Study on High-Speed Ultrasound Communication

A Thesis Submitted to the Department of Computer Science and Communications Engineering of Waseda University in Partial Fulfillment of the Requirements for the Degree of Master of Engineering

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Abstract

Short-range wireless communication system that is used radio and microwave communication has been widely used in our daily life in recent years. However, it has high exposure of radiation, which is even in relatively small amounts can cause irreparable damage to cells and tissues and it can cause information leakage and apparatus malfunction.

One of the solutions is to employ ultrasound waves because it has lower risk to human body and will not cause other medical devices' apparatus malfunction. Ultrasonic transducers(UT) can be used reciprocally as transmitter and receiver in an ultrasonic communication system. The sound waves are emitted at frequencies from the transmitter transducer corresponding to that of the alternating voltage applied to the receiver transducer. Nowadays, 40kHz ultrasound communication in the air became a mature method applied to park a car or indoor localization. Comparing with low frequency ultrasound wave, high frequency ultrasound wave has less distortion, good recoverability and it is good at anti jamming ratio. Moreover, low frequency ultrasound is easy to be obstructed by other things in the air. Therefore, it is meaningful for us to achieve high frequency ultrasound long distance air propagation. The aim of this thesis is to introduce the basic low frequency ultrasound long distance air propagation method, and base on this method to establish a method to achieve high frequency ultrasound long distance air propagation. Finally, we take advantage of ultrasound superposition to establish an ultrasound array.

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Chapter 1
Introduction

1.1 Sonic Waves and Ultrasonic Waves

Short-range wireless communication system used radio and microwave communication has been widely used in our daily life in recent years. However, it has high exposure of radiation, information leakage and apparatus malfunction. Ultrasound has lower risk to human body and will not cause other medical devices' apparatus malfunction.

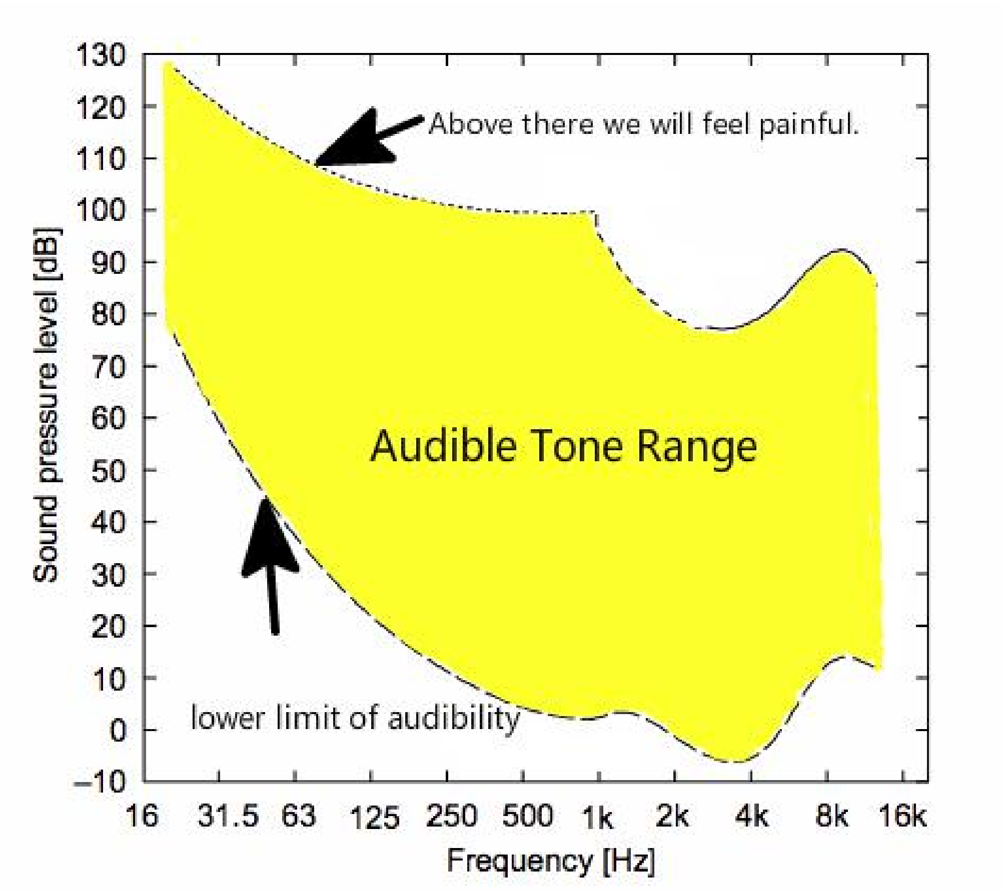

Figure 1 Audible Tone Range

Although ultrasound has very minimal in comparison to other methods, it also has some dangers. It can lead to development of heat, tissues or water absorb the ultrasound energy which increases their temperature locally. And when ultrasound causes local heat, dissolved gases will come out of solution. Because these dangers mainly appear in high intensity systems used for therapy, in air propagation, these dangers could be ignored.

1.2 Ultrasound Propagation in the Air

Ultrasound attenuation values increase with frequency. Different with water has minimal attenuation to ultrasound, for example, attenuation of blood is 0.03dB/cm/MHz, soft tissue has an attenuation of 0.3dB/cm/MHz. Air and solidity of different materials will normally attenuate all the imaging ultrasound beam energy they encountered. Therefore, only low frequency ultrasound waves can propagate in air at a speed of 340m/s with a very high attenuation. The acoustic impedance of air near zeros. There are some parameters of ultrasound waves, frequency, propagation speed, wave length, amplitude, pressure, power and intensity. Among these parameters, amplitude is the most important parameter for ultrasound air propagation, because for vibration, the amplitude is maximal distance a particle moves away from its original position.

Nowadays, 40kHz ultrasound communication in the air has been widely used in our daily life and it has been a mature technology such as parking car and indoor localization, which has achieved 1.0 to 3.0 meters air propagation. From air absorption equation (1-1) we can see that high frequency ultrasound causes high attenuation in the air because of its high air absorption.

$$A_e = 7.4\frac{f^2 r}{\phi}\times 10^{-8} \qquad (1\text{-}1)$$

Where f is frequency of ultrasound wave, ϕ is relative humidity, the air temperature is 20 degree centigrade.

Different from low frequency ultrasound, high frequency ultrasound wave has less distortion, good recoverability and it is good at anti jamming ratio. Low frequency ultrasound is easy to be obstructed by other things in the air. Therefore, it is meaningful for us to achieve high frequency ultrasound long distance air propagation.

Chapter 2
Overview of System Architecture

Our architecture is designed for indoor ultrasonic communication showed as Figure2. Triangles stand for ultrasonic transducers and the receiver transducers connect with each other by cable and fixed on ceiling. transmitter transducers are free to move in the door. A man (especially the aged) can wear a wearable device where an ultrasonic transmitter transducer is implanted in on a wrist like a watch. This ultrasonic sensor takes the value of pulse or glucose of this man. Then the value is sent to the watch through the human body. Moreover, another ultrasonic sensor is installed in the room of the house. His health status is sent from the watch to the sensor in the room regularly, per several hours. These ultrasonic sensors also can be connected to a remote medical center or his family to check this man's health status. Furthermore, another sensor is installed in an entrance door. His family could know whether he go out or come into the room. This architecture system can be used for the healthcare of the elderly because the population of elderly people now in Japan or some other countries now in increasing while there is lack of the number of care workers. The problem of the aging society has been becoming more serious in recent years. As the nation's population rapidly grays, ensuring there are enough nursing care workers to meet growing demand has become a pressing issue. Our system architecture is to create a system to understand the living condition of the elder, even if there are no people who take cater of them.

Different from Wi-Fi, Bluetooth, Zigbee...etc, the new indoor wireless communication system that we proposed using ultrasound waves needn't complicated connecting means, and can enhance security strength because ultrasound waves can't through wall. This system is designed for healthcare of elderly people and help to prevent solitary death.

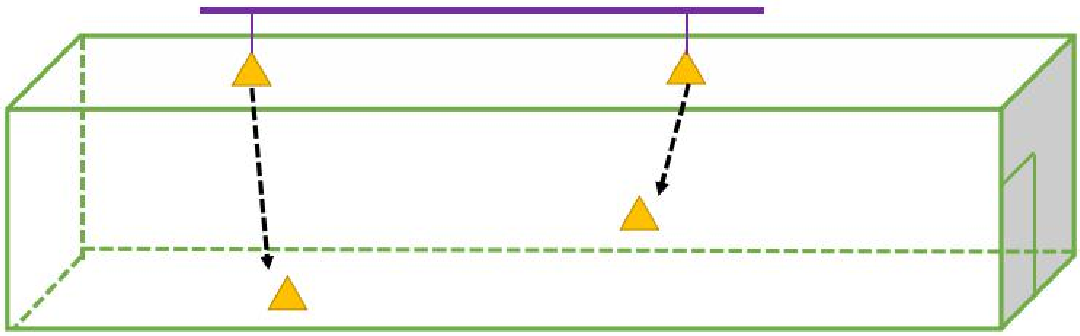

Figure 2 Overview Architecture

Chapter 3
Test Measurement

3.1 Modulation Groups

To establish an idea ultrasonic communication system, modulation method using for ultrasound waves should be considered, because digital modulation is the addition of information to digital signal. Thus, a suitable modulation technique should be used, a scheme can define how the carrier signal is controlled by a modulating signal. The choice of modulation technique affects the implementation complexity of the modulator and demodulator and EVM (Error Vector Magnitude) at a given speed. In our experiments, EVM is taken by changing symbol rate with three digital modulation groups, FSK(Frequency Shift Keying), PSK(Phase Shift Keying) and ASK(Amplitude Shift Keying).

3.2 Beam Pattern Formation of Ultrasonic Transducers

Ultrasonic transducers can be used reciprocally as transmitter and receiver. In an ultrasonic communication system, ultrasonic transmitter converts electrical signals into ultrasound while ultrasonic receiver converts ultrasound into electrical signals.

Figure3 and Figure4 show the transducers that we used in different experiments. Both these two kinds of transducers are sensors including oscillator that generates or receives ultrasonic waves. And pulse voltage of high frequency is added to material of piezoelectric element.

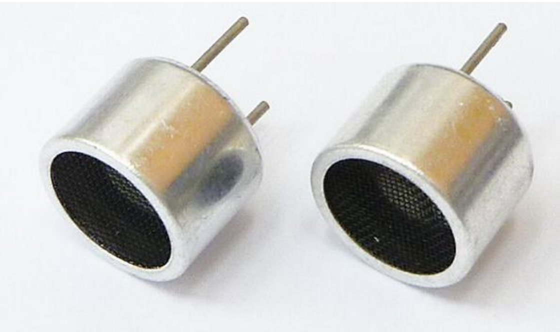

Figure3. UT1612 Ultrasonic Transducer with 40kHz Center Frequency

Figure4. BP520 Ultrasonic Transducer with 5MHz Center Frequency

Material of piezoelectric element has the ability to generate an electric potential in response to applied mechanical stress. Applied electrical charge on both sides of a piece of piezoelectric material, it will cause stress inside and thus generate deform. If the electrical charge is alternative, the piece of material will oscillate and generate mechanical wave. The piezoelectric material has a special structure that will cause positive and negative charge center mismatch when an external stress is introduced from certain direction. Piezoelectric ceramic have many small regions inside it, called “domain”, and each domain has its own piezoelectric direction.

A simple field pattern model is shown in Figure5. The most simple transducer shape is a piston transducer. The beam from a piston transducer is similar to a flash light beam. At each sound field point location, the acoustic pressure is the summation of contributions from each point at transducer surface. When aperture size is much bigger than the wavelength, the points locations within the transducer area and close to the center see an unlimited aperture, at same depth, will receive the same amount of acoustic contribution from the nearly unlimited transducer surface, and thus ultrasound wave behaves like plane wave. The horizontal axis is angle from -90 to +90 degree, the beam width will be the angle difference between the two dB level points.

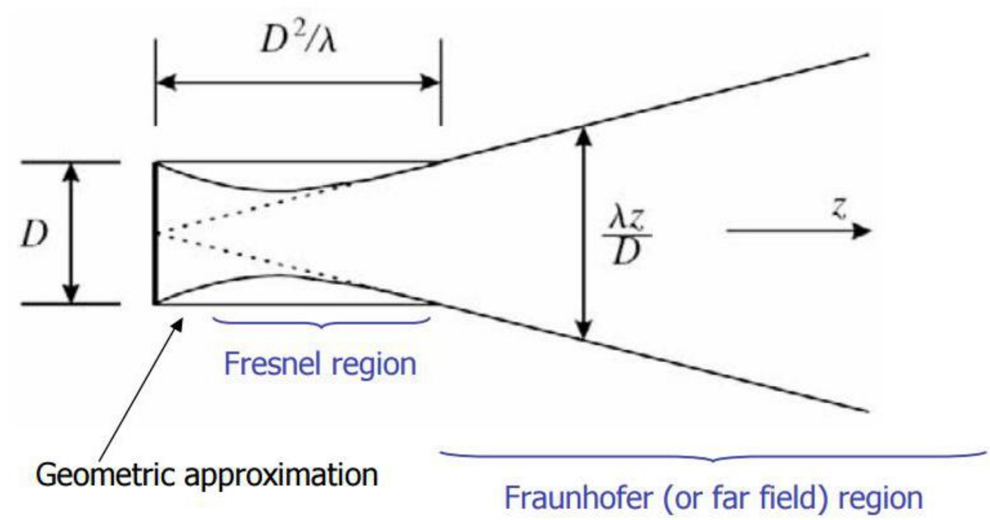

Figure5. Simple Field Pattern Model

3.3 EVM

EVM (Error Vector Magnitude) is a measurement used to quantify the performance of a digital radio transmitter or receiver. A signal sent by an ideal locations if there was not various imperfections in the implementation like carrier leakage, low image rejection ratio and phase noise. As a measure of overall modulation accuracy, EVM reflects many different signal distortions. The proportionality depends on the particular modulation scheme. QPSK (Quadrature Phase Shift Keying) is related to only phase rather than a signal vector because QPSK is not related to information of amplitude.

VSAs （Commercial vector signal analysers） have been largely responsible for popularising EVM measurement techniques. These anlysers provide an impressive collection of tools to help the system designer pinpoint and solve digital communications problems as various as matched filter errors, local oscillator phase noise, and output amplifier intermodulation distortion.

In our experiments, we use VSA89600 to get EVM's result by changing frequency and symbol rate with three digital modulation groups, PSK, FSK and ASK. If the value of EVM is below 20%, we consider the modulation performance is good.

3.4 Symbol Rate

Symbol rate decides communication efficiency. In digital communications, symbol rate is known as baud rate and modulation rate, is the number of symbol changes, waveform changes, or signaling events, across the transmission medium per time unit using a digitally modulated signal or a line code. The symbol rate is measured in baud (Bd) or symbols per second. In the case of a line code, the symbol rate is the pulse rate in pulses per second. Each symbol can represent or convey one or several bits of data.

Chapter 4

Low-frequency Range Ultrasonic Communication in the Air

4.1 Experiment Setup

Figure6 is the experiment setup for low-frequency range ultrasonic communication in the air. The pair of ultrasonic transducers are UT1612 transmitter and receiver with the center frequency is 40kHz. The signal generator is Agilent's EXG Vector Signal Generator with the maximum value of transmission power is 19dBm. The oscilloscope is Agilent's EXA Signal Analyzer. A low noise amplifier is used. Signal generator sends signals to the ultrasonic transmitter, then ultrasonic transmitter converts electrical signals into ultrasound while receiver converts ultrasound into electrical signals. The sound waves are emitted at frequencies from the transmitter transducer corresponding to that of the alternating voltage applied to the receiver transducer. The simulation of transmitter's beamforming showed as Figure7.

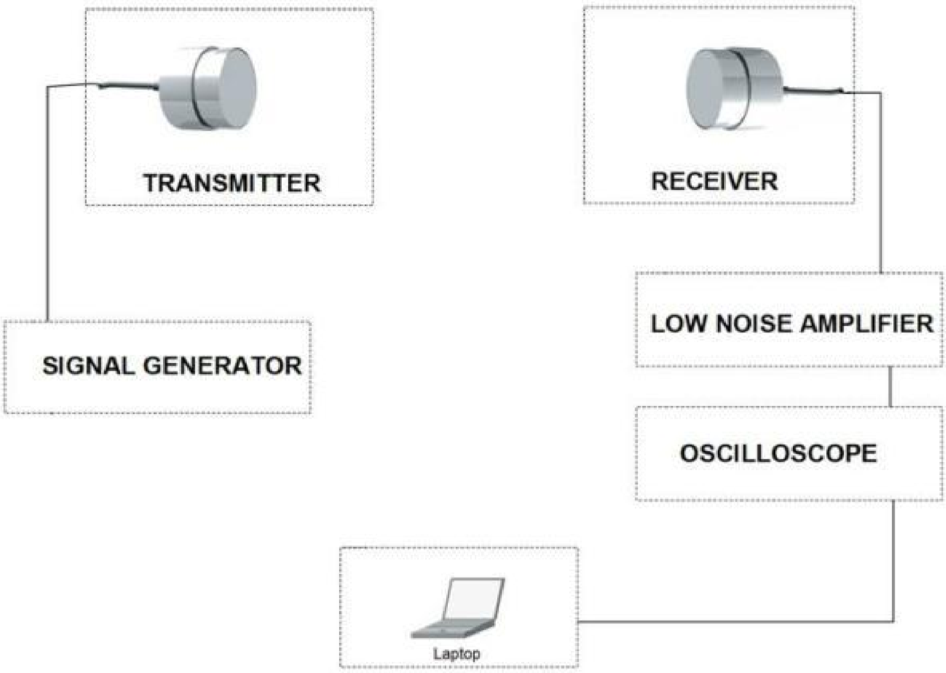

Figure6. Setup of Low-Frequency Communication

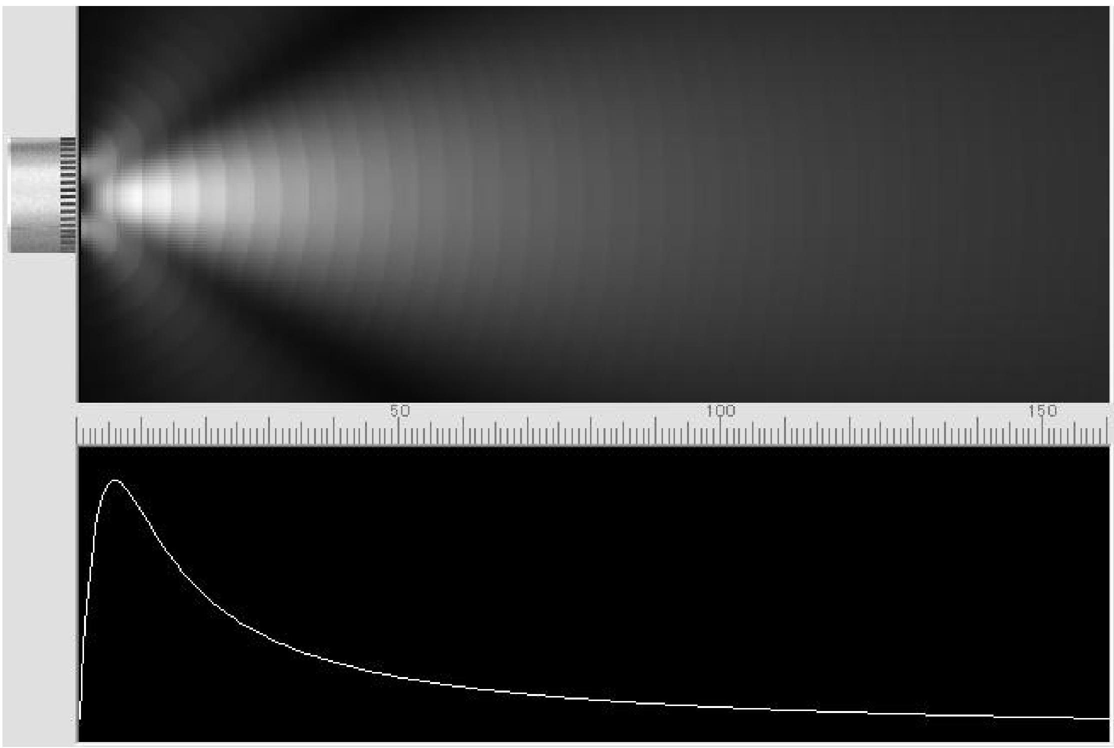

Figure7. 40KHz,16mm Ultrasonic beam in the air

4.2 Low Noise Amplifier

The ultrasonic transducer is excited by an electrical pulse and transmits the ultrasonic pulse into air and only then a signal is entering the medium under investigation. The ultrasonic pulse travels in the material and is emitting some energy into air. This energy is picked up by a receiving air-coupled transducer. Development of air-coupled ultrasonic is raising demands for electronics used. Because of large difference of acoustic impedances of solid body under investigation and air, testing signal is attenuated. Attenuation can reach up to 100dB, so powerful transmitters and low noise receivers should be used.[5] Figure8 is a low noise amplifier that we used both in low-frequency range ultrasonic communication in the air and high-frequency range ultrasonic communication in the air. When the frequency is from 40kHz to 30MHz, it has 30dB gain.

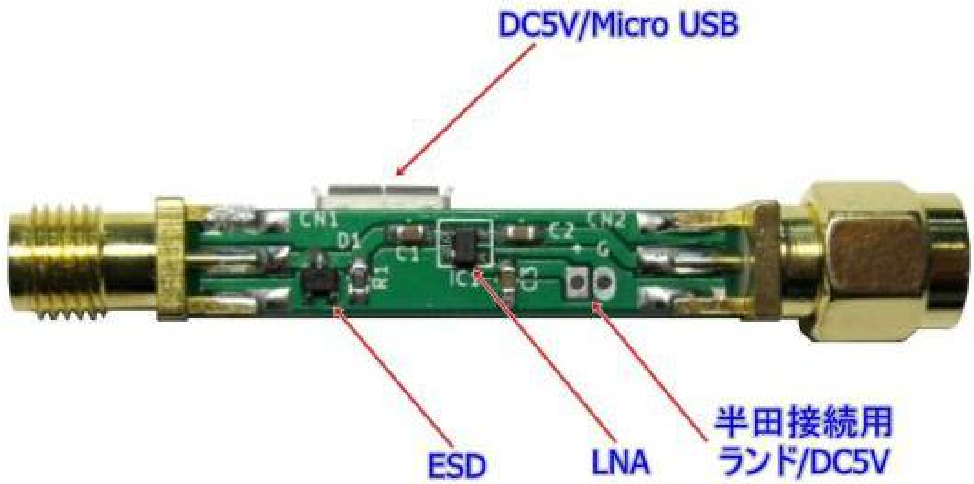

Figure8. Low Noise Amplifier

4.3 Experimental Results and Analysis

A plot of the distance versus receiving power is illustrated in Figure9. Because this pair of ultrasonic transducers is used for air propagation, the data was taken at operating frequency of 40kHz and an input power of 19dBm. A low noise amplifier designed for 40kHz connects with the receiver UT. The transmitter UT was placed statically at one end and the receiver UT was moved along the straight line at the other line. The receiving power decreases as the distance becomes farther. Especially after 240mm, the receiving power decreases sharply. Thus, EVM is taken by changing symbol rate at 240mm with three digital modulation groups.

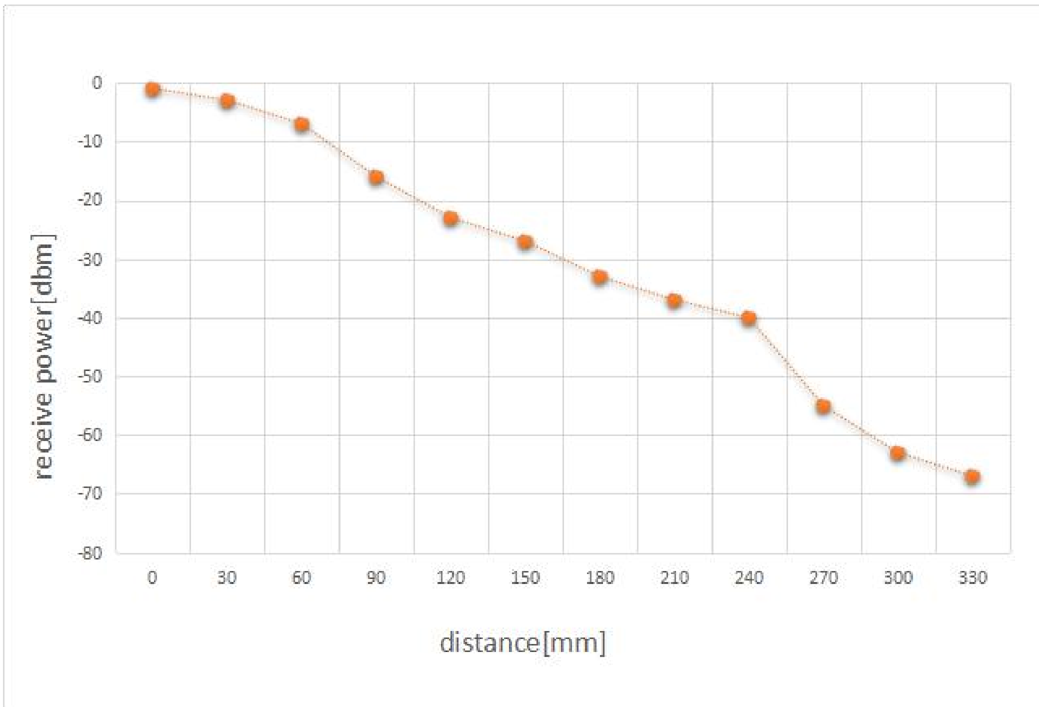

Figure9. Distance and Receiving Power

Next, we change symbol rate to find out the most suitable symbol rate for each digital modulation groups. There are 3 ranges of symbol rate that we conducted, 10k~100ksps, 100k~1000ksps and 5M~35Msps.

Figure10, 11 and 12 are results of EVM that is taken by changing symbol rate range with three digital modulation groups, PSK, FSK and ASK. EVM is a measurement used to quantify the performance of a digital radio transmitter or receiver[6].A signal sent by an ideal transmitter or received by a receiver would have all constellation points precisely at the ideal locations, however various imperfections in the implementation like carrier leakage, low image rejection ratio and phase noise. If the value of EVM is below 20%RMS, the performance is good. We choose three range symbol rate range. Figure10 is the result of 10k~100k sample per second range, for PSK and FSK modulation groups, EVM is from 8% to 33% while for ASK modulation, is the symbol rate is over than 20ksps, it's not suitable to use it. Figure11 is the result of 100k~1000k sample per second range, all digital modulations' EVM is from 30% to 55%. Figure12 is the result of 5M~35M sample per second range, EVM is from 50% to 60%, all of results of EVM are over 20% and unstable.

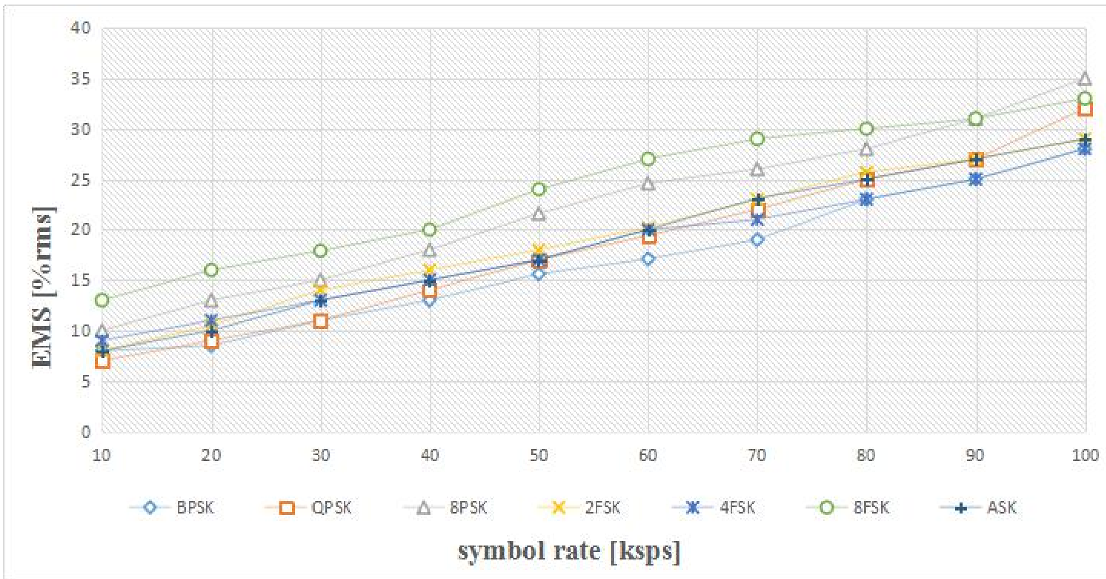

Figure10. Symbol Rate and EVM (10k~100ksps)

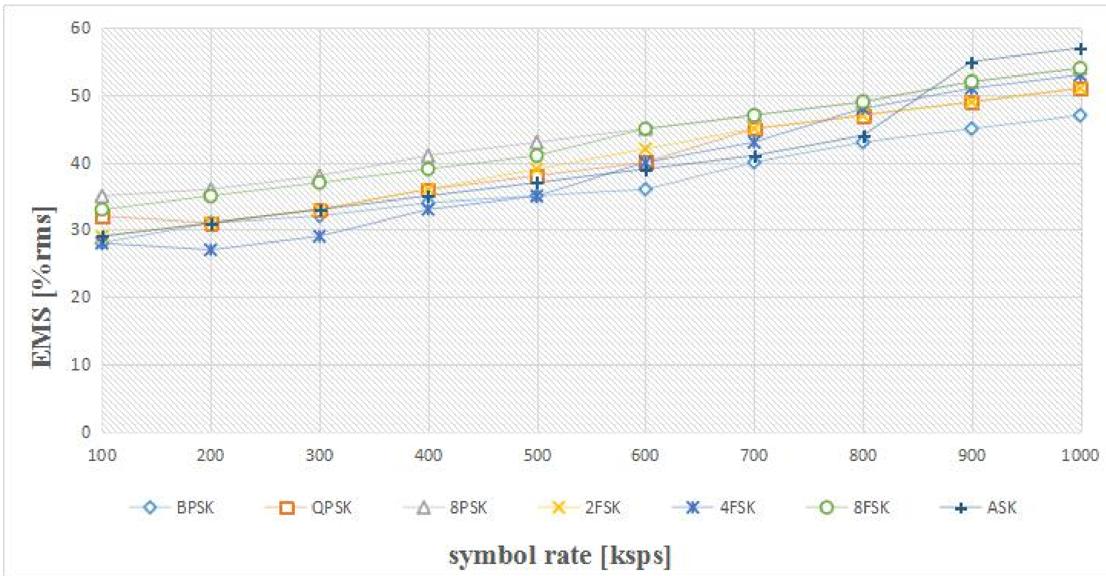

Figure11. Symbol Rate and EVM (100k~1000ksps)

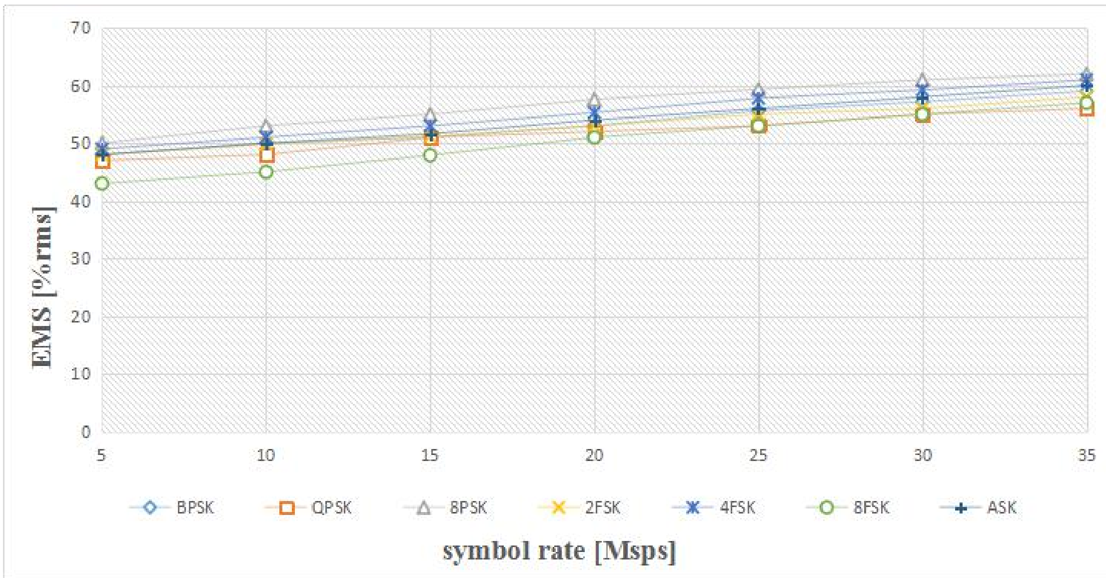

Figure12. Symbol Rate and EVM (5M~35Msps)

Table 1 Symbol Rate and EVM at Low-Frequency Ultrasonic Communication in the Air

symbol rate [sp/s]	EVM
10k~100k	10%~30%
100k~1000k	30%~55%
5M~35M	50%~60%

Chapter 5
High-frequency Ultrasound Non-Array System

5.1 Previous Experiment

Our second method to achieving indoor ultrasonic communication is to use high-frequency rage ultrasound. The pair of ultrasonic transducers are Tru-Sonics BP520-3007 transmitter and BP520-3009 receiver. Because this pair of ultrasonic UT is not for air propagation, at first we try to contact ultrasonic UT with metal to achieve its air communication, then the operation frequency is to be found out.

Figure13 is the previous experiment to find out the influence of material to high-frequency ultrasonic communication. The signal generator is Agilent's EXG Vector Signal Generator with the maximum value of transmission power is 19dBm, the symbol rate is 15MHz. The oscilloscope is Agilent's EXA Signal Analyzer. A low noise amplifier is used.

Figure13. Previous Experiment

Figure 14 is the result of transducers touch directly and transducers touch through material. we evaluated 3 kinds of materials to do ultrasonic communication experiments, iron, bronze, aluminum. The size of them are all the same, the thickness is 0.5mm, the length is 200mm, the width is 100mm, and iron plate is the only one can be used because it can enhance receiving power as Figure11 shows. Moreover, if the ultrasonic transmitter and receiver contact to iron plate tightly, whichever the position of them will not influence the result. Thus, the relative area and thickness of iron plate could be two key parameters. However, in practical condition the relative area of the iron plate which used in previous experiment is too big and is better to make its weight lighter, and shape of iron plate should be also deliberated.

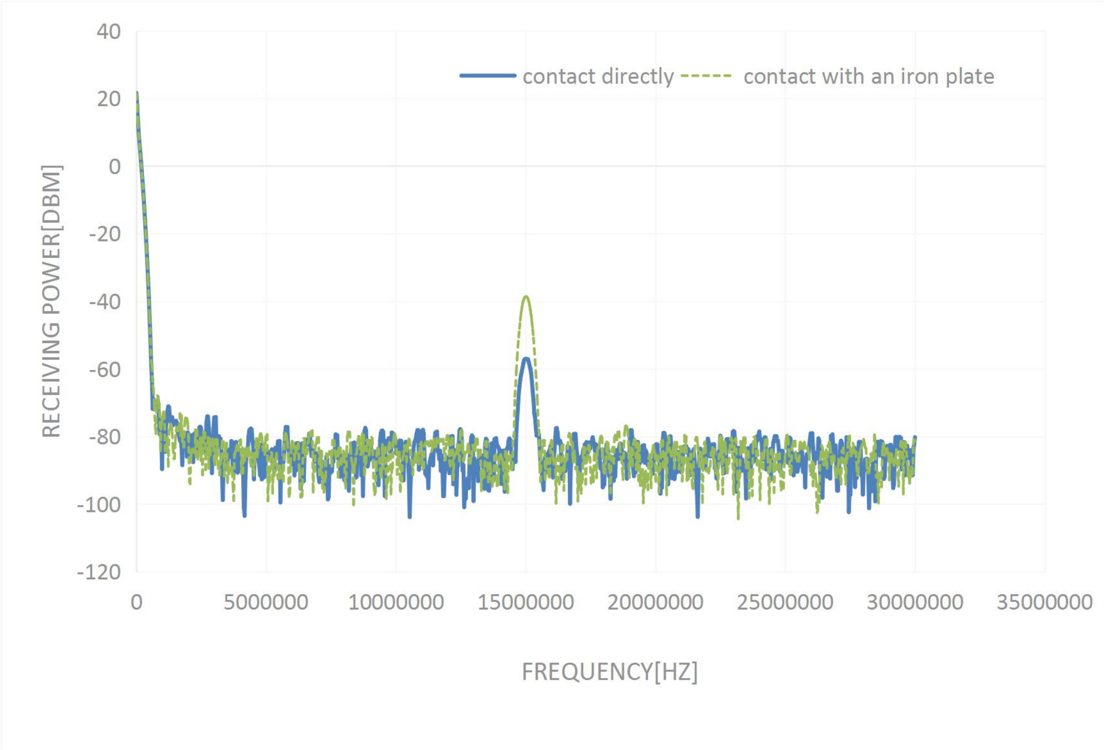

Figure 14. UT Touch Directly versus through Metal

5.2 Metal Choose

Figure15 is to find the relationship between the thickness of iron and attenuation of ultrasonic communication. Thickness is from 0.02mm to 0.30mm per 0.02mm. The transmission distance is 50mm. From figure16, if the transducers not touch iron, there is almost no receiving power. And 0.22mm is the best suitable iron plate thickness. Figure17 is the iron plate in 3 shapes, circle, triangle and square. Their thickness are all 0.22mm, relative area are all 49 cm^2 .

Figure15.   Comparison of Different Shape of Iron Plates

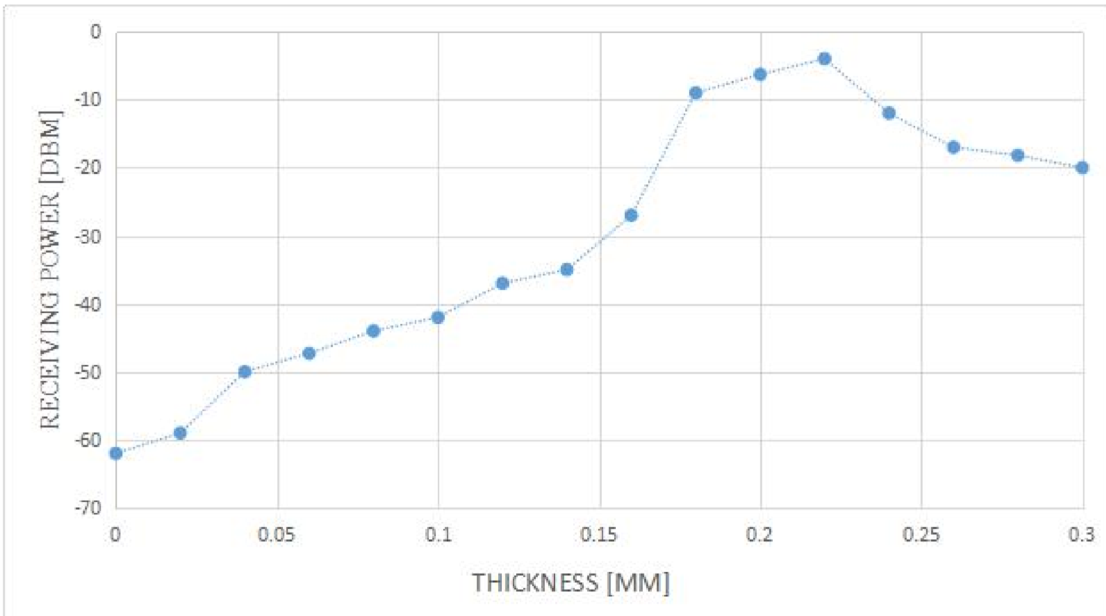

Figure16-1.   Iron Foil's Thickness and Receiving Power

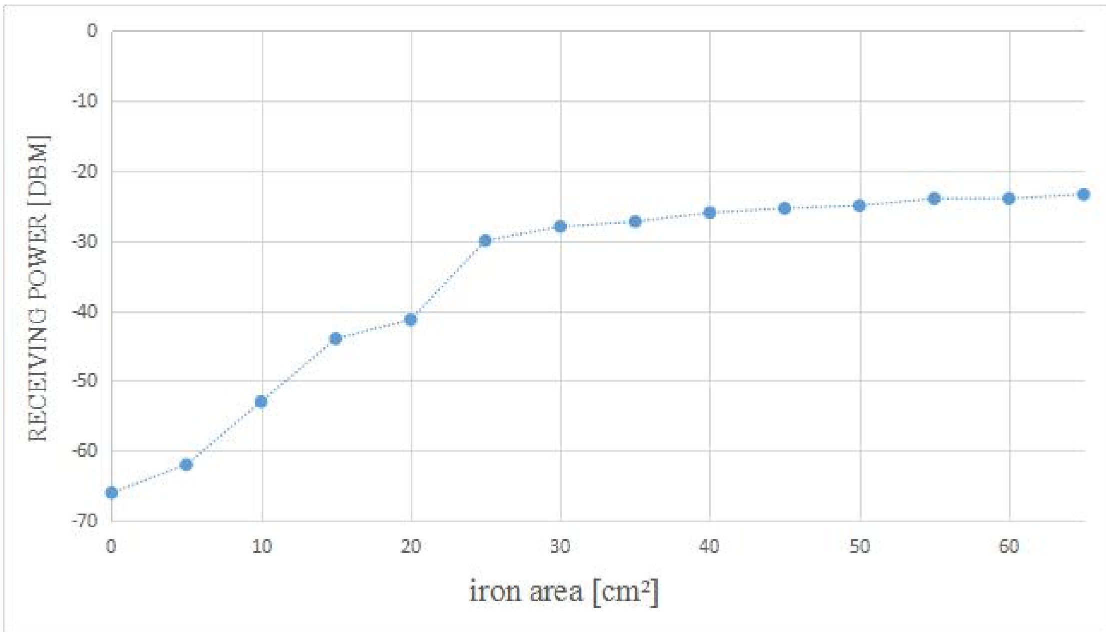

Figure16-2.　Iron Foil's Area and Receiving Power

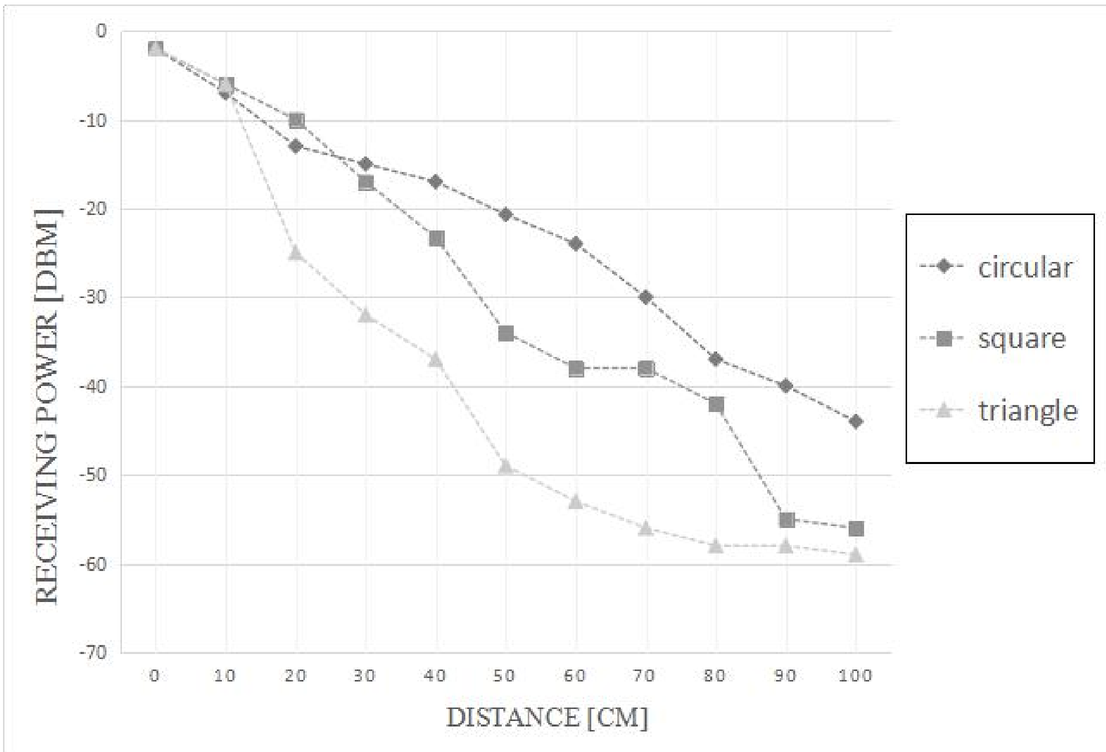

Figure17.　Different Shape and Receiving Power

Figure17 is the result of the relationship between different iron plate shapes and receiving power. The thickness are all 0.22mm. It clearly shows that circle shape is the best, and the best suitable distance to do next experiment is 50mm. Then, we do experiments to find the suitable frequency for high-frequency ultrasonic communication in the air with 0.22mm circle iron plate. A low noise amplifier is also used. The propagation distance is 50mm. Frequency is from 1MHz from10MHz per 1MHz.

5.3 Experiment Setup

Our second method to achieving indoor ultrasonic communication is to use high-frequency range ultrasound. Figure18 is the experiment setup. The pair of ultrasonic transducers are Tru-Sonics BP520-3007 transmitter and BP520-3009 receiver. Signal generator sends signals and this transducer changes from electromagnetic waves to ultrasonic waves. Iron plate which contacted with the transducer tightly achieve its air propagation. Then the receive transducer changes from ultrasonic waves to electromagnetic waves. A laptop connects with the vector signal analyzer shows EVM. The simulation of transmitter's beamforming showed as Figure19.

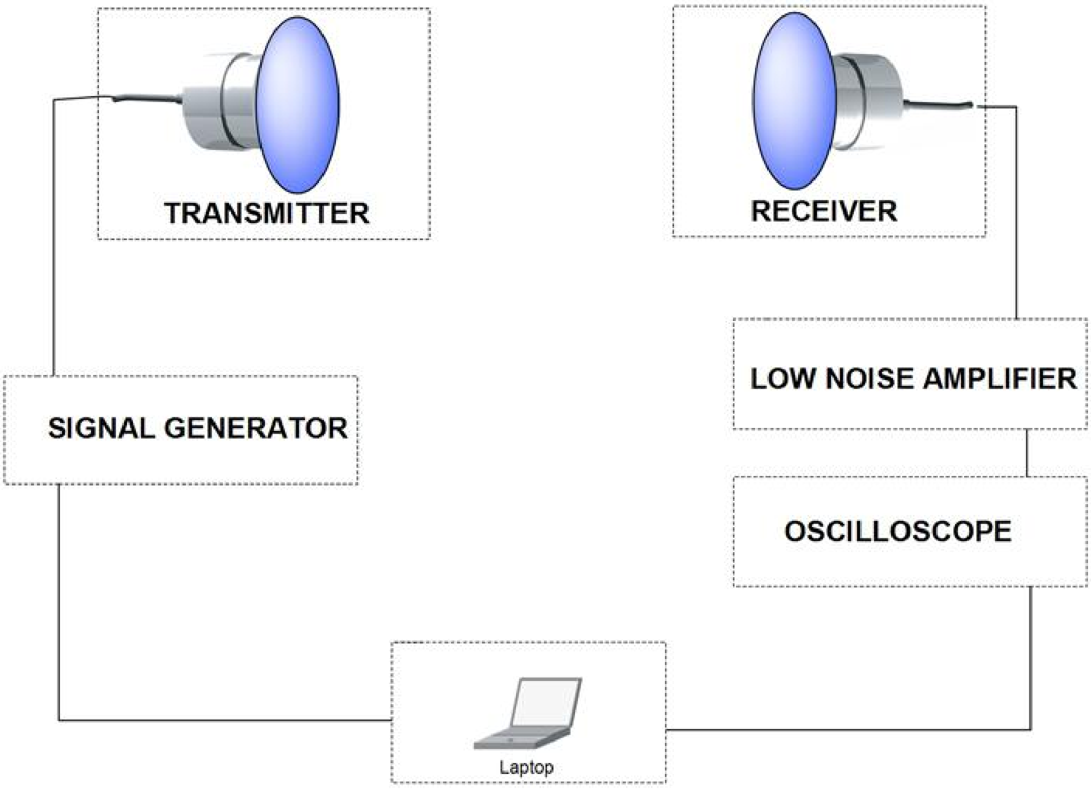

Figure18. Setup of High-Frequency Communication

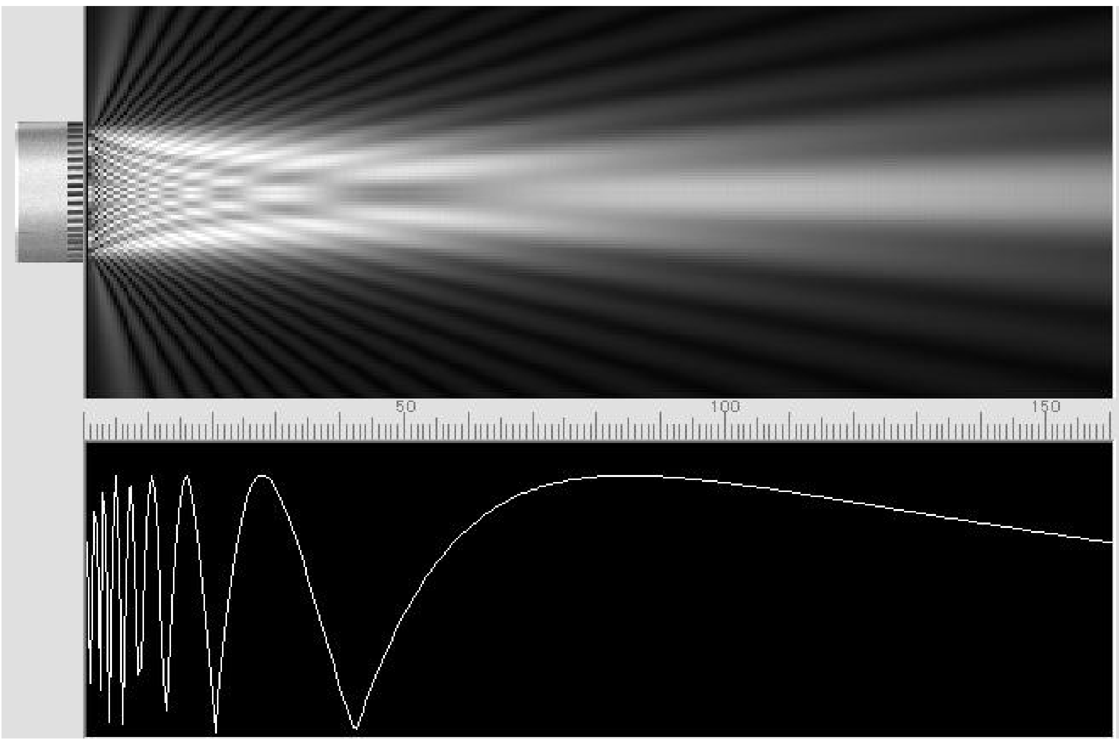

Figure19. 5MHz,20mm Ultrasonic beam through iron

5.4 Experimental Results and Analysis

Because the pair of 5MHz ultrasonic transducers is used for crack detection, not for air propagation. Although the center frequency of it is 5MHz, it doesn't mean the transducer only works at exactly 5MHz, and it won't work at 5.1MHz or 4.9MHz. It always has a range that called spectrum if it drawn with vertical axis as receiving power and horizontal axis as frequency. Therefore, we should find out the best suitable frequency for each digital modulation group at first. Figure20 is the result of EVM that is taken by changing frequency with three digital modulation groups, PSK, FSK and ASK. For PSK and ASK group, 5MHz is the best suitable frequency while for FSK group, 6MHz is the best.

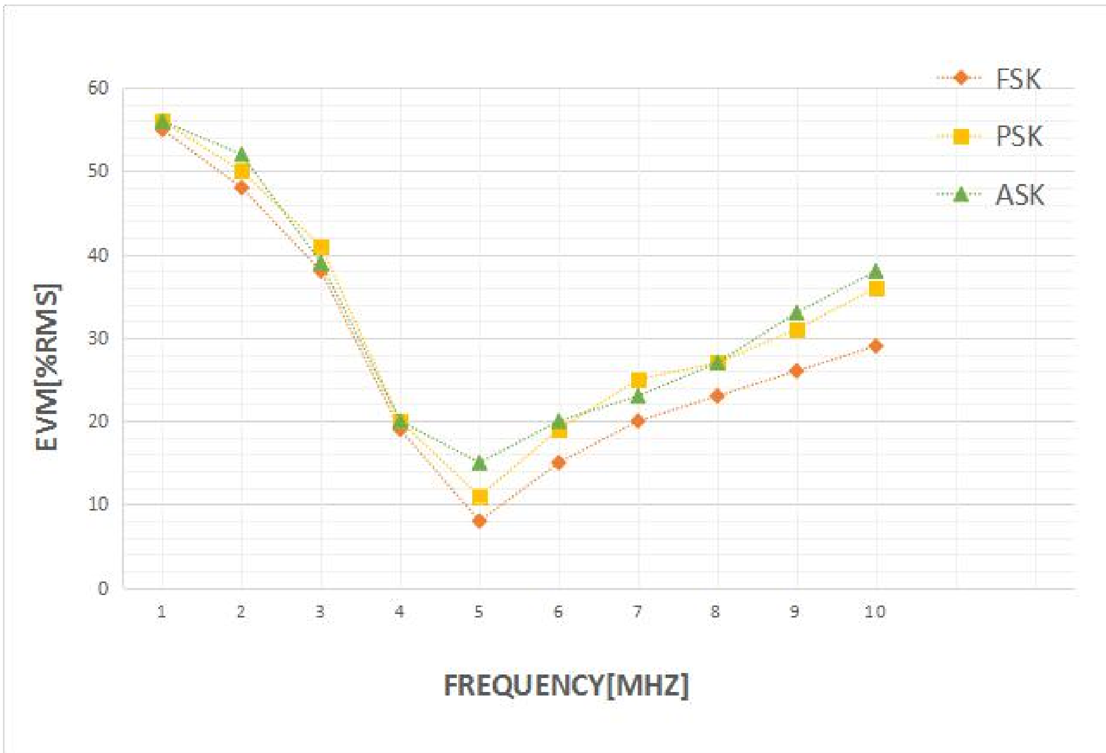

Figure20. Frequency and EVM

Next, EVM is taken by changing symbol rate for each digital modulation groups at the most appropriate frequency. Symbol rate is from 100k sample per second to 500k sample per second every 50k sample per second. As Figure 15 shows, when the symbol rate is over 100k sample per second, ASK modulation group performs badly. For PSK modulation group, symbol rate can be until 300k sample per second. For FSK group, if symbol rate is set over 250k sample per second, signal transmission will be unstable.

From above experiment, for each digital modulation group, we get the best combination of transmission frequency and symbol rate. Finally, we take EVM to evaluate the distance of two transducers covering with iron metal. The shape of iron plate is circle, and its thickness is 0.22mm. The distance is changed from 0 to 20cm per 2 cm. The transmission power is 19dBm. A low noise amplifier is used.

Table2 The Best Combination of Frequency and Symbol Rate of Each Modulation Group

Modulation	Frequency (MHz)	Symbol Rate (ksps)
ASK	5	100
PSK	5	300
FSK	6	250

And then EVM is taken by distance of two transducers covered with iron plate at the most appropriate frequency and symbol rate. The distance is changed from 0cm to 20cm every 2cm. The transmission power is 19dBm.

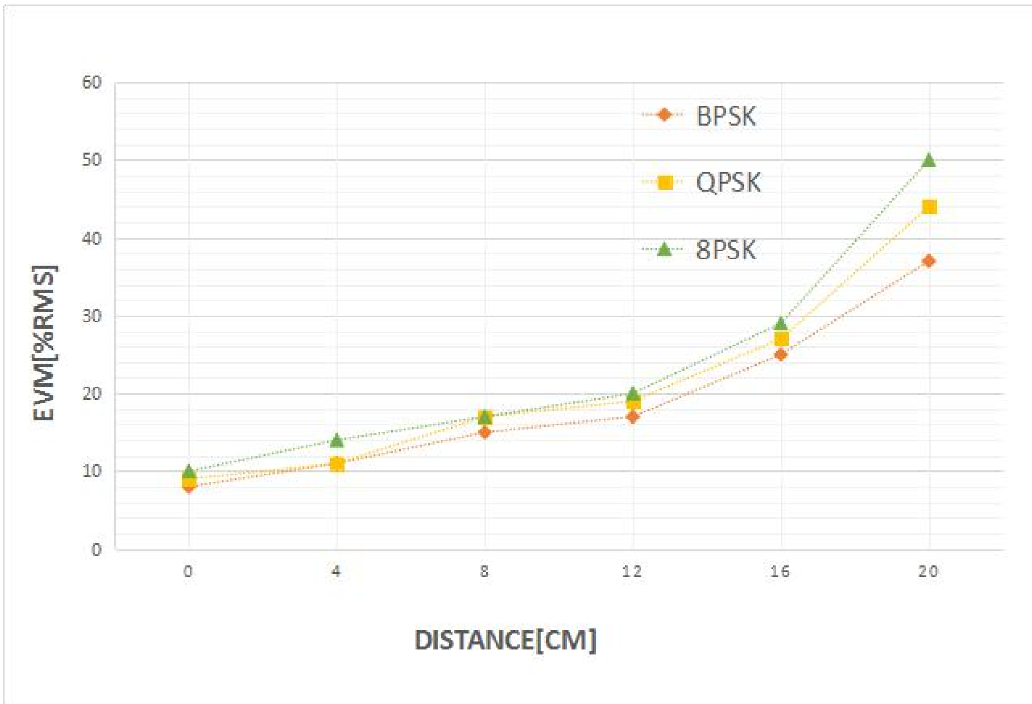

Figure21. Distance and EVM (PSK)

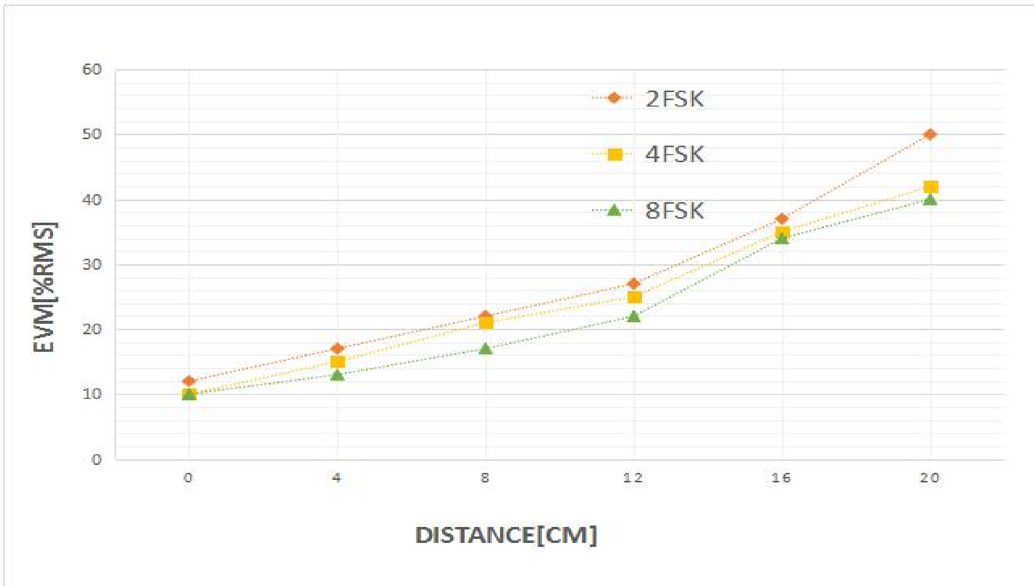

Figure 22. Distance and EVM (FSK)

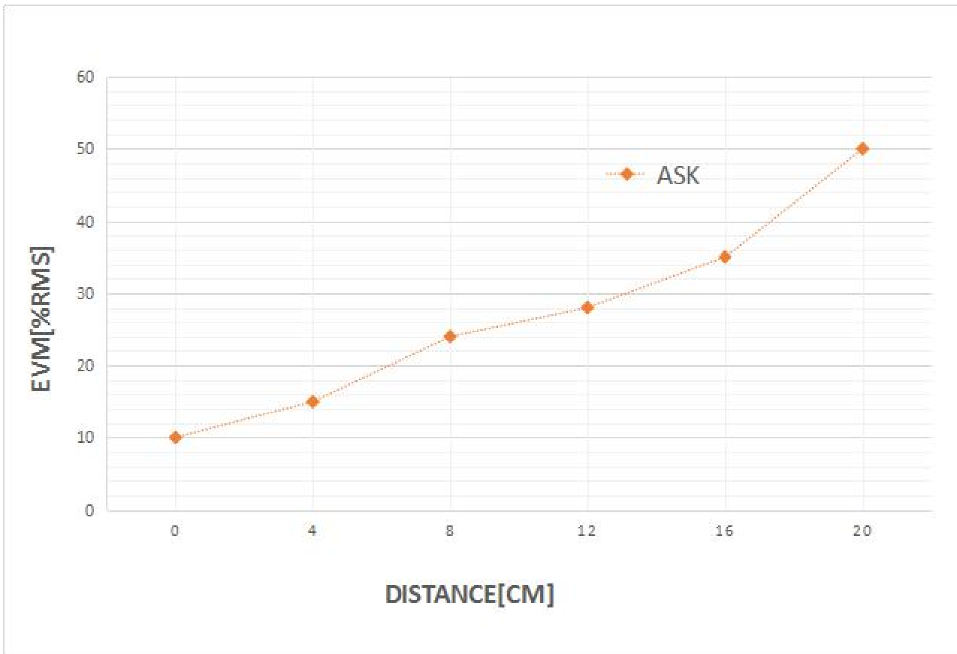

Figure23. Distance and EVM (ASK)

Because EVM should be under 20%, with PSK modulation, the distance can be enhanced to 10cm while with ASK and FSK modulation the effective transmission distance is within 6cm at each of their most appropriate combination of frequency and symbol rate. Therefore, from Figure21, 22 and 23 we can see for the high-frequency ultrasonic communication in the air, the best modulation in each modulation group is PSK, and BPSK performs the best in its group.

Chapter 6

High-frequency Ultrasound Array System

6.1 Array Calculation and Experiment Setup

In Chapter5, with high-frequency ultrasound non-array system we just achieved 10cm stable air propagation by PSK modulation, thus, high-frequency ultrasound array system should be considered. The aperture is the active area that transmits or receives acoustic wave at certain moment. For a single-element transducer, the aperture size is the transducer element size. For array transducer, the aperture are all the elements that works together simultaneously. To achieve a confined beam, the aperture size need to be much larger compared to the sound wave length. At 5MHz, the ultrasound wavelength is about 0.3mm in water, and a 5mm diameter transducer will give a decent beam. However, at normal sound frequency such as 1kHz, the wavelength is about 0.3m, it need a 5m diameter speaker to give a sound beam that propagate forward. Since most speakers are small compared to the sound wavelength, and they behave like a point source, with sound spread all the directions.

Because each transducer element has its own electrical connection, we can use antenna splitter which can divide signal into two or more signals and each output way can carry a selected frequency range and power. Figure24 showed the one input three output splitter that we used.

Figure24. One Input Three Output Splitter

High frequency ultrasound wave will cause serious attenuation during air propagation, an electronic amplifier that converts a low-power radio frequency signal into a higher power signal could be used. We added an RF power amplifier with 20dB gain drive the antenna of a transmitter. Figure25 showed the power amplifier that we used. It is used for 5~6000MHz frequency range.

Figure25. Power Amplifier

Ultrasound array also is based on principles of wave physics. Air absorption should be considered because high frequency ultrasound wave will also cause high air absorption. Thus, air absorption will significantly affect ultrasound attenuation. Air temperature, humidity, even air compression and so on could make serious affection on ultrasonic communication in the air, especially high frequency. In general the decibel(D) decreases with distance(L) and the air absorption can be defined by the following formula (6.1) and (6.2), when the air temperature is 20 degree centigrade and the humidity indoor ϕ is 55% ,and f is ultrasonic frequency.

$$D = 20 \lg L \tag{6.1}$$

$$A_e = 7.4 \times \frac{f^2 L}{\phi} \times 10^{-8} \tag{6.2}$$

Thus, in ideal conditions, the final needed decibel(D_F) :

$$D_F = 20 \lg L + 7.4 \times \frac{f^2 L}{\phi} \times 10^{-8} \tag{6.3}$$

Therefore, if we want to achieve more than 1 meter high frequency ultrasonic communication in the air, we need 35.6dBm transmit power at least. And with the ultrasound superposition formula:

$$D = 10 \lg(10^{\frac{D1}{10}} + 10^{\frac{D2}{10}} + \ldots + 10^{\frac{Dn}{10}}) \tag{6.4}$$

We can see that three BP520 ultrasonic transmitter transducers are enough. Therefore, proposed high-frequency ultrasound array system with a 30dB gain low noise amplifier and a 20dB gain power amplifier is showned as figure26.

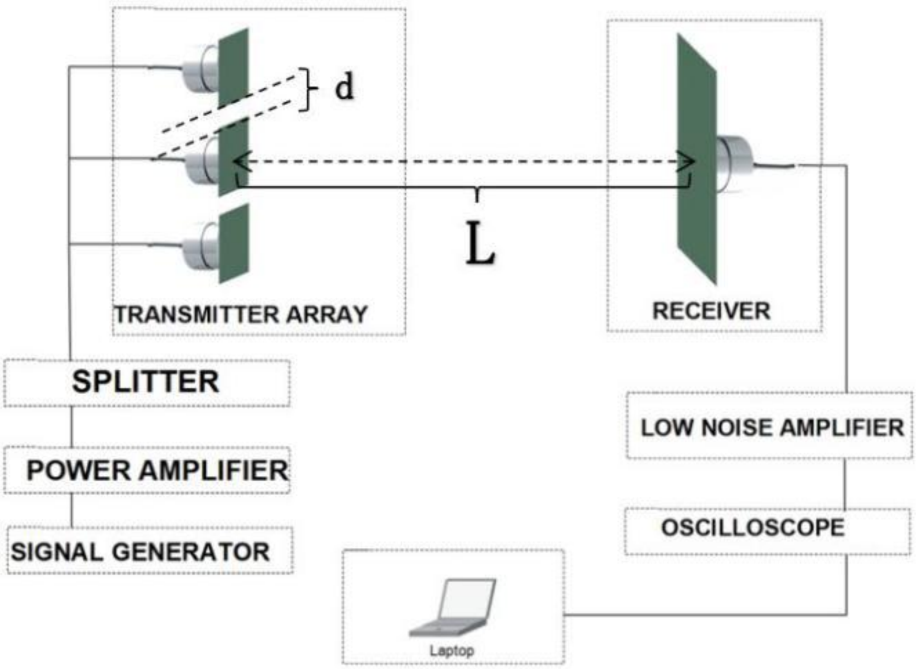

Figure26. Setup of High-Frequency Array System

The reason why we separate the iron plate for each ultrasonic transmitter transducer is that ultrasound wave beams would interfere with each other when propagate through iron plate. And because the shape of iron plate isn't an important factor for ultrasound array, thickness is 0.22mm rectangular iron plates are used. The most appropriate transmitted frequency is 12MHz and the initial setting power is 19dBm (adding power amplifier's 20 dB, the final transmitting power is 39dBm). The d value is a significant factor. First, we just want to find how long propagation distance we can achieve, d is random. Results showed as Figure27 that we can achieve more than 1.5m high-frequency ultrasonic communication by this split iron plate array system. Next, we adjust d from 0cm to 6cm per 1.5cm to talk about receiving with distance in Figure28.

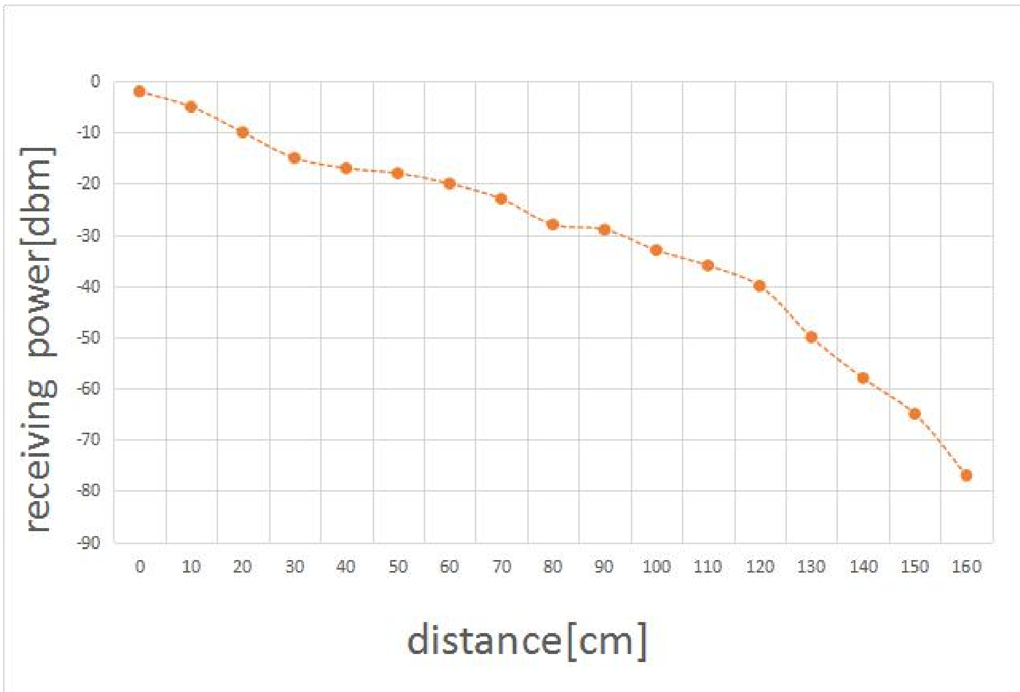

Figure27. Receiving Power with Distance (at random d)

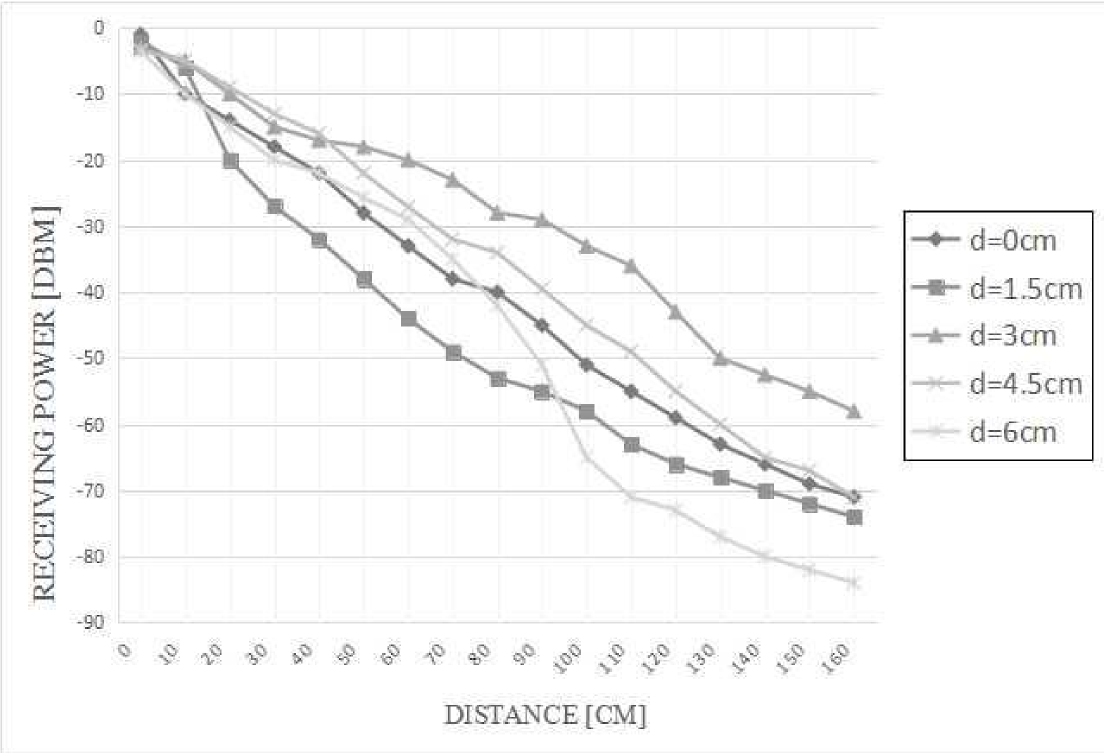

Figure28. Receiving Power with Distance (at different d)

6.2 Experimental Results and Analysis

Figure27 showed that if we want to achieve 50cm~150cm air propagation, it's better to set d as 3cm. Figure29, Figure30 and Figure31 are the results of EVM taken by distance of modified ultrasound array system at different frequencies and symbol rates with ASK, PSK and FSK, d is 3cm. Table2 shows that when EVM=20%, the distance at different frequencies and symbol rates with each modulation. The frequency is 12MHz and 5MHz, the symbol rate is 50,100,200,300,400ksps.

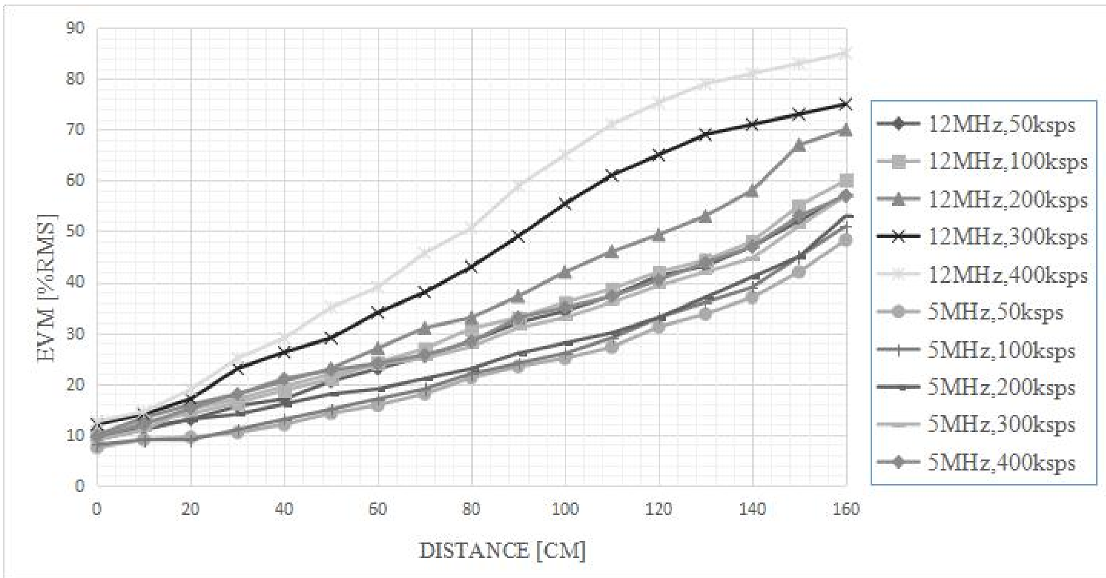

Figure 29. EVM with Distance (ASK)

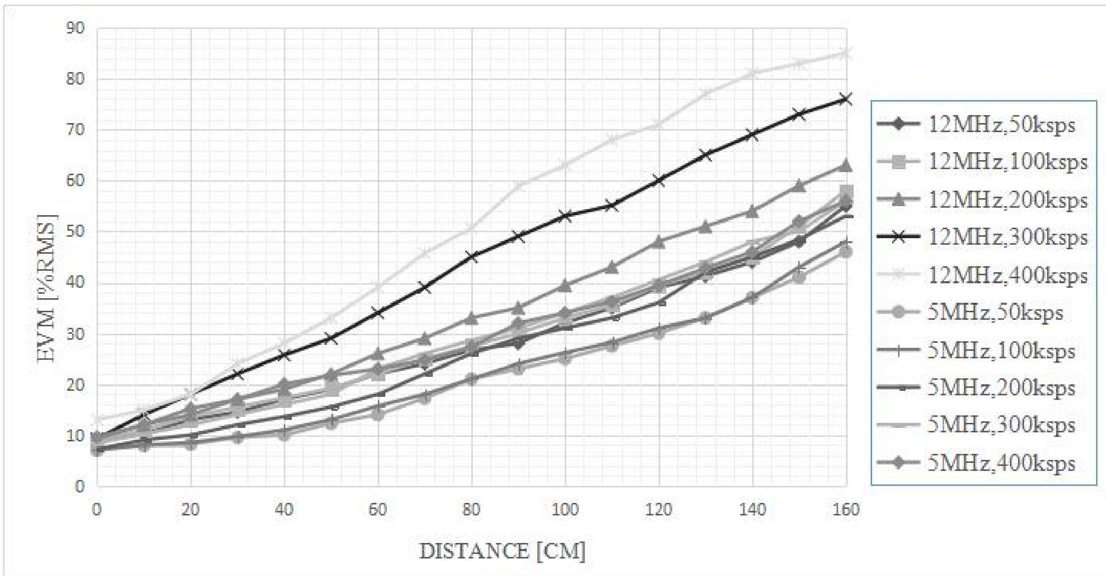

Figure 30. EVM with Distance (PSK)

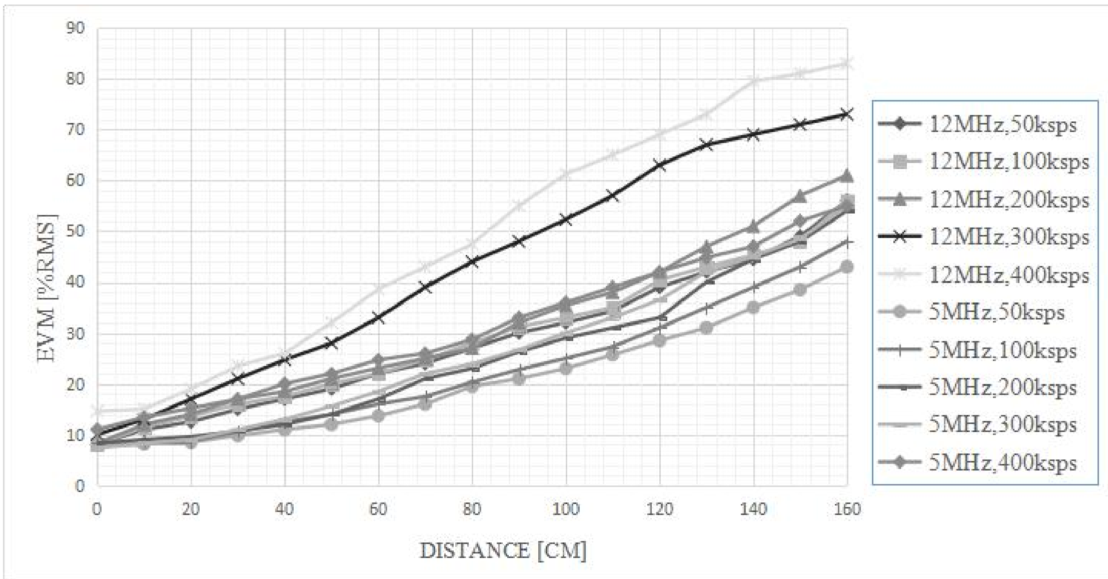

Figure 31. EVM with Distance (FSK)

Table 2 Distance(cm) at Different Frequencies and symbol rates with ASK, PSK and FSK when EVM=20%

	ASK	PSK	FSK
12MHz,50ksps	49	50	51
12MHz,100ksps	48	50	50
12MHz,200ksps	39	45	43
12MHz,300ksps	25	28	27
12MHz,400ksps	22	24	21
5MHz,50ksps	75	78	72
5MHz,100ksps	73	78	76
5MHz,200ksps	55	66	65
5MHz,300ksps	43	63	63
5MHz,400ksps	37	40	30

The longer the distance is, the more EVM rises. And at the same symbol rate, higher the setting frequency is, the more unstable propagation. From Table2 we can see In case that for ASK modulation, with 5MHz and 50ksps, within 75cm, EVM is below 20%. For PSK modulation, with 5MHz the sample rate can be enhanced to 100ksps and the longest stable propagation distance is 78cm while for FSK modulation is 76cm under the same conditions. Therefore, we consider to use QPSK (Quarter Phase Shift Keying) modulation because with four phases, QPSK can encode two bits per symbol to minimize the BER. Phase shift is not relative to a reference signal but relative to the phase of previous two bits. The receiver does not need the reference signal but only compares two signal to reconstruct data. Figure32 is the results of EVM taken by distance of modified ultrasound array system at different frequencies and symbol rates with QPSK.

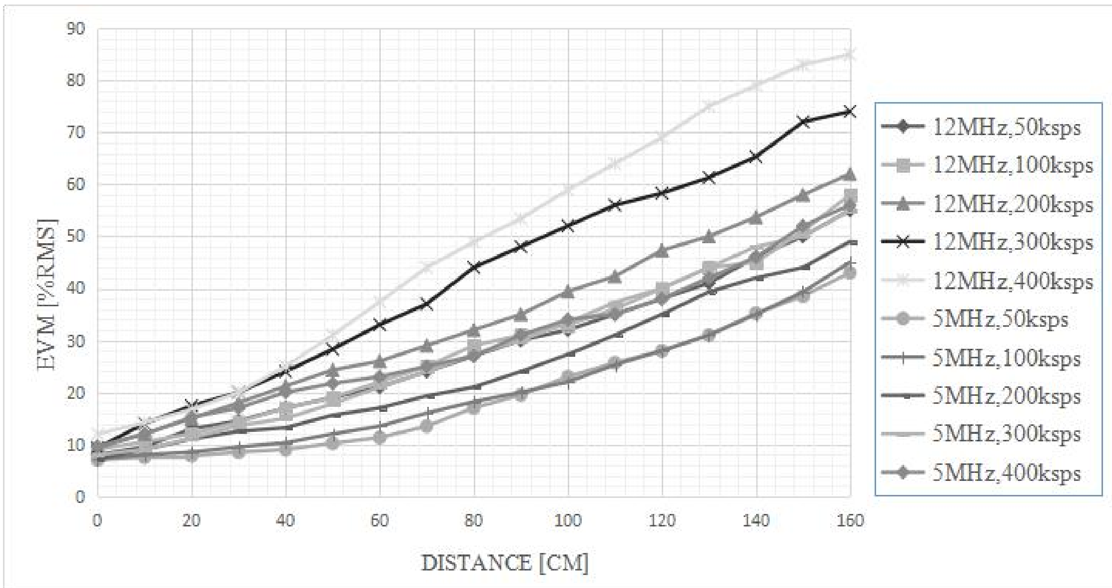

Figure 32. EVM with Distance (QPSK)

Table3 Distance(cm) at Different Frequencies and symbol rates with QPSK when EVM=20%

12MHz, 50ksps	12MHz, 100ksps	12MHz, 200ksps	12MHz, 300ksps	12MHz, 400ksps	5MHz, 50ksps	5MHz, 100ksps	5MHz, 200ksps	5MHz, 300ksps	5MHz, 400ksps
50	52	39	30	30	91	91	73	57	40

From Table we can see that with QPSK modulation results get better. Through this method the high-frequency ultrasound wave could achieve 91cm stable air propagation according to use the advantage of ultrasound array and modify the surface of transducers by covering iron plate.

Chapter 7
Conclusions and Future Works

As we know, only low frequency ultrasound waves can propagate in the air at a speed 340m/s with a very high attenuation. However, it’s easy to be obstructed by other things in the air. Our aim is to use high-frequency ultrasound wave to transmit data indoor. First, we conducted experiment employing a pair of ultrasonic transducers whose the center frequency is 40kHz in order to find attenuation of EVM by transmission speed. We conducted experiment by changing symbol rate at three range when the distance between the transmitter transducer and receiver transducer is 2.4m. For 10k~100k sample per second range, EVM is from 10%~30%. For 100k~1000k sample per second range, EVM is from 30%~55%. And 5M~35M sample per second range, EVM is from 50%~60%. Results show that for low-frequency ultrasonic communication in the air, at low symbol rate, data could be transmitted well.

Next, basing on the low-frequency ultrasonic communication system we did previous high-frequency ultrasonic communication experiment in order to achieve high-frequency ultrasound waves air propagation. We find that if suitable iron plate contact with ultrasonic transducer tightly the problem can be solved. However, with non-array system high-frequency ultrasonic communication system, the propagation distance just 10cm, it is still so short. Therefore, we consider to establish a high-frequency ultrasound array system. Because each transducer element has its own electrical connection, we used antenna splitter which can divide signal into three signals and each output way can carry a selected frequency rage and power. High frequency ultrasound wave will cause serious attenuation during air propagation, an electronic amplifier that converts a low-power radio frequency signal into a higher power signal was used, its gain is 30dB. And we added an RF power amplifier with 20dB gain drive the antenna of a transmitter. According ultrasound superposition, we finally chose three BP520 ultrasonic transmitter transducers to form the ultrasound array. Each of the transducer's surface contacts with an iron plate tightly. Then, EVM is taken by distance of modified ultrasound array system at 12MHz and 5MHz, the symbol rate is 50,100,200,300,400ksps, the distance between beside iron plate and middle plate d is 3cm with ASK, PSK and FSK modulation groups. Finally, we achieved 91cm stable high-frequency ultrasound air propagation with QPSK modulation according to use the advantage of ultrasound array and modify the surface of transducers by covering iron plate.

For future work we can consider iron split screen and change the angle between the side and middle iron plates for ultrasound array. Air absorption is a major factor that affects the ultrasonic attenuation. Because this work is performed in a laboratory environment where other factors could influence the results, such like temperature and humidity. Next time, we need to talk about the relationship between environment conditions and air absorption and try to extend the propagation distance until more than 4 meters.

Chapter 8
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Research Achievement

1. Chenlu Liu, Shigeru Shimamoto, Yoshimitsu Nagao, Jiang Liu, "Studying on Achieving Long Distance High-Frequency Ultrasound Air Propagation", in Network and Service Design, Control and Management, IEICE, Sep, 2017