Comprehensive Analysis and Quantification of Key Performance Metrics in a SWIPT System

Guided by:
Prof. SALIM PAUL
Associate Professor,
Dept. of ECE,SCTCE

Presented by:
MP FARDEEN(SCT21EC069)
RAJARAM G(SCT21EC083)
SANDEEP S(LSCT21EC126)

CONTENTS

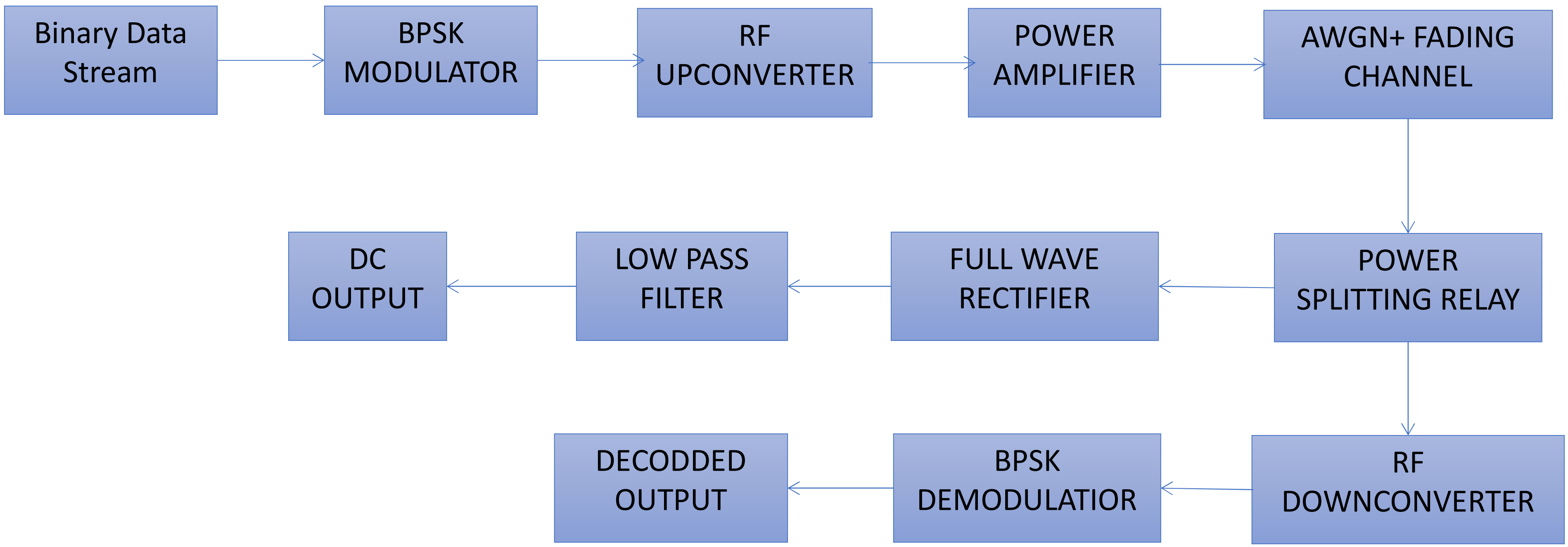
INTRODUCTION

- In Phase 1 of the project the model of the SWIPT system had been developed in SIMULINK and Observed the processing of the signals.
- Mathematically Modelled the SWIPT transmitter, channel and Receiver.
- In phase 2 of the project, we mainly derived the SNR,BER and outage probability of the SWIPT system
- Coded and plotted the SNR v/s BER and SNR v/s Outage probability.

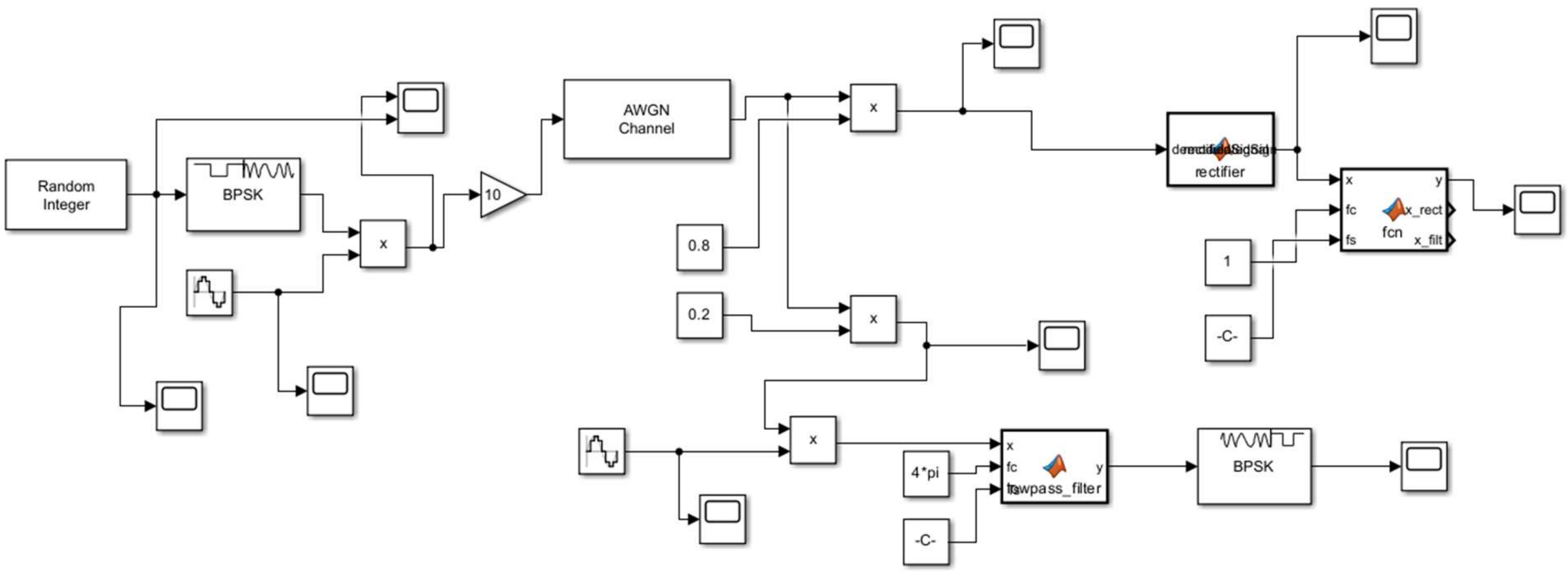
AIM

- Developing a SWIPT model in SIMULINK and analyze the processing of signals.
- Theoretical analysis of the SWIPT system parameters like SNR, BER and outage probability analysis for different power splitting ratios
- Conducting the Experimental analysis of the system by using Monte Carlo simulations.

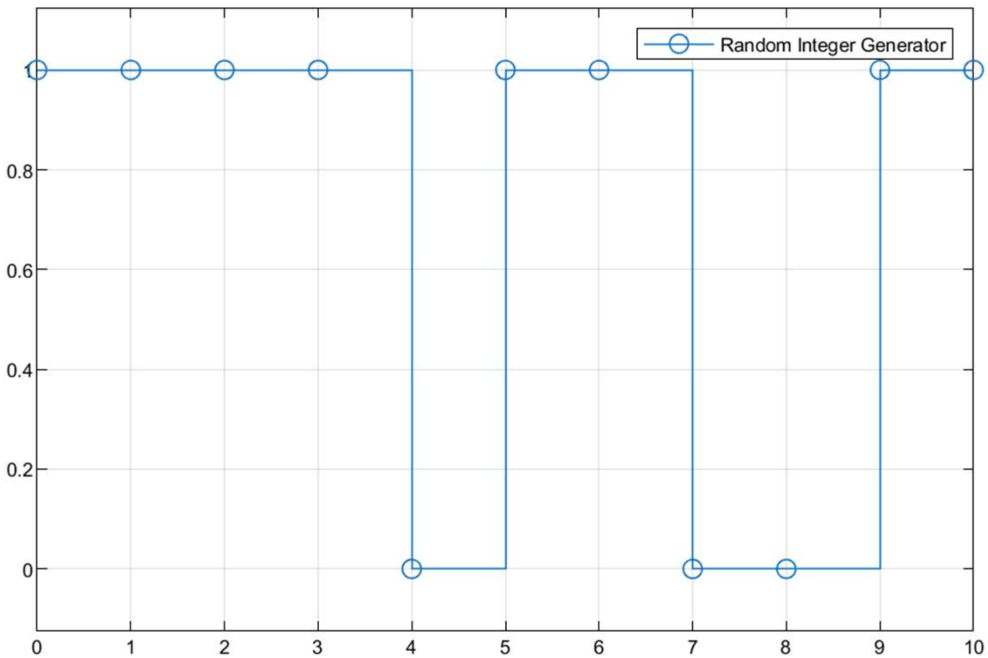
Block Diagram



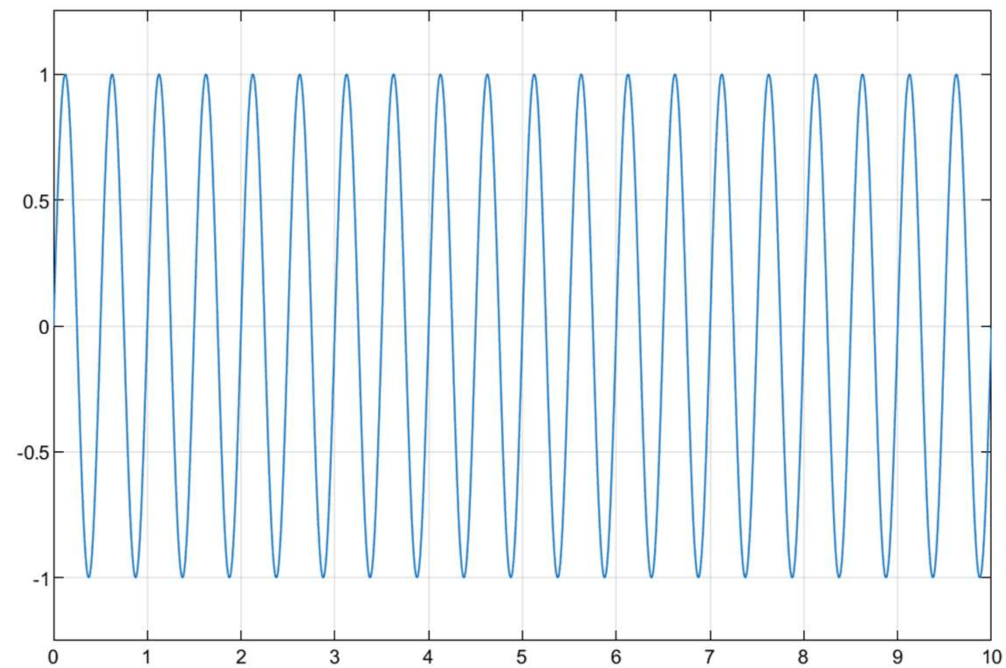
SWIPT MODEL IN SIMULINK



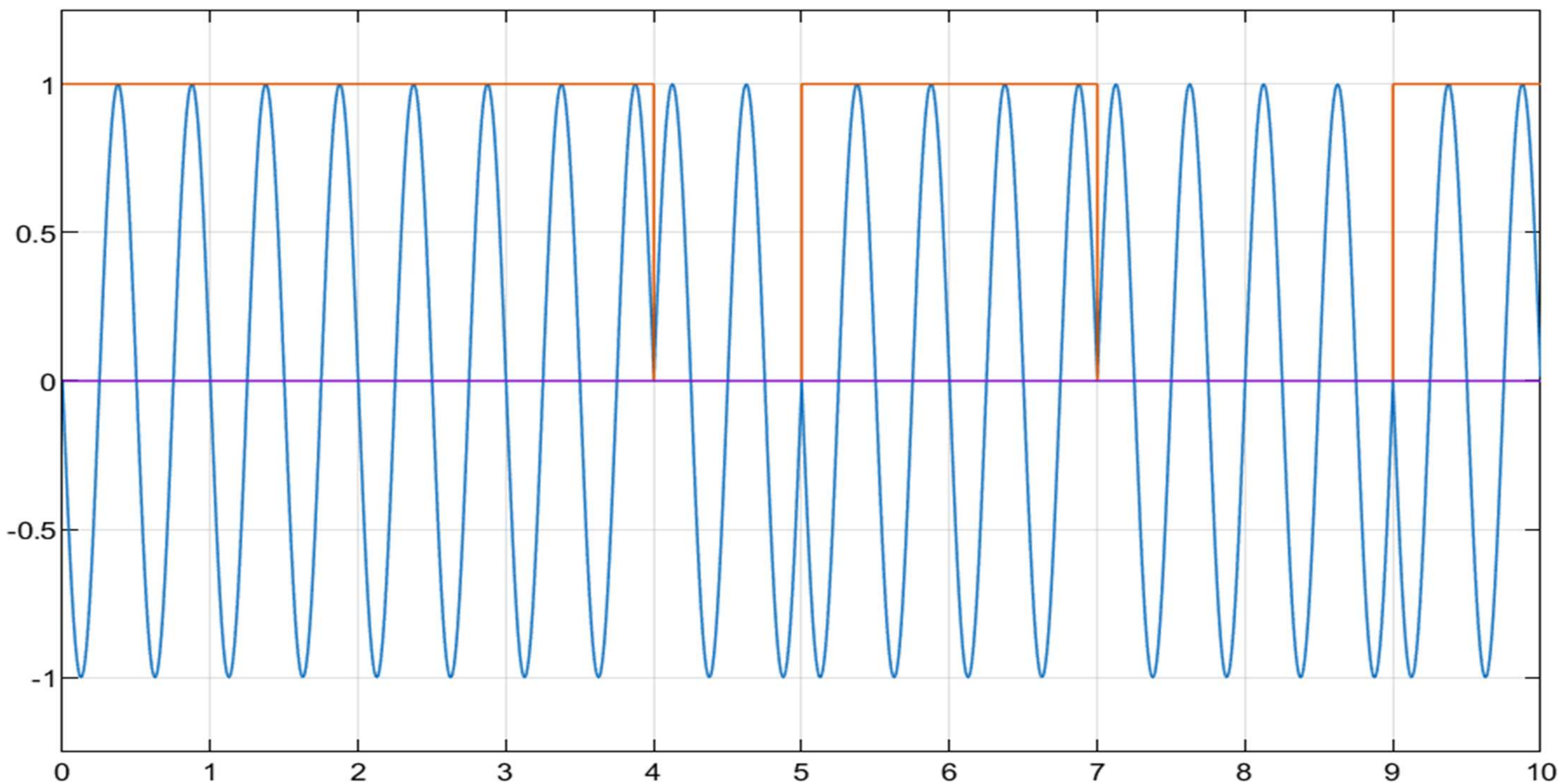
Processing of signals



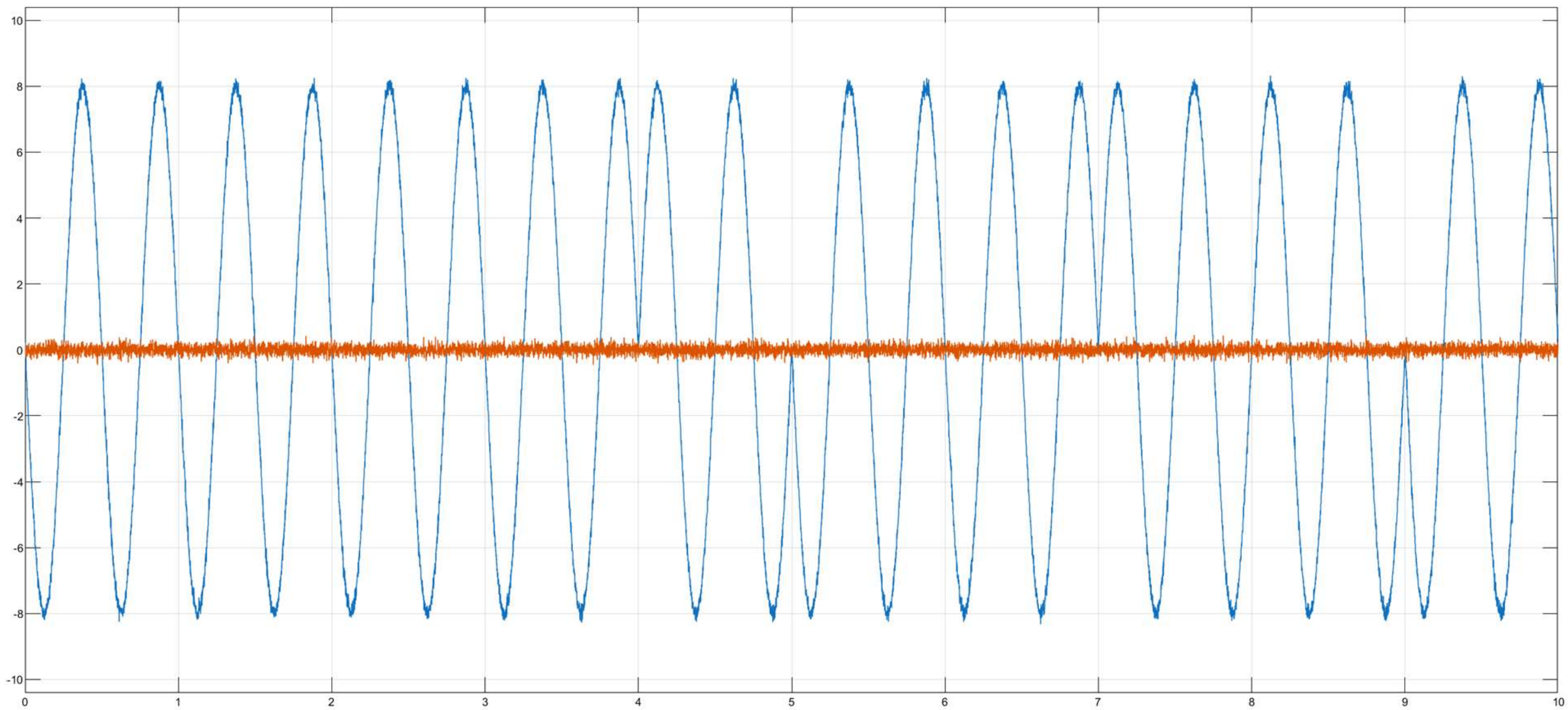
Binary data stream



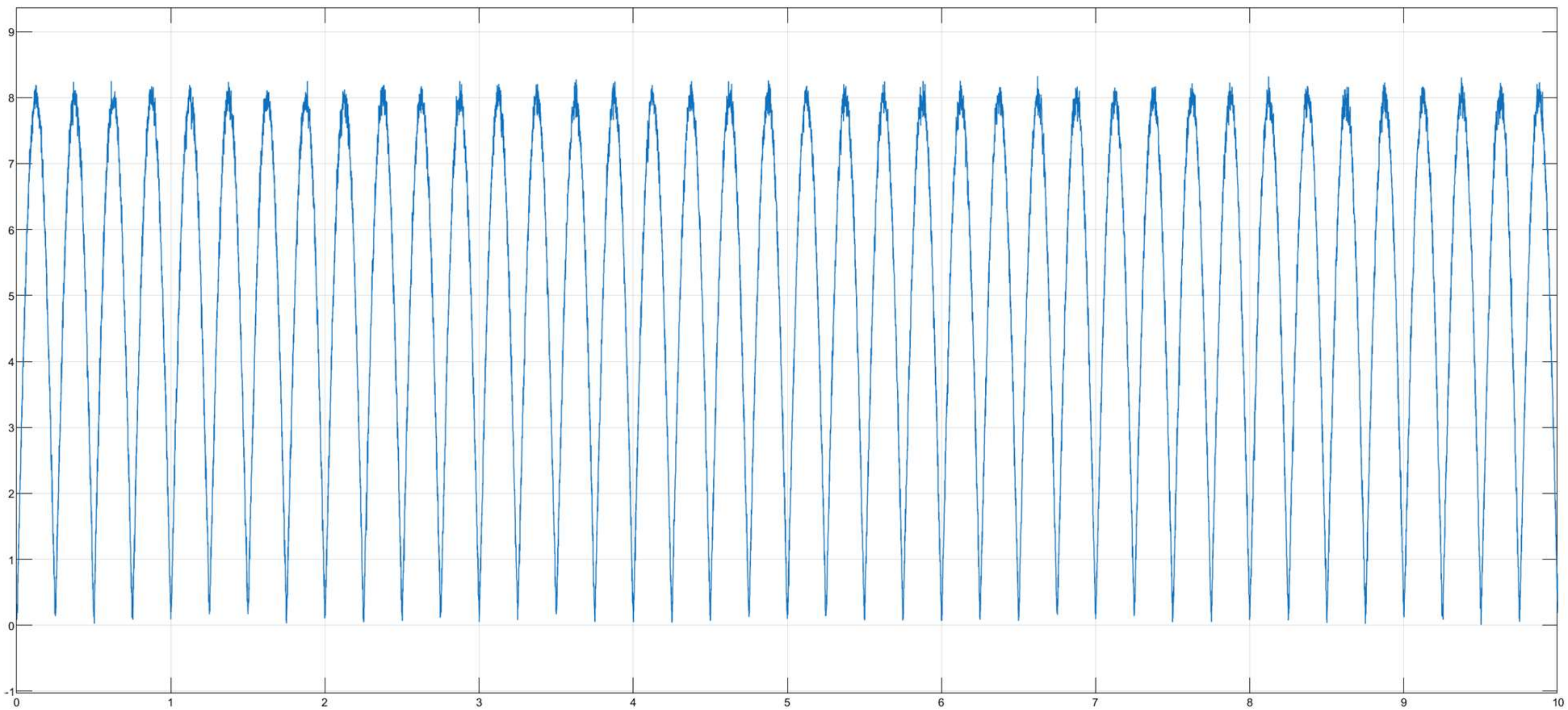
Carrier signal for RF up conversion



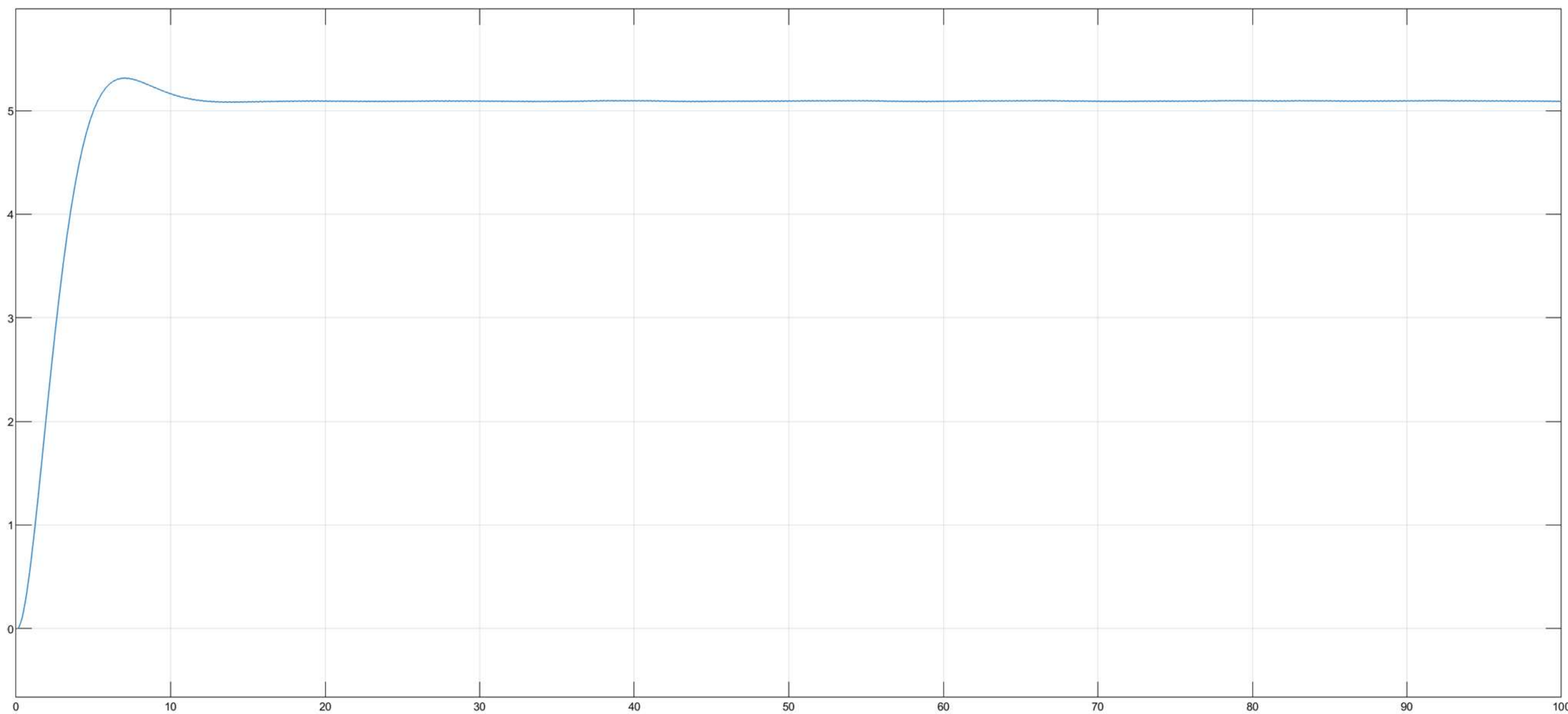
BPSK Modulated signal



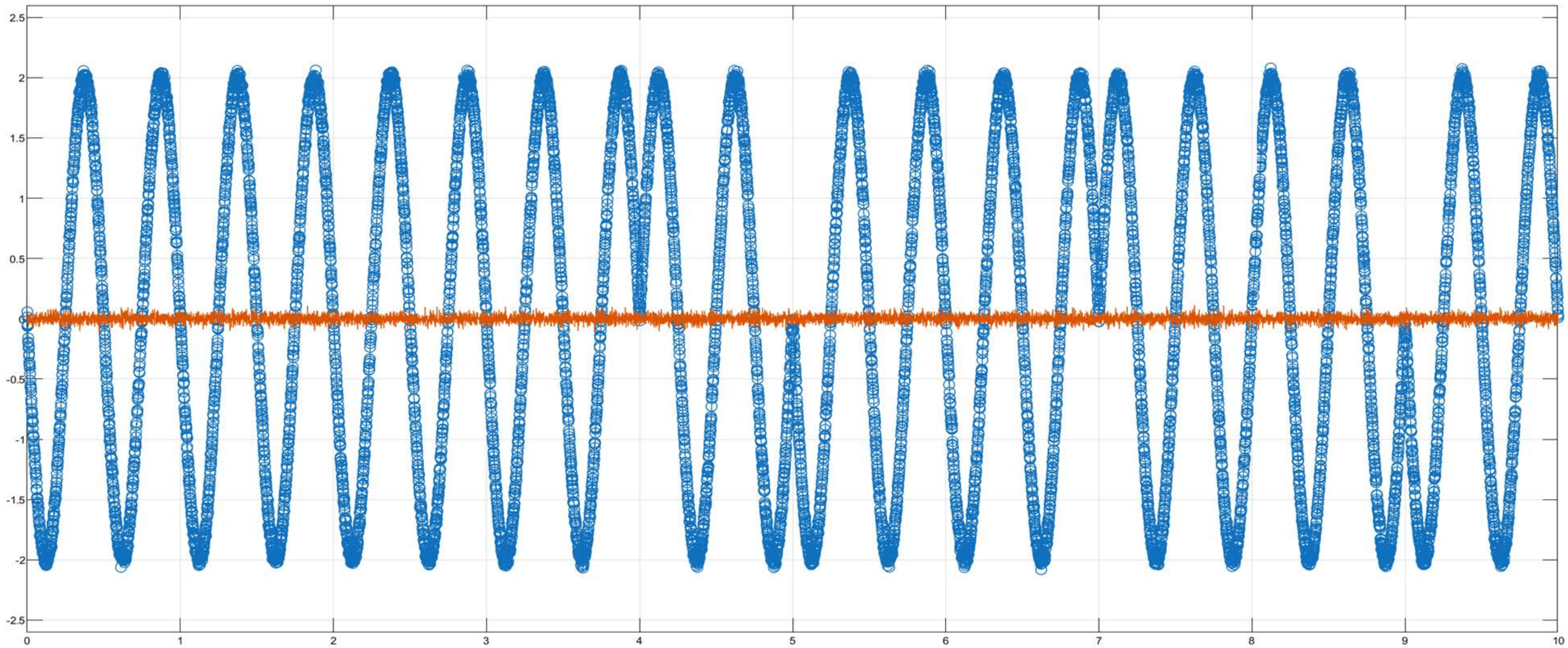
EH path signal after passing through AWGN channel



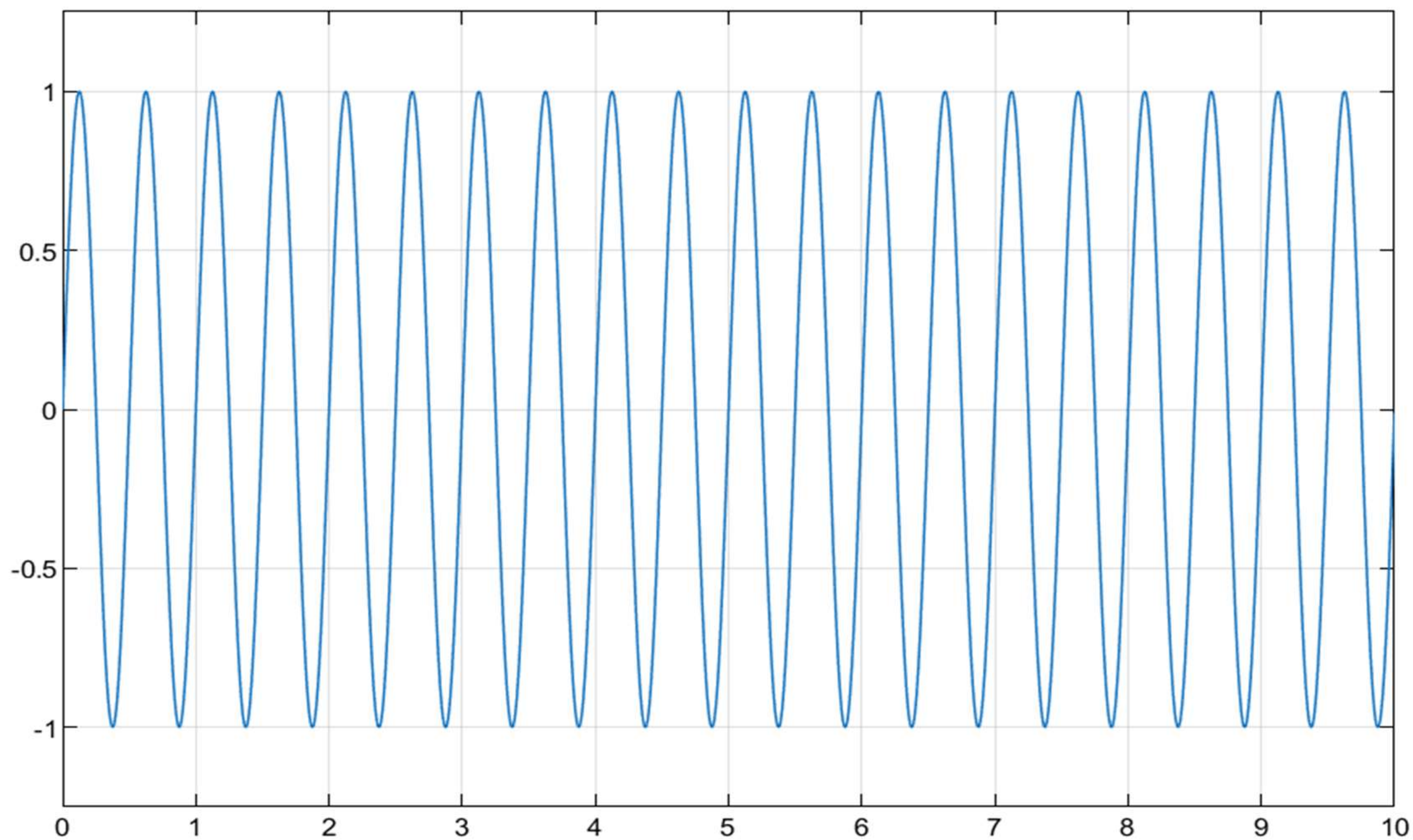
Rectified signal



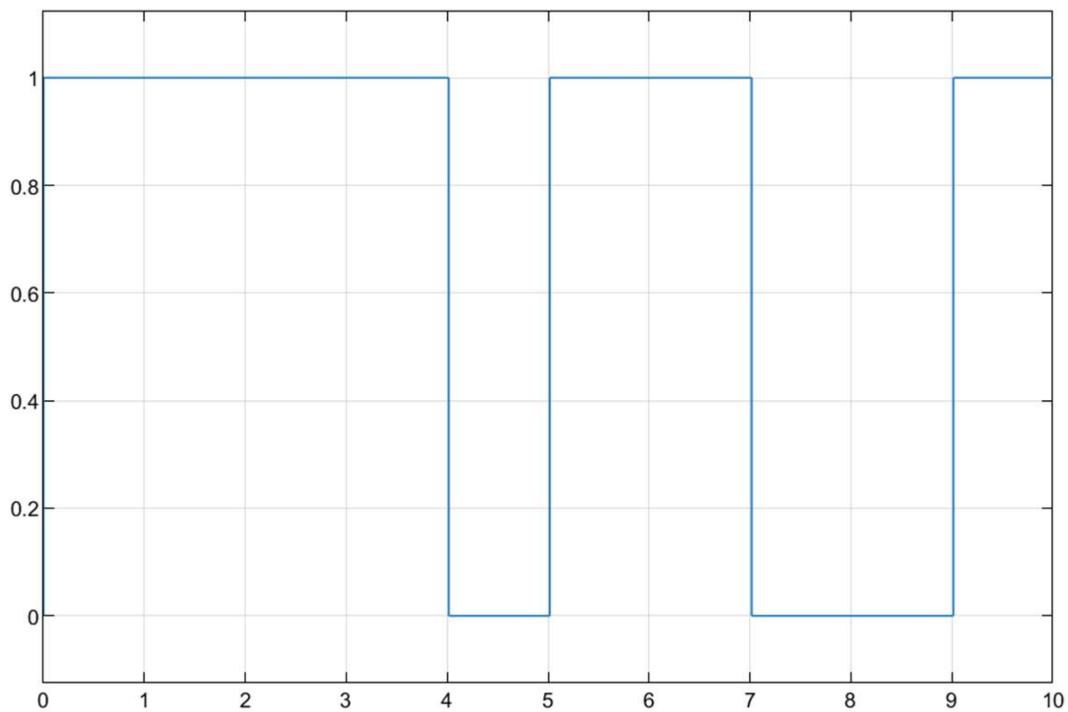
DC Output



ID path signal with noise



Carrier signal used for RF Down conversion



Received Binary data stream

Mathematical Model

- Transmitted signal

$$s_{txn}(t) = G.\, s_{RF}(t) = A.\, cos(2\pi f_{RF} t + \theta_i)$$ ………….(1)

- Channel model

$$r(t) = |h(t)|.\, G.\, A.\cos(2\pi f_{RF} t + \theta_i + \emptyset(t)) + n(t) \ldots\ldots\ldots\ldots..(2)$$

- Received signal

At energy harvesting path:

$$r_{rect}(t) = \sqrt{\rho}\left||h(t)|.\, G.\, A.\cos(2\pi f_{RF} t + \theta_i + \emptyset(t) + n(t)\right|$$ ……..(3)

At information decoding path:

$$r_{base}(t) = \sqrt{1-\rho}.\, (|h(t)|.\, G.\, A.\cos(2\pi f_{RF} t + \theta_i + \emptyset(t) + n(t)).\, \cos(\, 2\pi f_{RF} t)$$ …………………(4)

Performance Analysis

From the received signal equation, we can derive the equations for the performance matrices and analyze them in MATLAB.

From equation (4)

The **signal component** is:

$$s(t) = \sqrt{1-\rho}.\,|h(t)|.\,G.\,A.\cos(\theta_i + \emptyset(t)) \text{............}(5)$$

The **power** of the signal is calculated as:

$$P_{Signal} = E[s(t)^2] \text{.................}(6)$$

Substituting (5) in (6) and simplifying:

$$P_{Signal} = \ 1-\rho.\,|h(t)|^2.\,G^2.\,A^2.\,E\left[\cos^2\left(\theta_i + \emptyset(t)\right)\right] \text{.......................}(7)$$

Since, $\sqrt{1-\rho}, |h(t)|, G\ and\ A\ are\ constants, lets\ assume = 1\ for\ theoretical\ analysis$

For BPSK, $\cos^2(\theta_i + \emptyset(t))$ Has an average power $\frac{1}{2}$

$$P_{Signal} = \frac{1-\rho.|h(t)|^2.G^2.A^2}{2} \text{.................(8)}$$

The **noise component** is: $n_{base}(t)$

Since $n_{base}(t)$ is AWGN, its power spectral density N_0.

The **noise power** is:

$$P_{noise} = N_0 \text{......................(9)}$$

The **SNR** is defined as the ratio of signal power to noise power:

$$SNR = \frac{P_{Signal}}{P_{noise}} \text{...................(10)}$$

Substituting (8) and (9) in (10)

$$SNR = \frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0} \text{...............................(11)}$$

The **Bit Error Rate (BER)** for BPSK under AWGN is given by:

$BER = Q(2.\sqrt{SNR})$……………..(12)

The average probability of error is computed by integrating the error probability in AWGN over the fading distribution.

$$\bar{P} = \int_0^\infty P_s(\gamma)P_{\gamma s}(\gamma)d\gamma \text{…………(13)}$$

Where $P_s(\gamma)$ *is the probabilty of error of under AWGN channel.*

$P_{\gamma s}(\gamma)$ is the probabilty of error under Rayliegh fading channel.

For a given distribution of the fading amplitude r, we compute $P_{\gamma s}(\gamma)$ by making the change of variable

$$P_{\gamma s}(\gamma)d\gamma = \mathrm{P}(r)\ dr \text{…………..(14)}$$

The received signal amplitude r has Rayleigh distribution

$$p(r) = \frac{r}{\sigma^2}e^{\frac{-r^2}{2\sigma^2}}, r \geq 0 \text{……………..(15)}$$

The SNR per symbol for a given amplitude r is

$$\gamma = \frac{r^2 T_s}{2\sigma_n^2} \ldots\ldots\ldots\ldots(16)$$

Differentiating both sides of this expression yields

$$d\gamma = \frac{rT_s}{\sigma_n^2} dr \ldots\ldots\ldots\ldots(17)$$

Substituting 16 and 17 into 15 and then 14 yields

$$P_{\gamma s}(\gamma) = \frac{\sigma_n^2}{\sigma^2 T^s} e^{-\gamma\sigma_n^2 / \sigma^2 T_s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

Since the average SNR per symbol $\bar{\gamma}$ is just $\frac{\sigma^2 T^s}{\sigma_n^2}$ we can rewrite 18 as

$$P_{\gamma s}(\gamma) = \frac{1}{\bar{\bar{\gamma}}_s} e^{\frac{-\gamma}{\bar{\bar{\gamma}}_s}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(19)$$

For binary signaling this reduces to

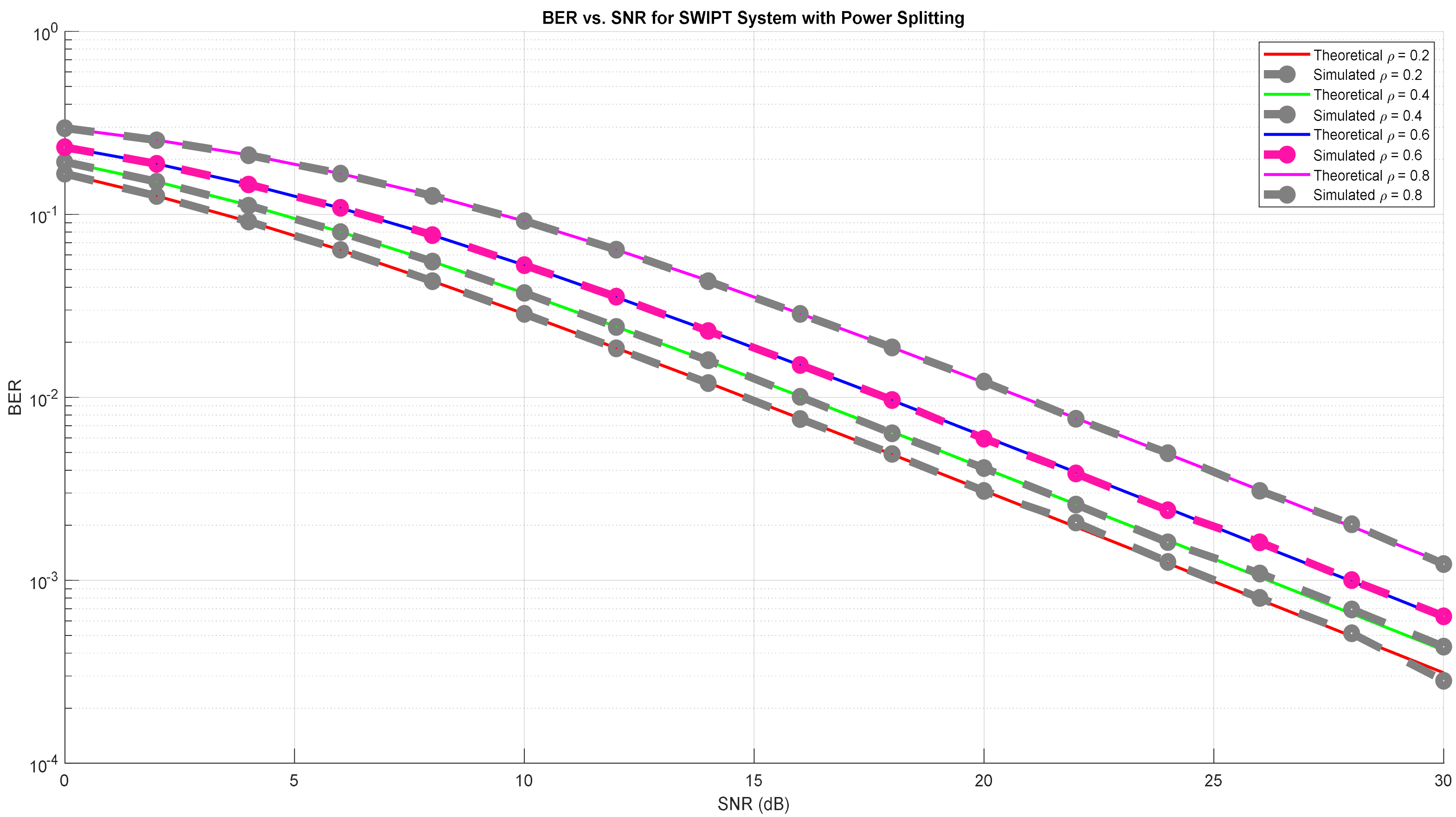
$$P_{\gamma_s} = \frac{1}{\bar{\gamma}_b} e^{\frac{-\gamma}{\bar{\bar{\gamma}}_b}} \ldots\ldots\ldots\ldots\ldots(20)$$

Integrating BER of AWGN over the distribution (20) yields the following average probability of error for BPSK in Rayleigh fading:

$$\bar{P}_b = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}}\right] \approx \frac{1}{4\bar{\gamma}_b} \text{..........(21)}$$

$$\bar{P}_b = \frac{1}{2}\left[1 - \sqrt{\frac{\frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0}}{1+\frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0}}}\right] \text{...........(22)}$$

Theoretical and Experimental simulation of BER v/s SNR



From the **BER vs. SNR plot** for different power splitting ratios , we can infer the following :-

General Trend

- The **Bit Error Rate (BER) decreases** as the **Signal-to-Noise Ratio (SNR) increases**, which is expected in wireless communication systems.
- Higher SNR values lead to improved detection performance, reducing BER.

Effect of Power Splitting Ratio (ρ) on BER

•Different power splitting ratios (ρ) affect BER performance.

•Lower values of **ρ (e.g., 0.2)** result in **higher BER**, meaning worse performance.

•Higher values of **ρ (e.g., 0.8)** lead to **lower BER**, indicating better performance.

Comparison of Theoretical vs. Simulated Results

•The **solid lines represent theoretical results**, while the **dashed lines represent simulated results**.

•The simulation results closely follow the theoretical predictions, validating the model's accuracy.

•The theoretical and simulated curves converge at higher SNR values, indicating that the analytical model accurately predicts BER behavior in strong signal conditions.

Outage probability analysis of SWIPT System

Outage probability relative to γ_0 is defined as

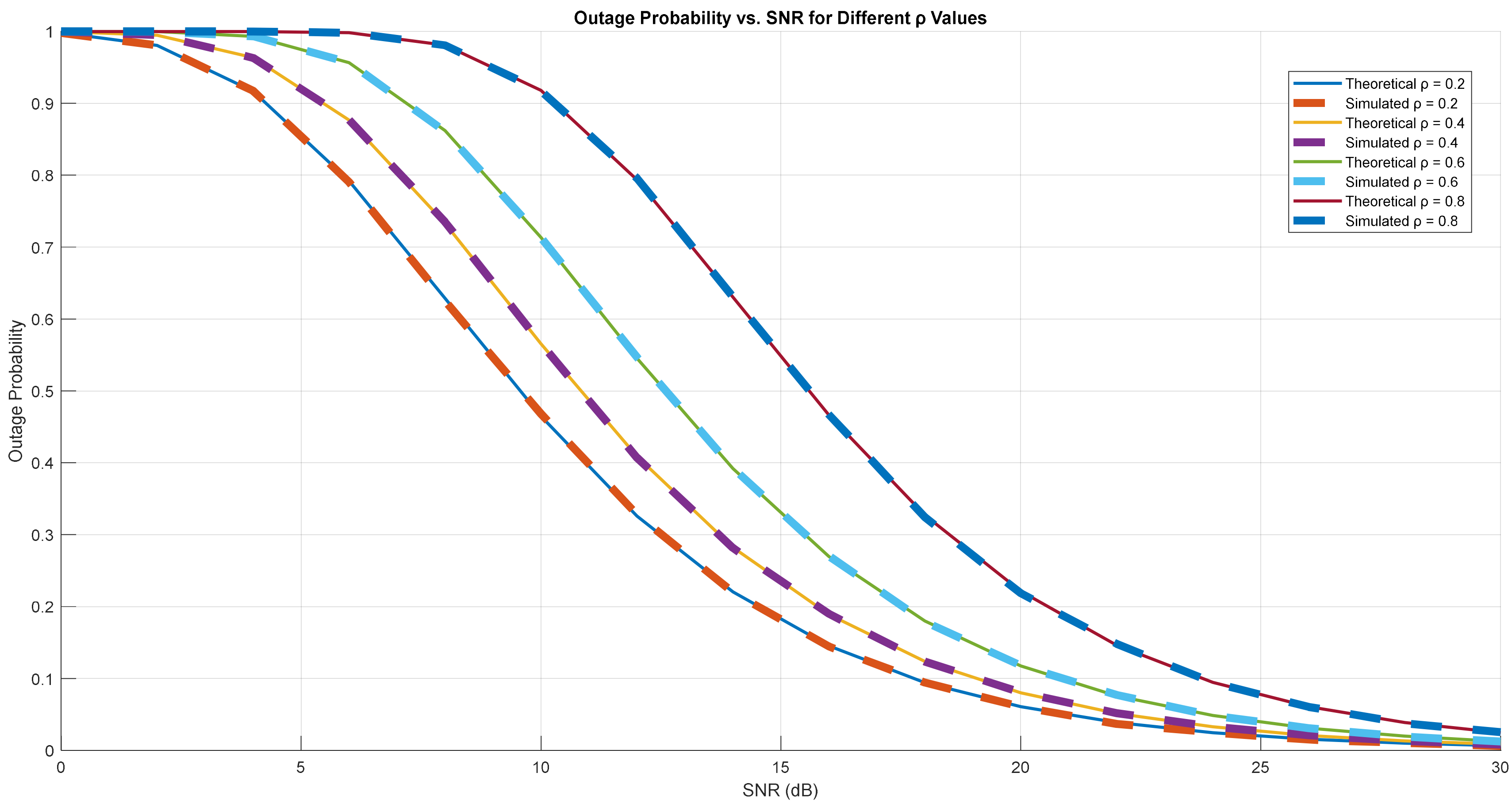
$$P_{out} = p(\gamma_s < \gamma_0) = \int_0^{\gamma_0} p_{\gamma_s}(\gamma)d\gamma \text{............(23)}$$

In Rayleigh fading the outage probability becomes

$$P_{out} = \int_0^{\gamma_0} \frac{1}{\bar{\gamma}} e^{\frac{-\gamma_s}{\bar{\gamma}_s}} d\gamma_s = 1 - e^{\frac{-\gamma_0}{\bar{\gamma}_s}} \text{................(24)}$$

By coding and plotting this equation we can plot SNR v/s outage plot

SNR v/s Outage probability



Observation from the plot

General Trend

- **Outage Probability decreases as SNR increases**, which is expected in wireless systems.
- At **low SNR values**, outage probability is close to 1 (meaning communication failure is highly likely).
- At **high SNR values**, outage probability approaches 0, indicating successful transmission.

Effect of Power Splitting Ratio (ρ) on Outage Probability

- Different power splitting ratios **affect the outage probability performance**.
- **Lower ρ (e.g., 0.2)** results in a **higher outage probability**, indicating poorer performance.
- **Higher ρ (e.g., 0.8)** leads to a **lower outage probability**, meaning better performance.
- This confirms that allocating **more power for information decoding (higher ρ)** improves reliability**.**

Comparison of Theoretical vs. Simulated Results

- **Theoretical results (solid lines) closely match simulated results (dashed lines).**
- The alignment of these curves validates the accuracy of the theoretical model**.**

Conclusion

- The results confirm the **trade-off between energy harvesting and data transmission reliability**.
- **For low-SNR scenarios, all ρ values show high outage probabilities**, meaning poor reliability.
- **For high-SNR values, increasing ρ significantly reduces outage probability**, improving the system's overall performance.
- The **optimal value of ρ depends on the system's energy and communication requirements**.

Power Trade off analysis

- To quantity the received power which gets splits in two paths we can derive and plot those in MATLAB.

$P_t = G_{PA}.P_{in}$.........(25)

$P_r = |h|^2.P_t.L_p + N_0$.......(26)

$P_{EH} = \rho.P_r$ ....(27)

$P_{ID} = (1-\rho).P_r$..........(28)

$\eta_{EH} = \frac{P_{EH}}{P_t}$......................(29)

$\eta_{ID} = \frac{P_{ID}}{P_t}$.............(30)

$$\eta_{total} = \frac{P_{EH}+P_{ID}}{P_t} \qquad (31)$$

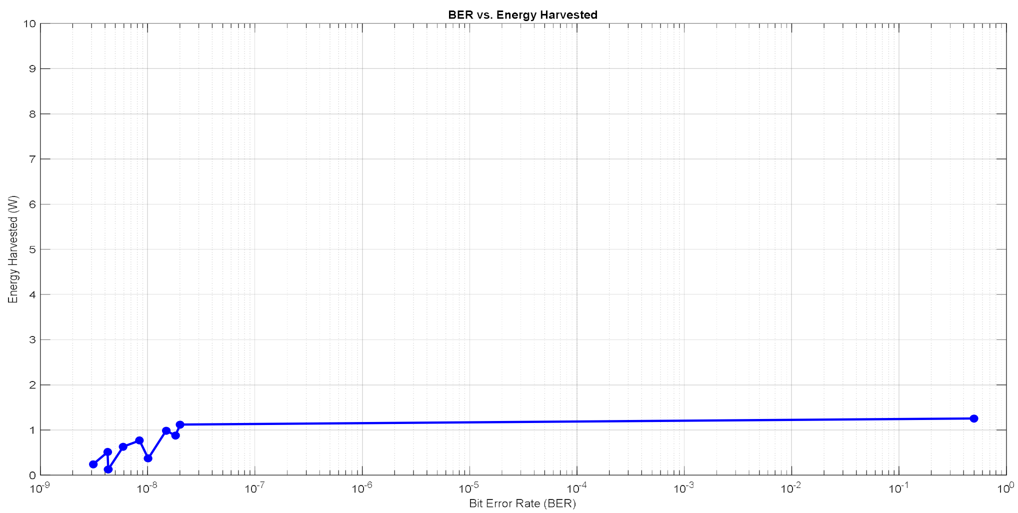
These equations gives when codded in MATLAB we can get the power trade off table.

Power Splitting Ratio	$P_t(W)$	$P_r(W)$	$P_{EH}(W)$	$P_{ID}(w)$	η_{EH}(%)	$\eta_{ID}(\%)$	η_{total} (%)
0.0	10.0	1.24999	0.00000	1.24999	0	100	12.50
0.1	10.0	1.24999	0.12500	1.12499	10	90	12.50
0.2	10.0	1.24999	0.25000	0.99999	20	80	12.50
0.3	10.0	1.24999	0.37500	0.87499	30	70	12.50
0.4	10.0	1.24999	0.49999	0.74999	40	60	12.50
0.5	10.0	1.24999	0.62499	0.62499	50	50	12.50
0.6	10.0	1.24999	0.74999	0.49999	60	40	12.50
0.7	10.0	1.24999	0.87499	0.37500	70	30	12.50
0.8	10.0	1.24999	0.99999	0.25000	80	20	12.50
0.9	10.0	1.24999	1.12499	0.12500	90	10	12.50
1.0	10.0	1.24999	1.24999	0.00000	100	0	12.50

Power trade off table

Feasible power Quantification

- Feasible power is being quantified from the EH power v/s BER plot.
- This plot can be used to quantify the point where the power harvested is more but the BER is less
- This plot signifies the point where the information can be decoded with minimal or no error and the rest of the signal power can be harvested.



Conclusion

- We modelled a SWIPT system and analyzed the processing of signals through the model
- Derived the BER and SNR and outage probability of the SWIPT system
- Simulated the experimental and theoretical analysis of BER v/s SNR plot and SNR v/s outage plot

References

1. S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: Opportunities and challenges," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 117–125, Apr. 2015.
2. L. R. Varshney, "Transporting information and energy simultaneously," in *Proc. IEEE International Symposium on Information Theory (ISIT)*, Toronto, ON, Canada, 2008, pp. 1612–1616.
3. X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Transactions on Communications*, vol. 61, no. 11, pp. 4754–4767, Nov. 2013.
4. Y. Zeng and R. Zhang, "Optimized training design for wireless energy transfer," *IEEE Transactions on Communications*, vol. 63, no. 2, pp. 536–550, Feb. 2015.
5. M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*, 2nd ed. Hoboken, NJ, USA: Wiley, 2005.
6. H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 418–428, Jan. 2014.

THANK YOU