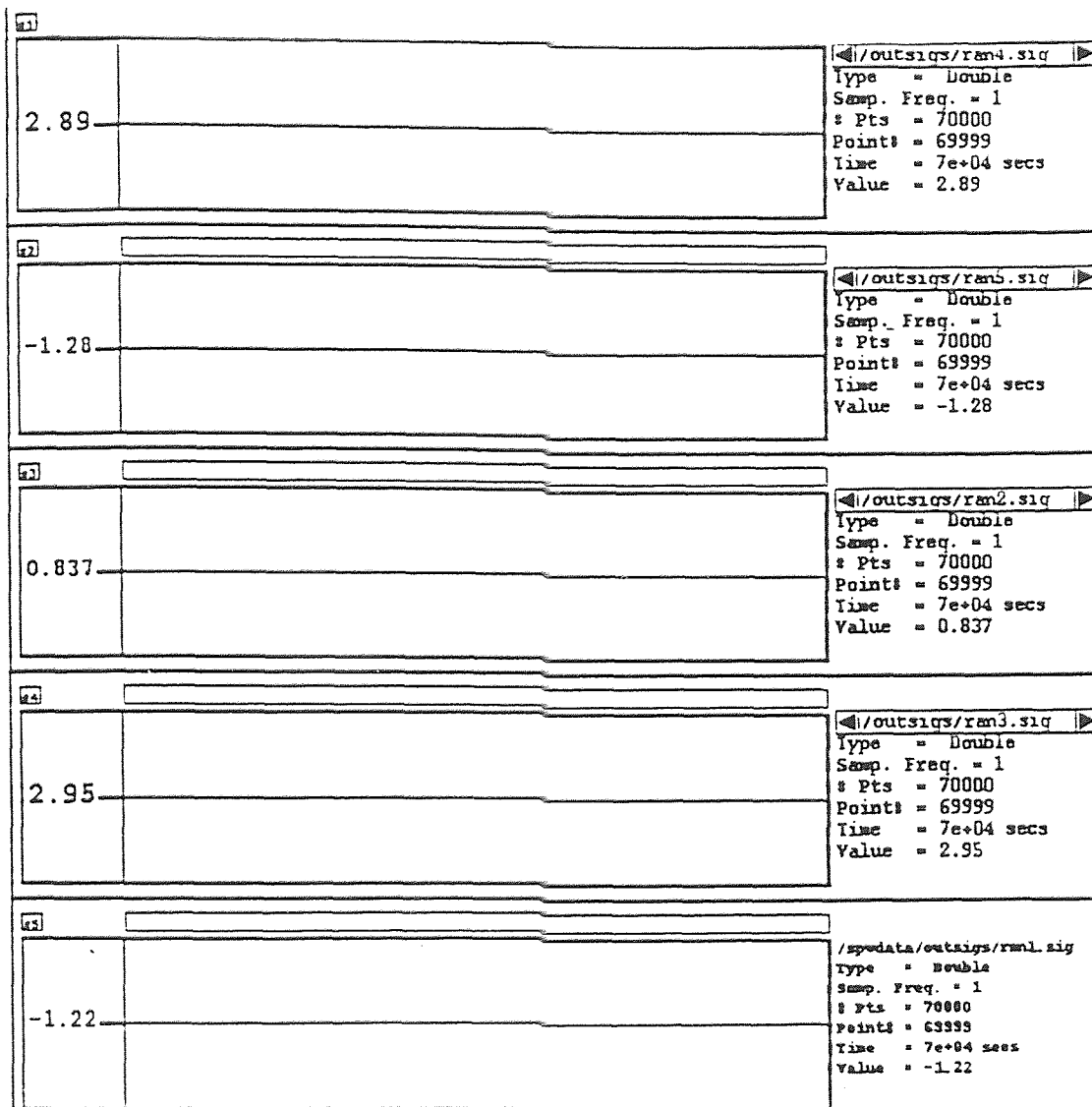


Figure A.4 Out of block Random-Phase-13 when seed# = 88777011

**Table A.1** List of all random phase numbers with seed = 87

<u>output of RANDOM-PHASE-1</u>	-2.32	<u>output of RANDOM-PHASE-8</u>	0.139
<u>output of RANDOM-PHASE-1</u>	0.379	<u>output of RANDOM-PHASE-8</u>	-1.72
<u>output of RANDOM-PHASE-1</u>	-2.18	<u>output of RANDOM-PHASE-8</u>	2.71
<u>output of RANDOM-PHASE-2</u>	0.112	<u>output of RANDOM-PHASE-9</u>	-1.50
<u>output of RANDOM-PHASE-2</u>	0.245	<u>output of RANDOM-PHASE-9</u>	-2.54
<u>output of RANDOM-PHASE-2</u>	0.379	<u>output of RANDOM-PHASE-9</u>	2.71
<u>output of RANDOM-PHASE-3</u>	2.14	<u>output of RANDOM-PHASE-10</u>	-0.54
<u>output of RANDOM-PHASE-3</u>	-1.82	<u>output of RANDOM-PHASE-10</u>	1.08
<u>output of RANDOM-PHASE-3</u>	0.512	<u>output of RANDOM-PHASE-10</u>	2.71
<u>output of RANDOM-PHASE-4</u>	1.17	<u>output of RANDOM-PHASE-11</u>	0.604
<u>output of RANDOM-PHASE-4</u>	0.326	<u>output of RANDOM-PHASE-11</u>	1.66
<u>output of RANDOM-PHASE-4</u>	0.512	<u>output of RANDOM-PHASE-11</u>	2.71
<u>output of RANDOM-PHASE-5</u>	-2.07	<u>output of RANDOM-PHASE-12</u>	-1.20
<u>output of RANDOM-PHASE-5</u>	1.85	<u>output of RANDOM-PHASE-12</u>	0.754
<u>output of RANDOM-PHASE-5</u>	0.512	<u>output of RANDOM-PHASE-12</u>	2.71
<u>output of RANDOM-PHASE-6</u>	-1.13	<u>output of RANDOM-PHASE-13</u>	0.533
<u>output of RANDOM-PHASE-6</u>	-2.94	<u>output of RANDOM-PHASE-13</u>	2.65
<u>output of RANDOM-PHASE-6</u>	0.512	<u>output of RANDOM-PHASE-13</u>	-1.52
<u>output of RANDOM-PHASE-7</u>	-0.872	<u>output of RANDOM-PHASE-13</u>	0.596
<u>output of RANDOM-PHASE-7</u>	0.917	<u>output of RANDOM-PHASE-13</u>	2.71
<u>output of RANDOM-PHASE-7</u>	2.71		

**Table A.2** List of all random phase numbers with seed = 88777011:

<u>output of RANDOM-PHASE-1</u>	-2.2	<u>output of RANDOM-PHASE-8</u>	2.50
<u>output of RANDOM-PHASE-1</u>	1.52	<u>output of RANDOM-PHASE-8</u>	0.64
<u>output of RANDOM-PHASE-1</u>	-2.07	<u>output of RANDOM-PHASE-8</u>	-1.22
<u>output of RANDOM-PHASE-2</u>	1.26	<u>output of RANDOM-PHASE-9</u>	0.86
<u>output of RANDOM-PHASE-2</u>	1.39	<u>output of RANDOM-PHASE-9</u>	-0.18
<u>output of RANDOM-PHASE-2</u>	1.52	<u>output of RANDOM-PHASE-9</u>	1.02
<u>output of RANDOM-PHASE-3</u>	-3.00	<u>output of RANDOM-PHASE-10</u>	1.81
<u>output of RANDOM-PHASE-3</u>	-0.67	<u>output of RANDOM-PHASE-10</u>	-2.84
<u>output of RANDOM-PHASE-3</u>	1.66	<u>output of RANDOM-PHASE-10</u>	-1.12
<u>output of RANDOM-PHASE-4</u>	1.28	<u>output of RANDOM-PHASE-11</u>	2.96
<u>output of RANDOM-PHASE-4</u>	1.47	<u>output of RANDOM-PHASE-11</u>	-2.27
<u>output of RANDOM-PHASE-4</u>	1.66	<u>output of RANDOM-PHASE-11</u>	-1.22
<u>output of RANDOM-PHASE-5</u>	-1.95	<u>output of RANDOM-PHASE-12</u>	1.16
<u>output of RANDOM-PHASE-5</u>	2.99	<u>output of RANDOM-PHASE-12</u>	3.11
<u>output of RANDOM-PHASE-5</u>	1.66	<u>output of RANDOM-PHASE-12</u>	-1.32
<u>output of RANDOM-PHASE-6</u>	0.01	<u>output of RANDOM-PHASE-13</u>	2.98
<u>output of RANDOM-PHASE-6</u>	-2.82	<u>output of RANDOM-PHASE-13</u>	-1.28
<u>output of RANDOM-PHASE-6</u>	1.66	<u>output of RANDOM-PHASE-13</u>	0.84
<u>output of RANDOM-PHASE-7</u>	1.49	<u>output of RANDOM-PHASE-13</u>	2.95
<u>output of RANDOM-PHASE-7</u>	-3.01	<u>output of RANDOM-PHASE-13</u>	-1.22
<u>output of RANDOM-PHASE-7</u>	-1.22		

## APPENDIX B

### LIST OF POWER FOR CHANNEL 3

#### B.1 The Summed Power for Channel 3 for Direct Modulation

**Table B.1** List of the power for channel 3 ( $\mu = 0.30$ ) for all 33 runs

seed# 87	<u>0.66E-9</u>	seed# 356711	<u>0.00</u>
seed# 8790	<u>30 E-9</u>	seed# 3567011	<u>0.00</u>
seed# 9282	<u>10.6 E-9</u>	seed# 3777011	<u>46.0E-9</u>
seed# 19282	<u>0.00</u>	seed# 8893711	<u>10.0E-9</u>
seed# 1488	<u>2.3 E-9</u>	seed# 88777011	<u>47E-9</u>
seed# 414881	<u>10 E-9</u>	seed# 3711	<u>1.0E-9</u>
seed# 414	<u>79 E-9</u>	seed# 87909	<u>0.00</u>
seed# 393931	<u>127 E-9</u>	seed# 202113	<u>33 E-9</u>
seed# 414882	<u>22 E-9</u>	seed# 3	<u>0.00</u>
seed# 49882	<u>40 E-9</u>	seed# 11	<u>0.00</u>
seed# 414883	<u>31 E-9</u>	seed# 10	<u>130 E-9</u>
seed# 414884	<u>130.0E-9</u>	seed# 40	<u>26 E-9</u>
seed# 414894	<u>0.00</u>	seed# 3566	<u>0.00</u>
seed# 414893	<u>0.00</u>	seed# 7282	<u>28.3 E-9</u>
seed# 614893	<u>0.00</u>	seed# 30	<u>0.00</u>
seed# 614093	<u>3.00E-9</u>		
seed# 71493	<u>9.00E-9</u>		
seed# 3567	<u>104.0E-9</u>		

**Table B.2** List of the power for channel 3 ( $\mu = 0.35$ ) for all 33 runs

seed# 87	<u>1.50E-7</u>	seed# 3567	<u>10.30E-7</u>
seed# 8790	<u>5.53E-7</u>	seed# 356711	<u>0.60E-7</u>
seed# 9282	<u>3.50E-7</u>	seed# 3567011	<u>0.10E-7</u>
seed# 19282	<u>0.50E-7</u>	seed# 3777011	<u>6.60E-7</u>
seed# 1488	<u>2.20E-7</u>	seed# 8893711	<u>3.40E-7</u>
seed# 414881	<u>3.50E-7</u>	seed# 88777011	<u>7.30E-7</u>
seed# 414	<u>7.80E-7</u>	seed# 3711	<u>1.60E-7</u>
seed# 393931	<u>1.70E-7</u>	seed# 87909	<u>0.20E-7</u>
seed# 414882	<u>4.60E-7</u>	seed# 202113	<u>5.70E-7</u>
seed# 49882	<u>6.30E-7</u>	seed# 3	<u>0.46 E-7</u>
seed# 414883	<u>5.50E-7</u>	seed# 30	<u>0.00</u>
seed# 414884	<u>1.70E-7</u>	seed# 11	<u>0.43 E-7</u>
seed# 414894	<u>1.00E-7</u>	seed# 40	<u>5.00 E-7</u>
seed# 414893	<u>0.20E-7</u>	seed# 0	<u>1.20 E-7</u>
seed# 614893	<u>0.50E-7</u>	seed# 2123	<u>2.80 E-7</u>
seed# 614093	<u>2.30E-7</u>	seed# 2	<u>9.90 E-7</u>
seed# 71493	<u>3.30E-7</u>		

**Table B.3** List of the power for channel 3 ( $\mu = 0.60$ ) for all 33 runs

seed# 87	<u>2.70E-5</u>	seed# 3567	<u>2.70E-5</u>
seed# 33	<u>3.30E-5</u>	seed# 356711	<u>2.70E-5</u>
seed# 9282	<u>2.70E-5</u>	seed# 3567011	<u>2.70E-5</u>
seed# 19282	<u>4.00E-5</u>	seed# 3777011	<u>3.20E-5</u>
seed# 3030	<u>3.40E-5</u>	seed# 8893711	<u>3.80E-5</u>
seed# 8091	<u>2.90E-5</u>	seed# 88777011	<u>1.40E-5</u>
seed# 1	<u>3.4E-5</u>	seed# 3711	<u>3.30E-5</u>
seed# 393931	<u>2.70E-5</u>	seed# 87909	<u>3.30E-5</u>
seed# 414882	<u>2.30E-5</u>	seed# 202113	<u>3.00E-5</u>
seed# 49882	<u>3.30E-5</u>	seed# 85	<u>2.60E-5</u>
seed# 393933	<u>1.9E-5</u>	seed# 90801	<u>2.30E-5</u>
seed# 414884	<u>2.40E-5</u>	seed# 83	<u>2.60E-5</u>
seed# 414894	<u>2.50E-5</u>	seed# 86	<u>2.00E-5</u>
seed# 414893	<u>2.40E-5</u>	seed# 88	<u>2.80E-5</u>
seed# 614893	<u>4.30E-5</u>	seed# 89	<u>3.20E-5</u>
seed# 2	<u>3.6E-5</u>	seed# 90	<u>3.20E-5</u>
seed# 71493	<u>2.60E-5</u>		

**Table B.4** List of the power for channel 3 ( $\mu = 0.70$ ) for all 33 runs

seed# 87	<u>4.30E-5</u>	seed# 8091	<u>7.70E-5</u>
seed# 33	<u>7.00E-5</u>	seed# 356711	<u>6.70E-5</u>
seed# 9282	<u>6.00E-5</u>	seed# 3567011	<u>4.60E-5</u>
seed# 19282	<u>7.00E-5</u>	seed# 3777011	<u>2.20E-5</u>
seed# 3030	<u>7.70E-5</u>	seed# 8893711	<u>6.00E-5</u>
seed# 1011	<u>7.50E-5</u>	seed# 88777011	<u>3.00E-5</u>
seed# 414881	<u>6.60E-5</u>	seed# 3711	<u>7.70E-5</u>
seed# 393931	<u>4.70E-5</u>	seed# 87909	<u>6.60E-5</u>
seed# 414882	<u>7.00E-5</u>	seed# 202113	<u>5.10E-5</u>
seed# 49882	<u>6.00E-5</u>	seed# 85	<u>5.30E-5</u>
seed# 414884	<u>4.60E-5</u>	seed# 90801	<u>4.90E-5</u>
seed# 5657	<u>6.40E-5</u>	seed# 83	<u>5.10E-5</u>
seed# 414894	<u>6.00E-5</u>	seed# 1	<u>8.00E-5</u>
seed# 414893	<u>4.00E-5</u>	seed# 88	<u>7.00E-5</u>
seed# 614893	<u>8.30E-5</u>	seed# 89	<u>5.10E-5</u>
seed# 33	<u>7.00E-5</u>	seed# 90	<u>6.00E-5</u>
seed# 71493	<u>6.00E-5</u>		

**Table B.5** List of the power for channel 3 ( $\mu = 0.95$ ) for all 33 runs

seed# 86	<u>15.0E-5</u>	seed# 3567	<u>20.0E-5</u>
seed# 8790	<u>22.0E-5</u>	seed# 356711	<u>30.0E-5</u>
seed# 9282	<u>15.0E-5</u>	seed# 11101111	<u>19.0E-5</u>
seed# 3	<u>31.0E-5</u>	seed# 11111111	<u>28.0E-5</u>
seed# 1488	<u>29.0E-5</u>	seed# 85	<u>14.0E-5</u>
seed# 414881	<u>19.0E-5</u>	seed# 83	<u>15.0E-5</u>
seed# 414	<u>19.0E-5</u>	seed# 3711	<u>28.0E-5</u>
seed# 90	<u>15.0E-5</u>	seed# 87909	<u>20.0E-5</u>
seed# 414882	<u>18.0E-5</u>	seed# 202113	<u>14.0E-5</u>
seed# 49882	<u>16.0E-5</u>	seed# 1011	<u>16.0E-5</u>
seed# 414883	<u>30.0E-5</u>	seed# 1111	<u>25.0E-5</u>
seed# 88	<u>32.0E-5</u>	seed# 1001	<u>18.0E-5</u>
seed# 414894	<u>28.0E-5</u>	seed# 4444	<u>27.0E-5</u>
seed# 1	<u>24.0E-5</u>	seed# 5657	<u>18.0E-5</u>
seed# 614893	<u>15.0E-5</u>	seed# 1010101	<u>19.0E-5</u>
seed# 614093	<u>26.0E-5</u>	seed# 10101011	<u>27.0E-5</u>
seed# 71493	<u>15.0E-5</u>		



## B.2 The Summed Power for Channel 3 for External Modulation

**Table B.6** List of the power for channel 3 ( $\mu = 0.30$ ) for all 33 runs

seed# 87	<u>0.15E-8</u>	seed# 3567	<u>20.00E-8</u>
seed# 8790	<u>6.00E-8</u>	seed# 356711	<u>0.00 E-8</u>
seed# 9282	<u>2.20E-8</u>	seed# 3567011	<u>0.00 E-8</u>
seed# 19282	<u>0.00E-8</u>	seed# 3777011	<u>9.00E-8</u>
seed# 1488	<u>0.50E-8</u>	seed# 8893711	<u>2.00E-8</u>
seed# 414881	<u>2.00E-8</u>	seed# 88777011	<u>9.00E-8</u>
seed# 414	<u>12.00E-8</u>	seed# 3711	<u>0.20E-8</u>
seed# 393931	<u>26.00E-8</u>	seed# 87909	<u>0.00 E-8</u>
seed# 414882	<u>4.30E-8</u>	seed# 202113	<u>6.50 E-8</u>
seed# 49882	<u>8.00E-8</u>	seed# 7282	<u>5.60E-8</u>
seed# 414883	<u>6.40E-8</u>	seed# 3	<u>0.00 E-8</u>
seed# 414884	<u>25.00E-8</u>	seed# 30	<u>0.00 E-8</u>
seed# 414894	<u>0.00E-8</u>	seed# 11	<u>0.00 E-8</u>
seed# 414893	<u>0.00E-8</u>	seed# 10	<u>26.0E-8</u>
seed# 614893	<u>0.00E-8</u>	seed# 40	<u>5.10E-8</u>
seed# 614093	<u>0.70E-8</u>	seed# 3566	<u>0.00 E-8</u>
seed# 71493	<u>2.00E-8</u>		

**Table B.7** List of the power for channel 3 ( $\mu = 0.35$ ) for all 33 runs

seed# 87	<u>3.00E-7</u>	seed# 3567	<u>20.00E-7</u>
seed# 8790	<u>11.00E-7</u>	seed# 356711	<u>1.40E-7</u>
seed# 9282	<u>7.25E-7</u>	seed# 3567011	<u>0.20E-7</u>
seed# 19282	<u>0.70E-7</u>	seed# 3777011	<u>13.00E-7</u>
seed# 1488	<u>4.20E-7</u>	seed# 8893711	<u>6.80E-7</u>
seed# 414881	<u>7.00E-7</u>	seed# 88777011	<u>14.00E-7</u>
seed# 414	<u>15.00E-7</u>	seed# 3711	<u>3.30E-7</u>
seed# 393931	<u>22.00E-7</u>	seed# 87909	<u>0.60E-7</u>
seed# 414882	<u>9.10E-7</u>	seed# 202113	<u>11.20E-7</u>
seed# 49882	<u>12.10E-7</u>	seed# 2123	<u>5.80E-7</u>
seed# 414883	<u>11.00E-7</u>	seed# 2	<u>20.00E-7</u>
seed# 414884	<u>22.00E-7</u>	seed# 3	<u>1.00E-7</u>
seed# 414894	<u>2.00E-7</u>	seed# 30	<u>0.00E-7</u>
seed# 414893	<u>0.70E-7</u>	seed# 11	<u>0.85E-7</u>
seed# 614893	<u>1.00E-7</u>	seed# 40	<u>10.00E-7</u>
seed# 614093	<u>4.60E-7</u>	seed# 0	<u>2.40E-7</u>
seed# 71493	<u>6.80E-7</u>		

**Table B.8** List of the power for channel 3 ( $\mu = 0.60$ ) for all 33 runs

seed# 87	<u>4.70E-5</u>	seed# 3567	<u>10.00E-5</u>
seed# 33	<u>6.20E-5</u>	seed# 356711	<u>8.00E-5</u>
seed# 9282	<u>9.00E-5</u>	seed# 3567011	<u>6.00E-5</u>
seed# 19282	<u>5.60E-5</u>	seed# 3777011	<u>4.30E-5</u>
seed# 3030	<u>5.40E-5</u>	seed# 8893711	<u>8.50E-5</u>
seed# 8091	<u>5.10E-5</u>	seed# 88777011	<u>5.20E-5</u>
seed# 1	<u>12.70E-5</u>	seed# 3711	<u>5.60E-5</u>
seed# 393931	<u>7.60E-5</u>	seed# 87909	<u>6.10E-5</u>
seed# 414882	<u>6.20E-5</u>	seed# 202113	<u>6.20E-5</u>
seed# 49882	<u>7.50E-5</u>	seed# 85	<u>7.90E-5</u>
seed# 393933	<u>6.10E-5</u>	seed# 90801	<u>6.20E-5</u>
seed# 414884	<u>8.00E-5</u>	seed# 83	<u>9.70E-5</u>
seed# 414894	<u>4.60E-5</u>	seed# 86	<u>5.30E-5</u>
seed# 414893	<u>5.00E-5</u>	seed# 88	<u>4.30E-5</u>
seed# 614893	<u>9.30E-5</u>	seed# 89	<u>8.10E-5</u>
seed# 2	<u>9.50E-5</u>	seed# 90	<u>3.40E-5</u>
seed# 71493	<u>9.00E-5</u>		

**Table B.9** List of the power for channel 3 ( $\mu = 0.70$ ) for all 33 runs

seed# 87	<u>9.50E-5</u>	seed# 8091	<u>12.00E-5</u>
seed# 33	<u>12.20E-5</u>	seed# 356711	<u>17.20E-5</u>
seed# 9282	<u>21.00E-5</u>	seed# 3567011	<u>13.00E-5</u>
seed# 19282	<u>13.70E-5</u>	seed# 3777011	<u>8.00E-5</u>
seed# 3030	<u>11.00E-5</u>	seed# 8893711	<u>16.50E-5</u>
seed# 1011	<u>14.20E-5</u>	seed# 88777011	<u>10.80E-5</u>
seed# 414881	<u>21.00E-5</u>	seed# 3711	<u>11.00E-5</u>
seed# 393931	<u>15.40E-5</u>	seed# 87909	<u>13.50E-5</u>
seed# 414882	<u>12.30E-5</u>	seed# 202113	<u>12.70E-5</u>
seed# 49882	<u>18.00E-5</u>	seed# 85	<u>17.90E-5</u>
seed# 414884	<u>16.00E-5</u>	seed# 90801	<u>15.20E-5</u>
seed# 5657	<u>25.00E-5</u>	seed# 83	<u>18.70E-5</u>
seed# 414894	<u>9.70E-5</u>	seed# 1	<u>32.00E-5</u>
seed# 414893	<u>10.70E-5</u>	seed# 88	<u>9.00E-5</u>
seed# 614893	<u>18.80E-5</u>	seed# 89	<u>14.40E-5</u>
seed# 33	<u>12.20E-5</u>	seed# 90	<u>7.10E-5</u>
seed# 71493	<u>21.00E-5</u>		

**Table B.10** List of the power for channel 3 ( $\mu = 0.95$ ) for all 33 runs

seed# 86	<u>29.00E-5</u>	seed# 3567	<u>55.00E-5</u>
seed# 8790	<u>76.00E-5</u>	seed# 356711	<u>47.00E-5</u>
seed# 9282	<u>52.00E-5</u>	seed# 11101111	<u>59.00E-5</u>
seed# 3	<u>93.00E-5</u>	seed# 11111111	<u>103.00E-5</u>
seed# 1488	<u>105.00E-5</u>	seed# 85	<u>52.00E-5</u>
seed# 414881	<u>60.00E-5</u>	seed# 83	<u>47.00E-5</u>
seed# 414	<u>70.00E-5</u>	seed# 3711	<u>31.00E-5</u>
seed# 90	<u>17.00E-5</u>	seed# 87909	<u>42.00E-5</u>
seed# 414882	<u>23.00E-5</u>	seed# 202113	<u>32.00E-5</u>
seed# 49882	<u>53.00E-5</u>	seed# 1011	<u>47.00E-5</u>
seed# 414883	<u>104.00E-5</u>	seed# 1111	<u>62.00E-5</u>
seed# 88	<u>33.00E-5</u>	seed# 1001	<u>48.00E-5</u>
seed# 414894	<u>31.00E-5</u>	seed# 4444	<u>103.00E-5</u>
seed# 1	<u>87.00E-5</u>	seed# 5657	<u>62.00E-5</u>
seed# 614893	<u>52.00E-5</u>	seed# 1010101	<u>69.00E-5</u>
seed# 614093	<u>94.00E-5</u>	seed# 10101011	<u>27.00E-5</u>
seed# 71493	<u>53.00E-5</u>		

## APPENDIX C

### NON-LINEAR DISTORTION (NLD) CALCULATION

#### C.1 Non-Linear Distortion (NLD) for Direct Modulation

The non-linear distortion (NLD) at a particular value of  $\mu$  was calculated as follows for the numerical simulation:

For  $\mu= 0.3$  and the values of power from Table B.1 the sum of all power in 33 runs is equal to  $919.86E-9$ . The average is then taken for all 33 runs, resulting in a value equal to  $27.87E-9$ , from this average value the NLD(dB) is calculated as follows:

$$\text{NLD} = 10\log\left[\text{average pwr} / \left(\frac{m / N / 2}{2}\right)^2\right] \quad \text{equ C.1}$$

from equation C.1 the NLD for  $\mu= 0.30$  equal to  $-45.84$  dB, as listed in Table 3.2.

For  $\mu= 0.35$  and the values of power from Table B.2 the sum of all power in 33 runs is equal to  $107.22E-7$ . The average is then taken for all 33 runs, resulting in a value equal to  $3.25E-7$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in NLD =  $-36.52$  dB, as listed in Table 3.2.

For  $\mu= 0.60$  and the values of power from Table B.3 the sum of all power in 33 runs is equal to  $95.2E-5$ . The average is then taken for all 33 runs, resulting in a value equal to  $2.885E-5$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in NLD =  $-21.72$  dB, as listed in Table 3.2.

For  $\mu= 0.70$  and the values of power from Table B.4 the sum of all power in 33 runs is equal to  $197.10E-5$ . The average is then taken for all 33 runs, resulting in a value equal

to  $5.97E-5$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in  $NLD = -19.90$  dB, as listed in Table 3.2.

For  $\mu = 0.95$  and the values of power from Table B.5 the sum of all power in 33 runs is equal to  $707E-5$ . The average is then taken for all 33 runs, resulting in a value equal to  $21.42E-5$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in  $NLD = -17.00$  dB, as listed in Table 3.2.

## C.2 Non-Linear Distortion (NLD) for External Modulation

The non-linear distortion (NLD) at a particular value of  $\mu$  was calculated as follows for the numerical simulation:

For  $\mu = 0.30$  and the values of power from Table B.6 the sum of all power in 33 runs is equal to  $178.65E-8$ . The average is then taken for all 33 runs, resulting in a value equal to  $5.41E-8$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in  $NLD = -42.96$  dB, as listed in Table 3.3.

For  $\mu = 0.35$  and the values of power from Table B.7 the sum of all power in 33 runs is equal to  $250E-7$ . The average is then taken for all 33 runs, resulting in a value equal to  $7.57E-7$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in  $NLD = -32.85$  dB, as listed in Table 3.3.

For  $\mu = 0.60$  and the values of power from Table B.8 the sum of all power in 33 runs is equal to  $226.30E-5$ . The average is then taken for all 33 runs, resulting in a value equal to  $6.86E-5$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in  $NLD = -17.96$  dB, as listed in Table 3.3.

For  $\mu = 0.70$  and the values of power from Table B.9 the sum of all power in 33 runs is equal to  $490.70E-5$ . The average is then taken for all 33 runs, resulting in a value equal to  $14.87E-5$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in  $NLD = -15.94$  dB, as listed in Table 3.3.

For  $\mu = 0.95$  and the values of power from Table B.10 the sum of all power in 33 runs is equal to  $1918E-5$ . The average is then taken for all 33 runs, resulting in a value equal to  $58.121E-5$ , from this average value the NLD(dB) is calculated using equation C.1 resulting in  $NLD = -12.67$  dB, as listed in Table 3.3.



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