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The Joint Channel Coding and Pre-Distortion Technique on the USRP-Based MIMO-OFDM System

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Abstract

Modern wireless communication systems use Orthogonal Frequency Division Multiplexing (OFDM), a multi-carrier modulation method that resists multipath channels and provides bandwidth efficiency. OFDM is generally used with a Multiple-Input Multiple-Output (MIMO) system to boost diversity gain and channel capacity. MIMO-OFDM has several advantages, but its high PAPR value is a drawback. A non-linear high-power amplifier (HPA) can distort signals with high PAPR values. This issue can be resolved by employing pre-distortion (PD), which compensates for non-linear HPA. In addition to PD, channel coding can be used to improve the quality of systems with high PAPR values by adding redundant bits to the bits to be sent. In this paper, we report the experimental evaluations of the joint channel coding and pre-distortion (PD) technique on a 2x2 MIMO OFDM system using USRP hardware. The experiments are conducted in two scenarios: line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. The channel coding that is used in this scenario is convolutional code with code rates of 1/2, 2/3, and 3/4. From the experiment results, it can be seen that the system using PD combined with the convolution code produces better performance in LOS and NLOS scenarios compared to the system without PD. In the LOS scenario, the use of PD can improve the SNR value of code rates 1/2, 2/3, and 3/4 by about 58.74%, 75.97%, and 96.20%. In the NLOS scenario, the use of PD can improve the SNR value of code rates 1/2, 2/3, and 3/4 by about 60.71%, 73.59%, and 71.84%. The LOS scenario measurement gives a better SNR value than the NLOS scenario, with a maximum SNR value of 30.86 dB, while the NLOS scenario maximum SNR value is 30.23 dB. This happened because the LOS scenario suffered minimal multipath fading compared to the NLOS scenario.

Keywords: *MIMO; OFDM; convolutional coding; USRP; pre-distortion*

1. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) as a multi-carrier modulation system has been adopted in several modern wireless communication systems because it can effectively eliminate inter-symbol interference (ISI) caused by the effect of multipath channels and increase bandwidth efficiency. OFDM can be combined with Multiple-Input Multiple Output (MIMO) systems, which use multiple antennas at the transmitter and receiver. By using the MIMO technique, the diversity gain and the system capacity are increased. Thus, MIMO-OFDM is the key technique for future wireless networks to increase high data rates and enhance the system's performance in multipath fading environments.

Since noise and other factors from wireless channels can alter the bit input stream, adding additional bits can make the bit error checking process at the receiver more successful. When a greater number of bits are transmitted than the original bit stream, redundancy is resulted, which can be used to determine the original bit stream or signal at the receiver. The redundancy can be generated by implementing the convolution code. As an error-correcting code, convolutional codes can improve the system's performance, as studied in a paper [1]. The authors in [1] report that the convolution coding may improve the symbol error rate (SER) performance of the OFDM system. The application of convolution code in MIMO OFDM systems has been studied in [2]–[4].

Papers [5], [6] describe experiments with forward error correction in software-defined radio (SDR). In paper [5], the authors describe the design and implementation of the Forward Error Correction (FEC) on a single carrier with a BPSK modulation scheme using a small form factor (SFF) SDR platform. In the paper [6], the authors use LabVIEW to develop a SDR-based PSK transceiver system and analyze its performance. The results show that the coding technique minimizes data

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errors and improves the signal-to-noise ratio (SNR). Then the experiments with multicarrier modulation, such as the OFDM system in software-defined radio (SDR), are reported in papers [7],[8]. In this paper [7], a SDR-based OFDM communication system using the GNU radio and the Universal Software Radio Peripheral (USRP) is proposed to transmit video signals. The experiment shows the video picture can be seen at the receiver. The paper [8] conducts an experiment on OFDM communication with 200 tones and 128 cyclic prefixes using the NI USRP-2901 and the GNU RADIO platform in the HF and UHF maritime bands. And the authors state that no communication errors were found during the experiments. The two experiments still use a single antenna on the transmitter and receiver sides, so they are called the SISO-OFDM system. The experiment with a MIMO system using USRP hardware is reported in papers [9,10]. In a paper [9], the authors conducted an assessment of the Selection Combining (SC), Maximum Radio Combiner (MRC), Alamouti Code, Zero Forcing (ZF), and MMSE algorithms on USRP devices. From simulations and experiments, it can be shown that the combination of multiple channels (MIMO scheme) may improve the reliability or throughput of a communication system, which are presented by BER curves and symbol constellations. The paper [10] studied the 2x2 MIMO Alamouti system using NI USRP in LabVIEW and presented the system's performances in BER and scatter plots.

With the advantages of OFDM and MIMO systems, the joint of the two technologies became the dominant air interface for 4G and 5G wireless networks. The studies of the MIMO-OFDM system in software and hardware have attracted many researchers, and some experiment studies of the MIMO-OFDM system using USRPs hardware are reported in papers [11]–[13]. In the paper [11], the authors conduct an experiment of 2 x 2 MIMO-OFDM with 16-QAM, 64-QAM, and 256-QAM modulations using USRP N210 hardware devices. The STBC algorithm was selected for the spatial diversity of MIMO-OFDM, and the results are presented in bit error rate (BER) curves and symbol constellations for different modulation levels. In this study, the system schemes used are Line of Sight (LOS) and Non-Line of Sight (NLOS). In the paper [12], the authors proposed an OFDM-MIMO transceiver design and used GNU Radio to evaluate the system's performance on the error rate term for different modulation techniques. Paper [13] demonstrates the performance of OFDM-MIMO with two antennas at the transmitter and receiver sides with convolution code using Matlab and USRP B210. Matlab software is used to simulate the AWGN, Rician, and Rayleigh channels, produce the bit error rate curves for different channels, and perform performance comparisons with and without using convolution code.

OFDM is a multi-carrier system where the OFDM signal is the superposition of several sub-modulated signals, resulting in a high peak-to-average power ratio (PAPR). The high PAPR signals will produce nonlinear distortions when passed through a nonlinear high power amplifier (HPA), since the HPA operates in its nonlinear region. Then the Peak-to-Average Power Ratio (PAPR) reduction technique became an interesting study to solve the high PAPR problem for OFDM and MIMO-OFDM systems. The disadvantage of the PAPR reduction technique is that it decreases the power efficiency of HPA since HPA works far below its saturation level. Therefore, another solution is proposed to increase the power efficiency of HPA by enlarging the linear region of HPA using a technique called pre-distortion. A pre-distorter (PD) must be applied prior to the HPA to provide complementary characteristics of the HPA or to compensate for the nonlinearity characteristics of the HPA. Since HPA is inherently a nonlinear system, the nonlinearity characteristics of HPA cause in-band signal distortion and spectral regrowth. Thus, PD is needed to improve the distorted signal or BER performance and reduce spectral regrowth. The utilization of Digital Predistortion (DPD) in OFDM systems has been widely investigated, e.g., in papers [14]–[16]. In the paper [14], the authors investigated the real-time implementation of a DPD algorithm in the CPU core of the laptop computer for two different external power amplifiers. Experiment results proved that DPD can reduce the spectral regrowth of two different power amplifiers and improve the symbol constellations. In the paper [15], the authors proposed utilizing DPD on the nonlinear weighted overlap and add OFDM (WOLA-OFDM) with nonlinear HPA. The simulation results verify that by utilizing DPD, out-of-band (OOB) performance can be improved or spectral regrowth can be significantly reduced. The modified differential evolution (MDE) algorithm to identify the optimal parameter of digital DPD models is proposed in the paper [16]. By using the MDE algorithm, the authors focus on computer resources and computational time to derive the optimal DPD models.

Then the implementation of DPD on MIMO-OFDM systems became an interesting research topic, and some studies on this topic have been reported in papers [17]–[20]. In the paper [17], the authors evaluate the MIMO-OFDM system performance using the digital PD (DPD) cascaded with nonlinear HPA. The result of this paper is that a system that uses DPD+HPA has the same performance as a linear system without HPA in multiple modulation scenarios and multiple MIMO-OFDM antenna scenarios. This happened because the cascaded DPD successfully compensated the non-linear HPA. The implementation of DPD before IDFT or OFDM signals as known frequency domain (FD) DPD is studied in [18]–[20]. Paper [18] investigates the impacts

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of DPD on spectral at the transmitter side for hybrid massive MIMO. Papers [19],[20] use a neural network (NN)-based DPD taking place before the precoding for the MU-MIMO system. And reported that the DPD may reduce the spectrum regrowth of transmitted signals. The paper [20] showed that the NN DPD produces better SER performance, close to the performance of MIMO systems with ideal HPA, than without using DPD.

In the paper [21], the author studied the neural network-based DPD for a 2x2 MIMO-OFDM system using USRP and LabVIEW software. And by changing the distance between the MIMO transmitter and receiver, the experiments results show that DPD can improve the symbol constellation of QAM signals at the receiver. Those experiments are evaluated for the LoS condition only. In NLoS conditions, the received signals are affected by the multipath fading effect. Therefore, we proposed the experiment of 2 x 2 MIMO-OFDM for Los and NLoS conditions using NI USRP and LabView software.

In this research, we will discuss a joint technique of channel coding and predistortion techniques to improve the quality of a MIMO-OFDM system that is distorted due to high PAPR values processed on non-linear HPA on USRP devices. The contribution to this research is to combine predistortion and channel coding with the convolutional coding type to improve system quality compared to systems that only use predistortion in research [21]. In addition, this system also uses the maximum-likelihood data-aided method to estimate the SNR value for USRP receivers since USRP devices are uncalibrated devices. Evaluation of this system will be carried out with LOS and NLOS scenarios with changes in the code rate value in convolutional coding. Furthermore, because the system is implemented on USRP devices, the channel conditions on this system are real-world channels.

2. Research Methods

2.1 MIMO-OFDM

We propose the MIMO OFDM system model with joint channel coding and pre-distorter (PD), which will be investigated by using USRP hardware and LabView software as shown in Figure 1.

First, a convolution encoder takes bit streams as input and turns them into codeword streams. The length of the codes depends on the code rate. The codeword streams are then mapped by the QAM modulation scheme to produce the symbol streams, which will be separated into two symbol streams by MIMO demuxing with a spatial multiplexing scheme. Each symbol stream is converted into an N-parallel symbol stream by the SP block, where N is the IFFT size or number of subcarriers, and then processed by the IFFT to generate an OFDM symbol.

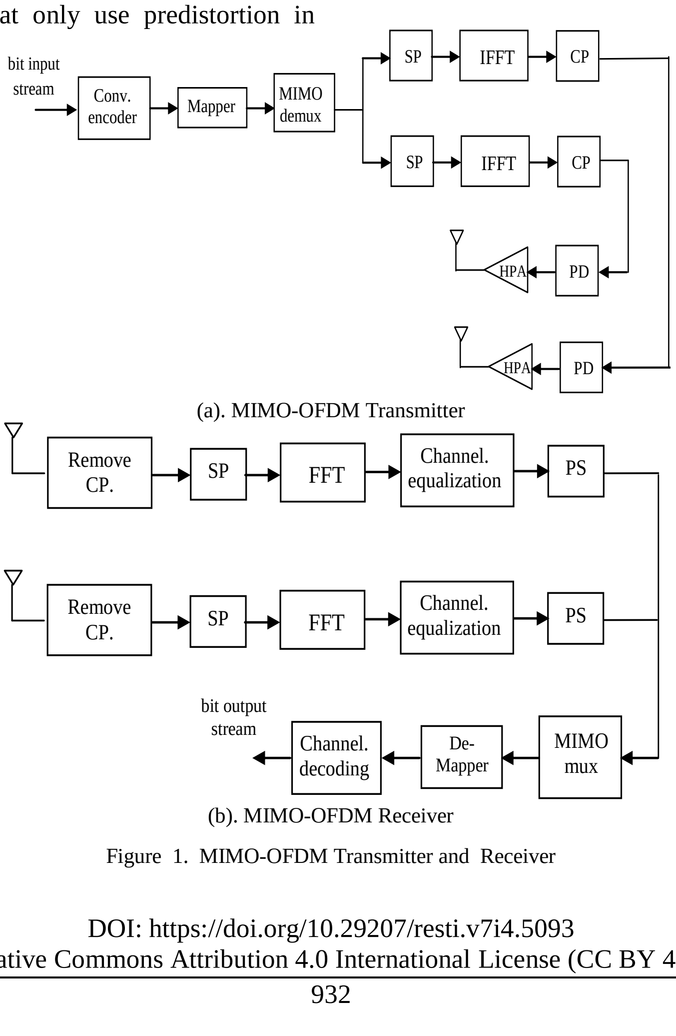

Figure 1. MIMO-OFDM Transmitter and Receiver

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After that, the cyclic prefix is inserted into the OFDM symbol and then passed through the pre-distorter and HPA to be transmitted via antenna. The baseband OFDM signal of the i-th transmit antenna can be written in Equation 1[22].

$$x_i(n) = \sum_{k=0}^{N} X_i(k) \exp\left(j2\pi n \frac{k}{N}\right) \quad (1)$$

where N and X_i are the number of sub-carriers or Inverse Fast Fourier transform (IFFT) size and a complex QAM modulated signal of the i-th transmit antenna, respectively.

On the receiver side, two OFDM signals that are received by two antennas will be processed by OFDM demodulators that consist of cyclic prefix removal, serial-to-parallel conversion, FFT, channel equalization, and parallel-to-serial conversion processes to produce two symbol streams. By using a combiner, two symbol streams are processed to result in a symbol stream that will be converted into a code stream by a demapper or QAM demodulator. Finally, by using a convolutional decoder, the output bit stream will be produced.

2.2 MIMO-OFDM

Block diagram of a simple convolution coding is shown in Figure 2.

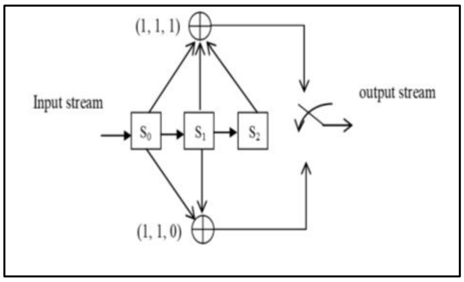

Figure 2. Diagram block simple convolution code

Figure 2 shows an example basic convolution coder with $K = 3$, $r = 2$, where K and r are the number of shift registers and summing operations, or modulo-2 adders, respectively. In this figure, the generator vectors are chosen as [1 1 1] and [1 0 1]. In the encoder, data bits are put into a shift register with a length of K. Each bit goes into the register on the far left. A bit in the first register is shifted to the second register, and a bit in the second register is shifted to the third register. Then bits values in register S_0, S_1, and S_2 are summed by the upper modulo-2 adder to create code x_1, while bits values in register S_0 and S_1 are summed by the lower modulo-2 adder to create code x_2 during one data flow period. Then a positional switch will compile x_1 and x_2 produce the overall output code in the manner described in Equation 2.

$$x = x_1, x_2, x_1, x_2, \ldots \quad (2)$$

2.2 Pre-Distortion (PD)

Signals with a high peak-to-average power ratio (PAPR) value, such as OFDM signals, require a large power backoff to push a HPA into its linear region. But this way may result in low power efficiency for HPA, and one promising solution to increase power efficiency is the PD technique. And the DPD is a popular linearization technique that uses digital signal processing in the baseband and may correct the inherent impairments of RF HPAs. These impairments cause out-of-band emissions, or spectral regrowth, and in-band distortion, which correlate with an increasing bit error rate (BER).

PD is the inverse of HPA's behavior and is placed before HPA to compensate for its nonlinear behavior. Thus, PD enlarges the linear region of HPA and may pre-distort the OFDM envelopes, and the signal distortions that are introduced by HPA can be removed. The basic principle of the PD technique can be seen in Figure 3.

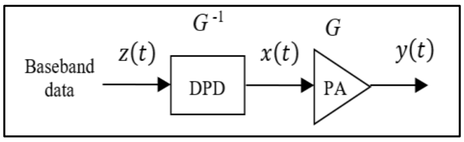

Figure 3. Basic Principle of PD technique

$z(t)$, $x(t)$ and $y(t)$ are assumed as input signal of pre-distorter (PD), output signal and input signal of HPA). When G is assumed as the transfer function of HPA and F as the transfer function of the pre-distorter, then the PD process can be explained as in Equation 3.

$$y(\mathrm{t}) = G\,x(t) = G\,(F(z(t))) = G.F = L(z(t)(3)$$

where $G.F = L$ represents a composite function from G and F. The linearity for HPA can be written as in Equation 4.

$$y(t) = L(z(t)) = g.z(t) \quad (4)$$

where g is ideal amplitude magnification of HPA, ($g > 1$). In this paper, we present a pre-distorter based on DPD for the HPA Saleh model. The Saleh model was first proposed in [23,24]. An input for this model can be written in Equation 5.

$$x(t) = r(t) \cos[\omega 0t + \varphi(t)] \quad (5)$$

where $r(t)$, ω_0 and φ are the envelope of the input signal, carrier frequency and the phase respectively. And the output can be written in Equation 6.

$$y(t) = A[r(t)] \cos\{\omega 0t + \varphi(t) + \Phi[r(t)]\} \quad (6)$$

where, $A[r(t)]$ is an odd function of the envelope, $r(t)$, while $\Phi[r(t)]\}$ is an even function of $r(t)$. The AM/AM and AM/PM characteristics can be written in Equations 7 and 8.

$$A[r(t)] = \frac{\alpha_A r(t)}{1+\beta_A \{r(t)\}^2} \quad (7)$$

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$$\phi[r(t)] = \frac{\alpha_\phi\{r(t)\}^2}{1+\beta_\phi\{r(t)\}^2} \quad (8)$$

where α is the small signal gain, and β is the gain compression. The PD for HPA Saleh model is reported in [25] and can be written in Equation 9.

$$F[x(t)] = G^{-1}[r(t)] = \frac{\alpha_A - \sqrt{\alpha_A^2 - 4\,\beta_A\{r(t)\}^2}}{2\beta_A r(t)} \quad (9)$$

2.3 SNR Calculation

In this paper, the SNR values are derived using the maximum likelihood data-aided estimator formula [26] that can be written in Equation 10.

$$\hat{y} = \frac{[\sum_{i=1}^{g}(r_{i_I}m_{i_I}+r_{i_Q}m_{i_Q})]^2}{\frac{\varepsilon_{av}^2}{g}\sum_{i=1}^{g}|r_i|^2 - \varepsilon_{av}[\sum_{i=1}^{g}(r_{i_I}m_{i_I}+r_{i_Q}m_{i_Q})]^2} \quad (10)$$

Where $\hat{y}$ is estimated SNR value, $r_{i_I}m_{i_I}$ is inphase component of i-th received symbol, $r_{i_Q}m_{i_Q}$ is quadrature component of i-th received symbol, g is the length of symbol. While the ε_{av} can be expressed in Equation 11.

$$\varepsilon_{av} = \sum_{i=1}^{g}(m_{i_I} + m_{i_Q}) \quad (11)$$

The values of $r_i, r_{i_I}m_{i_I}$ and $r_{i_Q}m_{i_Q}$ are read from USRP and used to calculate the SNR value based on formula (10) which are plotted for different schemes, LoS and NloS scenarios.

2.4 Universal Software Radio Peripheral (USRP)

The USRP is a software-defined radio platform that enables the design and construction of wireless communication systems. It is made up of a hardware module that connects to a host computer and can be programmed with software-defined radio (SDR) utilities like GNU Radio and LabVIEW. The USRP is a versatile and scalable platform for testing and prototyping a wide variety of wireless communication systems, including cellular networks, wireless local area networks (WLANs), and cognitive radio systems. It has a programmable RF front-end, digital signal processing based on an FPGA, and a wide range of interfaces for connecting to antennas and other hardware parts. In this paper, we use NI-USRP 2920 hardware to implement and run the model we proposed. This NI-USRP 2920 will then be programmed with LabVIEW and Python.

2.5 Experiment Topology

We use four USRP as transceivers to build the proposed MIMO-OFDM system with convolution coding and the PD technique. The four USRPs will be grouped into transmitters and receivers. Each device in the group will work synchronously by using a MIMO cable to synchronize the frequency and clock of each device. The transmitters and receivers will then be connected to the host PC using an Ethernet cable. The host PC is used to execute the programs of transmitters and receivers. The implementation of this topology is shown in Figure 4.

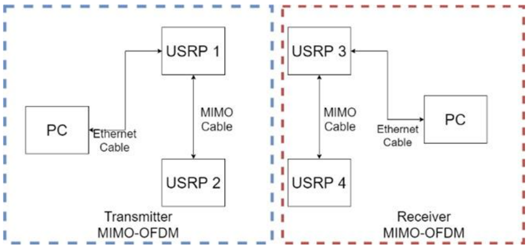

Figure 4. Experiment Topology

The realization of the experiment topology is shown in Figures 5 and 6. Figure 5 shows the realization of the experiment topology in the line-of-sight (LOS) scenario, and Figure 6 shows the non-line-of-sight (NLOS) scenario.

Figure 5. LOS Scenario

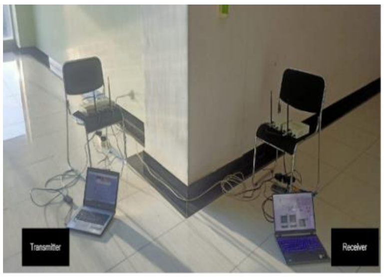

Figure 6. NLOS Scenario

The hardware specification of the setup in the figure 5 and Figure 6 can be seen in Table 1.

Table 1. Hardware Specification

Device Name	Specification
NI-USRP 2920	Frequency Range : 50MHz – 2.2 GHz Connector: Ethernet
Antenna VERT 900	Frequency Range: 824 MHz – 960 Mhz, 1710 MHz – 1990 MHz
Receiver PC	Operating System: Windows 11 RAM: 16GB, Processor: Intel Core i7 12700H 4.7 GHz
Transmitter PC	Operating System: Windows 10 RAM: 8GB, Processor: Intel Core i5 8th Gen 2.5 GHz

2.5 Experiment Topology

This section presents the experimental scenarios used in the proposed system. We conducted an experiment on the fourth floor of the Pascasarjana PENS Building and

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tested for two scenarios: line-of-sight (LOS) and non-line-of-sight (NLOS), as illustrated in Figures 5 and 6.

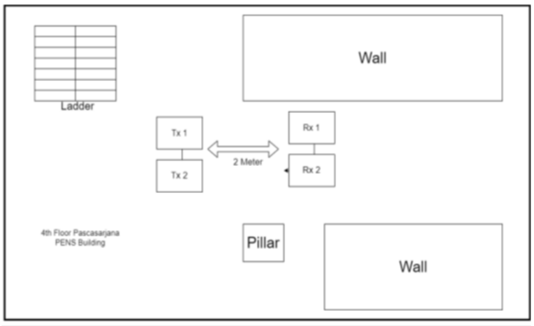

Figure 7. Layout of LOS Scenario

In the LOS measurement scenario, a distance of 2 meter is used between the MIMO-OFDM transmitter and receiver. In the NLOS measurement scenario, the transmitter and receiver are 1 meter from the corner of the dividing wall. The experiment layouts for the LOS and NLOS scenarios can be seen in Figures 7 and 8. For each scenario, we measured the signal-to-noise ratio (SNR) at the receiver of the proposed system. The goal of the experiment was to find out the performance of the MIMO-OFDM system when PD and convolution coding are used together.

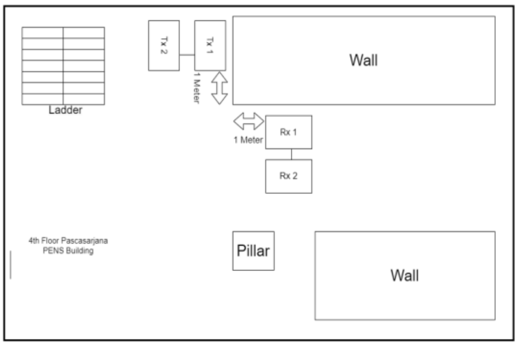

Figure 8. Layout of NLOS Scenario

PD is used to compensate for the non-linearity of the HPA. The HPA model used for this paper is a Saleh model with parameters $\alpha = 2.1587$ and $\beta = 1.517$ [32].

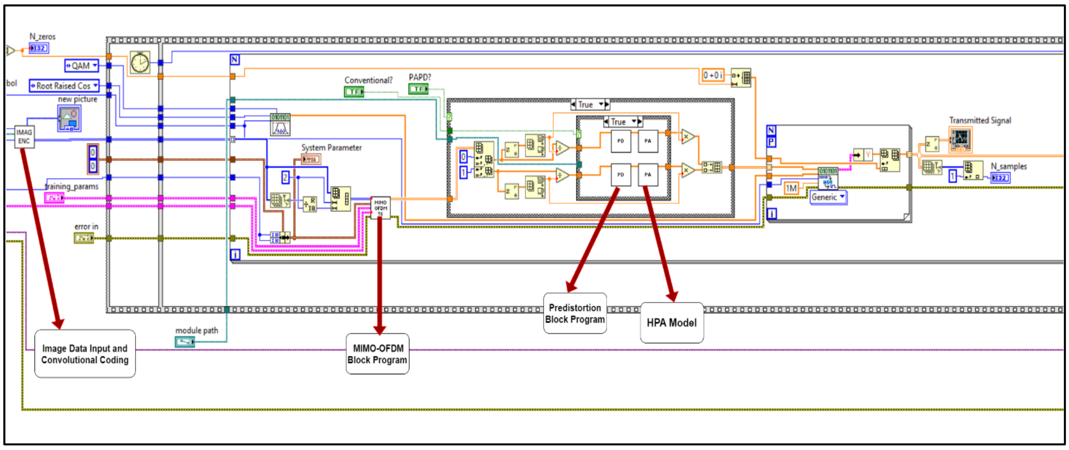

Figure 9. Transmitter Block Program LabVIEW

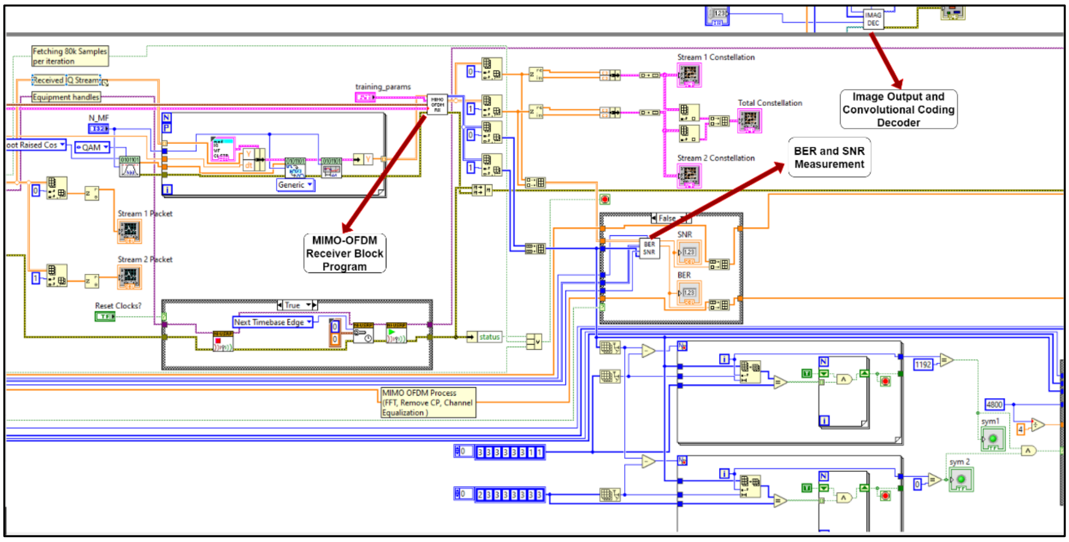

Figure 10. Receiver Block Program LabVIEW

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The PD method used is digital PD. We used convolution coding with code rates of 1/2, 2/3, and 3/4 with constraint length (k) = 3 and assessed the impact of code rates and PD on the proposed system's performance. These techniques were employed with the aim of improving the overall performance of the system. For implementing this system, we used a transmitter and receiver LabVIEW block program that can be seen in Figures 9 and 10.

3. Results and Discussions

In this section, we present the experimental results of the proposed system. The experiments were conducted in the Pasca Sarjana buildings of Politeknik Elektronika Negeri Surabaya, Indonesia. The parameters in Table 2 are used to conduct the experiment.

Table 2. Experiment Parameter

Session	Parameter	Value
Transmitter	Frequency	915MHz
	N-IFFT	128
	Data symbol	96
	Pilot symbol	9
	Null symbol	23
	CP	32
	IQ Rate	1M
	Antenna	2
	HPA	Saleh
	Channel Coding	Convolutional
	Rate	1/2, 2/3, 2/4
	Modulation	4-QAM
Receiver	Channel Equalization	*Zero-Forcing*
	Channel Estimation	*Least Square*
	Frame Sync	ZC
	Antenna	2

3.1 Results for LOS Scenario

In this scenario, the maximum SNR graphs and received data results are used to measure how well the proposed system works. Measurements were made for MIMO-OFDM systems using HPA without PD and for MIMO-OFDM systems using PD+HPA joint with convolution coding. The code rates of convolutional code are 1/2, 2/3, and 3/4. The input data in this experiment is image data in bmp format with a resolution of 360 x 480 pixels. The symbol modulation is the QAM modulation scheme. The received signal and QAM symbol constellations at the MIMO-OFDM receiver for LOS scenario for different code rate without PD are shown in Figure 11a-c.

While the received signal and QAM symbol constellations at the MMO-OFDM receiver for LOS scenario for different code rate by using PD are shown in Figure 12a-c. From Figure 12 and Figure 13, there are several SNR values that were obtained during the measurement. These SNR values for each scenario are provided in Table 3.

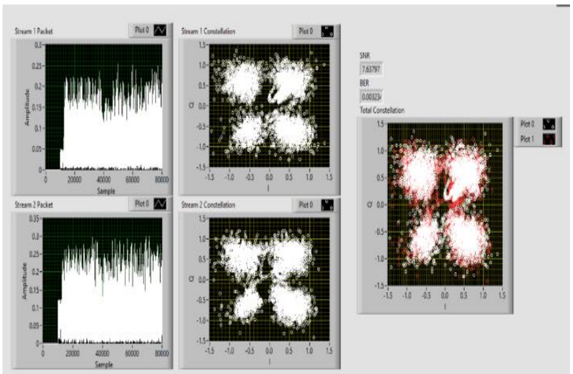

Figure 11a. The received signal and symbol constellation for LOS scenario, HPA and code rate = 1/2

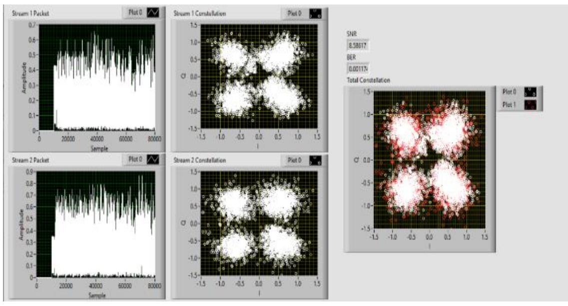

Figure 11b. The received signal and symbol constellation for LOS scenario, HPA and code rate =2/3

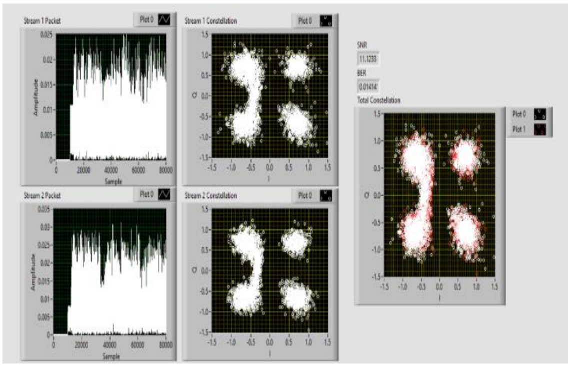

Figure 11c. The received signal and symbol constellation for LOS scenario, HPA and code rate = 3/4

Table 3. SNR Values for LOS scenario measurement

Scenario	SNR (dB)
HPA and Code Rate = 1/2	7.638
HPA and Code Rate = 2/3	8.586
HPA and Code Rate = 3/4	11.123
HPA+PD and Code Rate = 1/2	21.119
HPA+PD and Code Rate = 2/3	20.576
HPA+PD and Code Rate = 3/4	22.814

Comparing Figures 11 and 12 by evaluating the symbol constellations and SNR values at the receiver, it can be seen that the PD improves the system's performance. Where the spread of constellation nodes is not large and the SNR value for the system using PD with code rate = 3/4 is 22.814 dB, it is better than without PD, which is 11.123 dB. Next, this measurement is repeated several times and SNR Max value is obtained during this action shown in Figure 13.

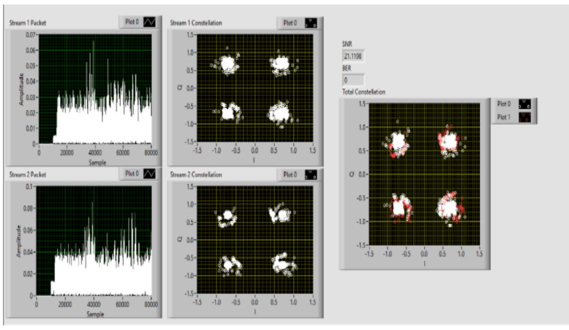

Figure 12a. The received signal and symbol constellation for LOS scenario, PD+HPA and code rate = 1/2

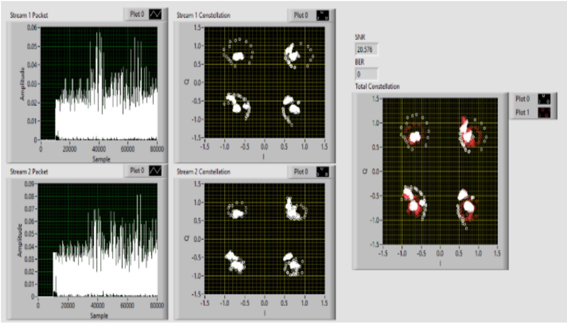

Figure 12b. The received signal and symbol constellation for LOS scenario, PD+HPA and code rate = 2/3

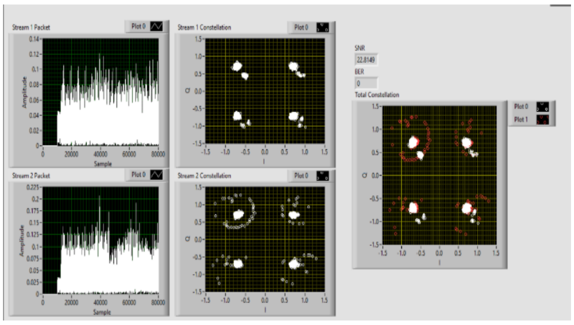

Figure 12c. The received signal and symbol constellation for LOS scenario, PD+HPA and code rate = 3/4

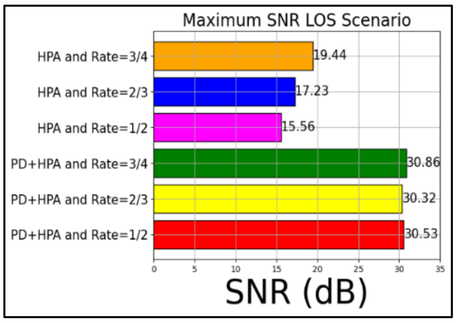

Figure 13. Maximum SNR plot in LOS Scenario

From Figure 13, it can be seen that the MIMO-OFDM system without PD and code rate = 1/2 gives the smallest SNR value of 15.56 dB, and the system using PD and code rate = 3/4 gives the highest SNR value of 30.86 dB. The percentage increase in SNR due to the use of PD for each LOS scenario with code rates 1/2, 2/3, and 3/4 is 58.74%, 75.97%, and 96.20%.

3.2 Results for NLOS Scenario

For the NLOS scenario, we use the same variables used for LOS. The received signal and symbol constellation at the receiver without PD are shown in Figure 14a-c.

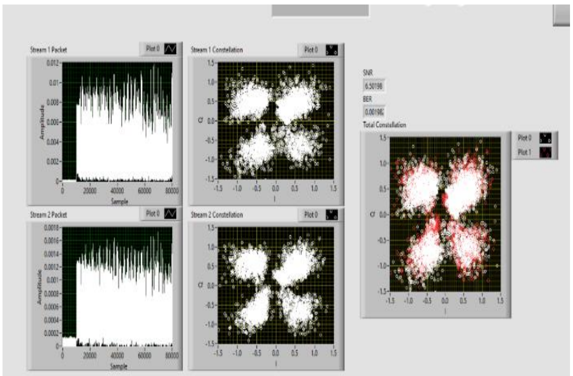

Figure 14a. The received signal and symbol constellation for NLOS scenario, HPA and code rate = 1/2

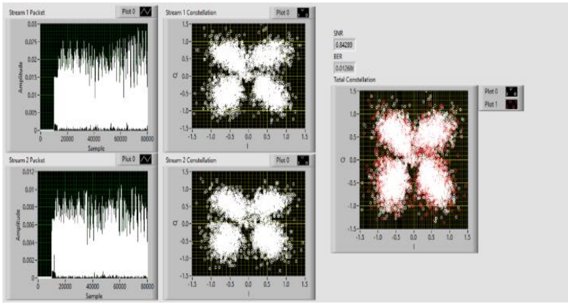

Figure 14b. The received signal and symbol constellation for NLOS scenario, HPA and code rate = 2/3

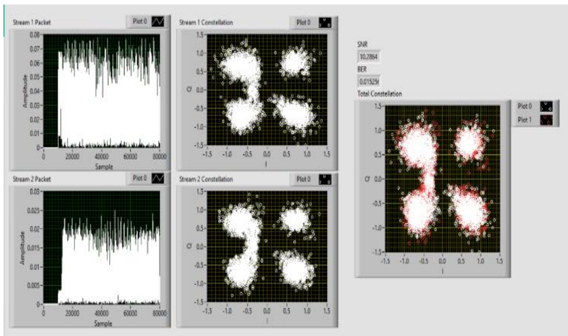

Figure 14c. The received signal and symbol constellation for NLOS scenario, HPA and code rate = 3/4

While the received signal and symbol constellation at the receiver by using PD are shown in Figure 15a-c.

From Figure 14 and Figure 15, there are several SNR values that were obtained during the measurement. These SNR values for each scenario are provided in Table 4.

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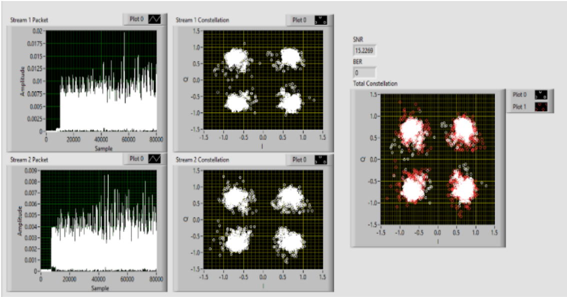

Figure 15a. The received signal and symbol constellation for NLOS scenario, PD+HPA and code rate = 1/2

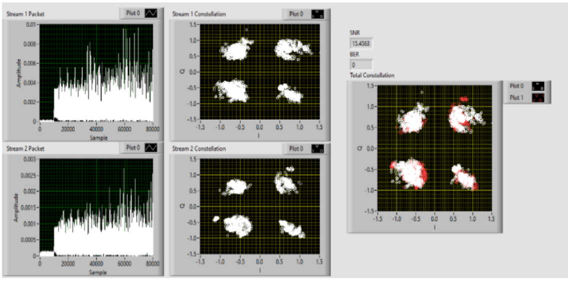

Figure 15b. The received signal and symbol constellation for NLOS scenario, PD+HPA and code rate = 2/3

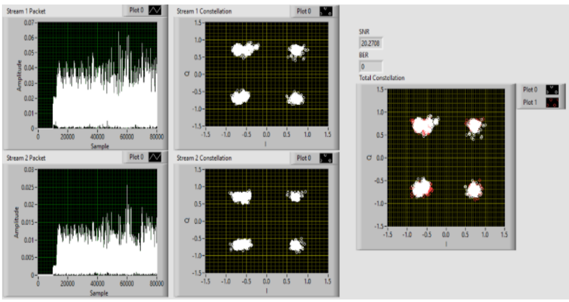

Figure 15c. The received signal and symbol constellation for NLOS scenario, PD+HPA and code rate = 3/4

Table 4. SNR Values for NLOS scenario measurement

Scenario	SNR (dB)
HPA and Code Rate = 1/2	6.501
HPA and Code Rate = 2/3	6.842
HPA and Code Rate = 3/4	10.286
HPA+PD and Code Rate = 1/2	15.226
HPA+PD and Code Rate = 2/3	15.456
HPA+PD and Code Rate = 3/4	20.27

By comparing Figures 14 and 15, we conclude that PD gives the system performance improvements, where the SNR value is 20.27 dB for a code rate of 3/4, better than without PD, which is 10.286 dB. This NLOS scenario measurement is repeated several times too, and the SNR max value is obtained during this action, as shown in Figure 16.

From the maximum SNR plot, it can be seen that the MIMO-OFDM system using PD and a code rate of 3/4 gives a maximum SNR value of 30.23 dB. While the system without PD and a code rate of 1/2 gives the smallest SNR value of 15.52 dB. The percentage increase in SNR due to the use of PD for each NLOS scenario with code rates 1/2, 2/3, and 3/4 is 60.71%, 73.59%, and 71.84%. So it can be concluded that PD and higher code rates give the highest SNR value for this scenario.

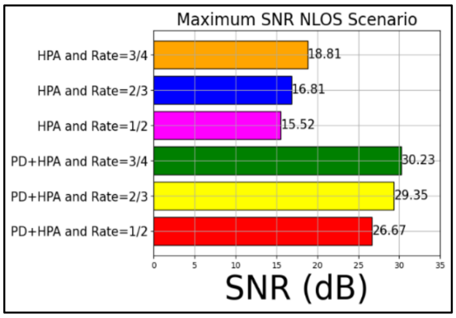

Figure 16. Maximum SNR plot in NLOS Scenario

4. Conclusion

From the experiment results, it can be verified that the pre-distortion technique can improve the signal quality or remove the in-band distortions generated by non-linear HPA. The improvements are shown as a constellation node in the received signal. Since we also transmit the signal through the NLoS condition, the multipath effects of the NLoS link influence the received signal. Therefore, we implement the convolution coding with different code rates to verify the improvements in the maximum SNR value. The simulation results show that a code rate of 3/4 produces the maximum SNR value.

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