ESTIMATION OF PHASE NOISE AND ERROR IN MIMO-OFDM

Santhiya.M[1], Dr.S.Dhandapani[2]
Department Of ECE,Saveetha engineering college,Chennai
M.E, Ph.D, Head Of department, Department Of ECE,Saveetha engineering college,Chennai

Abstract- **In this project, we present a multiple-input multiple output (MIMO) orthogonal frequency division multiplexing (OFDM) based backhaul link in the presence of hardware impairments, such as phase noise (PN), residual carrier frequency offset (RCFO), and sampling frequency offset (SFO). Focusing on these adverse hardware effects on the MIMO-OFDM system, we propose corresponding signal processing algorithms for compensating these impairments. Simulation results show that the Bit Error Rate (BER) performance of the system is identical with that of the effect of noise, when this technique is implemented for basic modulation schemes like PAM or QAM. Whereas, when the technique is implemented for Multiple Input Multiple Output (MIMO) system, or a Multiple Input Multiple Output (MIMO) system with Orthogonal Frequency Division Multiplexing (OFDM) modulation, it shows a better Bit Error Rate (BER) performance than that of the usual way of channel equalization in the respective systems.**

Index Terms- **MIMO, OFDM, Phase Noise, BER, QAM.**

I. INTRODUCTION

Communication, the activity of conveying information, is the distinctive ability which has made possible the evolution of human society. Better communication techniques were enquired upon and were being discovered, from Pigeon posts to Persian couriers, from telegraphy to telephony, every technique connected people separated by lands, further. Our planet started shrinking as the world of communication began to expand. But nothing changed the destiny of humanity as much as what James Clerk Maxwell's discovery did. Electromagnetic waves redefined limitations, it made wireless communication possible.

1.1 WIRELESS COMMUNICATION

Wireless communication is the use of EM waves to transfer data between two users. Wireless communications has developed into a key element of modern society. From satellite transmission, radio and television broadcasting to the now ubiquitous mobile telephone, wireless communications has revolutionized the way societies function [26].In a wireless communication system, a transmitter which is actually an electronic circuit with the aid of an antenna creates electromagnetic vibrations which are sent through space. These waves propagate through a channel (free space, buildings etc.). During this propagation various distortions are introduced into the signal. The receiver receives this signal. To successfully interpret the message in it, the receiver has to know about the nature of discrepancies introduced by the channel. The process of evaluating the way a channel behaves to EM waves is called Channel Estimation.

1.2 CHANNEL ESTIMATION

Channel estimation is required in wireless communication to counter the effects of channel on the signal. A defining characteristic of the wireless channel are the variations of the channel strength over time and over frequency. The variations can be roughly divided into two types: (i) Large-scale fading, due to path loss of signal as a function of distance and shadowing by large objects such as buildings and hills. (ii)Small-scale fading, due to the constructive and destructive interference of the multiple signal paths between the transmitter and receiver [25].

To counter these effects various techniques are adopted at the receiver side. Mathematical models are used to predict the general behaviour of the channel in concern. Some important channel models are:(i)Rayleigh channel: For this model to be used it is required that there be many scatters present, which means that Rayleigh fading can be a useful model in heavily built-up city centers where there is no line of sight between the transmitter and receiver and many buildings and other objects attenuate, reflect, refract and diffract the signal. (ii) Rician channel: Rician channel is a transmission channel that may have a line-of-sight component and several scattered of multipath components. (iii)Nakagami channel: The sum of multiple independent and identically distributed Rayleigh-fading signals have Nakagami distributed signal amplitude. This is particularly relevant to model interference from multiple sources in a cellular system.

Some popular techniques used at the receiver to detect the symbols sent through the channel are:(i) Detection by LSE(Least Square Error)(ii) MMSE (Minimum Mean Square Error)

Channel effects on signal and ways to rectify it in a single transmitter and single receiver systems, generally called SISO (single-input single-output) systems, has been discussed so far. One major drawback in any SISO system is that it is not resistant to the effect of multipath fading. A very effective way know to come over multipath is the technique of diversity. Diversity involves providing the receiver with multiple copies of the same signal. It works well when each of these copies independently arrives at the receiver, that is, each copy arrives via independent paths, experiencing independent fades. As the probability that at-least one of these paths transmit the symbol with high SNR (signal-to-noise ratio) is more, diversity is preferred.

1.4 MIMO

MIMO technology has attracted attention in wireless communications. MIMO systems have various advantages over SISO systems: (i)Significant increases in data transmission without additional bandwidth or transmit power. It achieves this by higher spectral efficiency (more bits per second per hertz of bandwidth) and link reliability or diversity (reduced fading).(ii) No need to alter the common air interface while upgrading. (iii)By various coding techniques, depth and duration of fades are reduced.

II. ARCHICTECTURE

2.1 INTRODUCTION TO OFDM

OFDM originated from the need of efficient communications through frequency-selective fading channels. OFDM can be simply defined as a form of multicarrier modulation (MCM). MCM is the principle of transmitting a high-rate serial data stream by splitting it into a set of parallel low rate sub-streams and modulating each of these data streams onto individual subcarriers, where carrier spacing is carefully selected to make each subcarrier orthogonal to the other subcarriers. It is possible to arrange the carriers in an OFDM signal so that the sideband of the individual carriers overlap and the signals can still be received without adjacent carrier interference.

In OFDM signaling, the following orthogonality condition is satisfied,

$$\int_0^t e^{j2\pi f_i t}.e^{-j2\pi f_i t}.d_t = \int_0^t e^{j2\pi(f_i - f_j)t}.d_t = 0$$

$$i \neq j$$

The space between the frequencies of the subcarriers should be

$$f = f_i - f_j = \frac{m}{T}$$

Where, m can be any positive integer. The smallest space for orthogonality is equal to the symbol rate l/r. With orthogonality, each subcarrier can be demodulated independently without ICI. It should be noted that the pass bands of the subcarriers may overlap in OFDM, as shown in figure

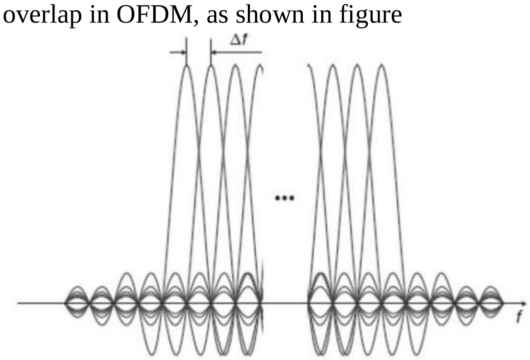


Figure 1 Spectrums of Subcarriers in OFDM

Compared with conventional non-overlapping multicarrier technique, OFDM can save almost 50% of bandwidth by using the overlapping multicarrier modulation technique, as shown in Figure 3.2

In digital communication Systems, the OFDM symbol is a sum of subcarriers that are individually modulated by using PSK or QAM. The expression for one OFDM symbol at t = ts as follows:

$$s(t) = Re\left\{\sum_{i=-\frac{N}{2}}^{\frac{N}{2}-1} d_{1+N/2}.exp\left(j2\pi\left(f_c - \frac{i+0.5}{T}\right)(t-t_s)\right)\right\}, \quad t_s \le t \le t_s + T$$

$$s(t) = 0, \quad t < t_s, t > t_s + T$$

where, di are complex modulation symbols, Ns is the number of subcarriers, T is the symbol duration, and fc is the carrier frequency. The equivalent complex baseband notation is given

$$s(t) = \left\{ \sum_{i=-\frac{Ns}{2}}^{\frac{Ns}{2}-1} d_{1+Ns/2} \cdot exp\left(j2\pi \frac{i}{T}(t-t_s)\right) \right\}, \quad t_s \leq t \leq t_s + T$$

$$s(t) = 0, \quad t < t_s, t > t_s + T$$

2.2 BASIC PRINCIPLE OF OFDM

At the transmission side, the binary information is first grouped and mapped into complex-valued symbols according to the modulation by different mapping schemes, such as BPSK, QPSK, 16QAM, and 64QAM. Then there is a series to parallel conversion to prepare different data groups for different OFDM subcarriers. The mapped signals are modulated onto N orthogonal subcarriers by the IFFT. A cyclic prefix (CP) is then added to the multiplexed IFFT output. Finally, the obtained signal is converted to a time continuous analog signal before it is transmitted through the channel. At the receiver side, an inverse operation is carried out and the information data is detected.

2.3 BLOCK DIAGRAM

The block diagram for a MIMO wireless communication system is shown illustrating transmitter and receiver respectively, between which is the communication channel

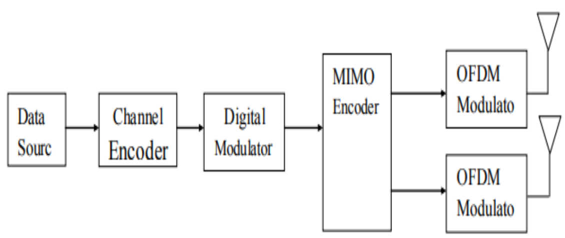


Figure 2: The block diagram at transmitter side

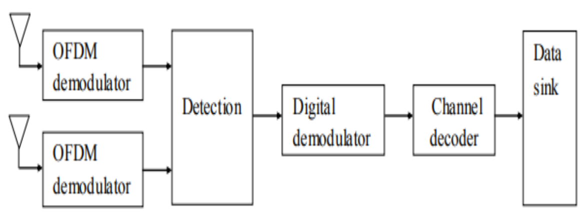


Figure 3: The block diagram at receiver side

The bit sequence is generated by the information source which contains information to be communicated. After the encoding and modulation processes, the bit sequence becomes the symbol stream. The symbol stream passes through the

MIMO

Multiple-input and multiple-output, or MIMO is the use of multiple antennas at both the transmitter and receiver to improve communication performance. MIMO technology [16] has attracted attention in wireless communications, because it offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. It is one of several forms of smart antenna technology. It achieves this goal by spreading the same total transmit power over the antennas to achieve an array gain that improves the spectral efficiency (more bits per second per hertz of bandwidth) and to achieve a diversity gain that improves the link reliability (reduced fading). Because of these properties, MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wi-Fi), 4G, 3GPP Long Term Evolution, WiMAX.

2.4 SIMO

Single Input Multiple Output (SIMO) [18] is an antenna technology for wireless communications in which a single antenna at the transmitter and multiple antennas are used at the destination (receiver). The antennas are combined to minimize errors and optimize data speed. SIMO technology has applications in digital television (DTV), wireless local area networks (WLANs), metropolitan area networks (MANs), and mobile communications. An early form of SIMO, known as diversity reception, has been used by military, commercial, amateur, and shortwave radio operators at frequencies below 30 MHz .

2.5 MISO

Multiple Input Single Output (MISO)[19] is a smart antenna technology that uses multiple transmitters and a single receiver on a wireless device to improve the transmission distance. MISO technology can be applied in areas of Wireless Local Area Networks, Metropolitan Area Networks and mobile communications. The implementation of MISO would include multiple antennas at the source, or transmitter, and the destination, or receiver, has only one antenna, the antennas are combined to minimize errors and optimize data speed. When an electromagnetic field (EM field) is met with obstructions such as hills, canyons, buildings, and utility wires, the wave fronts are scattered, and thus they take many paths to reach the destination. The late arrival of scattered portions of the signal causes problems such as fading and intermittent reception. In digital communications systems such as wireless Internet, it can cause a reduction in data speed and an increase in the number of errors. The use of two or more antennas, along with the transmission of multiple signals at the source, can reduce the trouble caused by multipath wave propagation.

2.6 MIMO-OFDM SYSTEM

OFDM & MIMO systems have some drawbacks. OFDM system has disadvantages like frequency error, phase error, synchronization of cyclic prefix. MIMO system has disadvantages like Complexity, Power consumption and Size of the mobile device. Increased component costs within an access point required for its implementation. Moreover OFDM & MIMO separately cannot serve high data rates applications. Multiple-input multiple-output (MIMO) wireless technology in combination with orthogonal frequency division multiplexing (MIMO-OFDM)[20] is an attractive air-interface solution for next generation wireless local area networks (WLANs), wireless metropolitan area networks and fourth-generation mobile cellular wireless systems. MIMO technology is predominantly used in broadband systems that exhibit frequency-selective fading and, therefore, inter symbol interference (ISI). OFDM modulation turns the frequency-selective channel into a set of parallel flat fading channels and is, hence, an attractive way of coping with ISI. One of the major concerns is Bit error rate. In MIMO OFDM systems the BER is reduced to quite smaller value compared to MIMO or OFDM because of combined properties of MIMO and OFDM.

Multiple input Multiple Output Orthogonal Frequency division multiplexing is a technology that uses multiple antennas to transmit and receive radio signals. When much higher throughputs are aimed at, the multipath character of the environment causes the MIMO channel to be frequency-selective. OFDM can transform such a frequency-selective MIMO channel into a set of parallel frequency-flat MIMO channels and also increase the frequency efficiency. Therefore, MIMO-OFDM technology has been researched as the infrastructure for next generation wireless networks.

MIMO wireless systems, combined with OFDM, have allowed for the easy transmission of symbols in time, space and frequency. MIMO-OFDM takes advantage of the multipath properties of environments [54] using base station antennas that do not have LOS and uses both the advantages of MIMO and OFDM. Combination of MIMO and OFDM techniques will impact the evolution of wireless LANs, and is a leading candidate for future fourth generation (4G) wireless communications systems. Therefore, MIMO-OFDM [55] system has become a welcome proposal for 4G mobile communication systems. Advantage is very high capacity, spectral efficiency and improved communications reliability i.e., reduced bit error rate (BER) [56] achieved at reasonable computational complexity.

At the transmitting end, a number of transmission antennas are used. An input data bit stream is modulated by OFDM and finally fed to antennas for sending out (radiation). At the receiving end, in-coming signals are fed into a signal detector and processed before recovery of the original signal is made.

In the area of Wireless communications, MIMO-OFDM is considered as a mature and well established technology. The main advantage is that it allows transmission over highly frequency-selective channels at a reduced Bit Error Rate (BER) with high quality signal. One of the most important properties of OFDM transmissions is the robustness against multi-path delay spread. This is achieved by having a long symbol period, which minimizes the inter-symbol interference. MIMO can be used either for improving the SNR [57] or data rate. The combination of OFDM and MIMO seems to be very promising when aiming at the design of very high-rate wireless mobile systems. While multiple antennas at the transmitter and receiver elevate channel capacity, i.e. the achievable transmission rate, OFDM converts the wideband frequency selective radio channel into a set of parallel flat-fading channels, thus simplifying signal processing required at the receiver.

MIMO OFDM technology enables high capacities suited for Internet and multimedia services, increases the range and reliability. It Increases diversity gain and enhance system capacity on a time-varying multipath fading channel improving power-spectral efficiency in wireless communication systems besides optimizing the power efficiency. This technology guarantees each user's quality of service requirements, including bit-error rate and data rate and as a result ensures fairness to all the active users.

2.7 MIMO OFDM SYSTEM ADVANTAGES

The disadvantages of MIMO and OFDM separately can be overcome by using MIMO OFDM system. MIMO-OFDM systems support high data rate and high performance.

- The coding over the space, time, and frequency domains provided by MIMO-OFDM
- enables a much more reliable and robust transmission over the harsh wireless environment. These enable high capacities suited for Internet and multimedia services, and also dramatically increase range and reliability. The major advantages are increased capacity, coverage, and reliability.
- MIMO-OFDM is a promising road to future broadband wireless access, enhanced spectral efficiency and multiuser downlink throughput.

III. IMPLEMENTING MODEL

3.1 IMPLEMENTATION

MIMO Multiple-input–multiple-output (MIMO) wireless systems are those that have multiple antenna elements at both the transmitter and receiver. The multiple antennas increase the average SNR seen at the combiner output. Multiple-input multiple-output (MIMO) systems are used in developments in antenna array communication. The channel of a two transmitter two receiver MIMO system can be represented by

$$y = Hx$$

$$H = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix}$$

This formula can be generalized to any number of transmit and receive antennas. By using MIMO there are two possible gains, multiplexing gain and diversity gain, where x and y are 2x1 matrix, representing transmitted and received signal on each antenna. The four entries of the channel matrix H correspond to the channel gains between antennas, as shown in Figure14. Several different antenna configurations are used in defining space-time systems. In MIMO system, a number of antennas are placed at the transmitting and receiving ends, separated by a considerable distance. The distance between different base station antennas can be set as 10 times the carrier wavelength and mobile station antennas can be separated by half carrier wavelength. In this way, independent channels between the transmitting and receiving ends are formed so as to achieve spatial diversity or space division multiplexing. The idea is to realize spatial multiplexing and data pipes by developing space dimensions which are created by multi-transmitting and receiving antennas.

3.1.1 MULTIPLEXING GAIN

To achieve multiplexing gain, multiple independent spatial channels is created (shown in Figure11 [76]). Independent information sequences can be transmitted on each channel at the same time. The maximum number of channels is min (M,N) where M is the number to transmission antennas (Tx) and N is the number of receive antennas (Rx). As min (M, N) increases, the number of spatial channels increase linearly. The system capacity also increases linearly

3.1.2 DIVERSITY GAIN

Instead of two independent information sources, we can send some processed representation of a single information source in order to achieve the diversity. The four channels can be seen as independent faded branches (shown in Figure16). So the MIMO channel now has a diversity order of 2 × 2 = 4. For the generalized MIMO channel, the diversity order is M × N.

channel where it experiences interference from the environment and the noise at the receiver. As a result, detection is needed at the receiver side. The detected symbols will be demodulated and decoded and finally sent to the data sink.

3.2 MIMO CHANNEL AND CAPACITY

There are several kinds of channel impairments in wireless communication.

This refers to power loss of electromagnetic wave when there is an unobstructed line-of-sight path exists between transmitter and receiver. The free space power received by receiving antenna, which is separated from transmitting antenna by a distance d, is given by

$$P_r(d) = \frac{P_t G_t G_r \beta^2}{(4\pi)^2 d^2 \mathrm{L}}$$

Where is transmitted power, is received power, is transmitting antenna gain, is receiving antenna gain, d is the transmitter-receiver (T-R) separation distance in meters, L is the system loss factor (not related to propagation, L≥1) and λ is the wavelength in meters.

The gain of an antenna is related to its effective aperture by

$$G = \frac{4\pi}{\beta^2} A_e$$

3.3 SINGLE CARRIER SYSTEM

In a single carrier system, signals are pulse-formed by a transmitter filter ht(t) before being applied to a multipath channel. At the receiver, the incoming signal is passed through a receiving match filter hr {t) to maximize the signal-to-noise ratio (SNR). The basic diagram of a single carrier system is shown in Fig

3.4 MULTICARRIER SYSTEM

In a multicarrier system, input signals which are divided by a multiplexer are applied to pulse-formed filters before being transmitted through multipath environment. The receiving ends consist of N parallel paths. Each one is passed through a respective match filter to realize maximum SNR. In a general wireless communication model, the transmitted signal arrives at the receiver via various paths. Thus, extracting the original signal at the receiving end becomes extremely difficult. If the signal is transmitted at time intervals T, then the parameter concerning the multipath channel is the delay of the longest path with respect to the earliest path. The received signal can be theoretically influenced by previous signals, which must be considered seriously by receiver

3.5 WORKING PRICIPLE OF OFDM

OFDM stands for "Orthogonal frequency division multiplexing". It is a technique for transmitting data in parallel by using a large number of modulated sub-carriers. In this a higher bit rate channel is divided into multiple orthogonal sub-channels in the frequency domain with lower bit rates. The Orthogonality [84] of the carriers means that each carrier has an integer number of cycles over a symbol period. Due to this, the spectrum of each carrier has a null at the center frequency of each of the other carriers in the system. This results in no interference between the carriers, although their spectra overlap. The separation between carriers is theoretically minimal so there would be a very compact spectral utilization.

OFDM systems are attractive for the way they handle ISI (inter symbol interference), which is usually introduced by frequency selective multipath fading in a wireless environment. Each sub-carrier is modulated at a very low symbol rate, making the symbols much longer than the channel impulse response. In this way, ISI is diminished. Moreover, if a guard interval between consecutive OFDM symbols is inserted, the effects of ISI can completely vanish. This guard interval must be longer than the multipath delay. Although each sub-carrier operates at a low data rate, a total high data rate can be achieved by using a large number of sub-carriers. ISI[85] has very small or no effect on the OFDM systems hence an equalizer is not needed at the receiver side.

At present OFDM is mostly used in digital audio broadcasting (DAB), digital video broadcasting (DVB), Wireless LAN and MAN such as IEEE802.11a, IEEE802.11g and IEEE802.16a, HIPERLAN/2 and other high speed data application for both wireless and wired communications. It is advantageous to combat frequency selective fading channels, especially in wide-band applications.

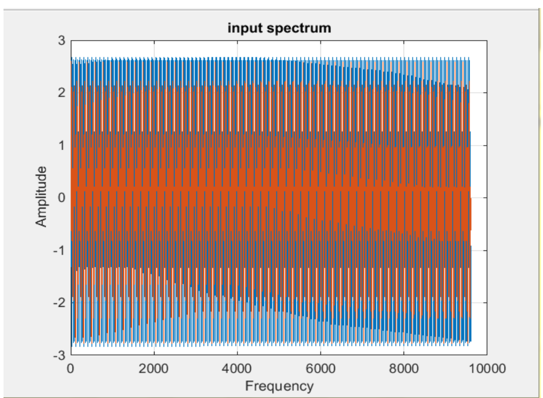
The subcarriers in OFDM have the minimum frequency separation required to maintain Orthogonality of their corresponding time domain waveforms, still the signal spectra corresponding to the different subcarriers overlap in frequency domain. The spectra of sub carriers overlap each other but individual sub carrier can be extracted by base band processing. This overlapping property makes OFDM more spectral efficient than the conventional multicarrier communication scheme.

This Orthogonality can be completely maintained with a small reduction in SNR, even though the signal passes through a time dispersive fading channel, by introducing a cyclic prefix (CP). In order for the cyclic prefix to be effective, the length of the cyclic prefix must be at least equal to the length of the multipath channel. The size of cyclic prefix is usually taken as one fourth the symbols. OFDM requires a relatively simple equalizer at the receiver and is well suited for transmission of high data rate applications in fading channels due to its robustness to inter-symbol interference. It is very easy to achieve accurate symbol synchronization. The nowadays solution method of frequency selective fading of the MIMO system is to use OFDM. It has quite good response, especially in indoor environments since fading caused by multipath can be combated with OFDM to improve quality of signal. Several research work has been carried out on the performance evaluation of an OFDM system both analytically and also by simulations.

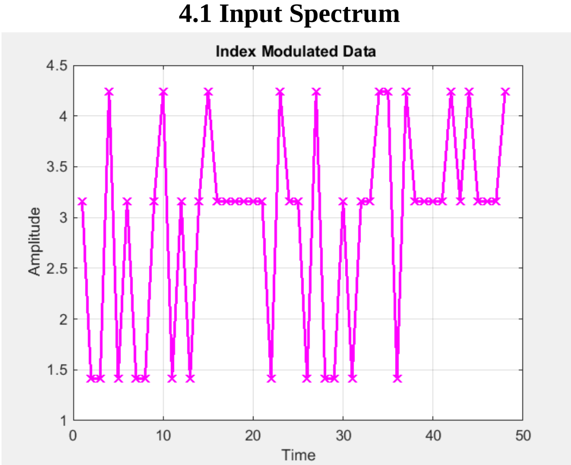
In existing wireless communications systems a user can choose between either a very high data rate or a high mobility [86]. For multimedia applications a high data rate is essential. A communications system based on OFDM seems to be suitable to provide such a high data rate even in a mobile environment. OFDM is also used for dedicated short-range communications (DSRC) for road side to vehicle communications and as a backbone for fourth-generation (4G) mobile wireless systems. If knowledge of the channel is available at the transmitter, then the OFDM transmitter can adapt its signaling strategy to match the channel. Combining of OFDM technology and cognitive radio technology could increase utilization of spectrum and enhance performance of Cognitive Radio system, and spectrum resource may be distributed reasonably. Different FFT sizes [87] have different impact on the BER.

IV. RESULTS

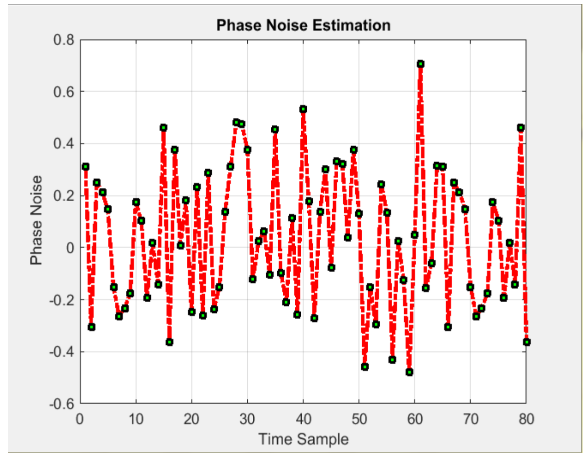
4.1 SIMULATION RESULTS



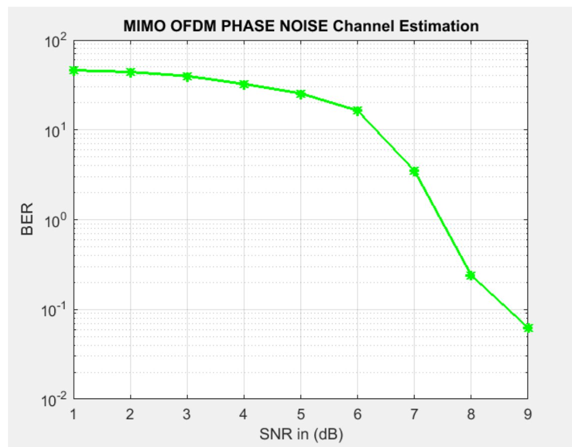
4.1 Input Spectrum



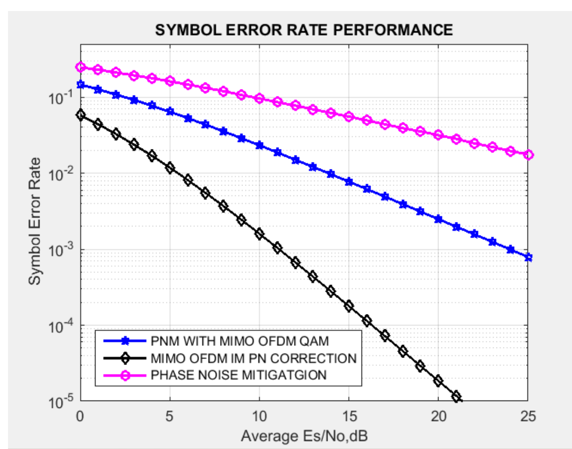
4.2 Index Modulated Data



4.3 Phase Noise Estimation



4.4 MIMO OFDM PHASE NOISE Channel Modulation



4.5 Symbol Error Rate Performance

V. CONCLUSION

In this project, we considered a MIMO-OFDM based small cell backhaul system in the presence of PN, SFO, and RCFO. A PN mitigation scheme for PN and RCFO compensation (for MIMO-OFDM systems) was presented. The SFO (and the remaining RCFO) was compensated by counter-rotating the frequency-domain phase rotation tracked by the Kalman filter. The Kalman filter was also used for the channel prediction for the PN mitigation. For simplicity, we employed the LS channel estimation using the frequency orthogonal preamble in the training stage and used the ZF MIMO decoder for data detection in the payload, whereas the PN mitigation and SFO correction were applied in both preamble and payload. We also included the filtering effects in the interpolation/decimation. It was shown that the proposed PN mitigation and SFO correction schemes can effectively compensate the impairments of the PN, the SFO, and the RCFO.

REFERENCE

[1] M. Coldrey, J.-E. Berg, L. Manholm, et al., “Non-line-of-sight small cell backhauling using microwave technology,” IEEE Comm. Mag., vol. 51, no. 9, pp. 78-84, Sep. 2013

[2] D. Petrovic, W. Rave, and G. Fettweis, “Effects of phase noise on OFDM systems with and without PLL: characterization and compensation,” IEEE Trans. Commun., vol. 55, no. 8, pp. 1607-1616, Oct. 2007. [3] N. N. Tchamov, J. Rinne, A. Hazmi, et al., “Enchanced algorithm for digital mitigation of ICI due to phase noise in OFDM receivers,” IEEE Wireless Commun. Lett., vol. 1, no. 1, pp. 6-9, Feb. 2013.

[4] Q. Zou, A. Tarighat, and A. H. Sayed, “Compensation of phase noise in OFDM wireless systems,” IEEE Trans. Signal Processing, vol. 55, no. 11, pp. 5407-5424.

[5] J. Zhang, H. Rohling, and P. Zhang, “Analysis of ICI cancellation scheme in OFDM systems with phase noise,” IEEE Trans. Broad., vol. 50, no. 2, pp. 97-106, Jun. 2004.

[6] P. Robertson and S. Kaiser, “Joint estimation of carrier and sampling frequency offset, phase noise, IQ Offset and MIMO channel for LTE advanced UL MIMO,” in Proc. IEEE Workshop Signal Process. Advances Wireless Commun. (SPAWC), Darmstadt, Germany, 16-19, Jun. 2013, pp. 520-524.

[7] X. Chen, A. Wolfgang, and A. Zaidi “CP-OFDM and UF-OFDM in the presence of phase noises and their mitigations,” in Proc. IEEE Veh. Technol. Conf., Montral, Canada, 1821 Sep. 2016.

[8] J.-J. Beek, M. Sandell, P. O. Borjesson, “ML estimation of time and frequency offset in OFDM systems,” IEEE Trans. Signal Process., vol. 45, no. 7, pp. 1800-1805, Jul. 1997.

[9] H. Minn, V. K. Bhargava, and K. B. Letaief, “A robust timing and frequency synchronization for OFDM systems,” IEEE Trans. Wireless Commun., vol. 2, no. 4, pp. 822-839, Jul. 2003.

10] T. M. Schmidl and D. C.Cox, “Robust frequency and timing synchronization for OFDM,” IEEE Trans. Commun., vol. 45, no. 12, pp. 16131621, December 1997.

[11] C.-D. Chang, “Effect and compensation of symbol timing offset in OFDM systems with channel interpolation,” IEEE Trans. Broad., vol. 54, no. 4, pp. 761-770, Dec. 2008.

[12] B. Yang, K. B. Letaief, R. S. Cheng, and Z. Cao, “Timing recovery for OFDM transmission,” IEEE J. Select. Areas Commun., vol. 18, no. 11, pp. 2278-2291, Nov. 2000.

[13] S. Gault, W. Hachem, and P. Ciblat, “Joint sampling clock offset and channel estimation for OFDM signals: CramrRao bound and algorithms,” IEEE Trans. Signal Process., vol. 54, no. 5, pp. 1875-1885, May 2006.

[14] Y. H. You, S. T. Kim, and H. K. Song, “An improved sampling frequency offset estimator for OFDM-based digital radio mondiale systems,” IEEE Trans. Broad., vol. 54, pp. 283-286, June 2008.

[15] D. D. Lin, R. Pacheco, T. J. Lim, and D. Hatzinakos, “Joint estimation of channel response, frequency offset, phase noise in OFDM,” IEEE Trans. Signal Process., vol. 54, no. 9, pp. 35423554, Sep. 2006.

[16] J. Tao, J. Wu, and C. Xiao, “Estimation of CTF and carrier frequency offset for OFDM systems with phase noise,” IEEE Trans. Veh. Technol., vol. 58, no. 8, pp. 43804387, Oct. 2009.

[17] R. Carvajal, J. C. Aguero, B. I. Godoy, and G. C. Goodwin, “EMbased maximum-likelihood channel estimation in multicarrier systems with phase distortion,” IEEE Trans. Veh. Technol., vol. 62, no. 1, pp. 152 160, Jan. 2013.

[18] O. H. Salim, A. A. Nasir, H. Mehrpouyan, et al., "Channel, phase noise, and frequency offset in OFDM systems: joint estimation, data detection, andhybrid Cramr-Rao lower bound," IEEE Trans. Commun., vol. 62, no. 9, pp. 3311-3324, Sep. 2014.

[19] M. Speth, S. A. Fechtel, G. Fock, and H. Meyr, "Optimum receiver design for wireless broad-band systems using OFDMpart I," IEEE Trans. Commun., vol. 47, no. 11, pp. 1668-1677, Nov. 1999.

[20] M. Morelli and M. Moretti, "Fine carrier and sampling frequency synchronization in OFDM systems," IEEE Trans. Wireless Commun., vol. 9, no. 4, pp. 1514-1524, Apr. 2010.

[21] S. Haykin. Adaptive Filter Theory, Prentice-Hall, 1996.

[22] T. C. W. Schenk, X.-J. Tao, P. F. M. Smulders, et al., "On the influence of phase noise induced ICI in MIMO OFDM systems," IEEE Commun. Lett., vol, 9, no. 8, pp. 682-684, Aug. 2005.

[23] P. Liu, S. Wu, and Y. Bar-Ness, "A Phase noise mitigation scheme for MIMO WLANs with spatially correlated and imperfectly estimated channels," IEEE Commun. Lett., vol, 10, no. 3, pp. 141-143, Mar. 2006.

[24] S. Bittner, E. Zimmermann, and G. Fettweis, "Iterative phase noise mitigation in MIMO-OFDM systems with pilot aided channel estimation," in Proc. IEEE Veh Technol. Conf., Sep. 2007, pp. 1-5.

[25] R. Corvaja and A. G. Armada, "SINR degradation in MIMO-OFDM systems with channel estimation errors and partial phase noise compensation," IEEE Trans. Commun., vol. 58, no. 8, pp. 2199-2203, Aug., 2010.