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Multiuser Coding and Signal Processing in a Low Power Sensor Network

Dongqi Lai
University of Nebraska - Lincoln, lai.dongqi@huskers.unl.edu

MULTIUSER CODING AND SIGNAL PROCESSING

IN A LOW POWER SENSOR NETWORK

by

Dongqi Lai

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MULTIUSER CODING AND SIGNAL PROCESSING

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Dongqi Lai, M.S

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Advisor: Andrew Harms

Backscatter communication system is a wireless communication system that is used by both academic community and industry circles in recent years. This communication system only requires ultra-low power usage and simple design of the sensors. This project is using backscatter communication system to transmit data with backscatter tags. The method we used is semi-passive backscatter communication. This project focuses on transmitting signals with multiple sensors so there is a problem about distinguishing the signal reflected by different nodes. We modulated the transmitting digital signal with Walsh function to solve the problem of separating the signals between different nodes. By using spread sequences we have interferences between different signals from each node and also from the bouncing and direct path signals. We want to estimate the channel between the sensors to suppress the effect of the interferences. In addition, to make the system more practical with multiple usages and applications, we made the receiver and the illuminator on a moving platform. With this dynamic system it is important to deal with the interference of bouncing signals by analyzing the Doppler shift of received signal. With these approaches the purpose of this project is having the reader of the sensor network to communicate with multiple nodes with backscatter communication. This system can be used on variety of applications such as

environmental sensing, signal recording and data communicating with less power usage compared with traditional communication systems.

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CHAPTER 1: INTRODUCTION

1.1 SENSOR NETWORK COMMUNICATION

1.1.1 TRADITIONAL COMMUNICATION AND BACKSCATTER COMMUNICATION

For this project the problem is setting up a power efficient sensor network communication system. Traditional communication systems require a power-hungry carrier waveform to be modulated. The most important advantage of backscatter communication is ultra-low power usage. The backscatter nodes reflects and modulates external waveforms with very low power consumption shown in Fig.1. It is very important to keep the sensor life longer in a sensor network for monitoring and recording in a large area and avoid frequent replacement of batteries. In real life, the lifetime of sensors are always one of the consideration of building a sensor network.

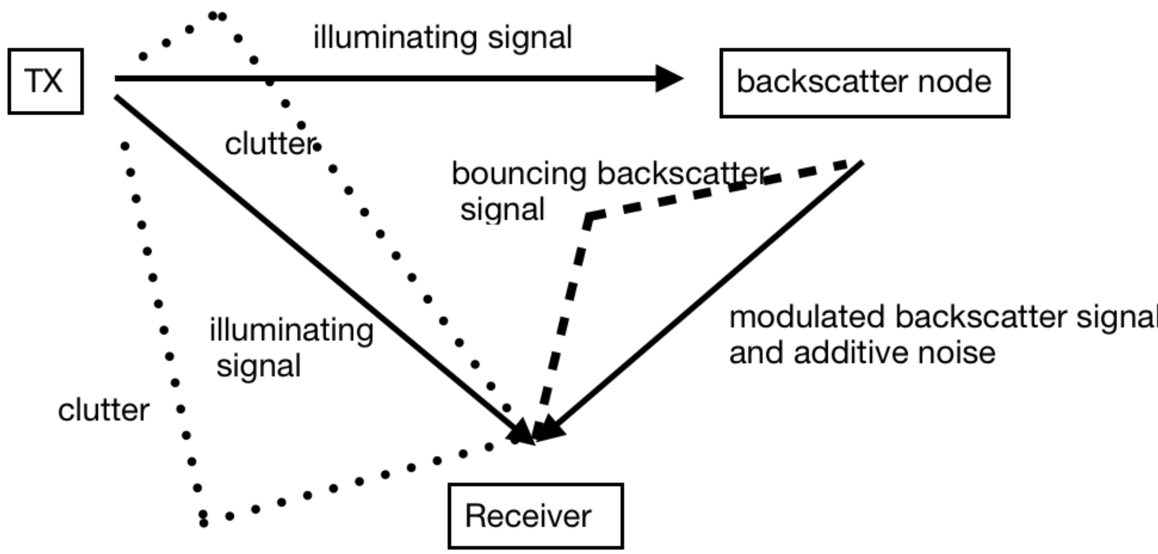

Figure 1. Overall diagram of multiuser backscatter communication system. backscatter nodes are illuminated by the carrier waveform and reflect the modulated signals back to the transmitter. In the system the interference comes from bouncing signal of both backscatter signals and illuminating signal

Sensor Network communication is widely used in military, industry, researching areas and daily life such as radar system, climate monitoring, agriculture detection and sensor data transmitting and analysis. Generally, a sensor network contains multiple sensing nodes to observe and send data with different sensors. It is desirable to make the entire network system power efficient. In general, Traditional communication method requires an energy-hungry carrier waveform to be modulated when transmitting data, which means the power consumption is an important issue to be considered when we have multiple nodes in the network[1]. Compared with traditional communication, Backscatter system take the advantage of saving power and easy to be designed. The nodes of backscatter communication system modulate the external waveform by reflection of the signal[2].

For a multiple user sensor network the reader is designed to be able to extract information from all of the sensors simultaneously. It is very important to separate the signals from different sensors. By using backscatter communication system to build the sensor network, the problem of the effect of interference need to be solved. In general the interference can be caused by two main reasons, one is the backscatter signal from one sensor interferes with the signal from others, the other one is the clutter interferes with the backscatter signals. Clutter is caused by the carrier signals reflecting with the objects in the environment. For different surface of objects in the environment of signal propagation, the strength of clutter returns are different.

In addition, to make the system more practical the communication system could be on a moving platform. The received signal can be interfered by clutter and bouncing signals with different Doppler shift and there will be delay on each backscatter signals. To ensure the accuracy of the recovered signal, several signal processing methods are considered to be used on the received signal.

1.1.2 THE USAGE OF BACKSCATTER COMMUNICATION

As the size of sensing devices is becoming smaller and amount of sensors in a network is increasing, the power consumption of an entire sensor network can be reduced by using backscatter communication. In many cases wired communication is not feasible. Batteries always add weight, bulk, cost, and require recharging/replacement that is impractical at large scales[3]. Solar panels may be a good solution to provide the power but it increases the size of backscatter nodes. In addition, usage of solar panels are very strict to the environment of the network. In many cases battery-assisted sensor nodes are more reliable[4]. There are multiple types of backscatter communication. One of the most popular techniques is radio-frequency identification(RFID). RFID is widely used in daily life[5]. RFID tags are very useful in daily life such as the anti-theft tags attached on merchandise for security in stores and entrance keys of garage. RFID tags have particular small circuit inside, the circuit can harvest the energy and reflect back the signal from a transmitter. Classical RFID systems and tags are typically severely limited in bandwidth[6]. There are many RF signals exist, ambient backscatter communication uses existing wireless signals as a source of power and a communication medium. It enables devices to communicate by backscattering waveforms without any external power supply[7]. The method used in this project is semi-passive backscatter communication. Semi-passive backscatter communication uses external power supply to control the backscatter nodes to generate signals. The nodes can be operated by a microcontroller to modulate the illuminating signal. With the data measured by the sensors, the antenna of the backscatter nodes can be switch between different impedance. With this operation the signals reflected by the backscatter nodes are modulated.

1.2 SEPARATION OF SIGNALS

1.2.1 MULTIUSER SIGNAL PROCESSING

Within the communication system we are building a network with multiple sensors and a receiver unit to receive and process the data from each sensor. The signal from each sensor must be separated by the reader when the signal is received. Multiuser problem need to be considered and solved. In different cases there are several different modulation that can be used. For instance, phase-shift keying(PSK)[8], amplitude-shift keying(ASK) and quadrature amplitude modulation(QAM)[9] are methods that modulate the signals with digital communication. Phase-shift keying is used in different wireless digital communication applications such as Bluetooth[10] and RFID[11]. Receivers are built with PSK schemes. In general, these modulation schemes can be represented by constellation diagrams. A constellation diagrams is a representation of a signal modulated by digital modulation scheme. It shows the signal as a two dimensional diagram in the complex plane with in-phase carrier and quadrature carrier. Fig.4 shows a constellation diagram. For different number of constellation points, there are binary phase-shift keying(BPSK), quadrature phase-shift keying(QPSK) and some higher order such as 8 phase-shift keying(8PSK).

Since the system contains multiple backscatter nodes and they communicate with the reader wirelessly, Code-division multiple access can be applied on the system. CDMA technique is one of the solutions for transmitting data over a single channel while sharing a fixed bandwidth among a large number of users[12]. This technique can help distinguishing between different signals from different sensors.

To apply CDMA on the communication, each sensor in the system should be assigned a different code to modulate the signal. Choosing the codes is very important to influence the performance of the communication system. To have the best performance of separating between the signals from different sensors the correlation between the signals should be as low as possible. Generally the codes should be orthogonal to each other to have the lowest cross correlation. In this project, the preferred property of the spread sequences should have small autocorrelation at non-zero delays and large autocorrelation at zero delay. The cross-correlation between different sequences assigned to different backscatter nodes also need to be small enough. There are many coding methods that are used in CDMA applications, such as Walsh functions[13], Gold code[14] and Kasami code[15]. Gold code and Walsh function are chosen to be used in this project to modulate the signals because the Walsh functions have the best property of small cross-correlation between different codes and Gold codes have the best characteristic of large autocorrelation at 0 delay.

1.2.2 THE USAGE OF MULTIUSER COMMUNICATION NETWORK

In this project, the setup and signal processing of the entire system is shown in Fig. 2. The illuminating signal are modulated by different backscatter nodes. After the AWGN channel the signal received at the reader is the summation of different modulated signals, clutter and noise. By implementing de-chirping and range induced carrier removal we can reduce the effect of error caused by the synchronizing between backscatter nodes and the reader. The delay of signals is where errors will occur in de-chirping process. Then the information signals from different nodes can be recovered by matched filtering with different spread sequences.

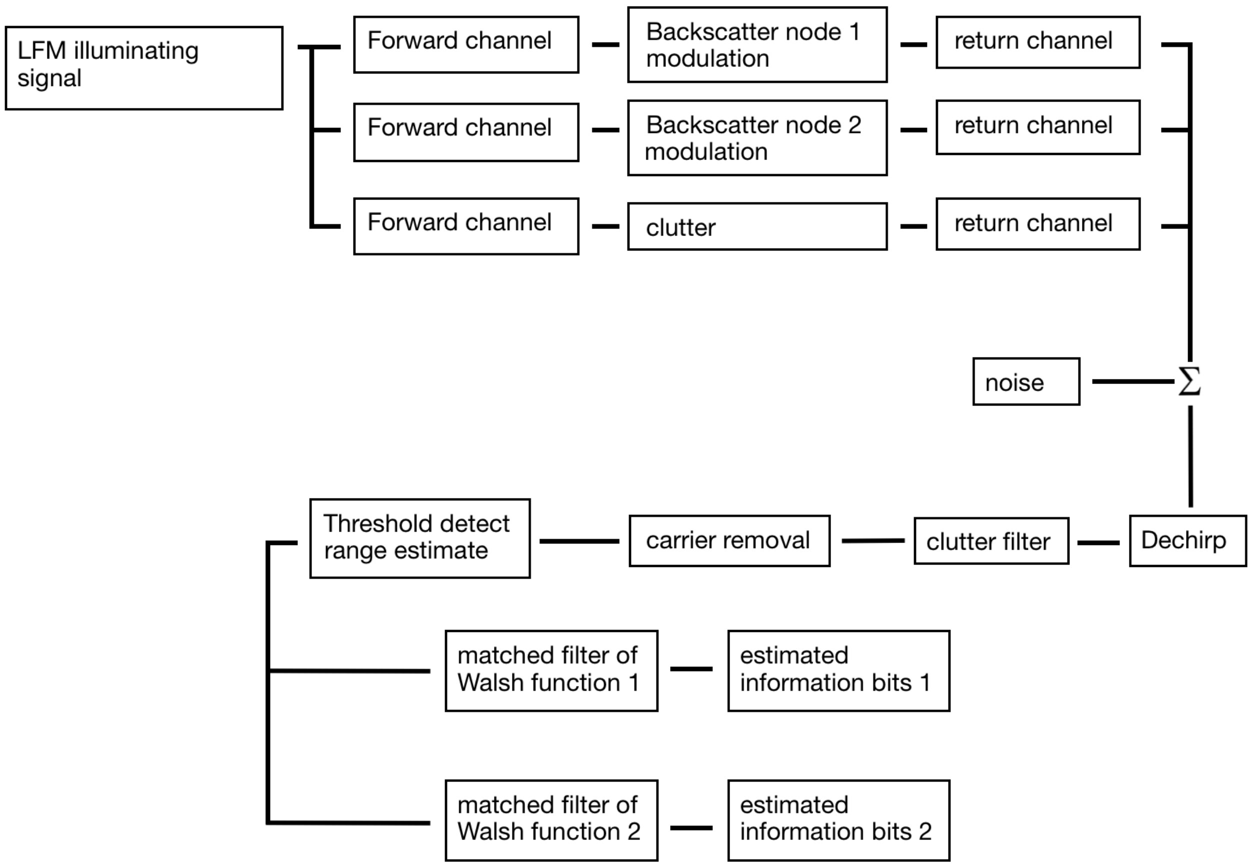

Figure 2. Block diagram of signal processing system framework. Channel model of signal propagation is shown. The reader receives different signals. Signal processing methods used to recover the original information bits measured by sensing nodes

1.3 LITERATURE REVIEW

Sensor networks are used in monitoring and recording the physical conditions of the environment. They measure environmental conditions such as temperature and moisture. Environmental monitoring is one of the application of sensor network benefits for scientific communities and society[16]. The development of Environmental Sensor networks needs a unique combination of technological and environmental understanding. Sensor networks can be wired together, especially some underwater projects use the method of cabled observatory. However, for many applications wireless sensor networks is developed so that the data measured by the sensing nodes can be transported wirelessly[17]. Wireless systems always avoid the environment from being disturbed by cables.

As remote sensing and measuring is getting more important with advances in technology, the ability to process large quantity of information by signal processing techniques leads to collecting, organizing and processing the data in an efficient way. Most of research projects about sensor networks are for applications such as surveillance[18], habitat monitoring[16], and area monitoring[19]. For some applications TDMA scheme is used where sensing nodes are programmed to have different sleep scheduling times[20].

Power efficiency is always one important consideration in communication systems. The node design of sensor network is one of the area that researchers are working on these days. The power consumption of nodes is reduced by software and hardware design. In general, lifetime of sensing nodes is determined by battery, data transmission and power consumed by other parts in the system include hardware and processor. Job has been done reducing the power consumed by sensing nodes using co-design of hardware and software[21].

Using backscatter communication is one way to reduce power consumption with design of data transmission. Backscatter communication has been used in many different areas. For semi-passive backscatter communication, works have been done transmitting and receiving signals. In particular, the application of backscatter from semi-passive RF sensor nodes for simultaneous ranging and wireless telemetry uplink to an radar was examined[22]. Backscatter communication is suited for sensor communication[22].

The idea of using subtraction across chirp pulses to reduce the interference of clutter has been developed[22]. The previous work concentrated on improve the performance of communication with one backscatter node in the system. Run-length limited codes is also implemented to reduce the Doppler-spread clutter interference[23].

1.4 CONTRIBUTION

In this project, the main contribution is using coding and signal processing to improve the reliability of communication in a sensor network. For the previous research and application related to low power environmental monitoring sensor networks there was a tradeoff between the communication performance and the amount of users. Multiuser system always have problem with signal interference with each other and for a backscatter communication system which is power efficient the performance is affected by self-interference of clutter. The way to improve the recovery performance in this project is using coding methods on the data transmission.

In the setup of a multiuser sensor network, the reader is required to receive and extract the information signals send by different backscatter nodes simultaneously. To improve the performance of communication, two problems of interference need to be solved: The self-interference caused by clutter and the interference between different backscatter signals. Basically, the main contribution of the work is:

- Using semi-passive backscatter communication in a sensor network to receive different information from multiple backscatter nodes simultaneously. In this project, the solution to this problem is applying BPSK with spreading sequence coding. Matched filtering is helpful with distinguishing different signals if the signals have small cross-correlation with each other. A proper spread sequence is very effective at recovering information data from different backscatter signal sources.

- Suppress the clutter interference by coding. Comparing different spreading sequences, Gold codes have 4dB smaller maximum correlation with clutter returns than Walsh functions. In the backscatter communication system. Clutter is one of the most important problem to be solved. In the signal propagation, clutter is caused by reflections of unmodulated illuminating carrier waveform. It is strongly related to the environment of the backscatter communication system. Making the correlation between clutter and modulated backscatter signals smaller is one of the efficient way to suppress the interference of clutter.

- Analysis on delay estimation and its effect on performance of communication. Accurate delay estimation can improve the communication performance by In the sensor network using backscatter communication, the illuminator and reader are always separated from the sensor nodes. In this case, at the receiver the modulated signal send by backscatter nodes always have delay. It will cause inaccurate result of signal recovery at the receiver. It is very important to estimate the delay of the backscatter signals. In order to estimate the delay, Linear frequency modulated(LFM) carrier waveform are used instead of continuous waveform. LFM waveforms sweep from its lowest frequency f_L to highest frequency f_H, and the difference between f_L and f_H is considered to be the bandwidth of LFM waveform. LFM signals have the property to observe the delay of signals compared with continuous sinusoid waveform. The bandwidth of LFM signals is wider than CW signals. Range detection can also be used to locate the backscatter nodes with LFM signals. Doppler effect is also one thing to be considered in the system. Modulation of the signals will produce Doppler shift. By using the difference between the Doppler shift of modulated signals and clutter the suppression of clutter can be improved by 5% bit error rate.

CHAPTER 2: APPROACH

2.1 BACKSCATTER COMMUNICATION

2.1.1 BACKSCATTER COMMUNICATION SETUP

The objective of the sensor communication network for this project is recovering the data that sent from multiple sensors individually. The communication nodes send different data at the same time and the reader is able to extract the signals, distinguish the source of different signals and recover the data has been sent. The system is called a semi-passive backscatter communication system which is able to read data from multiple sensors. The term “semi-passive” means batteries are employed to supply the functional circuits for signal processing, the microcontroller switches the impedance connected to the antenna according to the data measured by the sensors. The tags still operate in a passive manner in that they use “reader talk first” mode and backscatter mechanism for uplink (tag to reader) communication[24]. The backscatter nodes are sending information continuously, when the antenna of backscatter nodes are illuminated by the carrier signal and reflect the modulated signals back to the reader, the information is sent. For a transmitter, an illuminating signal is generated. The different backscatter nodes can modulate the illuminating signal with different coding methods. The reader will finally determine the source of received signal and extract information from the received signals. To make the system work properly and practically, the illuminating signal is chosen to be coherent and simple. A continuous LFM chirp signal in the baseband would help solve the problem. For this project, one of the chirp pulse in the baseband LFM pulse train of the illuminating signal is shown as:

$$C_{LFM}(t) = \exp\left(-j2\pi\frac{\beta}{2}t^2\right), 0 < t \leq T \quad (1)$$

Where C_{LFM} is the illuminating LFM signal, T is the time duration of one chirp pulse and β is the chirp rate that $B = \beta \times T$ is the bandwidth of LFM waveform. Fig.3 shows the change of frequency of a train of LFM pulses. The backscatter nodes would modulate the illuminating signal using BPSK modulation.

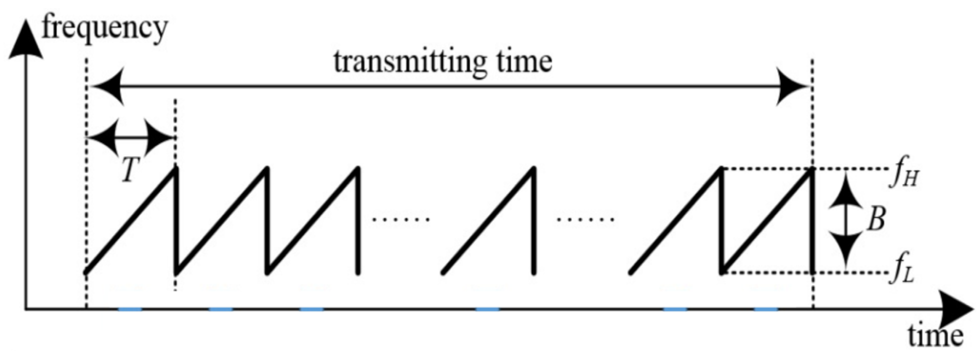

Figure 3. Frequency vs. time plot of LFM pulse train

Typically each of the nodes is formed by a sensor, a microcontroller and an antenna. The microcontroller would transform the data measured by the sensor into digital signals, then by switching the impedance connected to the antenna, the backscatter signals are generated. Once the nodes receive the illuminating signal, they can transmit data in a power-efficient way. In our case, the data measured by the sensor is the information to be sent. After measuring and recording the data from sensors the information bits can be generated by analog-to-digital converter.

2.1.2 BPSK DIGITAL COMMUNICATION

For this system the illuminating signal is chosen to be an LFM signal. The illuminating signal is modulated by the nodes with BPSK modulation scheme. BPSK is simple to be implemented in that only two different impedances are required to connect to the antenna shown in Fig.5. It will make the design of the backscatter nodes easier. Compared with QPSK and higher order phase-shift keying methods, BPSK have smaller error due to the small amount number of symbols. In our case, the information signal is a binary sequence of data. BPSK is implemented to represent the information bits because BPSK used two different constellation to indicate the information bits of 1’s and 0’s as in Fig.4.

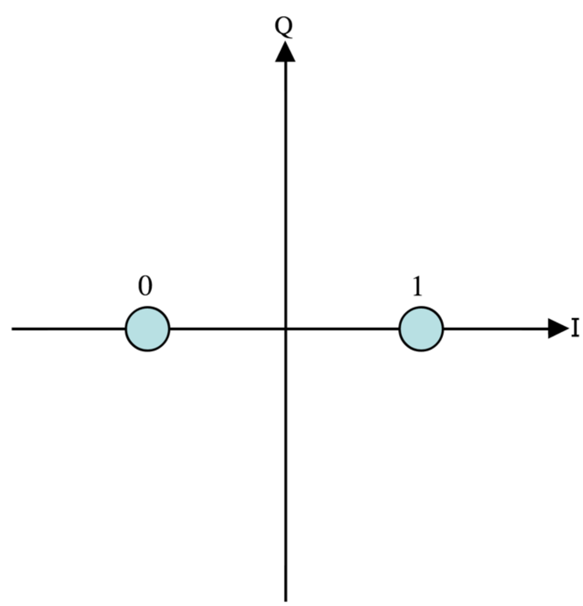

Figure 4. Example of constellation diagram of BPSK

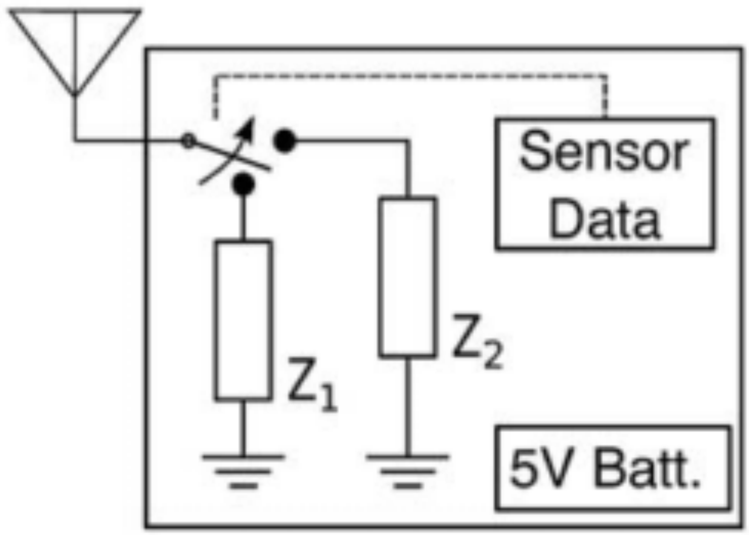

Figure 5. Model of design of backscatter nodes

2.2 MULTIUSER COMMUNICATION

2.2.1 MULTIPLE-NODE SYSTEM

To be more practical, the system should contain multiple backscatter nodes. For example, One of the applications of this system can be an environmental measurement system in a field. Multiple temperature and moisture sensors can be set at different locations and a transceiver can send out the illuminating signal and receive the signal from each sensor at the same time. From those data the environment of the entire area can be monitored. There is a problem that in a sensor network, each node transmits different information signal to the reader at the same time. As the result, the reader receives complicated signals including the clutter of illuminating signal, returned backscatter signals from different nodes, and additive noises. The received signal also contains the multi-path signal from illuminator and backscatter nodes. One way to separate the signals and recover the information signal from backscatter nodes is using coding methods on the information signals. This system in considered as a multiuser communication system. Code-division multiple access is a popular technique to be applied on this type of system to make it work properly. The signal received by the reader would be:

$$r(t) = \sum_i \alpha_i m_i s(t - \tau_i) e^{j2\pi\nu_i t} + \sum_k \alpha_k s(t - \tau_k)\, e^{j2\pi\nu_k t} + n(t)$$

Where $r(t)$ is the received signal at the reader, $s(t - \tau_i)$ is the illuminating carrier waveform with delay τ_i, α_i is the amplitude of signals from different nodes with delay of τ_i and Doppler-shift ν_i. k is the number of clutter returns. m_i is the spread sequence used to modulated the backscatter signals. $n(t)$ is the additive white Gaussian noise.

2.2.2 WALSH FUNCTION

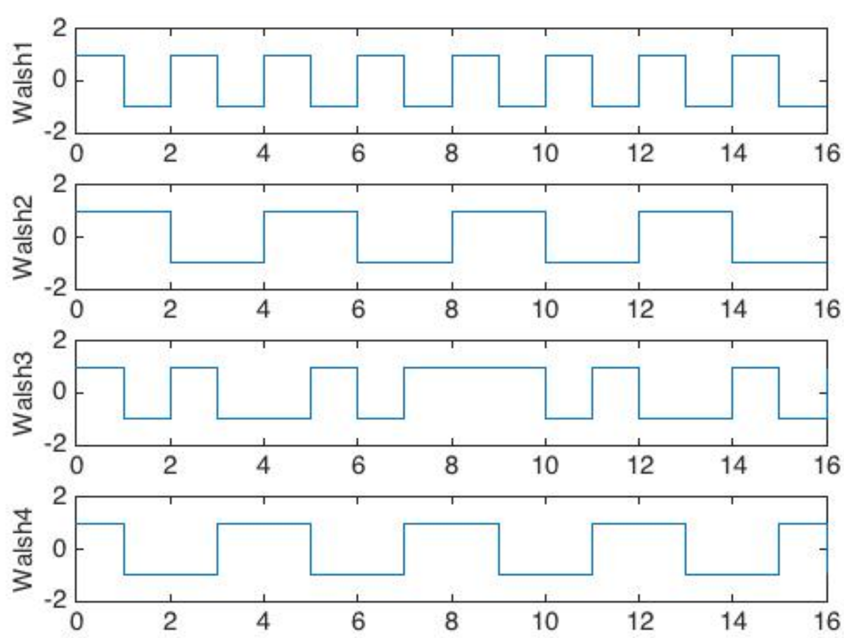

Figure 6. 4 Examples of 16-bit Walsh functions

The reader will receive multiple signals from different sources in the system with multiple sensors. To keep the performance of information recovery, the reader needs to separate and distinguish the different signals. One way to accomplish the requirement is precoding the signals. The coding methods need to satisfy some requirements. Firstly, signals from different nodes should have small cross-correlation. Smaller the cross-correlation is, the reader can easier separate the different signals. Then to separate the direct path signals and the multi-path components the autocorrelation should have a peak at zero time difference and small values at non-zero delay. The interference from multi-path signals have different delay compared with direct-path signals. So the smaller autocorrelation will give a better performance on suppressing the interference due to multi-path signals. To satisfy these requirements, Walsh function is selected to code the signals from different nodes. Walsh functions we selected are orthogonal to each other[13].

Multiple access is used on separating signals from different sources within a same channel[25]. Channel sharing is one of the popular way to transmit information more efficiently. For the Matlab simulation of Doppler-shift analysis, firstly we use the LFM chirp signal to be the illuminating signal. The illuminating signal is set to be a LFM waveform with each pulse as Equation.(1). Bandwidth of LFM waveform is considered to be the frequency range from the lowest frequency to the highest frequency. To simulate the corruption of the signals due to internal thermal noise AWGN was added to all the signals. For the next step, we assume the backscatter node is static so the modulated signal only have Doppler-shift because of the modulation. Also some small Doppler-shift corruption illuminating signals were added to the received signal to simulate the clutter.

We choose the Walsh functions for different backscatter nodes. For the first simulation we want to use the 16-bit long Walsh function sequence for a single node. The sequence is:

[+1 -1 +1 -1 +1 -1 +1 -1 +1 -1 +1 -1 +1 -1 +1 -1]

Which can have the most high frequency of phase modulation of the signal. In this case, one single information bit will be represented by 16-bit long sequence. The transmitted signal will be a modulated LFM waveform modulated by the information sequence. At the same time, clutter have small Doppler shift around 0 and have all possible delays due to multiple reflection of the signals in the environment.

2.2.3 INTERFERENCE CAUSED BY WALSH FUNCTION

In a sensor communication network, the communication channel is quite complicated. We have the interference between backscatter modulated signals, interference due to clutter and additive noise. It is important to suppress the interference and improve the accuracy of the recovered signals. We implement channel estimation to help getting lower bit error rate of the recovered information signal.

For this system we use orthogonal Walsh functions to code each backscatter signals. The signal from each node are coded with BPSK and orthogonal to each other. In practical systems, Communication channel is corrupted by clutter and additive noise. To obtain the accuracy of this communication sensor network, separation between modulated backscatter signals and clutter is necessary.

First, the carrier illuminating signal waveform was chosen to be a LFM chirp signal. By using LFM illuminating signal we can more easily determine the range of backscatter nodes from the delay and Doppler shift of the received signal. The signals transmitted from the backscatter node is phase-shifted LFM signal. Backscatter nodes are coded with separate Walsh function sequences. In conclusion, The communication channel of the entire backscatter sensor network contains the modulated backscatter signals, clutter and additive white noise.

In this sensor network, the accuracy of the recovered data is very important. The signal processing of the backscatter signals is considered to be a problem in this project. One of the most strong interference is the clutter which come from the multiple reflections of the illuminating carrier signal in the environment. The clutter is unmodulated LFM waveform and has very small Doppler-shift around zero and the backscatter signals are modulated by the node using BPSK and Walsh functions. Theoretically, clutter will have Doppler shift due to moving objects in the environment and the Doppler shift of backscatter signals is induced by the modulation.

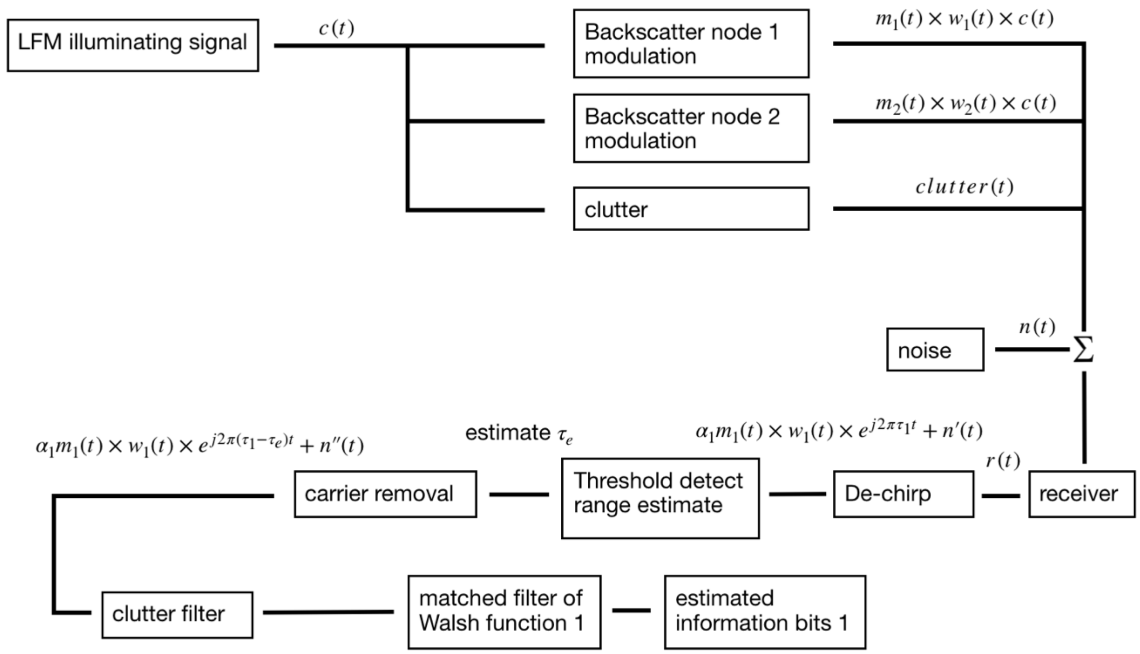

Figure 7. Signal processing for recovering signal from node #1 of the system

For the signal analysis, the illuminating carrier signal is:

$$c(t) = \exp\,(2j * \pi * \frac{\beta}{2} * t^2)$$

Where β is the bandwidth of the LFM chirp signal divided by the duration of one single chirp pulse. Then illuminating signal is phase modulated by the backscatter nodes with Walsh function using BPSK:

$$s(t) = c(t) * m(t)$$

Where modulation $m(t)$ indicates the information signal which is the information bits multiplied with spreading sequences. Then at the receiver, the signal received is a summation of several different signals:

$$r(t) = \sum_i \alpha_i m_i s(t - \tau_i) e^{j2\pi\nu_i t} + \sum_k \alpha_k s(t - \tau_k)\, e^{j2\pi\nu_k t} + n(t)$$

Where $r(t)$ contains the signals of backscatter signals and the multipath components of them, the clutter and additive noise $n(t)$. m_i is the message signal which is the information data sequence represented by the spreading sequences.

$$m_i = \sum_{j=0}^{\infty} d_j \times w_i$$

Where d_j is the j-th bits in the information sequence. w_i are the different spreading sequences. The de-chirped result of the received signal would be a sum of several sinusoid waveforms since the backscatter signals are modulated with BPSK and the clutter is phase shifted, the frequency of the sinusoid waveforms are corresponding to delays of the signals. For de-chirping, the complex conjugate of carrier waveform is multiplied to the received signal to remove the carrier waveform.

$$dechirp\big(\alpha_i c(t-\tau_i)\big) = \alpha_i e^{-j2\pi\frac{\beta}{2}t^2} \times e^{j2\pi\frac{\beta}{2}(t-\tau_i)^2}$$

$$= \alpha_i e^{j2\pi\beta\tau_i t} e^{-j2\pi\frac{\beta}{2}\tau_i^2}$$

Where the term of $e^{-j2\pi\frac{\beta}{2}\tau_i^2}$ is the range induced term when the received signal is delayed and α_i is the complex amplitude of the signal. The term $e^{-j2\pi\frac{\beta}{2}\tau_i^2}$ only depends on the delay τ_i. When τ_i is small enough the term $e^{-j2\pi\frac{\beta}{2}\tau_i^2}$ is approximately 1, the de-chirp process can remove the carrier waveform from the received signal and the effect of the term $e^{-j2\pi\frac{\beta}{2}\tau_i^2}$ is so small that can be neglected. Otherwise the delay must be estimated to reduce the error caused by the signal delay. The pattern of de-chirped result of backscatter signals and clutter are different. Because the waveform of clutter is just a delayed carrier signal with some Doppler shift, so in the result of de-chirping the waveform will be unmodulated sinusoid waveforms. The backscatter signals are phase coded using BPSK with Wash functions, so the pattern of de-chirping result is some modulated sinusoid waveforms. With this characteristic the backscatter signals which is the signal of interest can be separated from clutter. Matched filter can be applied to suppress the interference of the clutter. The clutter can be seen as unmodulated carrier signals and since the backscatter signals are coded with Walsh function, so the inner product of them is fairly small. In addition, channel estimation can also be implemented to suppress the interference of multipath components of the backscatter signals. We can send pilot signals to estimate the channel and using the estimation to improve the performance of information recovery.

2.2.4 SUPPRESSION OF INTERFERENCE USING WALSH FUNCTION

In this part of work, the first step is decrease the effect of clutter interference. Matched filter and range detection can help suppress the interference of clutter. However, the accuracy of the system is very important and it is necessary to improve the accuracy of recovery signal. In our case, the main problem comes from the self-interference of clutter. We can treat the problem as a joint channel estimation. The channel of clutter can be simulated as a multipath channel of the carrier signal. We have two different signal sources and two different channels. The receiver should estimate the channel and recover the signal of interest which is the backscatter signal.

We use Walsh function to code the signals. The interference of signals is reduced but the length of code increases. The signal has interference with each other because of the autocorrelation and cross correlation between the signals. The advantage of Walsh function is the Walsh functions assigned to nodes are orthogonal to each other and have very small cross-correlation with each other. After coding the BPSK information signals with Walsh functions, the length of information signals are extended. For this project we use 16-bit long Walsh functions which means we transmit 16 bits for one single bit. In this way, Walsh function can help suppress the interference between signals. The Walsh function assigned to the nodes have very small cross-correlation, after setting the matched filter for each Walsh functions we can recover the information bits.

Firstly at the backscatter node, we have the phase modulated illuminating LFM signal transmitted. About the signal received by the receiver, there will be the direct-path signal of illuminating signal, signals from backscatter nodes with additive white Gaussian noise and clutter of the illuminating signal. To recover the information of the backscatter nodes. We use a filter to filter out the low Doppler-shift signals because most of these signals is from clutter. Then we can detect the range of the backscatter nodes using Delay-Doppler analysis. We look for energy contained in some large Doppler-shift components of the received signal. After having the delay of the backscatter signals detected, we can determine the range of the nodes and using match filter to recover the original signals from the nodes.

At the receiver, the received signal contains multiple signal components. Ideally, the received signal only contains the direct-path backscatter signals from both nodes. In this case, at the receiver the received signal includes 2 backscatter signals and additive noise:

$$r_{nc}(t) = m_1 \times s(t) + \alpha \times m_2 \times s(t) + n(t)$$

Where $r_{nc}(t)$ indicates the received signal with two modulated signals and additive noise, $s(t)$ is the carrier waveform and m_i is the message signal from different nodes.

$$m_i = \sum_{j=0}^{\infty} d_j \times w_i$$

Where d_j is the j-th bits in the information sequence. w_i are the different Walsh functions that

$$w_i = \sum_{k=0}^{\infty} x_k \times u(t - kT)$$

Where x_k is the k-th symbol of Walsh function patterns. T is the time duration of the signal chip of the Walsh function

$$u(t = kT) = \begin{cases} 1, & (k-1)T < t < kT \\ 0, & else \end{cases}$$

We used the sequences of Walsh functions to symbol +1 and -1 in data sequence d. m_i is the modulation that is modulated by the backscatter nodes onto the carrier waveform. $c(t)$ is the carrier illuminating waveform and $n(t)$ is the additive white Gaussian noise. α is the amplitude of the second backscatter signal such that $SIR = \frac{1}{\alpha^2}$. In this case, the data sequences m_i is recovered by applying matched filter on the received signal. For the first condition, we assume there are 2 different sources of backscatter signal, the strength of the signals will be determined by the distance between the backscatter nodes and the reader. The ratio between the strength of backscatter signals which is considered as the signal to interference ratio (SIR) are set to be 0 dB, 6 dB, 12 dB, 18 dB and 24 dB. To estimate the performance of the system, the recovered bit error rate is calculated and it shows the performance of signal recovery with different SNR and SIR.

Theoretically, the performance of signal recovery depends on the cross-correlation and the autocorrelation of the Walsh functions. The Walsh functions are designed to be orthogonal to each other, so the cross-correlation between different Walsh functions is small compared with the autocorrelation of each Walsh function. Walsh function is widely used on coding and distinguishing between signals sharing one channel. The bit error rate can be calculated by probability of error of the matched filter result. The information bits in m_i is modeled as an uniformly random distributed random variable. In this case the information bits can be +1 or -1. After using matched filter on the received signal, the recovered information bit is determined by the matched filter result of the received signal:

$$y = < w_1, m_1(t) + \alpha \times m_2(t) + n(t) >$$

$$y = \int_0^{\infty} w_1 \times \left(m_1(t) + \alpha \times m_2(t) + n(t)\right) dt$$

Where the sign of y indicates the recovered information bits is +1 or -1 in this case when using BPSK. Because the matched filter we used contains no delay between the filter and the received signal, so they are perfectly matched to each other. Here the matched filter result is represented by the inner product between the Walsh functions and the received signal. The result can be written as:

$$y = d_1 < w_1, w_1 > + \alpha d_2 < w_1, w_2 > + < w_1, n(t) >$$

Because $SNR = \frac{1}{\sigma^2}$ so $\sigma * N(0,1)$ represents the additive white gaussian noise. The theoretical probability of error:

$$P_E = P\left(\widehat{E_1} \neq E_1\right) = \frac{1}{2} P(y \leq 0 | m_1 = 1) + \frac{1}{2} P(y > 0 | m_1 = -1)$$

$P(y < 0|m_1 = 1)$ and $P(y > 0|m_1 = -1)$ is equal because of symmetry, so the probability of error can be simplified to be

$$P_E = P(y \leq 0|m_1 = 1)$$

Because $< w_1, w_1 > = 1$ and the maximum and minimum of $< w_1, w_2 >$ is $\pm\frac{1}{16}$ because the maximum normalized cross-correlation of different 16-bit long Walsh functions is $\frac{1}{16}$. The noise term $< w_1, n(t) >$ is a normal distributed random variable. The probability of error can be calculated by

$$P_E = \frac{1}{2}P\left(1 \times 1 + \alpha \times \frac{1}{16} + \sigma \times N(0,1) \leq 0\right)$$

$$+\frac{1}{2}P\left(1 \times 1 - \alpha \times \frac{1}{16} + \sigma \times N(0,1) < 0\right)$$

$$P_E = \frac{1}{2}P\left(N\left(1 + \frac{\alpha}{16}, \sigma\right) \leq 0\right) + \frac{1}{2}P\left(N\left(1 - \frac{\alpha}{16}, \sigma\right) < 0\right)$$

The probability of error can be calculated with two different Q functions with random variables that have variance σ and mean $1 + \frac{\alpha}{16}$ and $1 - \frac{\alpha}{16}$ for the stronger signal $m_1(t) \times w_1 \times c(t)$. For the weaker one:

$$P_E = \frac{1}{2}P\left(1 \times \frac{1}{16} + \alpha \times 1 + \sigma \times N(0,1) \leq 0\right)$$

$$+\frac{1}{2}P\left(-1 \times \frac{1}{16} + \alpha \times 1 + \sigma \times N(0,1) < 0\right)$$

$$P_E = \frac{1}{2}P\left(N\left(\frac{1}{16} + \alpha, \sigma\right) \leq 0\right) + \frac{1}{2}P\left(N\left(-\frac{1}{16} + \alpha, \sigma\right) < 0\right)$$

The mean become $\alpha + \frac{1}{16}$ and $\alpha - \frac{1}{16}$. In the theoretical analysis, when calculating the probability of error of the weaker signal, $\alpha - \frac{1}{16}$ may be less than 0. In this condition, the term $P\left(N\left(-\frac{1}{16}+\alpha,\sigma\right)\leq 0\right)$ approaches 1 if the variance σ grows larger, so P_E will be approaching 0.5 when the SIR is higher than 24 dB.

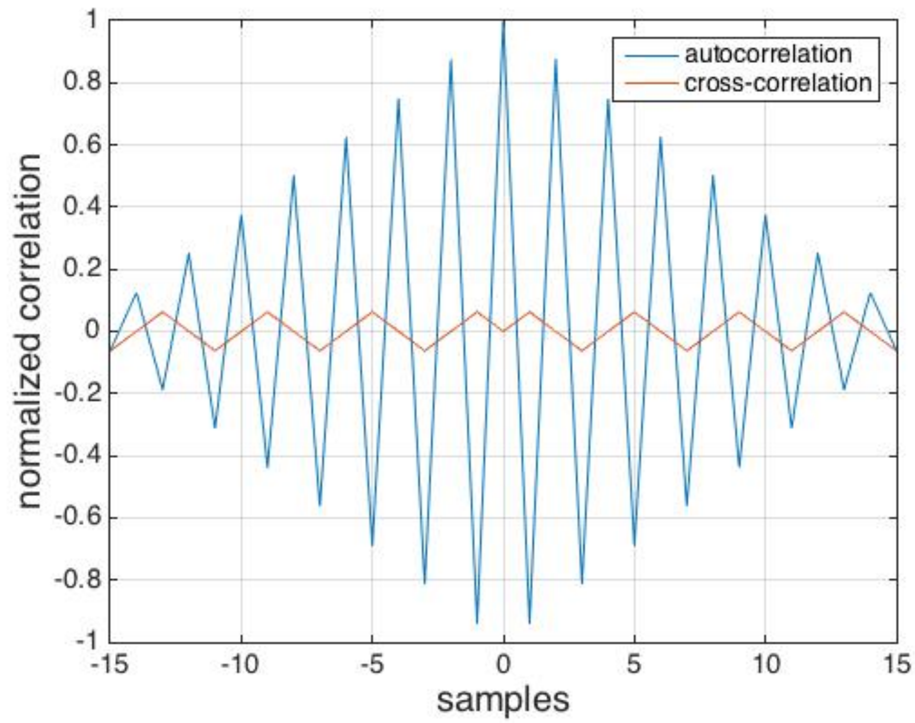

Figure 8. Autocorrelation and cross-correlation of Walsh function modulations

To make the system more practical, clutter is very important to be concerned about. In general, clutter is multiple reflection of the carrier waveform with small Doppler shift when the system is static[26]. In this case, Ground moving target indication(GMTI) process can efficiently reduce the interference of the clutter of a static communication system[22]. We are using LFM carrier waveform to be the illuminating signal. The clutter of each chirp pulse is very similar to each other. The stationary clutter can be rejected by doing subtraction across LFM pulses. At the receiver, the signal received is the summation of backscatter signals and their multipath components, clutter and additive white gaussian noise.

$$r(t) = m_1(t) \times w_1 \times c(t) + \alpha \times m_2(t) \times w_2 \times c(t) + clutter(t) + n(t)$$

By theoretical analysis, the de-chirp result of the received signal will have components due to the clutter, de-chirping of clutter will have multiple sinusoids added to the result. Then after the matched filter is implemented we will have a large probability of error on the recovering data. Matched filter can suppress part of the clutter interference due to the small cross-correlation between the Walsh functions and sinusoids. However, clutter can have all possible delays. Some of the clutter returns can have large cross-correlation with the Walsh functions. It will cause a large bit error rate. Fig.9 shows the cross-correlation between the Walsh function and all clutter returns with possible delays. From the figure, the clutter return with 0.5 sec delay have the largest correlation with the Walsh function used. The de-chirp result of this clutter return has the same frequency as the Walsh function. That is the reason why the interference caused by this clutter return cannot be suppressed by applying matched filter.

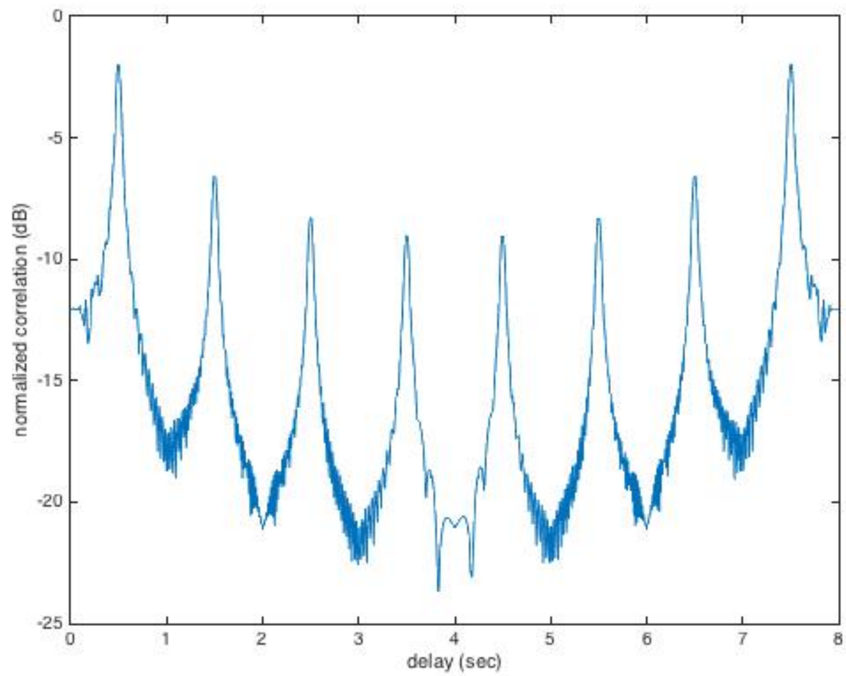

Figure 9. Cross-correlation between clutter returns with different delay and Walsh function

To solve the problem of suppressing the interference caused by clutter GMTI process can be implemented. In the case that the reader is static. The clutter is stationary with very small Doppler shift. For each chirp pulse the clutter is identical. The clutter can be simply reduced by subtracting the chirp pulse $n-1$ from the chirp pulse n. Firstly we used simple line coding method to reduce the clutter. In this case we send 8 information bits per chirp pulse. For the next chirp pulse we send the negated version of the same 8 information bits. Then we do the subtraction of chirp pulses after de-chirping.

$$r'(t) = (m_1(t) \times w_1 + \alpha \times m_2(t) \times w_2 + dechirp\big(clutter(t)\big) + n'(t)\,)$$
$$-(-m_1(t) \times w_1 + \alpha \times \big(-m_2(t)\big) \times w_2 + dechirp\big(clutter(t)\big) + n'(t)\,)$$

Then because the clutter is identical from pulse to pulse, ideally the clutter can be eliminated by using modified frequency modulation line coding. In this case, it requires twice the length of signal to transmit the same amount of information bits. The receiver decodes each pair of signal by subtracting the second data series from the first. With this method, the interference of clutter can be suppressed. However the communication rate is decreased to a half. We are sending 2n bits to just transmit n bit of information bits because one half of the bits sending are the negated copy of the original information bits.

To make the transmitting more efficient, differential coding method can be implemented. With differential coding we keep the performance of suppressing the clutter without losing the communication rate. Differential coding is the method that help with keeping the data rate when doing clutter suppression. In this case, because the method we use to suppress the clutter interference is doing subtraction of chirp pulses it is compatible to have differential coding implemented. Generally, for the first chirp pulse the signal is only modulated by the Walsh function, which means the information bits of the first chirp pulse is all 0's. Then the information data starts at the following chirp.

2.3 DELAY ESTIMATION AND INTERFERENCE SUPPRESSION

2.3.1 SIGNAL PROCESSING METHODS

Before demodulate the signal and applying the matched filter range induced carrier should be removed. Because there is delay of the line-of-sight backscatter signal that effect the de-chirping result. If the backscatter signal have a delay of τ_i and only one of the backscatter signal is considered. Then after de-chirping and subtracting the clutter from received signal the result is:

$$d(t) = (m_1(t) \times w_1) \times e^{j2\pi\beta\tau_i t} + n'(t)$$

Where $e^{j2\pi\beta\tau_i t}$ is the range induced carrier waveform that is caused by the delay τ_i. To make the matched filter working properly the range induced carrier has to be removed from the de-chirp result. Then range detection of the backscatter nodes is one of the most important problem to be solved.

Typically, when the reader is static, the Doppler shift of clutter will be very small around 0. At the same time the backscatter signals are modulated with Walsh functions and some information data. Then we can estimate the backscatter signals and distinguish different backscatter signals that are modulated with different Walsh functions with Delay-Doppler analysis. By taking the cross-correlation of the received signal and carrier signal the range of the backscatter nodes can be found by the Doppler shift caused by backscatter modulation. In the case of static reader system, the backscatter signal can be separated from clutter. Modulation of the backscatter signals produce Doppler shifts so that the delay of the backscatter signals can be estimated. When the backscatter signals are modulated with different Walsh functions, the Doppler shift of the signal corresponding to the backscatter nodes are different. From the pattern of the different Doppler shift the different backscatter signals can be separated and the delay of the actual backscatter signal can be estimated. In this case, the cross-correlation between the received signal and carrier waveform with every hypothesis Doppler shift is calculated. The cross-correlation shows the delay of the received signal. Ultimately, the larger cross-correlations will indicate the corresponding Doppler shift and delay of the received signal. As the reader is static, the clutter is approximately:

$$clutter(t) = \sum_i \alpha_i \, e^{-j2\pi\frac{\beta}{2}(t-\tau_i)^2 + j2\pi\nu t}$$

All of the different clutter returns are produced by the reflection of the carrier waveform around the environment. In a static situation, the Doppler shift of each clutter returns is approximately zero. Assume the modulated signal have a delay of τ, then the cross-correlation between the modulated signal and the carrier waveform with delay τ is shown in Fig. 10. Meanwhile the clutter return with the same delay as the modulated signal will have a different correlation since the clutter return is one of the bouncing signals of the carrier waveform.

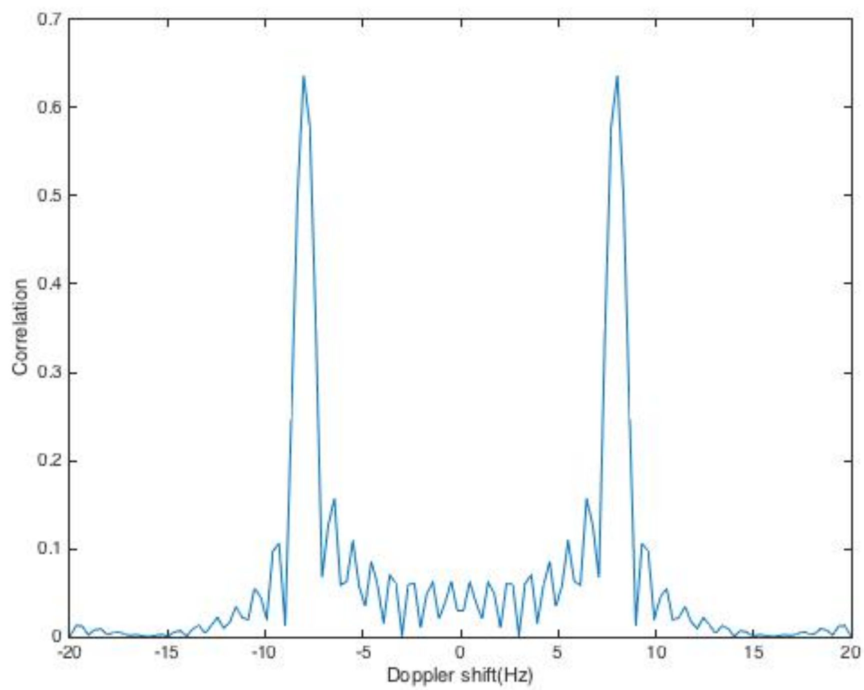

Figure 10. Correlation between modulated backscatter signal and carrier waveform

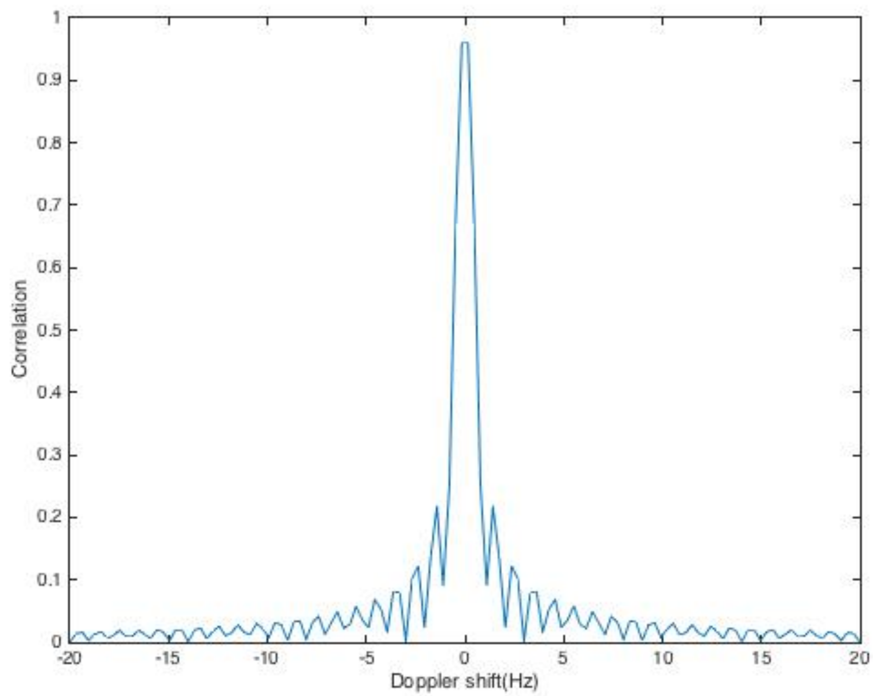

Figure 11. Correlation between one clutter return and carrier waveform with same delay

From this characteristic of correlation of modulated signal and clutter returns the delay of the modulated signal is able to be estimated. We firstly ignore the small Doppler shift around 0. Then the Doppler shifts left will indicate the modulated signals with a specific delay. By this different characteristic of the clutter and modulated signals. A clutter filter can be applied to suppress most of the clutter and estimate the delay more accurately. Because the correlation of clutter and the carrier waveform will form a ridge near 0 Doppler shift along the delay axis. First a filter near 0 Doppler can be applied to eliminate the ridge. Then the delay of the backscatter signals can be estimated by take the sum of the correlation with each delay and pick the largest one.

Other than the Walsh functions, there are many different coding methods to separate different signal sources. Gold code is one of the sequences that has very good property of separating different signal sources. Gold codes have very high autocorrelation only at 0 delay and the cross-correlation between different Gold codes is small enough. Unlike Walsh functions, one of the advantage of Gold codes is that Gold codes sequences are not harmonic. For instance, the Walsh function we used is 16-chip long, one of it is:

$$w1 = [+ - + - + - + - + - + - + - + -]$$

As a signal processing procedure, it is very important to reduce the clutter. In general, the clutter of a LFM carrier waveform is:

$$clutter(t) = \sum_i \alpha_i \, e^{-j2\pi\frac{\beta}{2}(t-\tau_i)^{2}+j2\pi\nu t}$$

Where $e^{j2\pi\beta t^2}$ is the LFM carrier waveform. τ_i is the delay of every clutter return. After de-chirp, the clutter will produce a sum of sinusoids with different frequencies. Then if we do the matched filter with Walsh functions, the sum of sinusoid will produce a strong interference when correlating a sinusoid with a Walsh function. That is one of the important reason to suppress the clutter before doing matched filter. However, Gold code sequences can easily solve the problem.

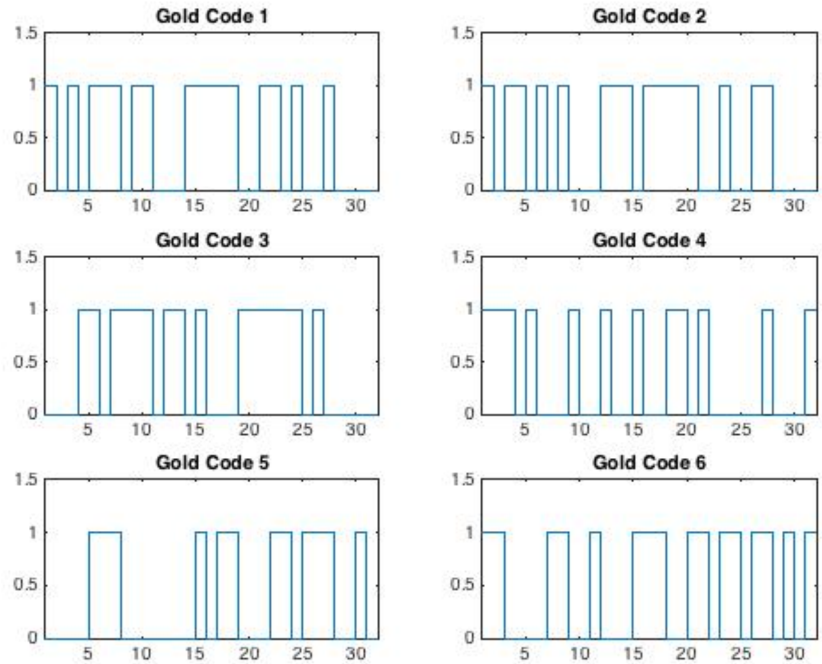

Figure 12. 6 examples of 31 chips long Gold code sequences

The sequence of Gold codes have no such characteristic of harmonic frequency as Walsh function sequences. Then the correlation between the de-chirped clutter returns and Gold code sequences will be small compared with the result of Walsh functions. Theoretically, Fig. 13 and Fig. 14 show the correlation between clutter de-chirp result and the modulation sequence.

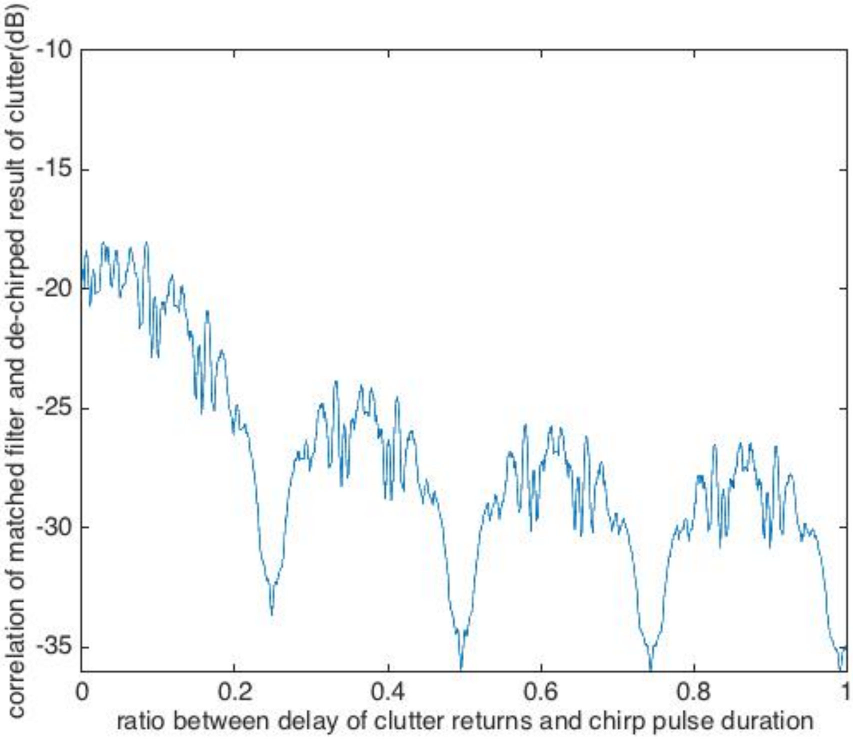

Figure 13. Correlation between Gold code and de-chirped clutter returns with different delays

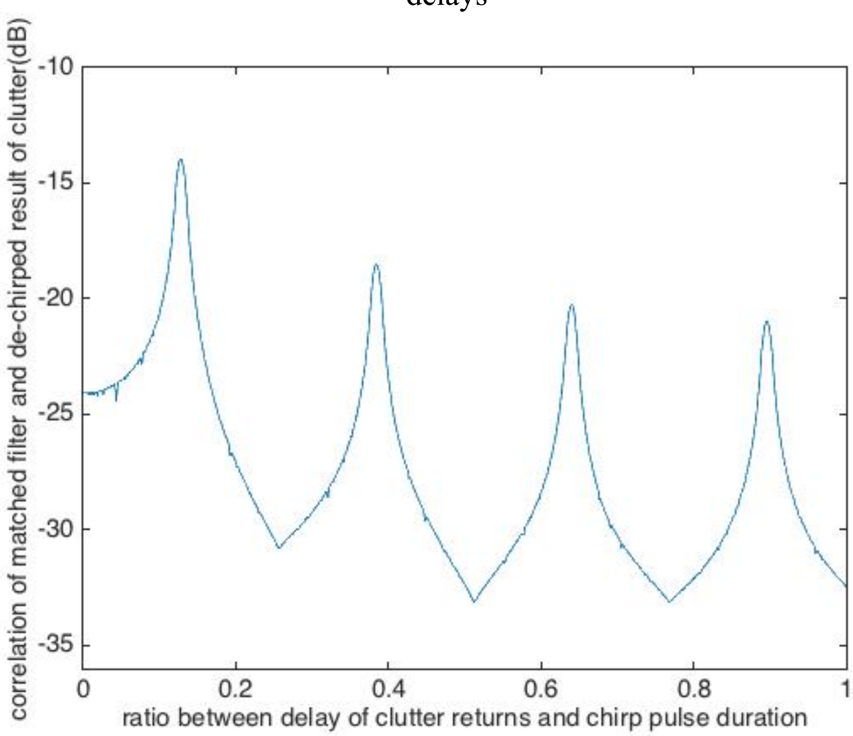

Figure 14. Correlation between Walsh function and de-chirped clutter with different delays

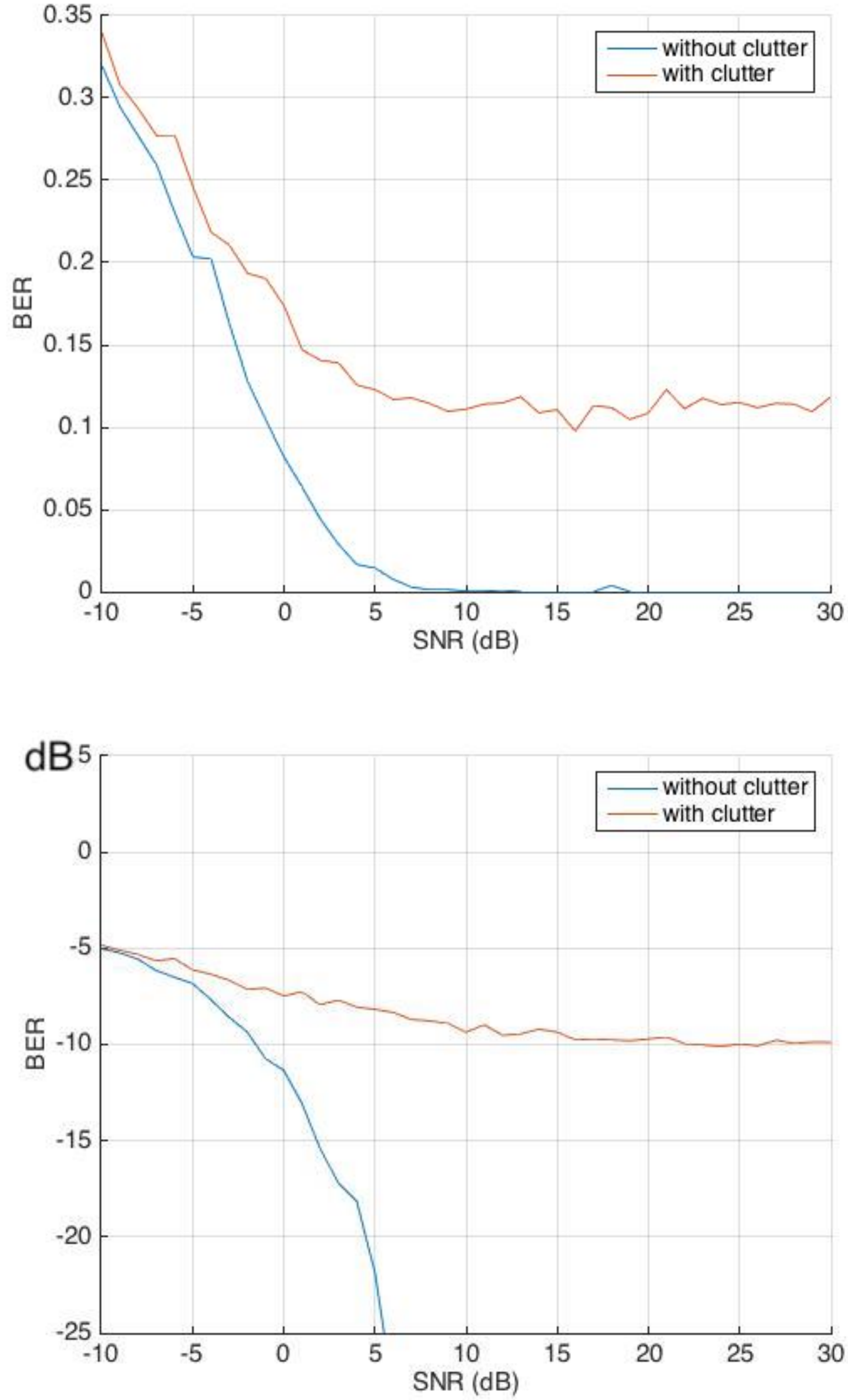

Figure 15. Performance of using Walsh function with/without clutter

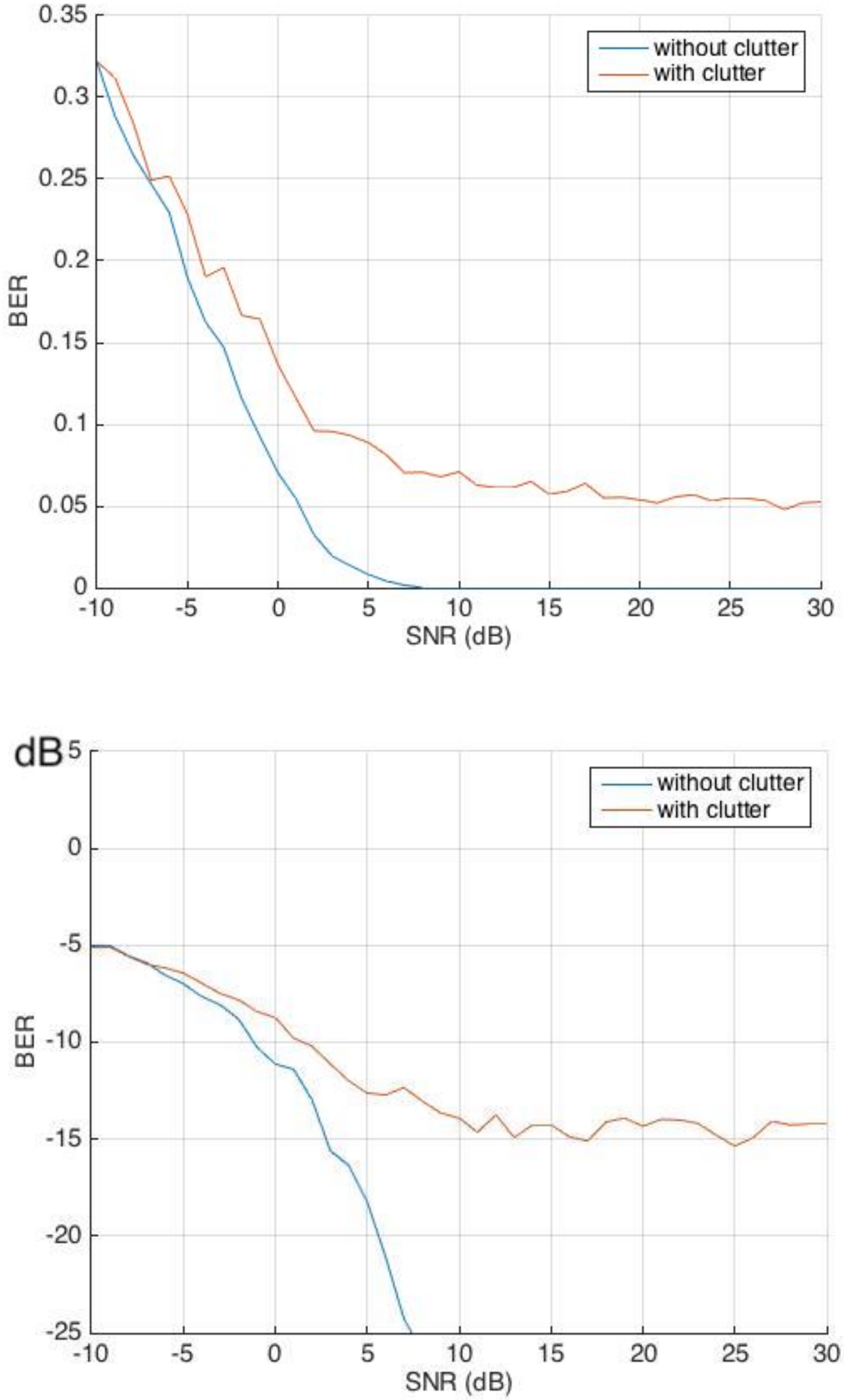

Figure 16. Performance of using Gold code with/without clutter

From Fig. 15 and Fig. 16, using Gold code the clutter will produce smaller interference to the matched filtering recovery result since the correlation between the matched filter and the performance is better compared with Walsh functions. Without GMTI processing the system can be weakly effected by the interference of clutter when using Gold code to modulate the information signals.

2.3.2 ACCURACY IMPROVEMENT USING SIGNAL PROCESSING METHODS

In this project, the performance of signal recovery depends on the accuracy of backscatter signal delay estimation. The delay estimated will affect the matched filter result. Theoretically, the received signal always has delay because of the range of the backscatter nodes. The range can be estimated by delay-doppler analysis. However, the delay of backscatter signals cannot be estimated perfectly due to noise channel and clutter interference. The difference between the actual delay of the backscatter signals and the estimated delay will affect the performance of data recovery.

In the signal processing procedure, assuming there are only 2 backscatter signal sources, we have the received signal to be:

$$r(t) = \alpha_1 \times signal_1(t - \tau_1) + \alpha_2 \times signal_2(t - \tau_2) + clutter(t) + n(t)$$

Where τ_1 and τ_2 indicates the delays of different backscatter signals, α_i are the amplitudes of the backscatter signals which depend on the range of the backscatter nodes. In this case, the estimation of the delay τ_1 and τ_2 can affect the performance of communication of the entire system. In reducing range induced carrier waveform procedure, the method used is by multiplying the complex conjugate of the carrier waveform with estimated delay of τ_e. As the result, the backscatter signal part of the received signal after de-chirp and range induced carrier removal is:

$$y'(t) = m_1(t) \times e^{-j2\pi\beta\tau_i t} \times e^{j2\pi\beta\tau_e t}$$

In this case, $e^{-j2\pi\beta(\tau_i-\tau_e)t}$ is a sinusoid that caused by the difference between the estimated backscatter signal delay and the actual delay of received backscatter signal. In realistic application, when the delay is not estimated perfectly the term $e^{-j2\pi\beta(\tau_i-\tau_e)t}$ will affect the performance of the communication.

In addition, how the delay affect the performance of recovery is related to the ratio between chirp rate and chip rate. If the chirp rate is fixed, delay estimation is required to be more precise when we want to send more information bits in one single chirp. The sinusoid term $e^{-j2\pi\beta(\tau_i-\tau_e)t}$ will make the matched filter result have smaller result so the additive white gaussian noise will be more effective on the probability of error of the recovery result.

Theoretically, after de-chirp, GMTI process and estimation of delay, the input of the matched filter would become the information signal multiply with $e^{-j2\pi\beta(\tau_i-\tau_e)t}$. Then the matched filter result would be

$$y = < w_1, m_1 \times w_1 \times e^{-j2\pi\beta(\tau_i-\tau_e)t} + n(t) >$$

The sinusoid term $e^{-j2\pi(\tau_i-\tau_e)t}$ will affect the result of matched filter and the difference between the actual delay and estimated delay $(\tau_i - \tau_e)$ determines the frequency of the sinusoid. In the realistic communication system, delay estimation is always an important problem to solve. Imperfect estimation of delay always influences the performance of communication.

Compared with the work that has been done, the change of performance of communication system is related to the bandwidth of LFM carrier waveform and the number of information bits sent in each chirp pulse. Basically, the delay estimation is not so strict when we use multiple chirp pulses to send 1 information bit. From the previous work, the only way to estimate the delay of backscatter signal is by delay-Doppler analysis. In real application, the estimation of the delay of backscatter signals is always imperfect. Larger ratio between the rate of chirp pulses and signaling rate can make the recovery of original information signal more reliable.

The static system is very reliable on recovering information signals. However, to make the system more practical, the illuminator and the reader can be on a moving platform to extract data from different sensors in an area. When the illuminator and reader are moving, Doppler effect must be considered. In this case, because the reader is moving, so the clutter received is Doppler-spread[27]. GTMI process cannot be applied because the environment is changing. One way to suppress the clutter and keep the performance of information recovery is using coding on the transmitted signals.

When the reader is moving, the clutter returns will have random Doppler shift. The Doppler shift depends on the angle of arrival of each signal return. In this case, one of the clutter returns is:

$$clutter(t) = \sum_{k} \alpha_k \, e^{-j2\pi\frac{\beta}{2}(t-\tau_k)^{2}+j2\pi v_k t}$$

Where τ_i is the delay of the clutter return and α_i is the amplitude of the clutter return. For the clutter returns which have delay of τ_i, assume the maximum Doppler shift of the clutter return is D_{max}, the Doppler shift of the clutter returns can be from $-D_{max}$ to D_{max}. Because the Doppler shift is determined by the angle of arrival, the clutter returns have longer delay will have greater Doppler shift D_{max}. Because the clutter returns are the carrier waveform reflected by the environment, the clutter is not similar to each other across chirp pulses. GTMI processing is no longer an efficient way to suppress the interference of the clutter in this case. As the result of the signal processing, the Doppler-spread clutter will generate a sum of sinusoids after de-chirping.

For one of the delay of clutter return,

$$dechirp\big(clutter(t)\big) = \sum_{i} \alpha e^{j2\pi\beta\tau_i t + j2\pi D_i t}$$

Where τ_i is the delay of the clutter return and D_i is the Doppler shift from $-D_{max}$ to D_{max}. The matched filter result of the sum of sinusoids is shown in Fig. 13 and Fig. 14 using different coding such as Walsh function and Gold code. Gold code have better performance of suppressing interference of clutter returns because the sequence of Gold code have smaller correlation with sinusoids.

CHAPTER 3. RESULTS

3.1 MULTIUSER INTERFERENCE USING DIFFERENT CODING SEQUENCES

From the work of this project, the signals from different backscatter nodes are separated by coding with Walsh functions or Gold codes. In general, Walsh functions have very small cross-product with each other. Specifically, in this project the Walsh functions used are orthogonal to each other. With the characteristic the signals from different backscatter nodes can be separated by applying different matched filter on the received signal. From the analysis about relationship between performance and delay estimation, the resolution of delay is very important to have better performance of information signal recovery. Compared with Walsh Functions, Gold codes have better autocorrelation characteristic. The autocorrelation of Gold code sequences have a large peak value at 0 delay. Gold codes are more sensitive to delay and the estimation of the delays of modulated signals can be close to actual delays. The results are shown in Fig. 17 and Fig. 18.

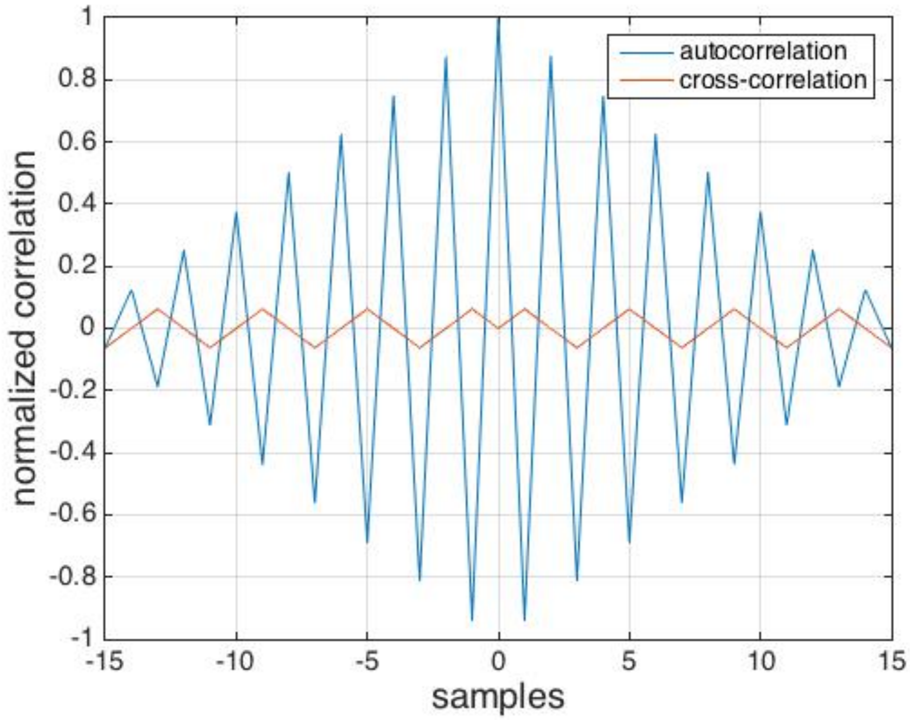

Figure 17. Walsh function autocorrelation and cross-correlation

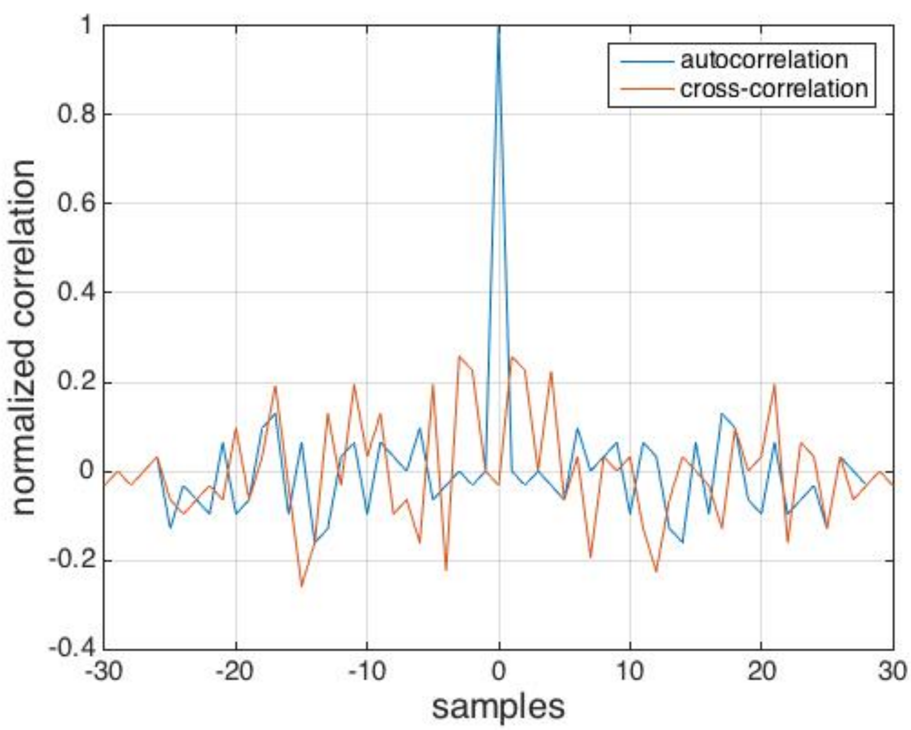

Figure 18. Gold code autocorrelation and cross-correlation

In the case of using Walsh functions to modulate the backscatter signals, the performance of communication is determined by SNR and SIR. Assume the clutter can be perfectly removed by delay estimation and GMTI process, the corruption of signals come from additive white gaussian noise and interference of other backscatter signals. In the simulation, two different backscatter signals are included. 0, 6, 12, 18, 24 dB SIR are considered. Theoretically, for the stronger signal the performance will not change too much as the SIR changes, in this case, the performance of communication is more related to the amplitude of additive noise. For the weaker backscatter signal, the recovery performance is related to both SNR and SIR. As the SIR increases, the performance of recovering the signal is affected by the stronger signal. In the theoretical analysis, when calculating the probability of error of the weaker signal, $\alpha - \frac{1}{16}$ may be less than 0. In this condition, the term $P\left(N\left(-\frac{1}{16} + \alpha, \sigma\right) \leq 0\right)$ approaches 1 if the variance σ grows larger, so P_E will be approaching 0.5 when the SIR is higher than 24 dB in Fig. 20. The simulated result is shown in Fig. 19. For the stronger signal, SIR is not changing the performance of recovery, Fig. 21 and Fig. 22 shows the simulation result and theoretical probability of error. Fig. 23 shows the case when the signals are perfectly synchronized.

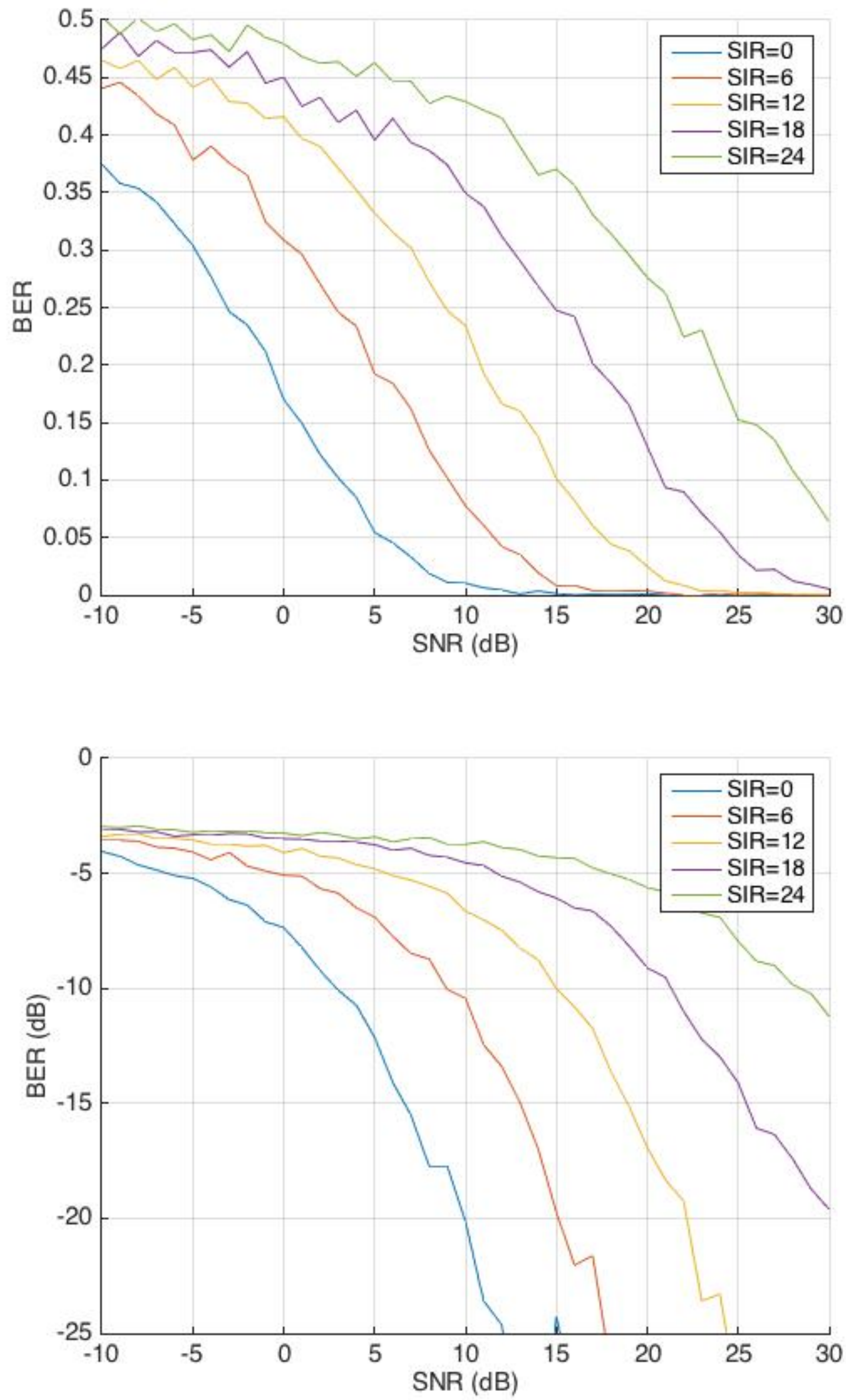

Figure 19.Simulation bit error rate of weaker signal

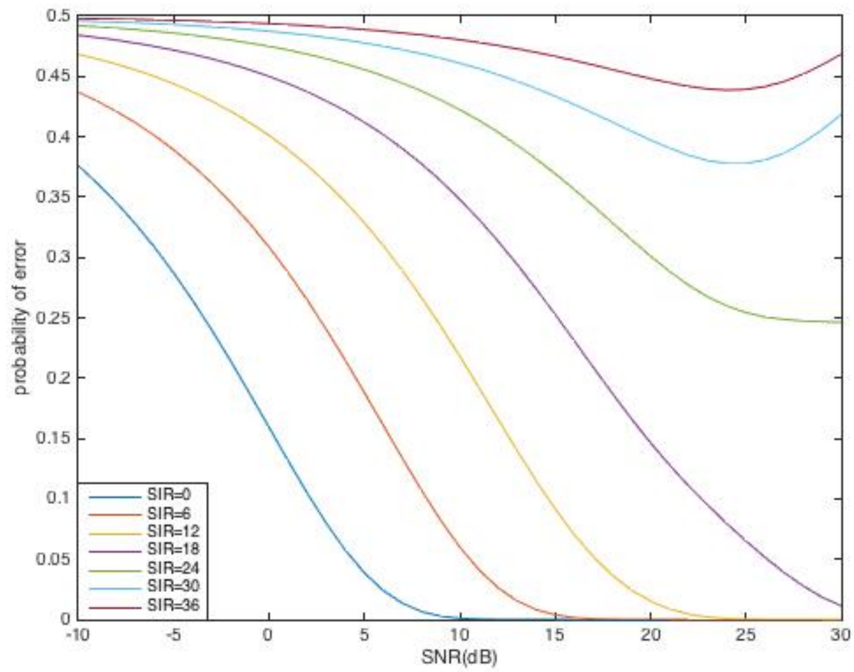

Figure 20. Theoretical bit error rate of weaker signal with different SIR

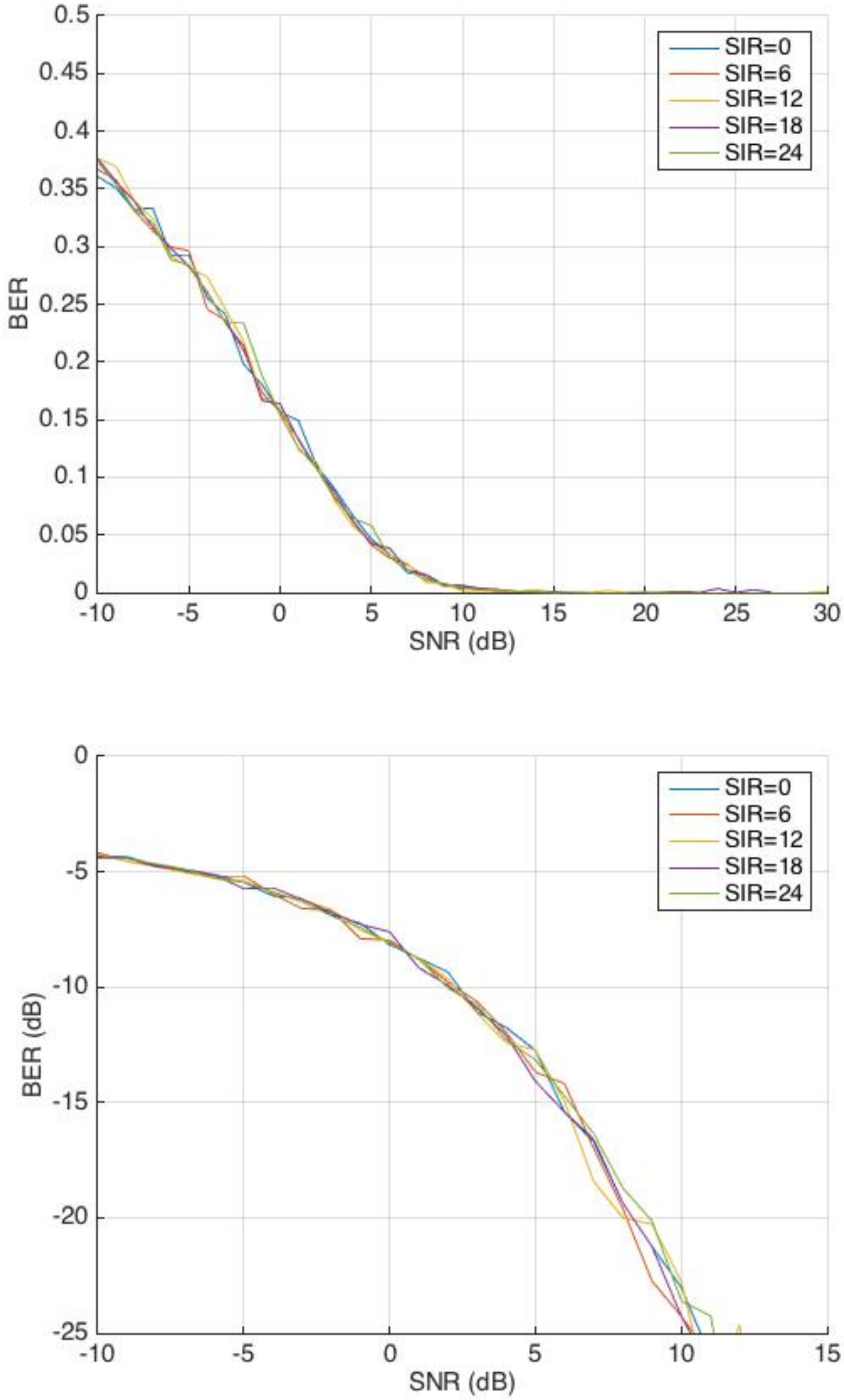

Figure 21. Simulation bit error rate of stronger signal

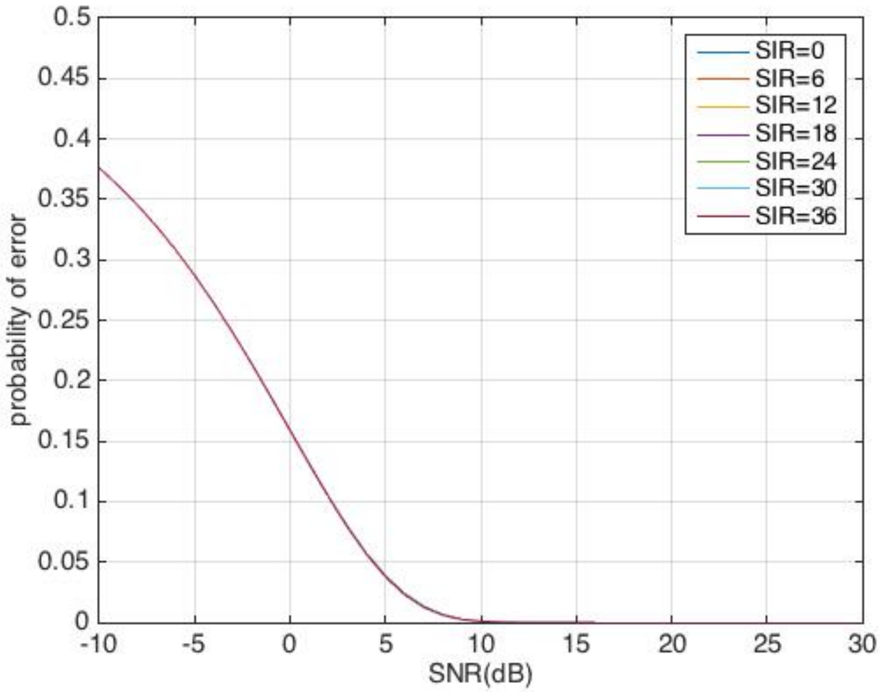

Figure 22. Theoretical bit error rate of stronger signal with different SIR

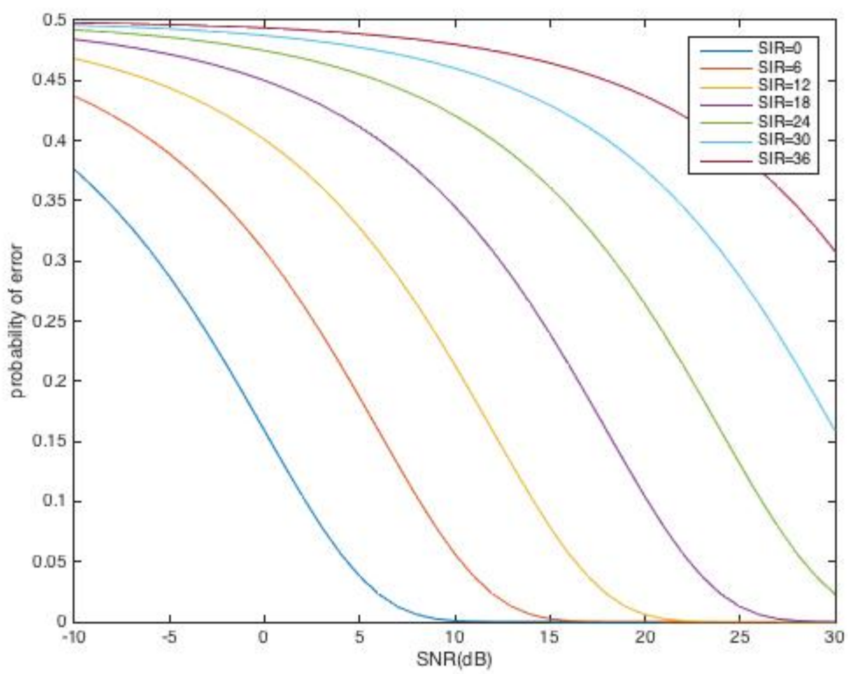

Figure 23. Theoretical bit error rate of weaker signal with different SIR (no delay between signals)

3.2 DELAY ESTIMATION AND RECOVERY PERFORMANCE

In this project, the performance of communication strongly depends on the estimation of delay when the system is static. The range induced carrier is come with the delay of backscatter modulated signals. In the procedure of reducing the residual carrier the estimation of delay is used to cancel out the residual carrier term.

In de-chirp:

$$dechirp\big(r(t)\big) = \alpha_i m_i(t) e^{-j2\pi\beta\tau_i t}$$

Where Doppler shift ν is close to 0 because the system is static and τ_i is the actual delay of the signal then in the reducing residual carrier step

$$r_e(t) = \alpha_i m_i(t) e^{-j2\pi\beta\tau_i t} \times e^{j2\pi\beta\tau_e t}$$

The matched filter of $r_e(t)$ will be shown in Fig. 24 when $(\tau_i - \tau_e)$ is chosen properly.

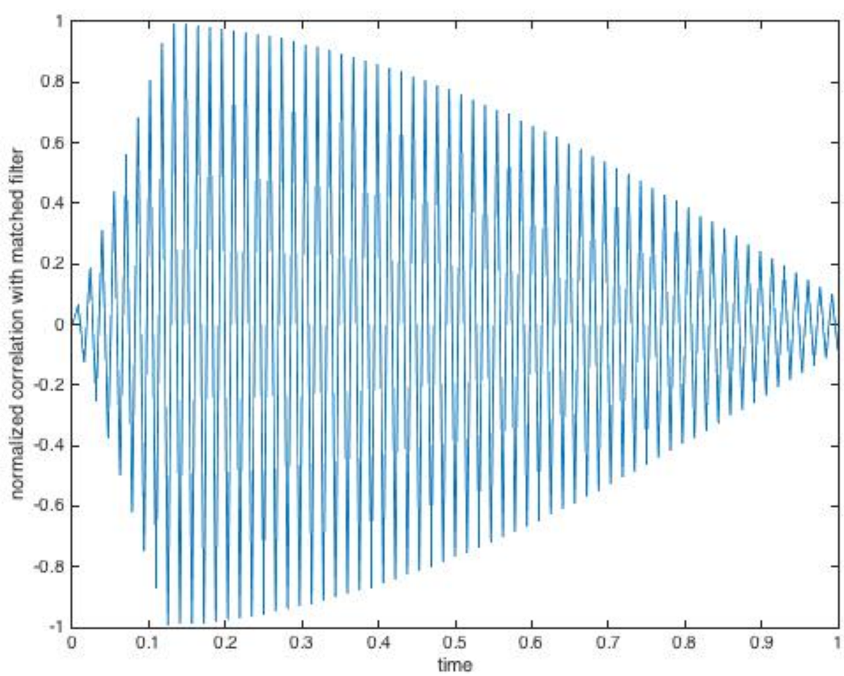

Figure 24. Matched filter result of delay estimated signal with modulation

From the result, the amplitude of the correlation between the matched filter and the estimated de-chirped signal is reduced because of the mismatch of estimated delay and actual delay. The performance of communication is related to how accurately the delay can be estimated. To achieve the goal of improving the recovery performance and low bit error rate, high resolution of delay-Doppler process is required.

In this case, the sinusoid term produced by the error of delay estimation is: $e^{-j2\pi\beta(\tau_i-\tau_e)t}$. Mathematically, the frequency of this sinusoid term is $\beta(\tau_i - \tau_e)$. In the case of transmitting 8 information bits within 1 chirp pulse, the upper bound of delay estimation that have the matched filter result not changing the sign is $(\tau_i - \tau_e) = \frac{0.5}{B}$. The envelop of the matched filter result with Walsh functions is effected by the sinusoid term shown in Fig.24. With this error of delay estimation, the probability of error curve requires higher SNR to level off.

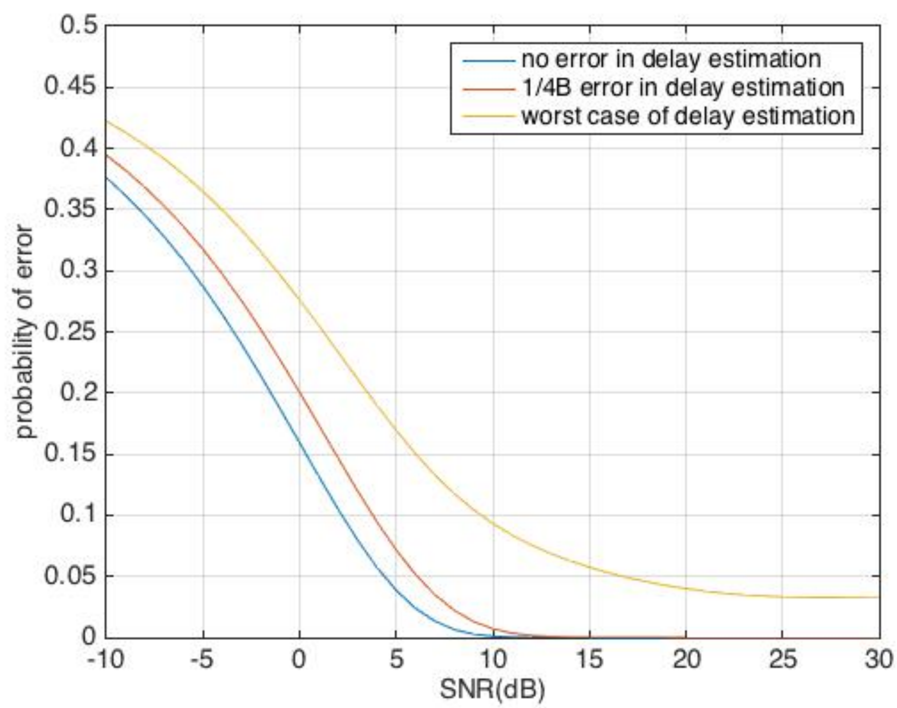

Figure 25. Theoretical probability of error of different errors in delay estimation

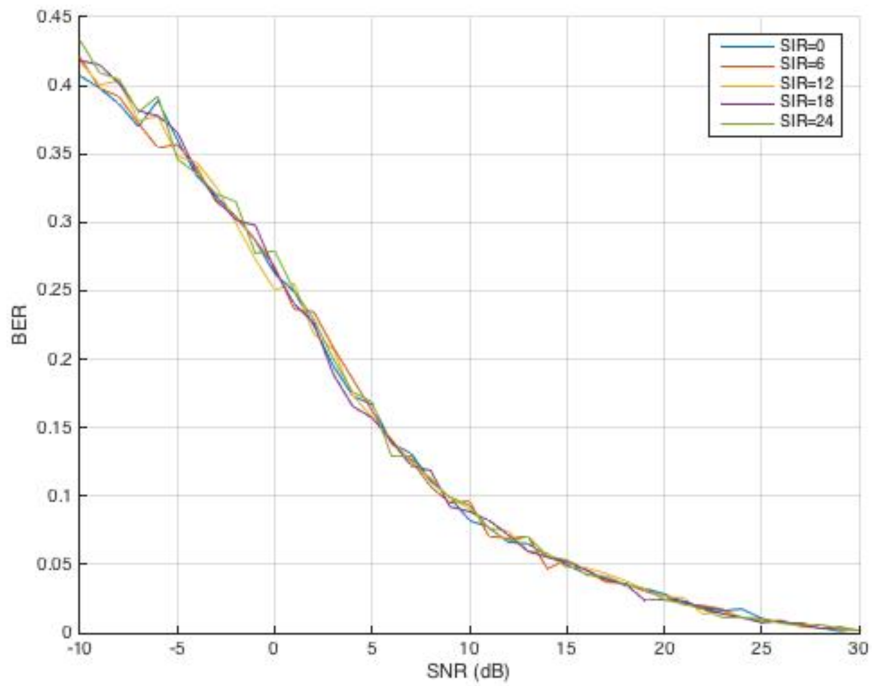

Figure 26. $0.5/B$ chirp duration difference between actual and estimated delay bit error rate

The ratio between signaling rate and LFM chirp rate is also affecting the change of performance of communication. In the case of sending multiple information bits in one chirp pulse, because the sinusoidal term have different value at different time. The effect of error of delay estimation will be different for each symbol. In the simulation, 8 information bits are sent within one single chirp pulse. For the first information bit the sinusoid part is closer to 1 and for the last information bit the sinusoid part is approximately 0. The probability of error of the last information bit is much larger than the probability of error of the first information bit with the same SNR. The theoretical probability is shown in Fig. 25 and Fig. 26 shows the simulated result. However, when the signaling rate and chirp rate are matched up, the probability of error curve is shifted compared with the probability of error with no error of delay estimation as Fig. 27.

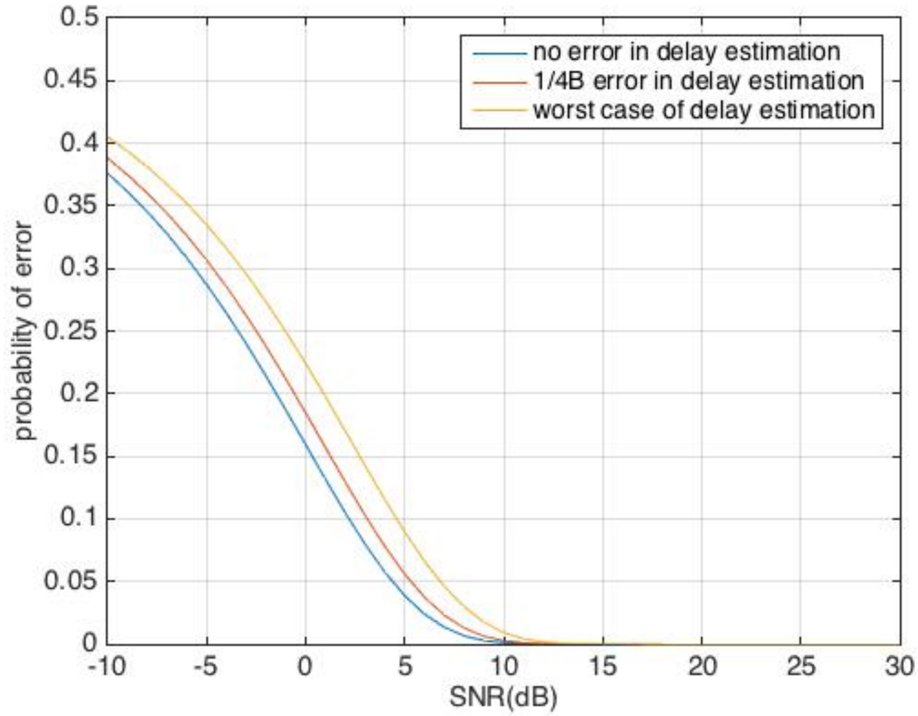

Figure 27. Theoretical probability of error when signaling rate and chirp rate are matched up

In additive, the signaling rate also can be smaller than the chirp rate. It mean we can use multiple chirp pulses to send one information bit. In this case, the error of delay estimation will have smaller effect on the performance of recovery. In general, the delay estimation is always related to the bandwidth of the signal. For the LFM signals, the bandwidth is approximately represented by the difference between the lowest frequency and the highest frequency.

$$B = \beta \times T$$

Where T is the duration of one chirp pulse. The resolution of delay estimation is $\frac{1}{B}$ so the bandwidth of LFM carrier waveform always effects the performance of communication.

3.3 DOPPLER SPREAD CLUTTER AND ITS EFFECT ON COMMUNICATION PERFORMANCE

The work has been done in this project developed an idea of extracting information signals from multiple sensors with a moving receiver. Because the performance of signal recovery is better when the signal is stronger. The information signals from all of the sensors in the network can be received with a higher SNR with a moving reader. One of the challenge is the recovery of information signals in a dynamic system. The clutter is Doppler-spread because the reader is not static in the environment. The clutter returns that have longer delay will have a larger range of Doppler shift. In this case, clutter filter and GMTI processing cannot be implemented to suppress the interference of clutter. Coding is one of the solution to improve the performance of signal recovery.

In signal processing of this project, the de-chirp result of clutter is a sum of sinusoids with different frequencies. As a result, the matched filter of the sum of sinusoids will affect the performance of signal recovery. It is necessary to suppress the interference of clutter. For the system that the backscatter signals coded with Walsh functions because the Walsh functions used are 2 of the sequences with 16 chips shown in Fig. 28, the Walsh functions have large correlation with sinusoid waveforms with some frequencies. Gold code is another reasonable spread sequence to be used in this situation. Because Gold codes have small correlation with sinusoids the performance of suppressing self-interference in this system can be improved.

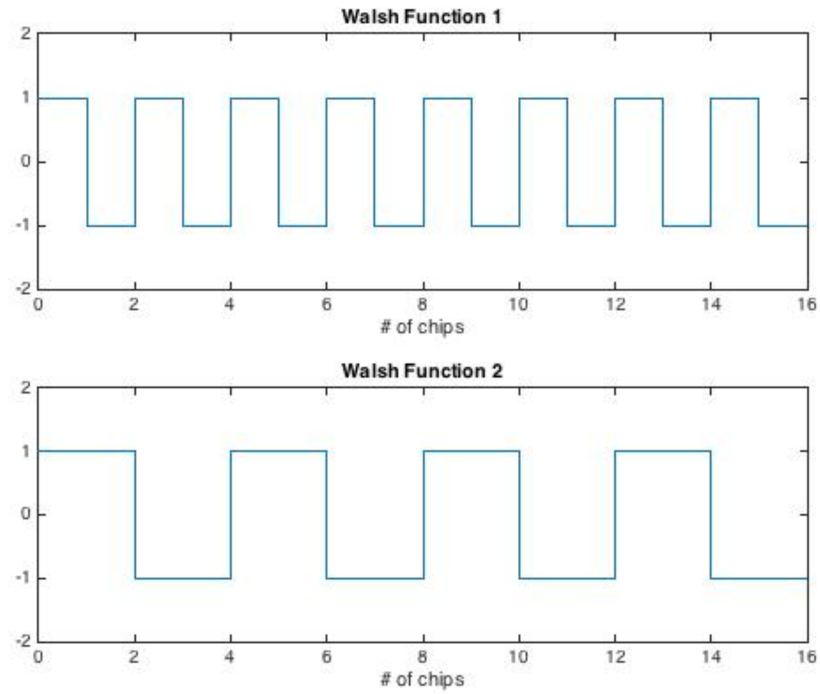

Figure 28. Walsh function used to modulate the signal

From the analysis of this system, in the case with moving receiver, longer delay of clutter returns can have larger possible Doppler shift. The Doppler shift range of the clutter filter needs to be increased to filter out the clutter with longer delay. The range of the clutter filter needs to be chosen carefully because the modulation of information signal also produces Doppler shift on the information signals.

At the same time, other coding methods can be also applied on the signal to separate the clutter and modulated signals more efficiently. Run length limited(RLL) channel coding is one of the methods to help suppress the self-interference from clutter[23]. As the RLL coding processing separates the Doppler spectrum of the information signal and the interference spectrum, clutter can be filtered out and the performance of information signal recovery can be improved.

CHAPTER 4. CONCLUSION, SUMMARY AND FUTURE WORK

4.1 CONCLUSION AND SUMMARY

In the work that has been done in this project, we developed the signal processing and coding methods in a multiuser backscatter communication sensor network. In general, compared with traditional communication, performance of backscatter communication is easy to be affected by interference. Backscatter communication is based on the reflection of signals so it makes the strength of backscatter signal small. In this system, suppressing self-interference and separating different backscatter signal sources are the most challenging problems to solve. Coding is one of the efficient ways to improve the performance of communication. The principle of CDMA is also used in the approach to distinguish the signals from different backscatter nodes. In communication system, clock synchronization of transmitter and receiver is very important to ensure the performance of information recovery. We also developed the relationship between accuracy of delay estimation and the performance of communication.

4.2 FUTURE WORK

To make the sensor network more practical, channel estimation methods and beamforming can be implemented. In signal communication, multi-path effect is always a problem corrupting the signal recovery accuracy. The bouncing signals can have interference with the line-of-sight signal. Because the multi-path components of the transmitted signal are also modulated, it is important to estimate the environment of signal propagation and use the model of environment to suppress the multi-path signal interference. In general, channel estimation is achieved by training with pilot signals. We use the known signals to estimate and rebuild the channel of signal propagation. By applying channel estimation the performance of the system can be improved.

Generally the wireless channel is highly complex. For a sensor network communication system multipath propagation must be considered as a challenge. Reflection interfere with direct-path signals and different signals from multiple nodes would interfere with each other. Unlike the additive noise which can be reduced the interference is hard to be suppressed[28]. Channel estimation is one way to estimate and model the communication environment. The interference can be suppressed by applying signal processing method on the estimation of the channel. Channel estimation simplifies the complex communication channel to a model where each path can be represented by parameters.

In addition, in the case of non-static system, Doppler-spread clutter interference is the most important problem to be solved to have the system work reliably. Clutter suppression with coding is insufficient in some situations. However, the network can be treated as a radar system as well. On the reader of the network, the backscatter nodes can be located if beamforming is implemented. Doppler shift of clutter is highly related to the direction of clutter returns. Once the nodes are located, beamforming can help suppressing a large amount of Doppler-spread clutter. The system can be developed to have better performance with combination of locating and communicating.

To suppress the interference beamforming can be applied on the system. Once the receiver is moving and the system has multi-path signals, the bouncing signals can be suppressed by using beamforming. Beamforming is a signal processing technique used in sensor arrays to transmit and receive signals in specific directions[29]. Beamforming is widely used in radar, sonar and wireless communications[22]. To detect and estimate the signal-of-interest, adaptive beamforming can be applied to achieve the goal.

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