Weighted-Probability Random Number Generator for PLC Channel Transfer Function Generation

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Abstract. The concept of randomization shows many realistic scenarios and has enormous applications in everyday life. However, existing random number generators have poor adaptability when representing some of the actual occurrences in natural environment, such as in biology, mobile communications, and even electrical behavior. For PLC channel transfer function generation, biased sampling of the channel is more applicable. This paper proposes a weighted-probability method to generate random numbers to emulate the real-world variations of a power line communications channel. Existing PLC channel emulator can mimic the random behavior of the channel, altered by several parameters such as cable length, cable type, presence of loads, and ejecting different noises. However, the scenario of integrating the effect of changing the state of the loads and channel variation due to time is not well represented in the normal random channel generation. The best concept for this scenario is the weighted random number generator (WRNG). This work developed an algorithm in Matlab and VHDL, implemented it in FPGA and integrated it with an existing PLC channel emulator. The emulator is implemented using Kintex-7 FPGA. In this study, ten different weights corresponding to the probability of occurrence of the actual household appliances and eighty transfer functions were used as inputs to the program. The randomness and periodicity of the WRNG are tested and passed the Runs test. Autocorrelation and histograms are used to determine the correct implementation of the weights.

Keywords: Random number generator, weighted probability distribution, PLC channel emulator, power line communications, die harder, runs test.

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1. Introduction

The theory of randomization is significant in human lives, as it shows real life and natural occurrences. From ancient civilization to modern era, fate, and decision making used the concept of randomization. A simple lottery, insect colony study, particles existence are some of the examples of the application of randomness. Development in producing random numbers can be seen over time, from flipping coins, throwing up dice and now, with the advent of computers, by running algorithms [1]. The 1st algorithmic Random Number Generator (RNG) was developed by Neumann [2] but shows poor source of random number. The three common RNGs are: (1) linear congruential generator (LCG); (2) multiple recursive generator (MRG); (3) matrix congruential generator (MCG) which are discussed in detail at [3]. But there are real life data such as environmental, ecological, as well as electrical data that can be considered in the category of random based on biased sampling. A weighted distributions approach puzzle out this problem. In [4], it was mentioned that: weighted distributions take into account the method of ascertainment, by adjusting the probabilities of actual occurrence of events to arrive at a specification of the probabilities of those events as observed and recorded.

A number of researches show the importance of weighted probability in randomization; each one has its own application. To name a few, the method was applied on the following: wildlife populations and human families [5], matching the internet recipe ingredients with food composition data [6]; resource selection which is useful in designing wildlife management [7]; industrial system modeling [8]; Nakagami-m envelope distribution simulation [9] and many more. In this research, the weighted probability random number generator aims at mimicking the weighted probability load occurrences in the power line channel for the development of a realistic PLC channel emulator.

The paper comprises of six sections. In Section 2, the basic concepts and PLC indoor channel model were discussed. Section 3 contains the design of the WRNG and its algorithm. Hardware implementation was discussed in Section 4, the evaluation of the WRNG and the conclusion are presented in Sections 5 & 6 respectively.

2. Power Line Communications

This section gives an overview of the power line communications concept and its channel model.

2.1. Basic Concepts

Powerline Communications (PLC) is regaining attention nowadays due to useful applications that it can offer along with the emergence of new technology. For several decades, the power transmission line intended to deliver electricity is being used in voice and data transmission [10]. The electrical layout inside the household or buildings has become a channel in data sharing and in-home networking. Nowadays, there are interfacing equipment like modem that are ready to use and commercially available [11]. But for a consumer to trust this modem, it must be efficient and reliable. However, studies show that power line is a very harsh environment to radio frequency signal, that its time-varying behavior crucially affects the reliability of the modem. Testing and verification on the live wire is hazardous and lacks statistical data that can prove the reliability of the modem [12], thereby developing an emulator is appropriate. By means of emulator, it can freely capture the different real-environment scenario of a power line channel repeatedly. It can create a mathematical model of the signal environment and by software and hardware-based algorithms, configuring the channel through the transmission line parameters are possible and repeatable. Through this data, modem and other PLC interfacing equipment can be verified and tested. Some of the notable studies on channel emulation and generation are listed in [12], [13], [14], [15], [16], [17], and [18].

There are two basic approaches in dealing with PLC channel models: the phenomenological (a.k.a top-down) approach and the deterministic (a.k.a bottom-up) approach [19]. Regardless of which approach to use, the effectiveness of the channel model and how well the existing model can mimic the PLC network is of what we are interested in. In [20], it was mentioned that every piece of equipment affects the communication channel, and this was supported by Sung in [21], that the channel transfer function of the PLC varies abruptly when the topology changes, which happens when the appliances are plugged in and out and switched on and off. In [22], Cañete provided software that generates the transfer function for a network topology with seven section lines and five terminations. The five terminations comprise of three stubs for individual load impedances of appliances, and at the two ends are impedances of the modems themselves. The generation, however, of the transfer functions has equal load occurrence distribution, which is far from the realistic scenario. Data gathered from BATELEC, an electric cooperative in the Philippines; show that there are appliances that are used more often than the other appliances [23]. Table 1 shows the commonly used appliances in the household of Batangas, Philippines and the usage in terms of hours per day.

2.2. PLC Indoor Channel Model

The simplest PLC channel model can be thought of as a transmission line with a linear time invariant (LTI) behavior. An LTI system is where an input-output pair exhibit an invariant response as time shift occurs. However, due to the inherent time-varying behavior of the devices that is a function of main's frequency, a

channel exhibits a cyclic short-variation known as the Linear Time Varying (LTV) system. Studies pertaining to LTI and LPTV in indoor PLC were discussed in [24] and [25]. The power line is often viewed as a uniform two-wire transmission line represented by two port networks (2PN). The concept of Transmission-line (TL) theory is widely used in obtaining the transfer function, impulse response, characteristics impedance and the propagation constant of the transmission line. In fact, the paper presented in [26] & [27], the generation and computation of the network transfer function is based on the TL principle. In 2PN, the relationships of the current (I) and voltage (V) at the input and output were presented by the ABCD matrix as shown in the Fig. 1:

Table 1. Top 10 commonly used household appliances in Lipa Batangas, Philippines [23].

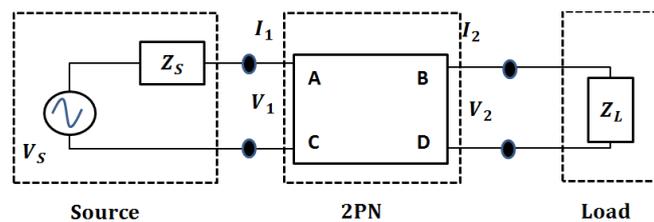| Rank	Appliance/s	Usage (Hrs/Day)
(1)	Incandescent Lamp	8
(2)	Compact Fluorescent Lamp	8
(3)	Stand Fan	8
(4)	Washing Machine	1
(5)	TV Colored Set	5
(6)	Refrigerator	24
(7)	Rice Cooker	2
(8)	Flat Iron	3 (hrs/week)
(9)	Light Dimmer	8
(10)	Air-conditioning Unit	8

Fig. 1. PLC Two-port network model.

The IV relationship from 2PN network is defined by:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = T \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (1)$$

where the ABCD parameters can be computed through the matrix:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh(\gamma l) & Z_0 \sinh(\gamma l) \\ \frac{1}{Z_0}\sinh(\gamma l) & \cosh(\gamma l) \end{bmatrix} \quad (2)$$

The transfer function is defined by

$$H(f) = \frac{Z_L}{CZ_L Z_S + AZ_L + B} \quad (3)$$

Calculating the ABCD matrix and configuring the cable, frequency and load parameters, the existing PLC channel emulator enabled the generation of transfer functions.

2.2.1. Effects of Load on PLC Network

Many research in indoor PLC noted the effect of the plugged appliances on the drastic inclusion of noise in the channel. In modeling the indoor broadband channel, the paper of [28] shows the different level of noises as the appliance is in the working state. In [29], household appliances were grouped according to the frequency behavior of their impedance. TV, PC, DVD player and Microwave are in the same class where the input impedance is the same in operating and non-operating state of the device. The impedance varies in two states every 5 minutes on Fluorescent lamp, mobile charger, internet box and TV box charger. The vacuum cleaner on the other hand has the same operating impedance with that of the power cable in short circuit. For electric heating appliances like steam irons, toasters and coffee maker, the impedance in the operating and non-operating state is different. The only device that cannot be modeled by power cable is the refrigerator. Once its plugged, it is considered as continuously 'on'. However its impedance changes based on the four conditions: door open, door closed, operating and non operating state. Table 2 shows the typical impedances of the top 10 household appliances. These impedances are used as the loads in the network topology discussed in Subsection 2.2.2.

Table 2. RF Impedance of the top 10 household appliance [30].

Appliance	RF IMPEDANCES MAGNITUDE @100kHz (kΩ)
Lamp	630
Fan	18900
Washing Machine	27200
Television	20
Refrigerator	1560
Flat Iron	400
Air-conditioning Unit	9750
Radio	6660
Personal Computer	300
Rice Cooker / Stove	20

2.2.2. Network Topology

The network topology previously used by [13] and [31] was the same topology adapted on this study. The loads of the given topology were varied according to the different combinations of appliances listed in Table 2. An actual residential wiring would normally have a separate circuit for the lighting. The use of the lamp in Fig. 2 is just illustrative and may represent any device with the

same impedance. Based on Canete's emulator, the transfer functions generated were assumed to have a load with uniform distribution. However, on the data shown in Table 1, loads have biased load occurrence and therefore a simple randomization will not be able to capture a realistic PLC scenario.
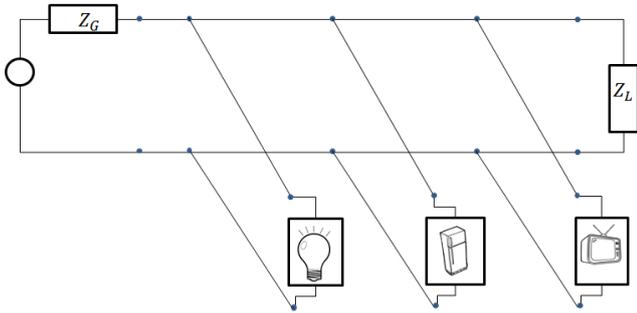

Fig. 2. Example of 2PN topology with actual load connections.

2.2.3. PLC Channel Transfer Functions

PLC channel transfer functions were generated based on the topology and load combination discussed in Subsection 2.2.2. The RF impedance of the top 10 household appliances listed in Table 2 were used as the load impedance of the network. The Transfer Functions (TFs) were clustered into 10 groups based on their plot characteristics for the purpose of identification during the hardware implementation. Figure 3 shows transfer function plots for each cluster. Each cluster contains eight transfer functions that has the same weighted probability of occurrence based on Table 1. Except for cluster RNG_01 and RNG_10, the transfer function plots of the eight possible load combinations of the seven-segment network for the other clusters are almost the same.
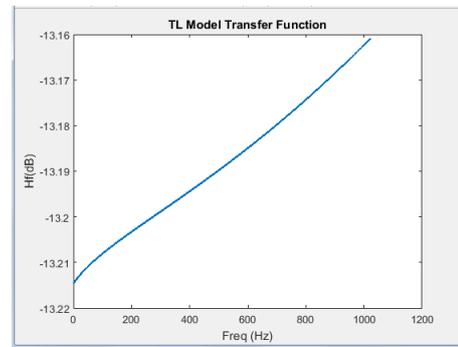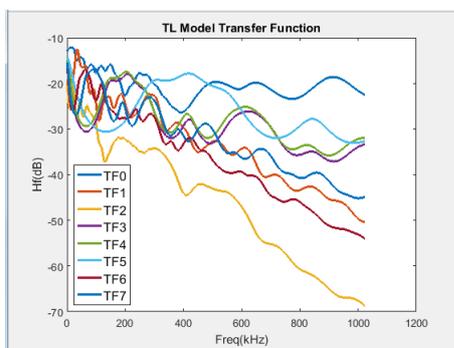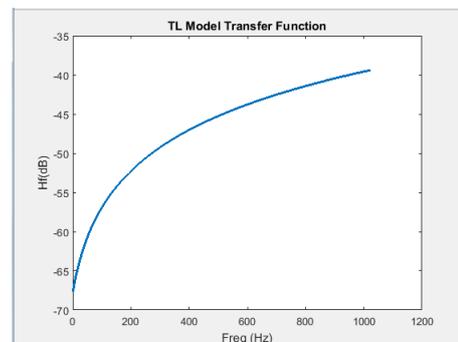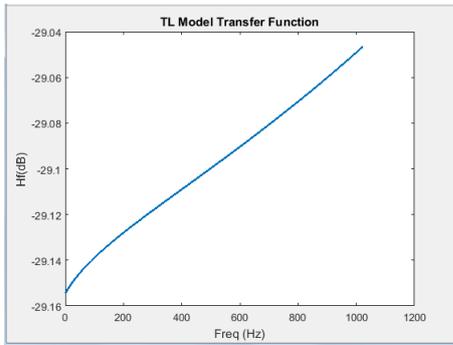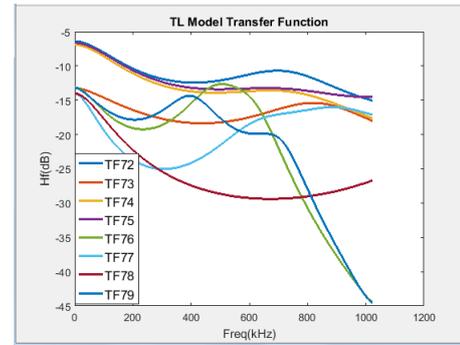

(b) RNG_02
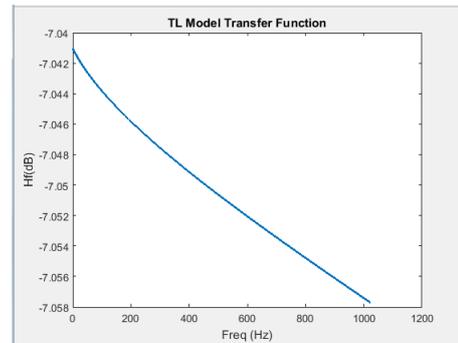
(c) RNG_03
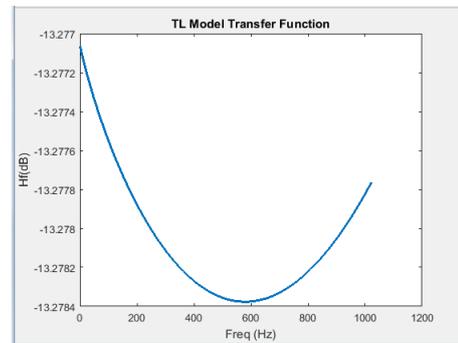
(d) RNG_04

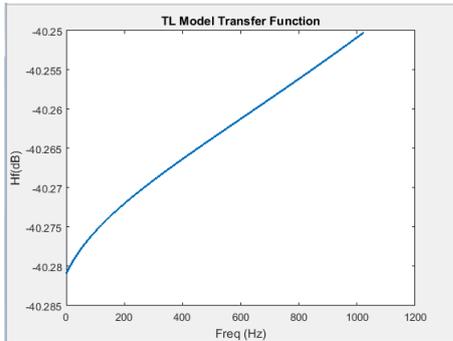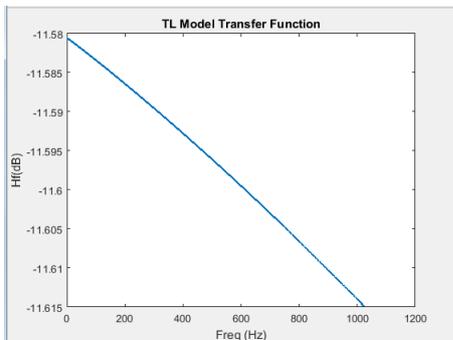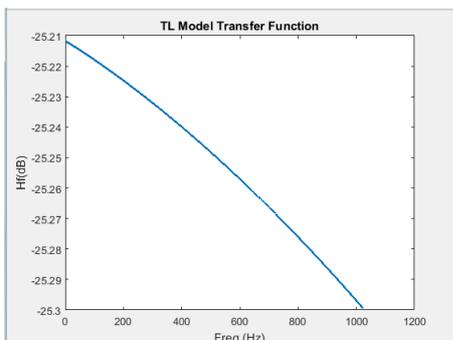(a) RNG_01

(e) RNG_05

(f) RNG_06

(j) RNG_10

Fig. 3. Transfer Functions Plot Characteristics of Groups 1 to 10.

3. Design of Weighted Random Number Generator

This section provides the mathematics, operations, and the integration of WRNG with the PLC channel emulator.

3.1. Weighted Random Number Generator (WRNG)

The generation of random numbers based on biased sampling starts with a set of weights for each item in a population. Once the weights are already determined, the weights are added cumulatively and the random number generator (RNG) generates a number between 0 and the total sum of weights. Table 3 shows the summary of the process. This process is applied to the generation of the PLC transfer functions of the PLC channel emulator discussed in the succeeding section.

(g) RNG_07

Table 3. Weighted Random Method [32].

1) Calculate the sum of the weights.
2) Get a random number between 0 and the sum of weights.
3) Check every random number if it is less than the cumulative sum.
4) Pick the number satisfying the conditions on step 3.

(h) RNG_08

3.2. Weighted Random Number Generator for PLC Channel Transfer Function Generation

The proposed scheme for WRNG is shown in Fig. 4. The Weighted Probability Random Number Generator block is designed using the concepts discussed in Sec. 3.1. The RNG blocks contain the basic random number generator and the transfer functions (TF) based on the weight assignments in Table 4. Instead of the usual 1 array with N number of elements, it has several arrays or random number generator. Each RNG block will be sampled uniformly and then weighted to derive on the desired sequence.
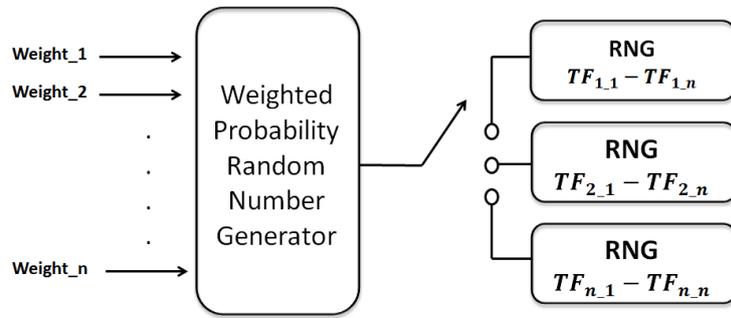

(i) RNG_09

Fig. 4.   Proposed weighted-probability number generator.

Table 4.   Transfer Functions generator groups according to weight assignments.

TF Blocks	Number Range	Assigned Weight
RNG_01	0 – 7	24%
RNG_02	8 -15	18%
RNG_03	16 - 23	15%
RNG_04	24 - 31	12%
RNG_05	32 - 39	10%
RNG_06	40 - 47	8%
RNG_07	48 - 55	6%
RNG_08	56 - 63	4%
RNG_09	64 - 71	2%
RNG_10	72 - 79	1%

The algorithm for the generation of the PLC channel transfer function is given in Table 5. As provided in Sec. 2.2.3, the groupings are based on the probability of occurrence of the scenario for the transfer function. Each group has uniform distribution. It is the weighted RNG that causes one of the groups to be chosen. The difference between the generated number and the cumulative sum is computed. If the difference is less than the cumulative sum, the associated number on the list will be picked, otherwise, it will continue iterating.

Table 5.   Algorithm in Generating the PLC channel transfer function based on weighted probability.

1) Run all RNGs with uniform distribution.
2) Run WRNG with weighted distribution.
3) Normalize the weights.
4) Construct the desired random numbers sequence.

The metrics in determining the correctness of the generated number based on the given weights are presented in the next section.

3.3. Weighted Random Number Generation Metrics

The concept in generating weighted numbers rooted from [33] where a list of fruits was biasedly selected according to its weighted probability.

$$\% \, Probability \, of \, Occurrence$$
$$= \frac{Number \, of \, actual \, outcomes}{Total \, number \, of \, possible \, outcomes} \quad (4)$$

The computed % probability of occurrence was statistically tested to check whether the value is greater than or less than to the set value. This test is known as the two-tailed test which states that if the sample being tested falls either of the critical areas, the alternative hypothesis is accepted instead of the null hypothesis [35]. The hypotheses are:

Ho: There is no significant difference between the computed value and the set value;
H_A: There is significant difference between the computed value and the set value.

Reject Ho if t-value (statistics value) is $\leq$ or $\geq$ 2.262 at 0.05 level of significance. The degrees of freedom *(DF)* and t-value were defined by the Eq. (5) and Eq. (6).

$$DF = N - 1 \quad (5)$$

where N is equal to the number of samples.

$$t = \frac{X - \mu_u}{S/\sqrt{N}} \quad (6)$$

where: X: mean; μ_u: set value; S: standard deviation

Randomness is only present in human minds, not in the objective world according to [34]. It is therefore necessary to test the random numbers if they meet some of the statistical tests ensuring that they are not

"decodable". There are softwares available that is being used in testing the randomness of the sequence. The popular test packages are DIEHARD, NIST test suite, CRYPTX and ENT. Runs test however is a type of random test that can be computed without requiring a different operating system. For numeric data, the "Runs above and Below the Median" is appropriate to use. A sample consisting of numerical measurements or observations can be treated similarly by assigning a "1" to values above the median and a "0" to values below the median. Numbers equal to the median is omitted. Equations 7, 8 and 9 were used to compute for the test statistics *(Z)* where n_1 and n_2 are the number of zeros and ones respectively in the series, μ denotes the number of observed runs, μ_u is the expected number of runs and σ_u is the standard deviation of the number of runs. At 5% significance level, a test statistics *(Z)* with an absolute value less than 1.96 indicates randomness.

$$\mu_u = \frac{2n_1 n_2}{n_1 + n_2} + 1 \qquad (7)$$

$$\sigma_u = \sqrt{\frac{2n_1 n_2 (2n_1 n_2 - n_1 - n_2)}{(n_1 + n_2)^2 (n_1 + n_2 - 1)}} \qquad (8)$$

$$Z = \frac{\mu - \mu_u}{\sigma_u} \qquad (9)$$

Another measurement tool applicable for the weighted probability are the histogram and autocorrelation. As histogram gives an accurate representation of the distribution of data, autocorrelation can measure the repeatability of the generated number on a given time. Given a random number sequence $x(n)$ with a period of *N*, where index *m* is called the shift or lag parameter. The autocorrelation $r_{xx}(m)$ of the sequence $x(n)$ to the shifted copy of the original sequence $x(n - m)$ is defined by:

$$r_{xx}(m) = \sum_{n=\infty}^{\infty} x(n)\, x(n - m) \qquad (10)$$

Therefore,

$$
\begin{aligned}
r_{xx}(m + N) &= \sum_{n=\infty}^{\infty} x(n)\, x(n - (m + N)) \\
&= \sum_{n=-\infty}^{\infty} x(n)\, x((n - m) - N) \\
&= \sum_{n=-\infty}^{\infty} x(n)\, x(n - m) \\
&= r_{xx}(m)
\end{aligned}
\qquad (11)
$$

and

$$
\begin{aligned}
r_{xx}(m - N) &= \sum_{n=\infty}^{\infty} x(n)\, x(n - (m - N)) \\
&= \sum_{n=-\infty}^{\infty} x(n)\, x((n - m) + N) \\
&= \sum_{n=-\infty}^{\infty} x(n)\, x(n - m) \\
&= r_{xx}(m)
\end{aligned}
\qquad (12)
$$

4. Hardware Implementation of Weighted Random Number Generator

The block diagram of the Weighted Random Number Generator (WRNG) is shown in Fig. 5. It comprises of the Cumsum module, the RNG module, the Index Finder module, the Transfer Function Generator Blocks (labeled RNG_01 to RNG_10) and a multiplexer (MUX). The ten (10) different weights are the inputs of the module "'cumsum'" and were added cumulatively to produce an array of cumulative weight. The "'RNG'" module generates a random number in uniform distribution between 0 and the total sum of the weights. At the "'Index Finder'" module, every number generated from the RNG module was subtracted to the cumulative weights starting from the first weight assignment. If the difference is less than or equal to zero at the first weight, then the index will be "'1'", otherwise the number will be subtracted to the next given weight. It simply find the index where the difference is not greater than zero. The output of the Index Finder will assert which TF generator block would perform the random number generation. Multiplexer has 10 select lines and generated one weighted random number every clock cycle. There are eighty PLC transfer functions grouped into ten groups (RNG_01 to RNG_10), where each group has a specific weight assigned to it according to the probability of usage mentioned in the previous section. Table 3 shows the assignment of weights. Weight assignment corresponds to the nominal hours of usage of a household appliances in Table 1. The network topology with refrigerator was assigned 24% probability due to its 24 hours "'on state'" operation. On the other hand, transfer function having washing machine as load has the smallest probability of occurrence with 1% weight assignment. The WRNG module was then interfaced to the existing emulator of [13] as shown in Fig. 6.
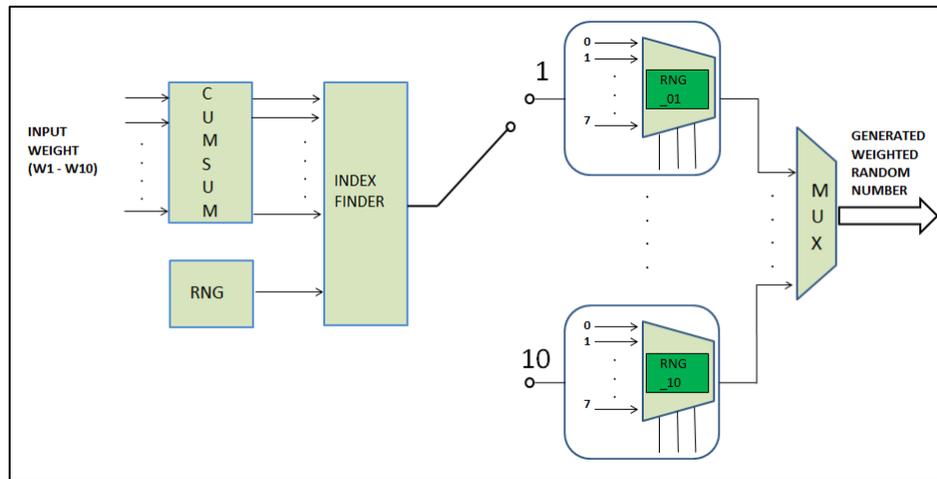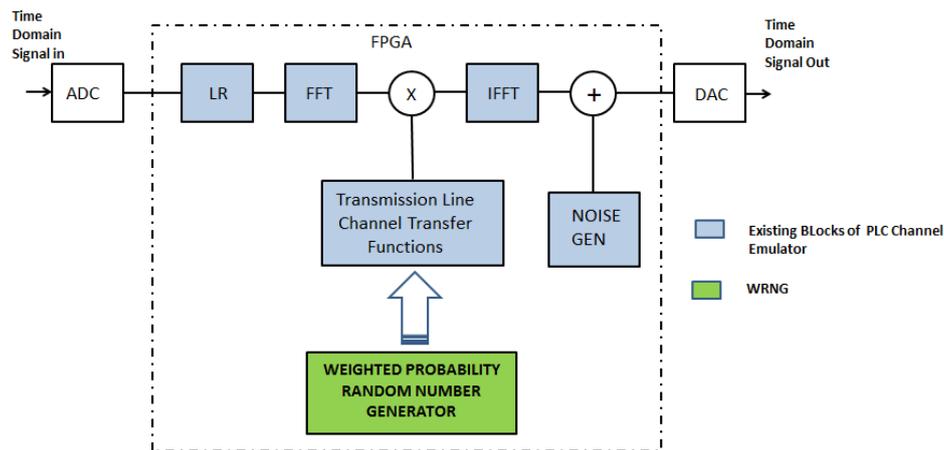
Fig. 5.   WRNG block diagram.

Fig. 6.   Hardware Implementation of PLC channel emulator with WRNG.

5.   Data and Results

5.1.   Evaluation of the Weighted Random Number Generator

The performance of the WRNG is measured using histogram and runs test. Figure 7 shows the histogram for the 1,000 samples generated both in Matlab and Xilinx, where the x-axis represents the range of numbers and y-axis displays how many times the number was occurred on a given run. The plots has different bar heights specifying that there are numbers appearing more than the other which is what is expected on the design. The corresponding mean and deviation from the assigned weights are presented in Table 6 and Table 7 using two-tailed test. Based on the t-values computation, the actual weighted percentage has no significant difference with that of the set value of the numbers generated in Matlab and Xilinx.

Runs test above and below the median were conducted on the generated numbers in Matlab and Xilinx. The computed Z-value was computed based on the equations discussed in Subsection 3.3. Table 8 summarized the test results conducted on 10 runs each in Matlab and Xilinx. All samples had a Z-value less than 1.96 which implies that the numbers were randomly generated.

### 5.2.   Evaluation of Emulator with WRNG

Different plot characteristics was intentionally selected to easily check if the emulator performs weighted random sampling of the transfer functions. Figure 8 shows the input and output waveform of the emulator. The top waveform is the input measured using Channel 1 of the oscilloscope and the bottom is the output (measured at Channel 2). The input is maintained at 1.07 V. It is evident at the output the change in amplitude and phase depending on the attenuation and phase margin caused by the generated transfer function. This mimics how signal gets attenuated as the PLC channel experiences different loading and channel scenario. Figure 9 shows the zoomed-out view of the waveform highlighting the phase difference between the input and output for each transfer function as it passes through the emulated channel. These measurements are used to demonstrate the success of the inclusion of the WRNG in the previously designed emulator that uses an

ordinary random number generator to generate the transfer function.

6. Conclusion

Weighted Random Number Generation offered a different approach in generating the transfer functions for PLC channel emulator. Its concept is best appropriate in PLC channels with time-varying behavior, a more realistic scenario compared to the emulator using a usual Random Number Generator. A simple mathematical equation like the cumulative sum mixed with the known random number generator (RNG) method made up the WRNG design. The RNG is implemented using the LFSR which was modified by using 32 bits as its seed, several bits were connected through an XOR gates. A 10 pseudo weight inputs formulated the probability of occurrence of the RNG, which must have a total of 100. Both the software simulation's result showed a biased sampling after generating a prescribed number of runs. Eighty (80) transfer functions with distinct waveforms are coded individually in VHDL as LUT. The step by step method in generating the WRNG in MATLAB was translated into individual VHDL module. This made the coding simpler and easier to synthesize before making up the whole module. Hardware implementation includes the interfacing done between the WRNG and the existing PLC channel emulator by [31]. Proper bit declaration, signal assignment and port connection are essential in interfacing. Based on the data gathered after the software simulation and hardware implementation, the proposed design is effective in changing the probability of occurrence of the transfer function. The data from

histogram and random testing showed that numbers are appearing in random following the probability of weights designated to each transfer function group.
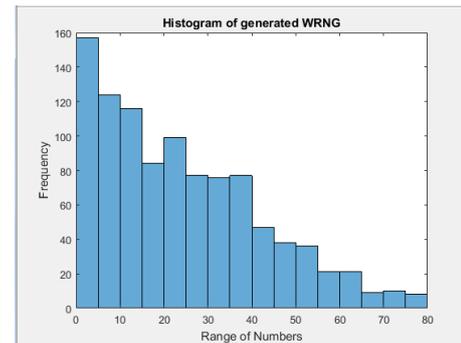
(a) Matlab Simulation Result
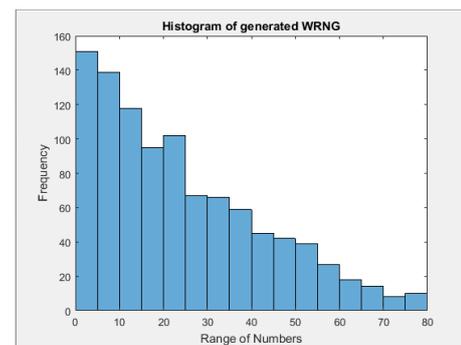
(b) Xilinx Simulation Result

Fig. 7. Histogram of Weighted Numbers Generated in Matlab Xilinx.

Table 6. Two-tailed test for % of probability of occurrence in Xilinx.

Set Value	Mean	Stdev	T-value	Decision	Interpretation
24	24.21	1.01	0.66	Accept H_o	NSD
18	18.09	1.35	0.21	Accept H_o	NSD
15	15.04	1.07	0.12	Accept H_o	NSD
12	11.86	1.52	-0.29	Accept H_o	NSD
10	9.55	0.63	-2.24	Accept H_o	NSD
8	7.82	0.94	-0.60	Accept H_o	NSD
6	6.25	0.68	1.17	Accept H_o	NSD
4	4.13	0.37	1.11	Accept H_o	NSD
2	1.93	0.44	-0.50	Accept H_o	NSD
1	1.12	0.31	1.22	Accept H_o	NSD

NSD: No significant difference.

Table 7.   Two-tailed test for % of probability of occurrence in Matlab.

Set Value	Mean	Stdev	T-value	Decision	Interpretation
24	24.50	0.98	1.61	Accept H_o	NSD
18	18.45	0.88	1.62	Accept H_o	NSD
15	14.71	0.72	-1.28	Accept H_o	NSD
12	12.14	0.87	0.51	Accept H_o	NSD
10	9.55	0.91	-1.56	Accept H_o	NSD
8	7.70	0.55	-1.74	Accept H_o	NSD
6	6.15	0.61	0.77	Accept H_o	NSD
4	4.16	0.42	1.21	Accept H_o	NSD
2	1.81	0.36	-1.68	Accept H_o	NSD
1	0.83	0.30	-1.80	Accept H_o	NSD

NSD: No significant difference.

Table 8.   Runs Test of the generated weighted random numbers.

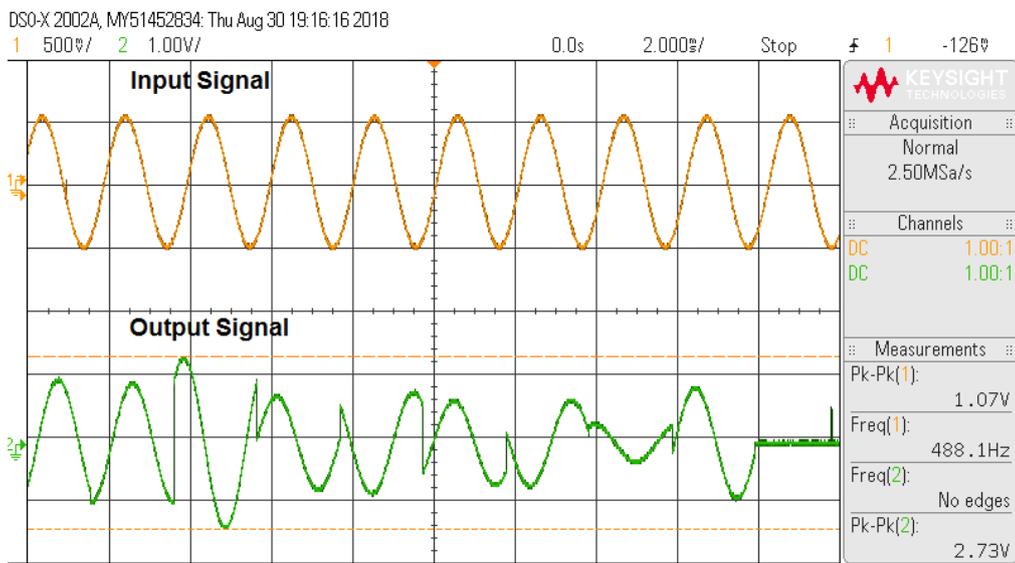| Run #:	Z-value (Matlab)	Result	Z-value (Xilinx)	Result
1	1.2061	Random	1.8277	Random
2	0.4122	Random	0.2010	Random
3	0.4900	Random	0.4020	Random
4	0.8208	Random	0.0765	Random
5	0.2010	Random	0.2010	Random
6	1.6081	Random	0.2010	Random
7	1.6081	Random	0.2010	Random
8	0.4063	Random	0.3052	Random
9	1.4364	Random	1.4071	Random
10	0.4063	Random	1.8434	Random

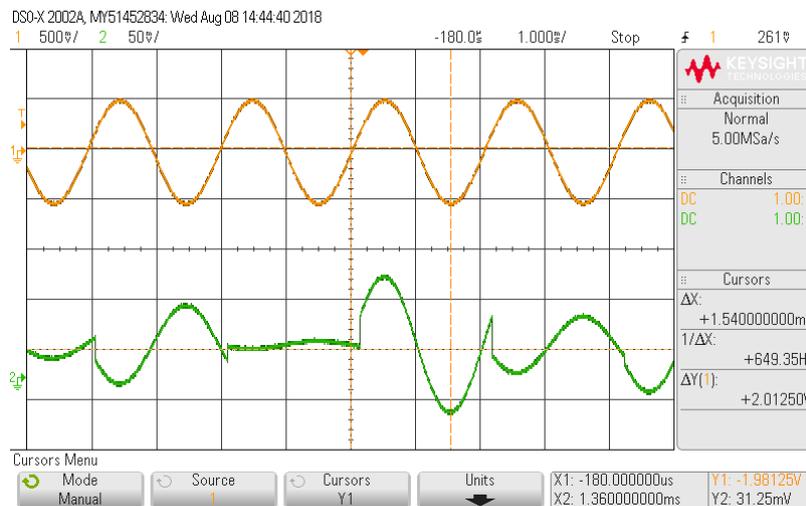Fig. 8.   PLC Channel Emulator Input and Output waveforms.

Fig. 9.   Emulator Phase difference between the input and output signals.

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Gicel Mari I. Oseña, photograph and biography not available at the time of publication.