Master's Thesis
석사 학위논문

Magnetic MIMO System using Signal Processing for Robustness to Misalignment

Sukhyun Hwang (황 석 현 黃 晳 鉉)

Department of Information and Communication Engineering
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Advisor: Professor Ji-Woong Choi
Co-Advisor: Professor Hongsoo Choi

by

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Department of Information and Communication Engineering
DGIST

A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics1).

May. 31. 2016

Approved by

Professor Ji-Woong Choi (Signature)
(Advisor)
Professor Hongsoo Choi (Signature)
(Co-Advisor)

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1) Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Magnetic MIMO System using Signal Processing for Robustness to Misalignment

Sukhyun Hwang

Accepted in partial fulfillment of the requirements for the degree of
Master of Science

May. 31. 2016

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Abstract

Nowadays, requirements of communication in special channel environments are increasing such as underwater, underground, and biological tissues which have a high permittivity characteristic. The conventional radio frequency (RF) communication, which is based on the principle of electromagnetic radiation, is not suitable in these channel environments due to a high path loss problem. Magnetic communication systems are not affected by the permittivity of channel environments. Therefore, the magnetic communication systems have attracted attention as an alternative communication in these channels. However, the magnetic communication has limitations such as a low data-rate, a short communication range and a sensitive in misalignment between transmit antennas and receiver antennas. Many research teams have tried to overcome these problems by various approaches. In this paper, we realize the magnetic MIMO communication test bed using the heterogeneous multi-pole loop antenna array to obtain the higher data rate and the enhancement of bit error rate (BER) performance in misalignment cases using various signal processing schemes. The proposed antenna array can satisfy a same BER performance of the conventional antenna array at the further distance. Furthermore, to obtain the enhanced BER performance in various misalignment cases, we apply signal processing schemes, which are used in the conventional RF communication, to the proposed test bed, such as maximum likelihood (ML), zero forcing (ZF), minimum mean square error (MMSE) and singular value decomposition (SVD). We verify to overcome the misalignment problems that magnetic communication can overcome the misalignment problem using the signal processing schemes. The SVD shows the lowest BER performance in large misalignment with a perfect channel information, and ML shows the best BER performance without the channel information. Other signal processing schemes present a same BER performance due to a high SNR channel condition.

Keywords: Magnetic communication, MIMO, Misalignment, Signal processing

Contents

Ⅰ. INTRODUCTION

Radio frequency (RF) communication technologies are widely used in our life. Demands of wireless communication systems are expanded to various high permittivity channel environments, such as underwater [1], underground [2] and biological tissues [3]. The conventional RF communication systems which are based electromagnetic wave propagation are not suitable to these special mediums due to a high path loss problem. Attenuations of the electromagnetic (EM) wave propagation depend on permittivity and conductivity of the channels. Differ from the EM wave propagation, the magnetic field is affected by permeability of the channels, and most of the channels have a same permeability of the air. For instance, a permeability of a water is almost same to an air which is equal to ‘1’. On the other hand, a permittivity of the water is about 80 times over the air. Therefore, the RF based communication methods have significant path loss in the water channel environments. Therefore, the magnetic communication systems become an issue as an alternative communication method since, the magnetic communication systems have robust characteristics in these channel environments [4]. Generally, the magnetic communication systems have been used in various fields such as payment systems, door lock systems, ticket systems and advertisements. Especially, many research groups have tried to apply the magnetic communication in implantable medical devices such as cochlear implants, visual prostheses and prosthetic limbs to transmit data and power.

However, there are three weakness in the magnetic communication. First, the magnetic communication systems cannot support an enough data-rate due to the low carrier frequency with narrow bandwidth. According to the near field communication (NFC) standard, the data-rate of NFC is 106 kbps to 424 kbps [5]. The magnetic communication systems need to increase the data-rate to satisfy the high data-rate applications such as endoscope, deep brain stimulator

(DBS), and electromyography (EMG) monitoring. Second, the magnetic communication systems only can support the short communication range. The transmission range of the magnetic communication systems is depended on a radius of loop antenna in practical cases in near-field. The general definition of the near-field boundary is at approximately $\lambda/2\pi$. For example, the near-field range of NFC is the 3.52 meters. Therefore, the magnetic communication systems usually can support a few cm or a couple of meter. Last thing is that the magnetic communication is sensitive to misalignment between transceiver antenna and receiver antenna. The misalignment between transmitter antenna and receiver antenna lead to degradation of transmission efficiency due to decrease of a coupling between transmitter and receiver.

In previous works, we presented a magnetic multi-input multi-output (MIMO) to increase the data-rate of magnetic communication using a heterogeneous multi-pole loop antenna array [6]. In this paper, a performance of the proposed system is provided to compared with the conventional circular loop antenna array MIMO system in terms of a bit error rate (BER) performance via measurement results. Furthermore, we investigate the BER performance of the magnetic MIMO system applying spatial multiplexing (SM) schemes to overcome the misalignment problems with various situations.

The rest of paper is described as follows. In section II, we will briefly explain a principle of the magnetic communication. The proposed magnetic MIMO system is presented in the section III. Then we mention about the magnetic MIMO test bed which includes SM schemes to compensate the misalignment problems, and experiment results is provided in section IV and V. finally, we will suggest a proper SM schemes in the proposed magnetic MIMO system for misalignment compensation in the conclusion.

II. NEAR FIELD MAGNETIC COMMUNICATION

2.1. Magnetic communication and applications

The region electromagnetic wave propagation is divided into two regions, near-field and far-field. Generally, the conventional RF communication systems is based on electromagnetic wave propagation in the far-field. On the other hands, the magnetic communication systems are operated in the near-field with inductive coupling between the two loop antennas. The near-field is usually called non-propagation area and, the region of the near-field is defined the area of $\lambda/2$ from antennas.

Nowadays, requirements of wireless communication system are increased in high permittivity environments such as the underwater, the underground and the biological tissue. The conventional RF communication has high path loss problem in these channel environments. In the magnetic communication, the permittivity is not a critical problem because the magnetic communication is influenced by the permeability of the channel. The magnetic communication systems provide a reliable communication in these channel environments. Therefore, the magnetic communication system is attractive solution for the underground facility management system, the environment management system, and medical applications which require communication inside the human body.

Except these special applications in the high permittivity channel, the conventional magnetic communications are already widely used in many standards such as NFC, radio frequency identification (RFID) and RuBee. These technologies apply to the mobile payment, home appliances, and health care systems. Many mobile devices companies include magnetic communication technologies in their products for the payment applications such as Apple pay, and Samsung pay. Furthermore, the home appliances have magnetic communication function to connect and control by mobile devices for smart environment. In recent years, IT companies has been trying to converge the communication systems with healthcare systems. The magnetic communication can provide the health monitoring and tracking systems.

2.2. Limitation and related research

The conventional magnetic communication systems have enough performance for the conventional applications which are mentioned previous subsection. However, the magnetic communication systems have inherent limitations such as the short communication range, low data rate, and sensitive to misalignment between the transmitted antenna and the received antenna. Theoretically, the magnetic communication only can operate in near-field. However, the realized magnetic communication systems have more shorten transmission range than the near-field range, since the range of transmission is depended on radius of loop antennas in practical case. Therefore, magnetic communication systems only can support a few centimeter or a couple of meter. The data rate of communication system depends on a bandwidth of the system. The magnetic communication cannot support the enough data-rate, since the magnetic communications use the low carrier frequency. For example, the data rate of the NFC is 106-424kbps at 13.56 MHz which is not enough to support high data rate applications such as, high quality multimedia applications, and medical applications requiring a large volume of data. Furthermore, misalignment issues are critical problem in the magnetic communication systems. Even if the align state between transmitter antennas and receiver antennas is slightly changed, the antenna transmission efficiency dramatically reduces due to reduced coupling. Many research groups have tried to overcome these limitations.

2.2.1 To expend the communication distance

Soljacic’s research team in MIT succeeded in delivering 60 watts of power at a distance of 2 m in 2007 [7]. The magnetic resonance method can transport the power at the further distance than the inductive method, however, the magnetic resonance method has a several problems, lower transmission efficiency than the induction method, and human safety. Akyldiz and Agbinya applied relay method to the magnetic communication to extend transmission range, respectively [8] [9].

2.2.2 To increase the date-rate of magnetic communication

As we mentioned the previous subsection, Akyildiz and Agbinya proposed the magnetic relay methods which are based on magnetic wave guide. Furthermore, these methods can obtain increased data rate [8] [9]. These methods require the high complexity and additional coils. Agbinya and Guttula research teams propose the magnetic MIMO [10] [11]. However, Agbinya's proposed method only considered an ideal situation where the distance between the antennas is far enough to ignore a crosstalk. Guttula's method considered the crosstalk between coils However, their proposed structure is not proper to implementation. Poon's research team in Stanford University tries to get the high data rate using the high carrier frequency in the low-gigahertz range for biomedical implants [12]. However, this solution only valid in very short range with a mm size receiver in the biological tissues.

2.2.3 To robust to misalignment

Luk's research team proposed resonance frequency compensation method to maintain the power efficiency which depends on the position. They adjust the resonance frequency depending on the position using an E-class inverter. However, this method consumes additional power for the inverter, and frequency shifting system is not suitable to communication system [13]. Cho's research team tried to improve the power transfer efficiency over all regions in angular misalignment by a multiple-transmitter [14]. This method simply uses additional transmit coils which have different position and angle around receiver coil. Lee's research group used a unit cell relay coil to increase the power transfer distance and withstand the misalignment between transmitter and receiver coil [15]. This method requires additional coils and high complexity.

III. MAGNETIC MIMO COMMUNICATION SYSTEM

3.1. Concept of magnetic MIMO

In this section, we briefly explain the magnetic MIMO communication system using the heterogeneous multi-pole antenna array which was previously proposed by our research team.

To obtain multiplexing gain with the MIMO system, MIMO system need to make parallel multiple streams. The conventional RF MIMO systems obtain the parallel multiple streams using complicated signal processing such as singular value decomposition (SVD) which can remove interference from undesired transmit antennas. However, the conventional magnetic MIMO, which consist of the circular loops, has additional interference signals via crosstalk between array components. Figure 3.1 shows a magnetic 2x2 MIMO simplified circuit model in terms of RF part and antennas. The blue arrows indicate the desired signal which is the parallel stream. The green arrows and the red arrows indicate the interference from array components and undesired transmit antenna, respectively. To obtain multiplexing gain in the magnetic MIMO system, the system need to remove the effect of interference signals to make parallel streams. However, the conventional magnetic MIMO studies did not consider the crosstalk issues, as we mentioned in Section II.

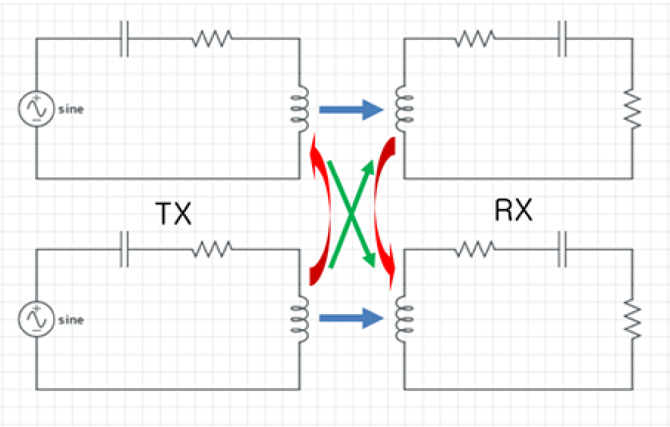


Figure 3.1. Magnetic 2x2 MIMO circuit

When a conventional MIMO structure is configured with the conventional circular loop antennas, strong inductive coupling between the antennas occurs. Therefore, our research team proposed the magnetic MIMO which use the cancellation effect of heterogeneous antenna.

The structure of the proposed MIMO antenna array is as follows Figure 3.2. The proposed magnetic MIMO can cancel the crosstalk using heterogeneous multi-pole loop antenna array. When we fed the middle of quadrupole loop antenna, each loop has opposite direction magnetic field by opposite direction current. This opposite magnetic field can be cancelled each other at the same distance from the center of each loops.

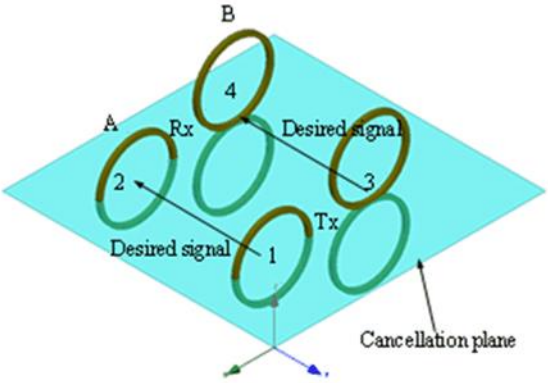


Figure 3.2. Proposed magnetic MIMO antenna array

In the previous work, the cancellation effect of the proposed antenna array was verified by the high frequency structure simulation (HFSS) simulation and measurement. It is confirmed that the proposed scheme can obtain a higher SIR than conventional antenna array by both results [6]. In addition, the channel capacity of the proposed magnetic MIMO increases, as the MIMO antenna increases through the calculation [18].

3.2 Misalignment in MIMO antenna array

The magnetic communication has a large performance variation which depends on the relative position between transmitter and receiver. To investigate the performance degradation, previous paper presented simulation results of the three misalignment cases as shown in Figure 3. 3, the front and rear case, the left and right case and the rotation case. This simulation is performed by varying the overlap between the transmit antenna and the receive antenna.

In the front and rear misalignment case, the diagonal crosstalk increase rapidly since the upper antenna array deviates the cancellation plane of the under antenna array. In this misalignment case, there are particular point which shows a significant performance degradation as shown in Figure 3. 4. When antenna arrays overlap about 70%, the gain of the desired signal of the quadrupole loop shows the significant performance degradation, since each circular loop of the quadrupole loop antenna is located on the cancellation plane of the faced quadrupole loop antenna. In the left and right misalignment case, the desired signal is still larger than the crosstalk. Because transmit antenna array and receive antenna array keep moving on each other's cancellation plane as shown in the Figure 3. 5. The rotation misalignment case shows the similar tendency of the left and right misalignment case shown in the Figure 3. 6 due to the same reason of the left and right misalignment case. In this paper, we present misalignment compensation method using an implementation of the proposed magnetic MIMO via a software defined radio (SDR).

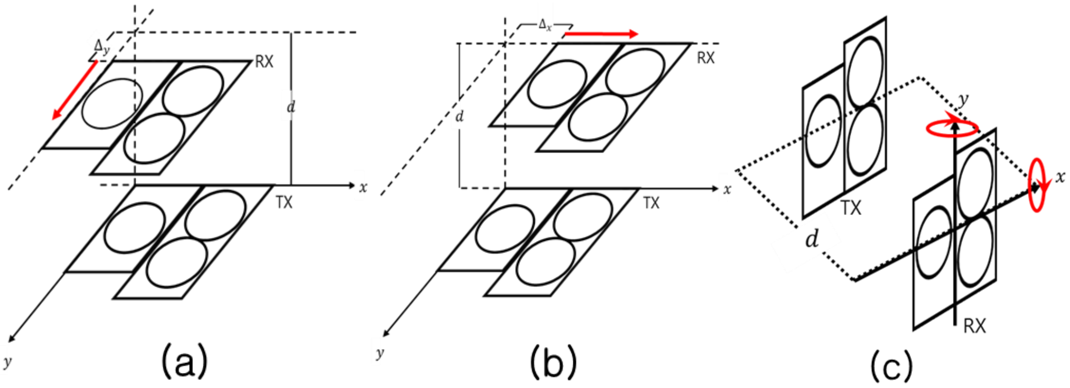


Figure 3. 3. Misalignment simulation (a) front and rear (b) left and right (c) rotation

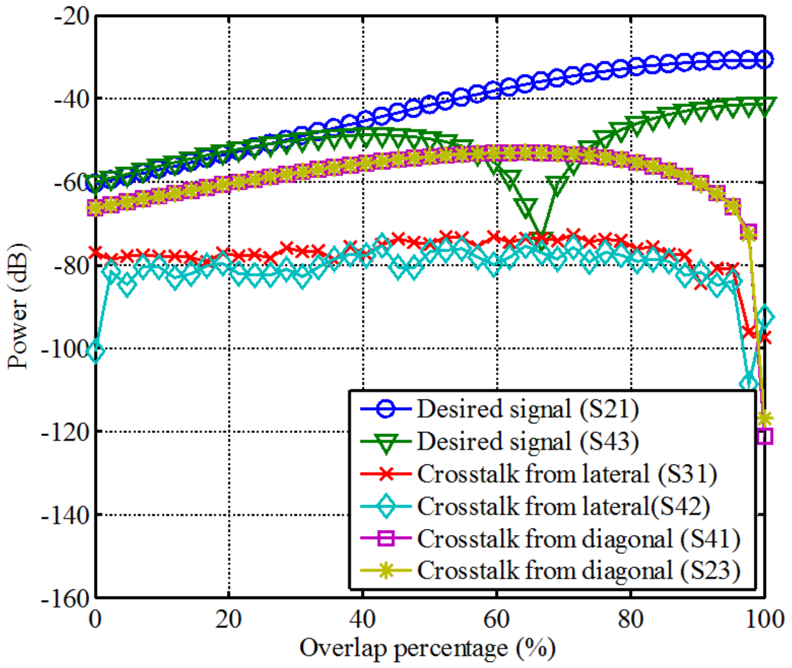


Figure 3.4 Gain of the front and rear case misalignment

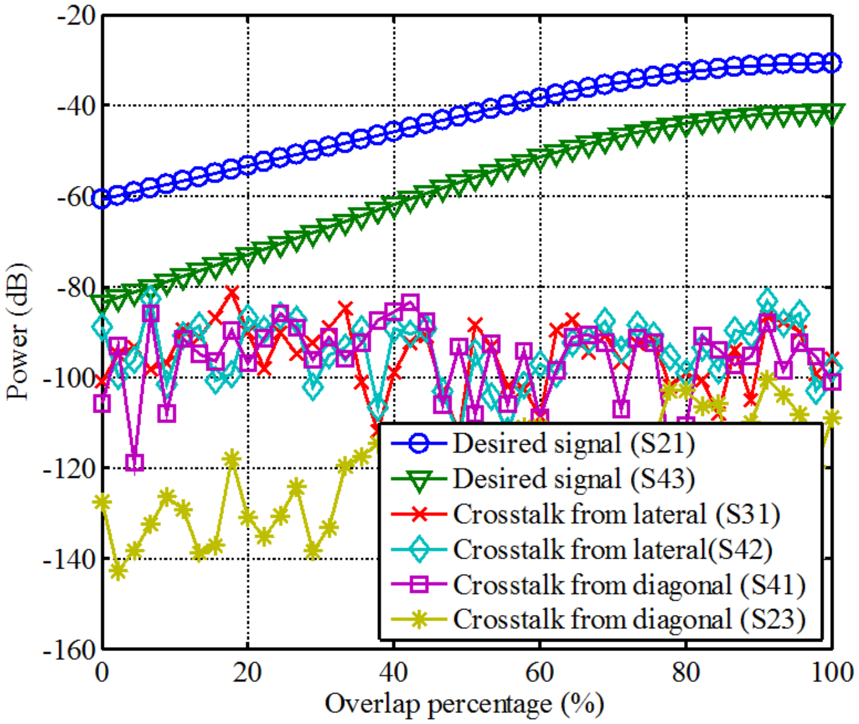


Figure 3.5. Gain of the left and right case misalignment

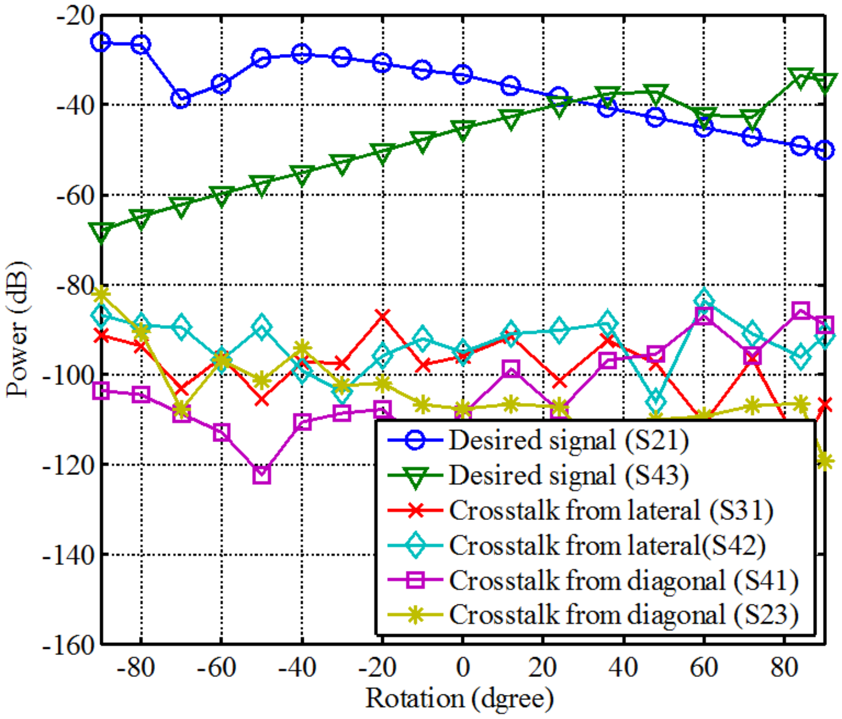


Figure 3.6. Gain of the horizontal rotation case misalignment

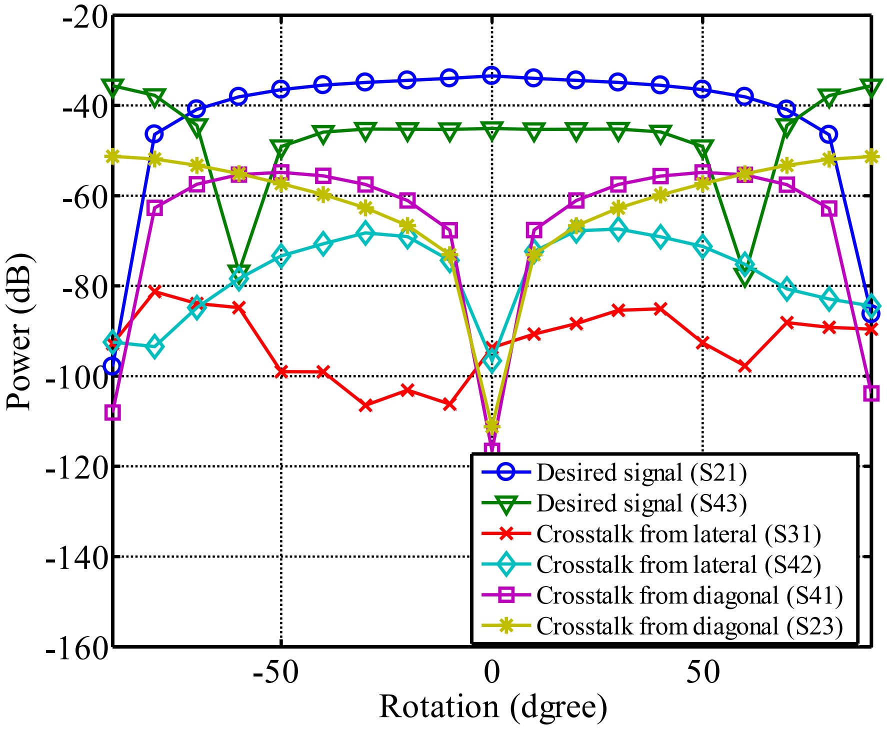


Figure 3.7. Gain of the vertical rotation case misalignment

IV. MISALIGNMENT INSENSITIVE COMMUNICATION SYSTEM TEST BED

4.1. Hardware configuration of the test bed

This Section presents the magnetic MIMO test bed using a software defined radio (SDR). The SDR provides complicated analog RF tasks using the programming environments such as frequency converting, modulation schemes and various filter. Therefore, new schemes can be easily tested by the SDR employing pre-installed baseband and RF components. The SDR is like a kind of bridge between the academy and the industry. It can accelerate validation of operation before mass production. Figure 4.2 depicts a role of SDR between academy and industry.

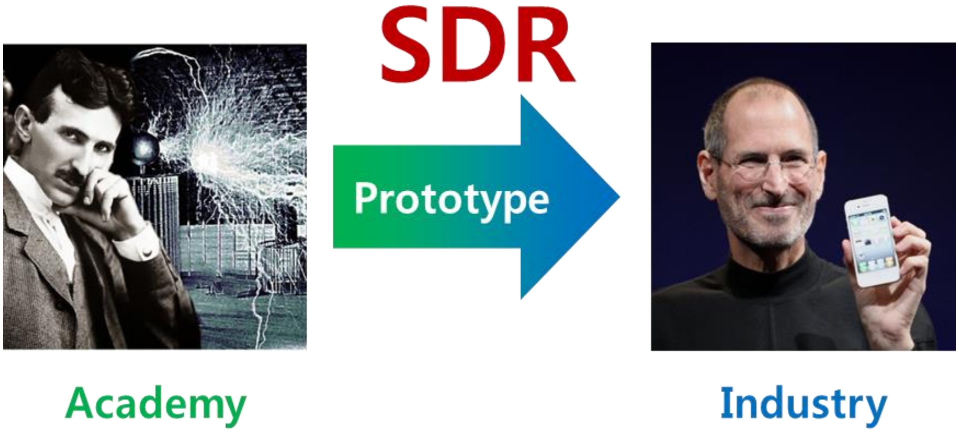


Figure 4.1 Role of SDR between academy and industry

The magnetic MIMO communication test bed include four components: antenna arrays including a conventional circular loop antenna array and the proposed heterogeneous antenna array, SDR for transmitters and receivers, gigabit Ethernet switch, and host computer. Figure. 4.2 shows the architecture of the magnetic MIMO communication test bed [16]. In this implementation, we use the SDR which is provided National Instrument (NI), universal software radio peripheral (USRP) with the Labview and MATLAB for programming. Figure 4.2 shows the configuration method to synchronize the four USRP. The host computer is connected to the gigabit Ethernet switch by the network cable, and the gigabit Ethernet switch is connected to the transmitter and the receiver USRP. Each transmitter and receiver USRPs are connected each other by the MIMO cable for synchronization with a clock source.

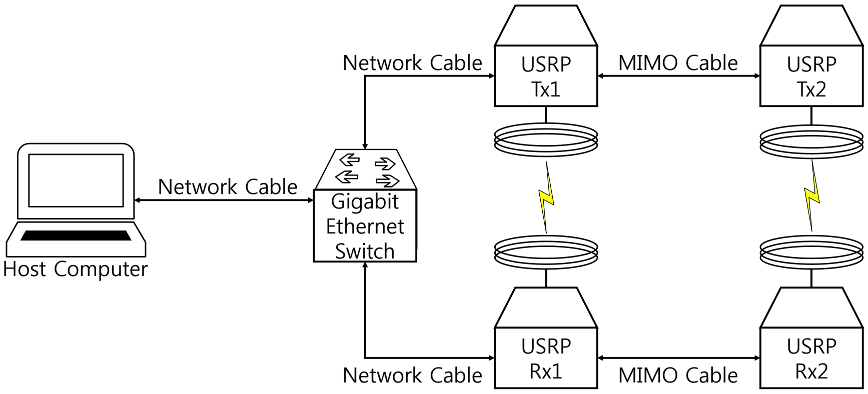


Figure 4.2 System architecture of the near-field magnetic MIMO system.

Figure 4.3 shows the USRP N210 equipped with Basic Tx, Basic Rx daughterboard. The USRP consists of an FPGA with digital signal processing (DSP) functions, analog to digital converter (ADC)s for sampling a received signal, digital to analog converter (DAC)s for generating a transmitted signal and a high-precision clock to be used as the clock reference. Basic Rx/Tx boards with no frequency conversion or filtering, and this daughterboard can support 1 to 250 MHz.

Figure 4.3 Software defined radio USRP N210 equipped with Basic Tx / Rx daughterboard

4.2. Software configuration of the test bed

The signal is going through these steps before the transition and after the reception as shown in Figure 4.4. First, data stream randomly generates 10000-bit, and the data bit is mapping to quadrature amplitude modulation (QAM) symbols. After mapping, the data is divided into two transmit data streams before adding the training sequence and pulse shaping that is used root raised cosine. This whole process is operated by host computer. These digital data streams are transmitted by the transmit USRP after analog converting and up conversion. The receive USRP transform the analog data streams received from the antenna to digital data streams after down conversion. These data streams pass through the matched filter to maximize the SNR. In addition, synchronization and channel estimation are provided by programming in host computer with the training sequence. Finally, BER is calculated by the demodulated bit data after integrating two digital data streams.

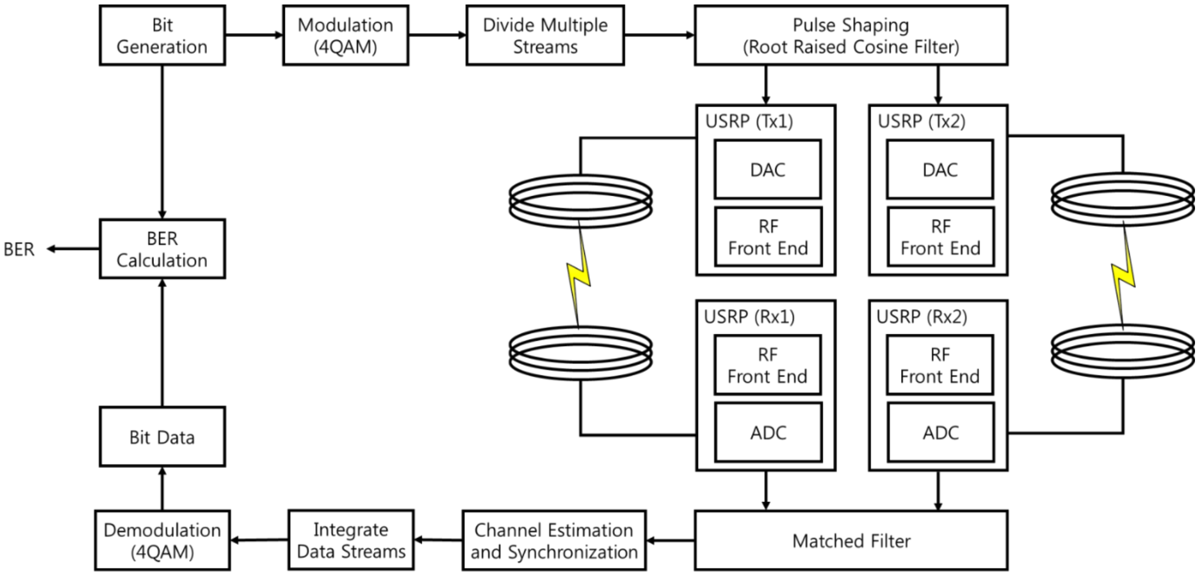


Figure 4.4. Transmitter and receiver data flow

In order to configure this communication system, we use the LabVIEW Communications made by the NI. The test bed code is divided by three parts, the transmitter part, the USRP block about the USRP setting and action, and the receiver part as shown in Figure 4. 5.

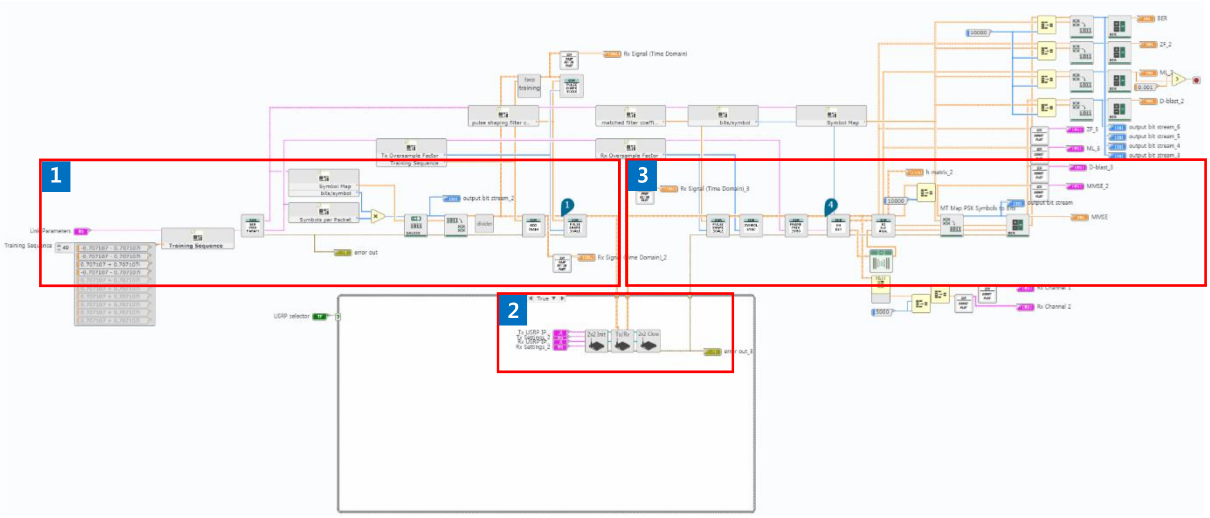


Figure 4.5. Communication system code using the LabVIEW Communications

In the first block, we define several initial setting such as the training sequence, the pulse shaping coefficient, and symbol map according to preset values. After initial setting, the data bit is randomly generated and the generated bit stream is mapped to the QAM symbol according to previous setting. Then, the data stream is divided into two data streams by the odd signal and even signal to transmit the two transmit antennas, and the training sequence is added forward the data streams. Finally, each data stream is sent to receiver by transmit antenna after the pulse shaping as shown in Figure 4.6.

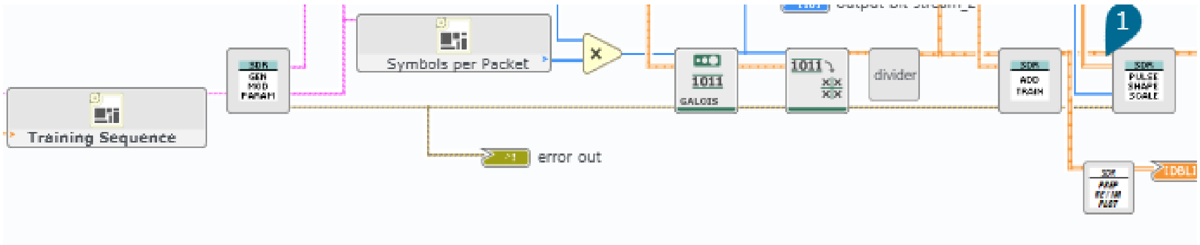


Figure 4.6. Transmitter code part

Figure 4.7 presents setup block for the USRP. To operate the USRP, a few initial values are decided in this step such as the operating time, the carrier frequency, the sampling rate, the reference frequency and the reference clock in USRP. In the first block, initial values of the USRP is set up to operate the USRP, and the second block controls the data transmission and reception of the USRP. In the last third block, the USRP shut down to perform the next command.

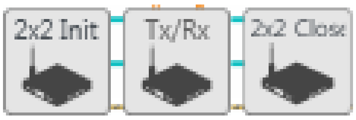


Figure 4.7. USRP control part

Figure 4.8 shows the receiver part which is important part in this communication system. In the first block, the received data streams pass through the matched filter to maximize the SNR, and the second block finds a highest magnitude to synchronize the symbol time. After symbol time synchronization, next block searches starting point of frame using autocorrelation, and compares phase difference between bits to adjust frequency synchronization. After synchronization, the channel information is estimated using the least square (LS) with the training sequence through the channel and the training sequence known by the receiver. Up to this step, it is the processes for recovering the transmission signal. The following block of the channel estimation is the signal processing block to compensate the data streams. In the following subsection, we present detail explanation and discussion to compensate the misalignment effect. After signal processing block, the data stream is converted from the QAM signal to bit data, and the BER performance is calculated by the bit data.

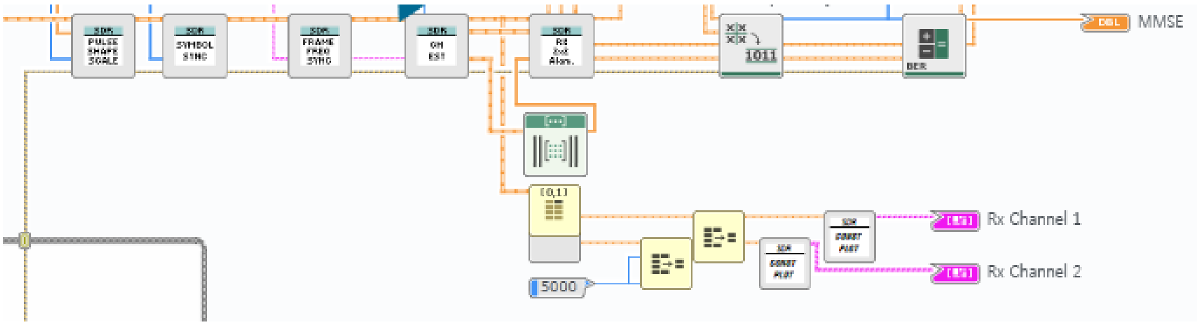


Figure 4.8. Receive code part

4.3. MIMO signal processing scheme

When the misalignment between the transmitter and receiver occurs in magnetic MIMO communication system, the proposed system suffers from the multi-stream interference (MSI) problem [17]. Therefore, the several signal processing schemes apply the proposed magnetic

MIMO system to overcome the misalignment and is compared with each other. Before we discuss about our results, we briefly explain the spatial multiplexing schemes which are applied in the proposed system. The channel is assumed a frequency flat MIMO channel, the signal model is

$$y = \sqrt{\frac{E_s}{M_T}} Hs + n \text{ (1)}$$

The y is the received signal. The E_s is the transmitted signal power. The M_T is the number of the antennas. The H is the channel information. The s is the transmitted signal. The n is the noise power.

4.3.1 Singular value decomposition (SVD) based estimator

When the transmitter has the perfect channel information, the system compensates the data to use the channel information. The channel information is decomposed into left singular vector U, singular values of channel matrix Σ and right singular vector V through the SVD block as shown in Figure 4.8. The transmit data is multiplied by the V before the transmission and the received data is multiplied by the U^H. Then the channel will only remain the diagonal matrix Σ. The SVD can remove the MSI due to remaining the diagonal channel information [17].

$$H = U\Sigma V^H \text{ (2)}$$

$$y' = U^H y = U^H \sqrt{\frac{E_s}{M_T}} U\Sigma V^H V s + U^H n = \sqrt{\frac{E_s}{M_T}} \Sigma s + U^H n \ (3)$$

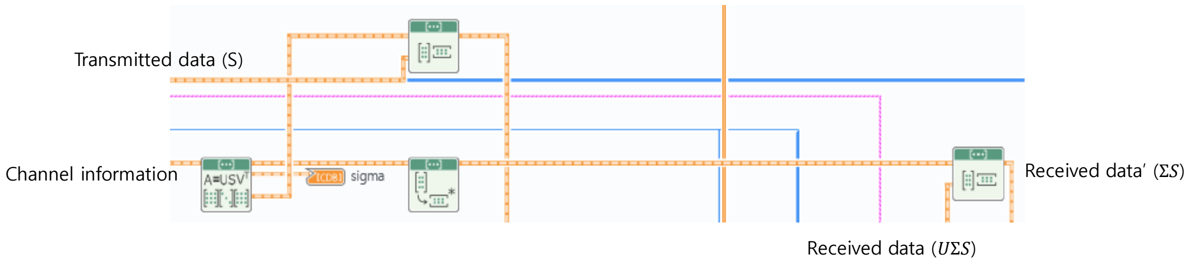


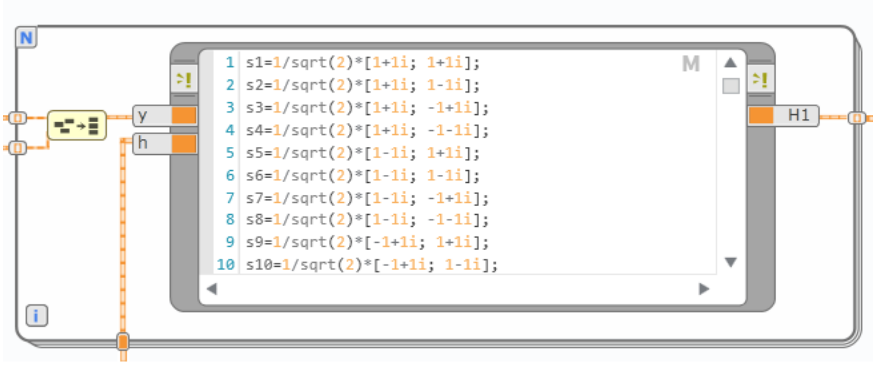
Figure 4.8. SVD code

4.3.2 Maximum likelihood (ML) detector

When the transmitter does not have the channel information, the ML receiver is the optimal performance receiver. The ML finds the vector case which has the minimum difference between the received y and the estimated ŷ [17]. Figure 4.9 shows a realize ML code in the Labview. However, the decoding complexity of the ML receiver increases exponentially depending on the number of the antennas and symbol. When we assume the equally likely, ML is formulated as

$$\hat{\mathbf{s}} = \arg\min_{\hat{\mathbf{s}} \in \mathbf{s}^{\mathbf{m}}} \left\| \mathbf{y} - \sqrt{\frac{E_s}{M_T}} \mathbf{H}\hat{\mathbf{s}} \right\|_F^2 \quad (4)$$

The ML detector of (4) represents a discrete optimization problem over $|S|^m$ candidate vector $\hat{s} \in S^m$.



```
s1=1/sqrt(2)*[1+1i; 1+1i];
s2=1/sqrt(2)*[1+1i; 1-1i];
s3=1/sqrt(2)*[1+1i; -1+1i];
s4=1/sqrt(2)*[1+1i; -1-1i];
s5=1/sqrt(2)*[1-1i; 1+1i];
s6=1/sqrt(2)*[1-1i; 1-1i];
s7=1/sqrt(2)*[1-1i; -1+1i];
s8=1/sqrt(2)*[1-1i; -1-1i];
s9=1/sqrt(2)*[-1+1i; 1+1i];
s10=1/sqrt(2)*[-1+1i; 1-1i];
```

Figure 4.9. ML code

4.3.3 Zero forcing (ZF) receiver

The zero forcing equalizer is a form of linear equalization used in communication which applies the inversed the frequency response of channel. The ZF has the simplest method due to the just multiplies the inverted channel to the received signal. The ZF removes the all MSI in ideal when the channel is noiseless. However, when the channel is noisy, the ZF will amplify the noise greatly at frequencies where the channel response has a small magnitude. Figure 4. 10 presents implemented code in the Labview. The ZF equation is as follows

$$\mathbf{G_{ZF}} * \mathbf{y} = \mathbf{s} + \sqrt{\frac{M_T}{E_s}}\mathbf{H}^{\dagger}n,\ \boldsymbol{G}_{ZF} = \sqrt{\frac{M_T}{E_s}}\mathbf{H}^{\dagger}\ (\mathbf{5})$$

```
a1=(H'*H)^(-1)*H';
H1=a1;
%ZF
```

Figure 4.10. ZF code

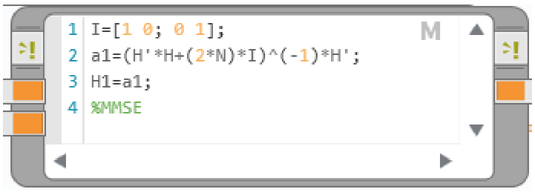
4.3.4 Minimum mean square error (MMSE) receiver

The ZF can remove MSI using the inverted channel. However, the ZF has the lowest performance among the receiver schemes due to the enhanced noise. The MMSE receiver balances MSI mitigation with noise enhancement and minimizes the total error. The MMSE equation is as follows

$$\mathbf{G}_{\mathrm{MMSE}} = \arg\min_{\mathbf{G}} \varepsilon\{\|\mathbf{Gy}-\mathbf{s}\|_F^2\}$$

$$= \sqrt{\frac{M_T}{E_s}}\left(\mathbf{H}^H\mathbf{H}+\frac{M_T}{\rho}\mathbf{I}_{M_T}\right)^{-1}\mathbf{H}^H \quad (6)$$

The MMSE approximates a matched filter at the low SNR and approximates a ZF receiver at the high SNR.



```
I=[1 0; 0 1];
a1=(H'*H+(2*N)*I)^(-1)*H';
H1=a1;
%MMSE
```

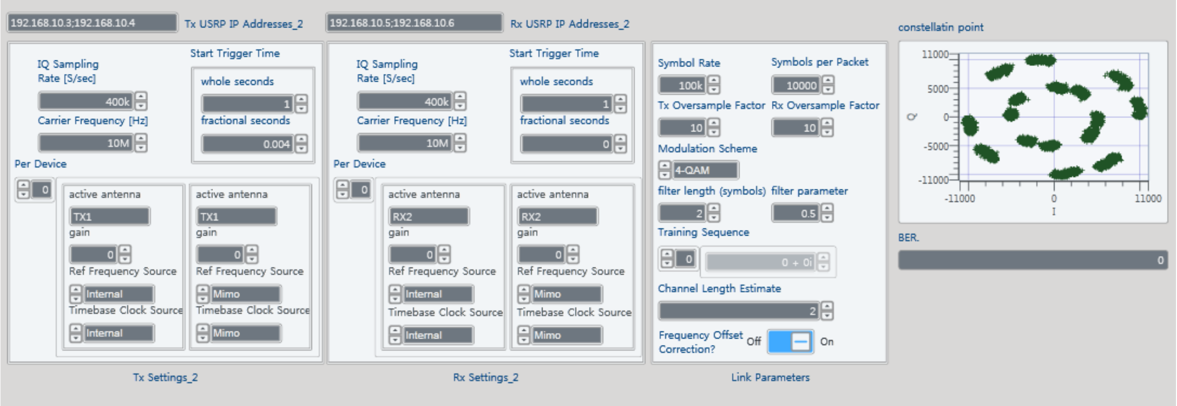
Figure 4.11. MMSE code

V. MISSALIGNMENT EXPERIMENT RESULTS

This section presents the BER performance of the test bed with various signal processing schemes at the four misalignment conditions, as we mentioned in Section III. This section provides measurement setup and results to decide a proper signal processing scheme for the magnetic MIMO communication.

5.1. Experiment setup

The hardware and software configuration require for the experiment which is described in Section IV. The Figure 5.1 shows the parameter setup, such as carrier frequency, sampling rate, oversampling value and filter parameter and modulation scheme. The carrier frequency is 10 MHz; the sampling rate is 400 kbps; the modulation is QAM; and the number of symbols per packet is set to 10,000. In other to use two USRPs to realize the MIMO, the first USRP has to have requires a reference frequency source and a time-base clock source, and the second USRP uses the same frequency source and time source from the first USRP for synchronization. To identify the USRPs for the control, the host computer allocates the internet protocol (IP) to each USRP, and sets up the trigger time to wait the initializing time of the receiver. When the program is executed, the constellation point and the BER result are displayed on the right side of the Figure 5.1. Figure 5.2 (a) is the proposed antenna array test bed and Figure 5.2 (b) is the conventional antenna array test bed. We measure the BER performance of the test bed to verify the crosstalk cancellation effect with the distance between the transmitter and the receiver.. Following the previous results of the first experiments, we set the misalignment experiments at the maximum distance which shows the ‘0’ BER performance of the aligned case. During the experiments, this perpendicular distance between the transmitter and receiver is fixed on the maximum distance. We provide the BER performance of the four misalignment cases, which are considered in Section III, with various signal processing schemes.



Tx USRP IP Addresses_2: 192.168.10.3;192.168.10.4

Rx USRP IP Addresses_2: 192.168.10.5;192.168.10.6

Tx Settings_2
IQ Sampling Rate [S/sec]: 400k
Carrier Frequency [Hz]: 10M
Start Trigger Time
whole seconds: 1
fractional seconds: 0.004
Per Device: 0
active antenna: TX1 | TX1
gain: 0 | 0
Ref Frequency Source: Internal | Mimo
Timebase Clock Source: Internal | Mimo

Rx Settings_2
IQ Sampling Rate [S/sec]: 400k
Carrier Frequency [Hz]: 10M
Start Trigger Time
whole seconds: 1
fractional seconds: 0
Per Device: 0
active antenna: RX2 | RX2
gain: 0 | 0
Ref Frequency Source: Internal | Mimo
Timebase Clock Source: Internal | Mimo

Link Parameters
Symbol Rate: 100k
Symbols per Packet: 10000
Tx Oversample Factor: 10
Rx Oversample Factor: 10
Modulation Scheme: 4-QAM
filter length (symbols): 2
filter parameter: 0.5
Training Sequence: 0 | 0 + 0i
Channel Length Estimate: 2
Frequency Offset Correction? Off / On

BER.: 0

Figure 5.1 Parameters of USRP for magnetic MIMO

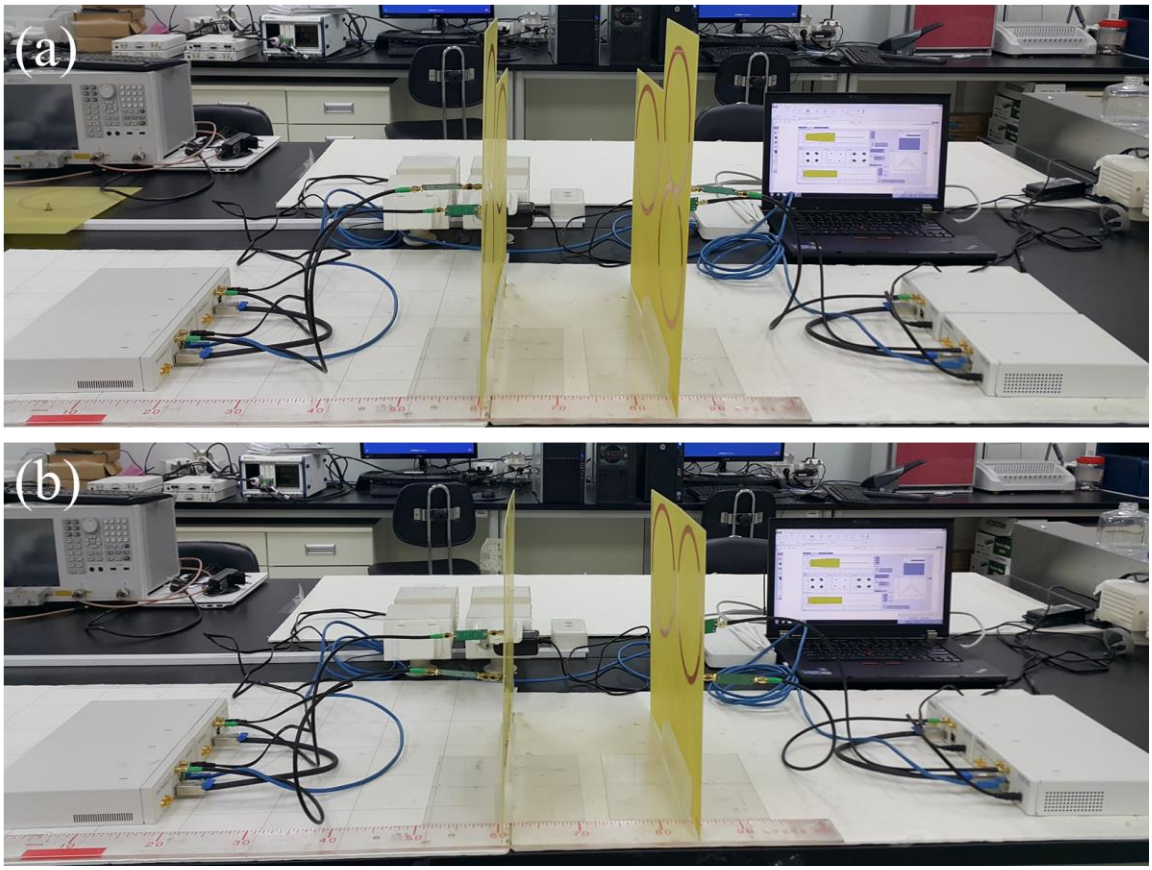


Figure 5.2 Magnetic MIMO communication test bed (a) conventional method (b) proposed method

5.2 BER performance results

Figure 5.4 shows the BER performance which depends on the distance with the conventional magnetic MIMO and the proposed magnetic MIMO. The circle line is the conventional method and the rectangular line is the proposed method. The proposed method can satisfy the same BER performance of the conventional array at the further distance, as shown in Figure 5.4. In these results, we confirm the crosstalk cancellation of proposed method in terms of the BER performance.

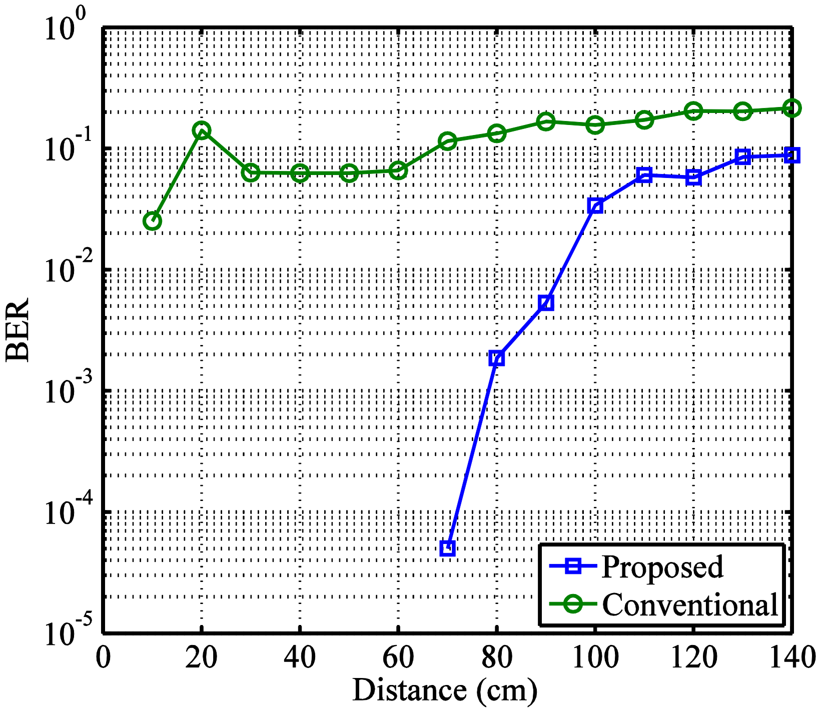


Figure 5.4 BER performance of conventional and proposed antenna array depend on transmission range

The Figure 5.5 – Figure 5.8 show the BER performance results of the various signal processing in the four misalignment cases. The front and rear misalignment case in Figure 5.5 has the critical degradation of BER performance, since the transmit antenna array and the receive antenna array cannot satisfy the crosstalk cancellation condition. When the overlap rate of transmitter and receiver is around 70%, the front and rear misalignment case shows dramatic

BER performance degradation, because the SIR of the quadrupole loop has the lowest value due to cancellation effect and increased crosstalk signal as shown in Figure. 5. X. The BER of the front and rear case misalignment case is higher than the right and left misalignment case because of the crosstalk between transmitter and receiver. This measurement result is the similar tendency of the 3D EM simulation, as shown in Figure 3. 4. When the BER performance is satisfied lower than '10^{-3}', the overlap rate is larger than 85 % in case of the ZF and MMSE. In order to the ML and SVD schemes satisfy the same BER performance, the overlap rate is 78 % and 70 % respectively.

In case of the left and right misalignment, a misalignment loss, which is caused by decreased magnetic flux through the receiver antenna from the transmitter, dominantly affect to the BER performance. However, an effect of crosstalk is not significant issue in this case due to crosstalk cancellation effect. When the BER performance is satisfied lower than '10^{-3}', the overlap rate is larger than 55% in case of the ZF and MMSE. In order to the ML and SVD schemes satisfy the same BER performance, the overlap rate is 47 % and 40 % respectively. In these two misalignment cases, the difference of BER performance between ZF and SVD is 15% and the difference of BER performance between ZF and ML is about 7%. The ZF and MMSE's BER performance is same because of the low ambient noise and high interference.

In case of the vertical rotation misalignment, when the ZF and MMSE are used, the errors start to occur from 40 degrees. When the BER performance is satisfied lower than '10^{-3}', the SVD is more robust than the ZF and MMSE by 30 degrees and the ML is more robust than the ZF and MMSE by 10 degree. In the lateral rotation misalignment case as shown in the Figure 5.8, When the BER performance is satisfied lower than '10^{-3}', the SVD is more robust than the ZF and MMSE by 30 degrees and the ML is more robust than the ZF and MMSE by 10 degree. The four SM schemes show similar tendencies in the two rotation misalignment cases. However, vertical rotation misalignment case is worse than the lateral rotation misalignment case because this case is not satisfied the crosstalk cancellation condition between the transmitted antenna array and the received antenna. The ZF and MMSE BER performance is same because of the low noise environment.

This measurement experiment shows that the performance of magnetic MIMO communication decrease in four misalignment cases. In all of the measurement results, It shows that crosstalk which is caused by the misalignment between transmitter and receiver can be diminish by the signal processing. The SVD scheme robust the largest misalignment when it satisfies the same BER performance of other schemes. In addition, the ML scheme is medium to strong in misalignment and the ZF, MMSE is the worst case in this experiment. The ZF, MMSE is same BER performance because of the low noise environment. However, the SVD scheme can only be used when the transmitter knows channel information. The receiver should transmit the channel information to the transmitter. Therefore, the SVD scheme has high complexity and is only available for full duplex communication systems when the transmitter not has the channel information. If the transmitter does not know the channel, ML has the highest complexity. Because the complexity of ML increases exponentially depends on the number of antennas. The ZF has the simplest structure and the worst performance in all of SM schemes.

Therefore, when the transmitter knows the channel information like a static situation and has the large misalignment, the magnetic communication is suitable for using the SVD. When the transmitter does not know the channel information and consist of a lots of antennas, the magnetic communication is suitable for using the ZF. When the transmitter do not know the channel information and has the large misalignment, the magnetic communication is suitable for using the ML.

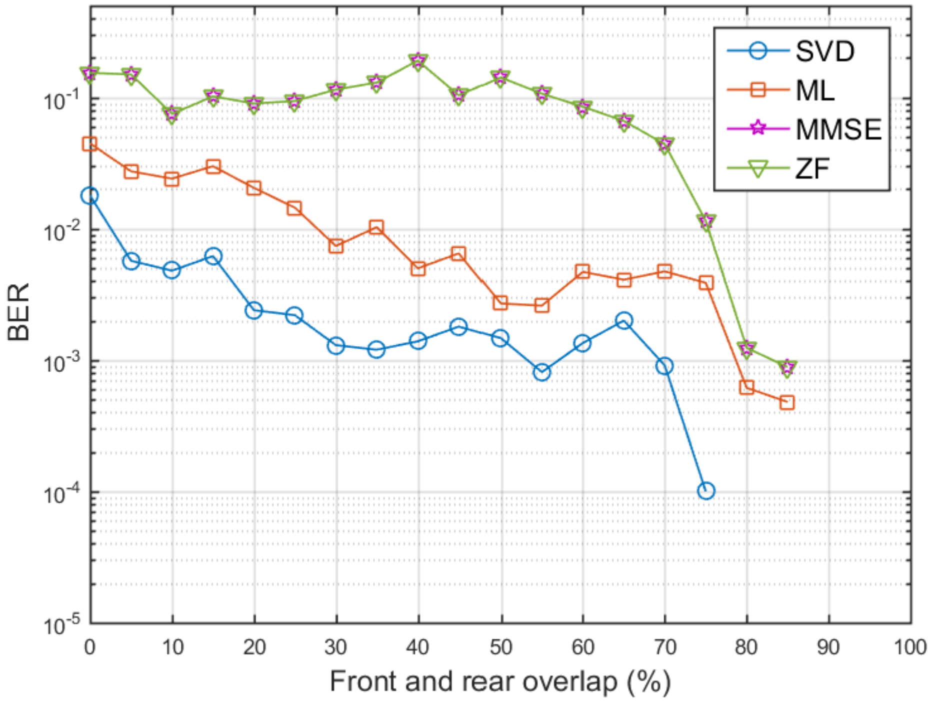


Figure 5.5 BER performance of the various signal processing depend on the front and rear misalignment

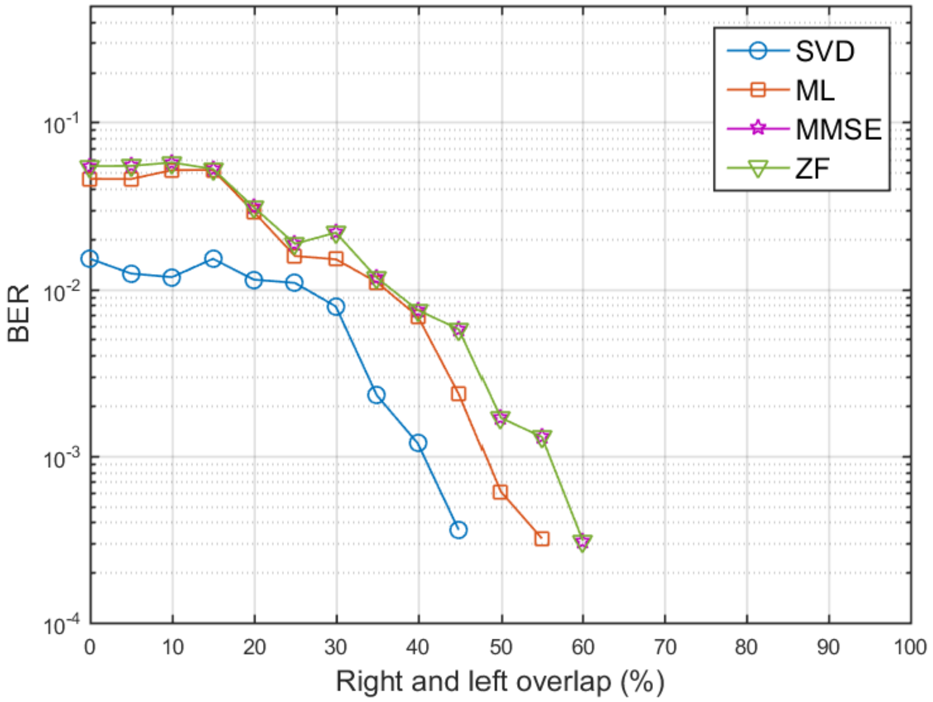


Figure 5.6 BER performance of the various signal processing depend on the left and right misalignment

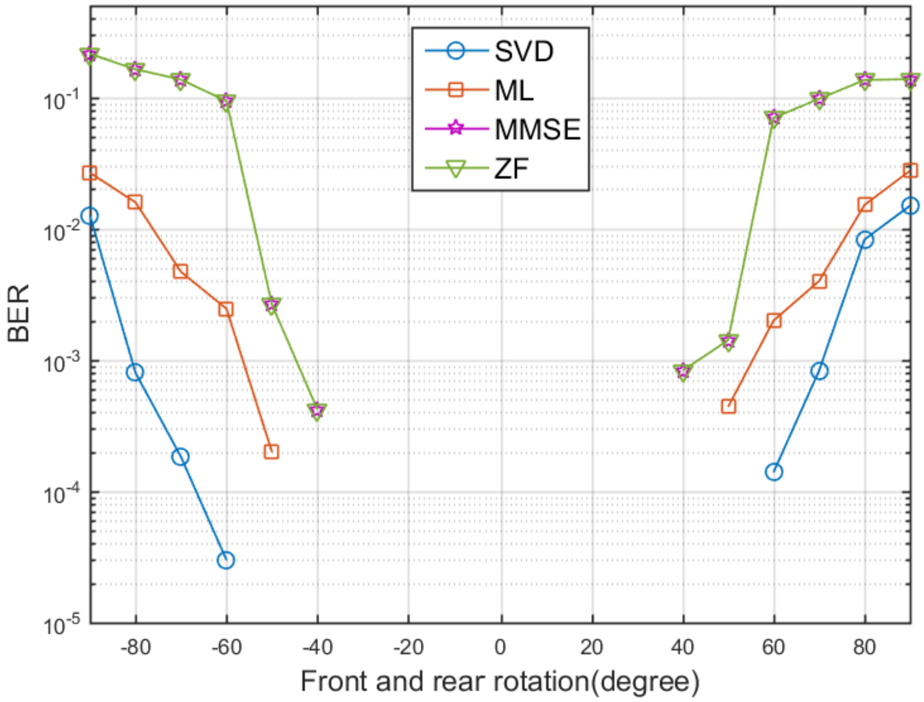


Figure 5.7 BER performance of the various signal processing depend on the vertical rotation misalignment

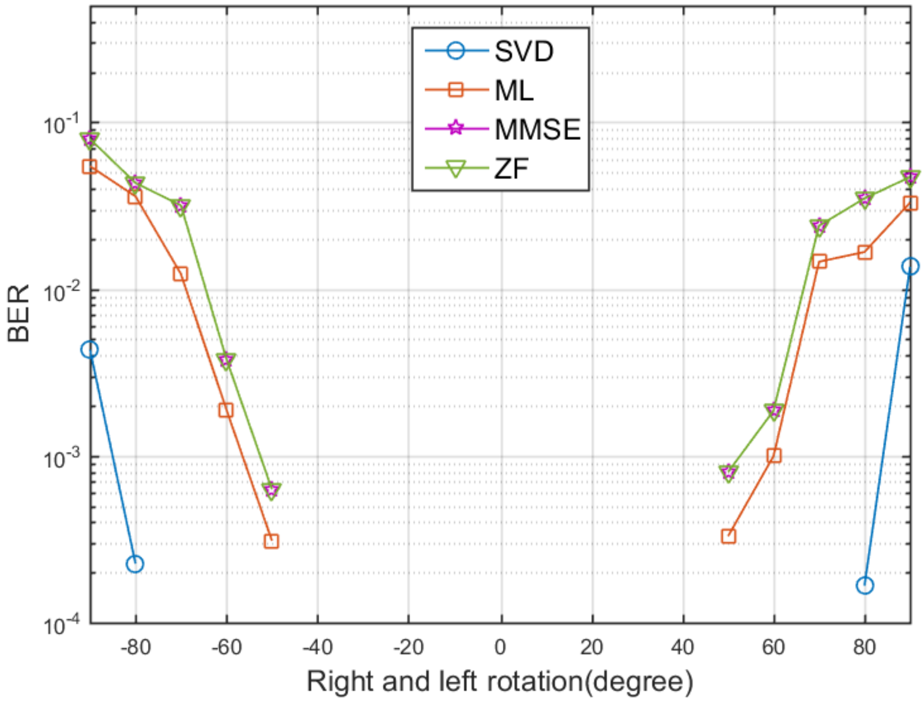


Figure 5.8 BER performance of the various signal processing depend on the lateral rotation misalignment

VI. CONCLUSION

In this paper, we propose the test bed of the proposed magnetic MIMO system with the signal processing schemes to overcome misalignment problems. We realize the SDR based magnetic MIMO test bed that can measure the BER performance of the various signal processing schemes in the four misalignment cases. The SVD shows the highest complexity and the lowest BER performance in large misalignment situations, when the transmitter knows the channel information. If the transmitter does not know the channel information, the ML satisfy the same BER performance of other SM schemes at the larger misalignment situations. According to these results, in the lateral misalignment case, the SVD is more robust than the ZF by 15% and the ML is more robust than the ZF by 7%. In angular misalignment case, the SVD is more robust than the ZF over the 30 degree and the ML is more robust than the ZF about 10 degree. The proposed magnetic MIMO system can make communication even with a larger misalignment. Lots of Bio-medical application such as robotic arm, cochlear implant and artificial retina often require a misalignment or a high degree of freedom. The proposed system can improve the communication system for various bio-medical applications which are difficult to maintain the alignment between the transmitted antenna and the received antenna.

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요 약 문

신호처리기법을 이용하여 오배열에 강인한 자기장 다중입출력 통신시스템

최근에 수중, 지중 그리고 인체내부와 같은 고유전율의 극한 채널 환경에서의 통신의 수요가 늘어나고 있다. 기존의 전자기파 방사를 원리로 하는 RF 통신은 심한 감쇄 때문에 이러한 채널 환경에 적합하지 않다. 그러므로 유전율에 영향을 받지 않는 자기장 통신은 이런 환경에서 대체 통신으로 주목을 받고 있다. 그러나 자기장 통신은 낮은 중심주파수로 인하여 높은 전송률을 지원 할 수 없다. 더욱이 짧은 통신범위와 송수신 안테나간 오배열에 민감하다는 단점을 가지고 있다. 많은 연구 팀들이 여러 접근법을 이용하여 이 문제를 극복하려 노력하였다. 이 논문에서 자기장 통신의 정보 전송율을 올리기 위해 이종의 다중극자 안테나를 구현하고 다양한 신호 처리 기법을 사용하여 오배열 상황에서 BER 성능을 향상시키려 한다. 제안된 안테나 배열은 더 먼 거리에서 기존의 안테나 과 같은 BER 성능을 만족한다. 추가적으로 기존 RF 통신에서 사용되는 maximum likelihood (ML) , zero forcing (ZF) , minimum mean square error (MMSE) and singular value decomposition (SVD) 와 같은 신호처리 기법들을 사용하여 다양한 오배열 방법에서 향상된 BER 성능을 보이려 한다. 실험을 통해 자기장 통신이 신호처리를 사용해 오배열을 극복할 수 있다는 것을 입증하였고 채널정보를 송신부에서 알고 있다고 가정을 하였을 때 큰 오배열에서 가장 낮은 BER 성능을 가진다는 것을 알 수 있었다.

핵심어: 자기장 통신, 다중입력 다중출력, 오배열, 신호처리