IEEE 802.11n MIMO Modeling and Channel Estimation Implementation

Master thesis performed in Electronics Systems by

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Abstract

With the increasing demand of higher data rate for telecommunication, the IEEE802.11n standard was constituted in 2009. The most important character of the standard is MIMO-OFDM, which not only improves the throughput but also the spectrum efficiency and channel capacity. This report focuses on the physical layer IEEE802.11n model. By utilizing an existing Simulink based IEEE802.11n system, functionalities like MIMO (up to 4*4), OFDM, STBC, Beamforming, and MMSE detector are simulated. The results such as bit error rate, packet error rate and bit rate with different system settings are given. Furthermore, the channel estimation process is clarified, and a DSP builder based MMSE detector is realized, which can fulfill exactly the same function as the Simulink model.

Keywords
Simulink, MIMO, OFDM, STBC, Beamforming, MMSE detector, channel estimation
ABSTRACT

With the increasing demand of higher data rate for telecommunication, the IEEE802.11n standard was constituted in 2009. The most important character of the standard is MIMO-OFDM, which not only improves the throughput but also the spectrum efficiency and channel capacity. This report focuses on the physical layer IEEE802.11n model. By utilizing an existing Simulink based IEEE802.11n system, functionalities like MIMO (up to 4*4), OFDM, STBC, Beamforming, and MMSE detector are simulated. The results such as bit error rate, packet error rate and bit rate with different system settings are given. Furthermore, the channel estimation process is clarified, and a DSP builder based MMSE detector is realized, which can fulfill exactly the same function as the Simulink model.

Key words: Simulink, MIMO, OFDM, STBC, Beamforming, MMSE detector, channel estimation.
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1 INTRODUCTION AND BACKGROUND

1.1 Introduction

Telecommunication has been developed for a long time, and now the whole world has come to the information generation. However, the maximum data rate that 3G can offer is 2Mbit/s, which is not enough to satisfy the user's demand for higher speed. Therefore advanced telecommunication technology is the fundament of information industry.

Nowadays, multiple kinds of wireless communication and broadband data services have been developed. However, limited spectrum resource makes competition for it even stronger. People focus on raising the spectrum efficiency in order to provide high rate, dependable broadband data services. In the fourth generation communication system, multiple input multiple output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), and smart antennas become the key points.

MIMO is a very important breakthrough in Wireless Local Area Network (WLAN) research, because space resources can be utilized efficiently without adding bandwidth and antenna power. Moreover, due to its influence to multipath fading, spectrum efficiency and channel capacity are improved also. OFDM is now the common transmission technique to control spectrum resources.

IEEE 802.11n applies MIMO techniques to increase the throughput dramatically compared to the previous IEEE 802.11 standard sets. Meanwhile, by the support of OFDM multicarrier modulation, using 40MHz channel can improve the transmission performance a lot.

1.2 IEEE802.11n background

The IEEE802.11 standard was released in June 1997 [22]. Its carry frequency is 2.4GHz, and its transfer rate is up to 2MHz. The main modulation techniques are direct sequence spread spectrum (DSSS) and frequency-hopping spread spectrum (FHSS).

IEEE finished the 802.11b standard during 1998 to 1999 [22]. IEEE 802.11b uses a carry frequency of 2.4GHz, and Complementary Code Keying modulation technique (CCK) [22]. CCK comes from DSSS. The Medium Access Control (MAC) applies a multi-rate mechanism to make sure the transfer rate can decrease from 11Mbps to 5.5Mbps when the distance between stations is too far, or the interference is too strong, or SNR is less than threshold. Sometimes, the MAC can adjust the transfer rate to 2Mbps or 1Mbps according to DSSS. The significant contribution of IEEE 802.11b is that it can support two additional rates, 5.5Mbps and 11Mbps.
At the same time, IEEE constituted the IEEE 802.11a standard. It makes use of multi carrier modulation of OFDM to get better multipath performance. IEEE802.11a uses a carry frequency of 5GHz, and provides 8 channels, supporting transmission speed up to 54Mbit/s.

In 2003, IEEE802.1g was set up to be used as the high rate version of 802.11b. It works in 2.4GHz band and can reach 54Mbps transfer rate [22]. IEEE802.11g applies OFDM which is different to CCK. Meanwhile, IEEE802.11g also supports the same modulation technique as IEEE802.11b to be compatible, so that it can switch modulation according to different communication object.

In January 2002, IEEE set up a new workgroup to establish higher rate standard, which is IEEE 802.11n [21]. After 7 years amendment, the final version 802.11n-2009 was published. MIMO-OFDM is the core technology of the physical layer. It operates at 2.4GHz or 5GHz band, and can offer OFDM 40MHz [21] channel bandwidth. At most it supports up to 4*4 configuration antennas. The highest transmission rate is 600Mbps [21].

Due to its advantage of high throughput, Intel, Cisco, Aruba, SMS etc. have already published lots of products supporting IEEE802.11n.

<table>
<thead>
<tr>
<th>IEEE WLAN standard</th>
<th>Physical layer rate</th>
<th>Modulation technique</th>
<th>Space dimension</th>
<th>Channel bandwidth</th>
<th>frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>11Mbps</td>
<td>DSSS/CCK</td>
<td>1</td>
<td>20MHz</td>
<td>2.4GHz</td>
</tr>
<tr>
<td>802.11a</td>
<td>54 Mbps</td>
<td>OFDM</td>
<td>1</td>
<td>20 MHz</td>
<td>5GHz</td>
</tr>
<tr>
<td>802.11g</td>
<td>54 Mbps</td>
<td>DSS/CCK/OFDM</td>
<td>1</td>
<td>20 MHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>802.11n</td>
<td>600 Mbps</td>
<td>DSS/CCK/MIMO-OFDM</td>
<td>1,2,3 or 4</td>
<td>20 MHz/40 MHz</td>
<td>2.4GHz/5 GHz</td>
</tr>
</tbody>
</table>

**Table 1: IEEE802.11 a/b/g/n parameters**

### 1.3 Purpose of the project

In the area of WLAN, IEEE802.11n standard has been followed closely by equipment manufacturers and service providers. There is obvious research significance brought by the breakthrough of related technology.

In the transmission rate part, 802.11n can provide 108Mbps and 600Mbps which is much higher than the upper limit rate of 54Mbps provided by 802.11a and 802.11g. Meanwhile, utilizing MIMO and OFDM combination [21], IEEE802.11n not only raised the transport rate, but also improved the transmission quality.
In the channel bandwidth part, IEEE802.11n support 40MHz channel bandwidth, at the same time it also can support 20MHz used by 802.11a/b/g. The transmission performance can be highly improved by OFDM multi carrier modulation.

In the compatibility part, IEEE802.11n uses Software Radio Technology, which improves the compatibility of WLAN a lot [21]. In addition, with 802.11n, WLAN and wireless wide area network can integrate together.

Channel estimation is the key point of MIMO-OFDM systems. Because of multipath and time-variation brought by the wireless channel, accurate channel estimation is vital in wireless communication. Meanwhile, receiver has to know channel characteristics to decode efficiently when the system applies Space Time Block Coding (STBC) [5]. In MIMO-OFDM, as the number of antennas of the transmitter and receiver increased, the complicity of channel estimation rapidly increased. The performance of channel estimation will be influenced then. So people are trying to search for some arithmetic of channel estimation to decrease the complicity of calculation and to improve the performance of channel estimation.

According to the above, IEEE802.11n MIMO system was chosen as the thesis subject, and the detection part is discussed in detail.

**1.4 Problem statement**

At the beginning of the thesis, the plan is to set up an IEEE802.11n model and run some simulation based on different channel models to get their BER and PER. After a period of studying the theory of IEEE802.11n standard, a model on internet was found which is already satisfied all the requirements. So the plan is changed to figure out how the author set up the model, and how to do the simulation within requirements. After finishing this part, the supervisor suggested me to realize part of the model in DSP Builder. Channel estimation turned out to be the target. However, the channel estimation model of DSP Builder only considers one specific situation that is different from the Simulink model.

This thesis focuses more about the theory related to MIMO-OFDM and IEEE802.11n, and explains clearly how the channel estimation DSP Builder based model is designed composed.

**1.5 Report overview**

In the first chapter of the report, a brief introduction of IEEE802.11n is given, including its characteristics and background. A simple explanation of the thesis process is provided, too.
In the second chapter, most of the key problems of mobile channel characteristics are introduced.

In the third and fourth chapters, an explanation of the theory of MIMO-OFDM system is presented, and then more details about its actual application in IEEE802.11n according to the final design are offered. After the two chapters, the evolution process coming from MIMO-OFDM to IEEE802.11n can be understood.

In the fifth chapter, the simulation results of T Gn channel and AWGN channel with Matlab Simulink blocks are shown. Some tests using beamforming and STBC are run, and their PER and BER results are then shown.

In the sixth chapter, specific channel estimation theories in IEEE802.11n standard are explained in detail.

In the seventh chapter, the whole procedure and result of the channel estimation model with DSP builder blocks are demonstrated in detail.

In the final chapter, the whole report is summarized, and some parts which can be improved and can be realized in future task are provided.
2. WLAN CHANNEL MODELLING

One of the most important characteristics of mobile communication is that it allows users to move in a certain range while transmitting information without restriction, but usually wireless transmission does not perform very well. There are two reasons causing this. One is that the operating environments of mobile communication are quite complicated. Radio waves not only experience dispersion loss with the increase of transmit distance, but there also exist shadow effect and multipath effects due to the terrain or buildings. The other is that it happens so often that the clients use mobile communication when they are moving fast, which will cause Doppler effects and random frequency modulation.

It is easy to tell that the wireless mobile channel limits the performance of mobile communication system. The mobile communication system has to be designed according to the mobile channel features. However, it is very difficult to describe channel characteristics efficiently. Calculating the signal intensity and the propagation loss is very hard. The wireless channel does not behave the same as a wired channel, which is fixed and can be predicted. The wireless channel is extremely random, and its channel characteristics can change anytime anywhere. Even the speed of mobile station movement can influence the attenuation of the signal level.

2.1 Mobile channel characteristics

2.1.1 Multipath propagation

The main characteristic of the mobile channel is the multipath propagation [29]. If radio waves meet buildings, trees, or topographic relief during the transmitting process, the power can be lost and the waves can be reflected, scattered, or diffracted.

In a mobile transmission environment, there is not only one path to receive the mobile antenna signals. The received signal is usually the combination of multiple reflection waves coming from different paths. Because of the difference between the path distances, each wave arrives at different time, and they thus have different phase position. Those waves with different phase will be superimposed at the receivers. Sometimes signals will be stronger due to adding, sometimes, signals will be weaker due to decreasing [30]. So, the amplitude of the receiving signals can be changed rapidly, which causes multipath fading.

Multipath fading can be described and measured in time domain and space domain. In space domain, toward mobile receiver, the amplitudes of received signals are going to decrease with the distance increase. Multipath fading caused by local reflecting object changes the amplitude faster. In space domain, because that signals
arrives at different time, the received signals will not only include the pulse signal from base station, but also include other time delayed signals.

Generally, analog mobile system mainly considers changing amplitude of received signals caused by multipath effect. Digital mobile system mainly considered delay spread of pulse signal caused by Doppler Effect [29].

2.1.2 Delay spread

When multipath transmission happens, received signals can create delay spread. If the sender sends a quite narrow pulse signal, since there are multiple paths, and the distances are different, the signals along distinct paths will arrive at different time. Delay spread can be quantified through different metrics, and the most common one is the root mean square (rms) delay spread. According to Gold smith, let $A_c(\tau)$ be the power delay profile of a channel, and then the mean delay of the channel is

$$\tau = \frac{\int_0^\infty \tau A_c(\tau) d\tau}{\int_0^\infty A_c(\tau) d\tau}$$  \hspace{1cm} (2.1)$$

Thus, the rms delay spread is

$$\tau_{\text{rms}} = \sqrt{\frac{\int_0^\infty (\tau - \bar{\tau})^2 A_c(\tau) d\tau}{\int_0^\infty A_c(\tau) d\tau}}$$  \hspace{1cm} (2.2)$$

Moreover, the transmission paths can change with the movement of the mobile station. Therefore, the received signals are composed by many delayed pulses. With the movement of mobile station, those pulses can be scattered or gathered.

2.1.3 Coherence bandwidth

In a certain frequency range, two frequency components have strong amplitude correlation. For a Rayleigh-fading of the wide-sense stationary uncorrelated scattering (WSSUS) channel with an exponential delay profile, one finds

$$B_c \approx \frac{1}{2\pi \tau_{\text{rms}}}$$  \hspace{1cm} (2.3)$$

where $\tau_{\text{rms}}$ is the rms delay spread.

2.1.4 Doppler shift

Frequency is going to change when an observer moves relative to the source of the wave, which is called the Doppler Effect. Additional frequency shift caused by the Doppler Effect is called the Doppler shift, and Doppler shift can be represented as [25]
\[ f_d = \frac{2 \cdot v}{\lambda} \cos \alpha \]  

where, \( \alpha \) is the angle between the direction of the transmitted signal and the direction of the flight of the target, \( v \) is the speed of mobile station, and \( \lambda \) is the wave length.

### 2.1.5 Coherence time

In Communication systems, Coherence Time is expressed as the time over which the channel impulse is essentially invariant. Coherence time can be used to describe time variant characteristic of frequency spreading in time domain [24].

\[ T_c \approx \frac{1}{f_d} \]  

Coherence time refers to a time interval, which is related to the amplitude coherence of two arriving signals. If the inverse of base-band signal bandwidth is larger than coherence time, the transmitting base-band signal may change, leading to decoder distortion[24]. Using Clarke’s model, coherence time can be represented as

\[ T_c = \frac{9}{16\pi f_d} \]

### 2.2 Mobile channel classification

#### 2.2.1 Fading caused by multipath time delay spread

Multipath time delay spread and coherence bandwidth are two parameters to describe local channel time-diffusion characteristics. When the signal bandwidth is narrower than coherence bandwidth [25], the changes of frequency component passing through channel have a kind of coherence, which is called flat fading.

\[ B_s < B_c \]

If it is flat fading, the multipath structure can keep the frequency characteristic inside the receivers. However, due to fluctuation of channel gain, the received signal strength will change with time.

When the signal bandwidth is larger than coherence bandwidth [25], the changes of frequency component passing through channel are not stable, causing wave distortion, which is called frequency selective fading.

\[ B_s > B_c \]
2.2.2 Fading caused by Doppler shift

Time delay spread and coherence bandwidth are two parameters to describe local channel time-diffusion characteristics, but they didn’t provide the channel time variability. This kind of time variability is caused by the movement between mobile station and base station, or the movement of objects through the channel path. Doppler spread and coherence time are the two parameters to describe this time variability.

Doppler spread is the measured value of frequency spread. It is usually defined as a frequency range. In this range, the received signals have non-zero Doppler spread. Received signal frequency changes between \( f_c - f_m \) and \( f_c + f_m \), in which \( f_m \) is the biggest Doppler shift.

Channels can be divided into fast fading channels and slow fading channels. In fast fading channels the impulse response changes during the signal period, which means the coherence time of channel is shorter than the signal period. Therefore, the condition of fast fading is \( T_s > T_c \) [25]. Doppler shift will lead to signal distortion. In frequency domain, signal distortion gets stronger with the increase of Doppler shift.

When impulse response changes much slower than the signal code period, it can be defined as slow channel. In slow channel, channel parameters in one or more signal code periods are stable. The condition of slow fading is \( T_s < T_c \) [25].

2.3 Propagation models

The propagation models of wireless channels can be characterized as large scale path loss model and small scale signal fading model. Large scale path loss model is mainly used to describe the signal strength changes during long distances between transmitters and receivers [29]. Large scale path loss stands for average received signal strength changes at a certain distance from the transmitter caused by coverage area. Small scale signal fading stands for rapid fluctuating in the short receiving signal period [29]. These two models are not independent. In the same wireless channel, both large scale path loss and small scale signal fading exist. Wireless channel fading factor can be expressed as

\[
\eta(t) = \xi(t)\varsigma(t)
\]  \hfill (2.9)

\( \xi(t) \) is small scale signal fading, and \( \varsigma(t) \) is large scale path loss.

2.3.1 Large scale path loss

Large scale path loss is used to identify the strength changes in a long distance [26] between transceivers and receivers. Actually, it is not only related to time, but also
related to distances and carrier frequency. Based on theory and measurement the received signal power decreases exponentially with distance.

\[
\zeta(t,d)[dB] = \zeta(t,d_0)[dB] + 10n \log_{10}\left(\frac{d}{d_0}\right)
\]

Among the function, \(n\) is path loss exponent. \(d_0\) is breakpoint distance, which is decided by test. \(d\) is the distance between transceivers and receivers. Slope \(n\) is equal to 3.5 if the pass loss beyond distance \(d_0\). \(n\) is 3.5 for the free space case.

In telecommunication, resulting from a line-of-sight path through free space, the loss in signal strength of an electromagnetic wave with no obstacles nearby to cause reflection or diffraction is called free-space path loss. The term \(\zeta(t,d_0)[dB]\) stands for the free space path loss equation. If influence of time is ignored, \(L_{FS}(d)\) can be written as [26]

\[
L_{FS}(d) = -10\log_{10}\left(\frac{G_t G_r \lambda^2}{(4\pi d)^2}\right)
\]

In the equation above, \(G_t\) refers to transmitter antenna gain, and \(G_r\) refers to receiver antenna gain. \(d\) is the distance between transmitter and receiver in meters. \(\lambda\) is the wave length of the carrier frequency. If it is assumed that the antennas have unity antenna gains \((G_t = G_r = 1)\), and the carrier frequency \(f_c = 5.25GHz\). Then the equation above can be written as

\[
L_{FS}(d) = 10\log_{10}\left(\frac{(4\pi d)^2}{\lambda^2}\right)
\]

\[
= 10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^2
\]

\[
= 2 \cdot 10\log_{10}(\frac{4\pi}{\lambda}) + 2 \cdot 10\log_{10}(d)
\]

\[
= 47dB + 2 \cdot 10\log_{10}(d)
\]

If the shadow fading is included, path loss \(\zeta(t,d)[dB]\) follows normal distribution, which can be characterized as

\[
\zeta(t,d)[dB] = \zeta(t,d_0)[dB] + X_\sigma \quad d \leq d_0
\]

\[
\zeta(t,d)[dB] = \zeta(t,d_0)[dB] + 10n \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad d > d_0
\]
2.3.2 Small scale signal fading

Small scale fading refers to fading of wireless signal through short time or short distance [25], so that large scale loss can be ignored. When one signal transmitting by multipath, and these signal arrived receivers with tiny time difference, this kind of situation can cause fading.

There are three main reasons for this fading [25]. One is that signals are rapidly changed after a short period transmission. Second is the random frequency modulation caused by Doppler Shift. Third is multipath delay spread.

In an urban district, because the mobile antennas are much shorter than the buildings around, there is no direct transmission route from mobile station to base station. Even if there is a direct route, due to reflection by land and buildings, multipath propagation still exists. When those signals arrive at the receivers, they have different amplitudes, phases and incident angles.

If the mobile receivers are stable, fading of received signals can occur because of the movement of obstacles through the wireless channel. If the obstacles through wireless channel are stable, and the mobile station moves, fading will only relates to the spatial route. When the mobile station passes through multipath region, those spatial changes of signals are considered as short term fluctuation. Sometimes, the receivers remain a position of huge fading. In this situation, trying to maintain good communication state is very difficult. Space diversity of antennas can prevent extreme fading and invalid transmission.

When there are some small changes, which are as small as a half wavelength, between transmitter and receiver in the spatial position, this brings dramatic signal amplitude and phase changes that can be called small scale fading.

Consider the transmit bandpass signal

\[
s(t) = \Re\{u(t) \cdot e^{j2\pi f_s t}\}
\]

(2.14)

where \(u(t)\) is the equivalent complex baseband of the bandpass transmit signal [27]. If there are N waves arriving at the mobile station, the received bandpass signal is

\[
x(t) = \Re\{r(t)e^{j2\pi f_s t}\}
\]

(2.15)

In which

\[
r(t) = \sum_{n=1}^{N} \alpha_n(t) \cdot e^{-j2\pi f_s \tau_n(t)} u(t - \tau_n(t))
\]

(2.16)
\[ \phi_n(t) = (f_c + f_{D,n}(t))\tau_n(t) - f_{D,n}(t)\cdot t \]  

(2.17)

Here, \( \phi_n(t) \) is the phase associated with the \( n^{th} \) wave.

If the received signal consists of many reflective signals without fading, the channel can be called a Rician fading channel.

\[
p(r_0) = \begin{cases} 
\frac{r_0}{\sigma^2} \exp \left[ -\frac{(r_0^2 + A^2)}{2\sigma^2} \right] & r_0 \geq 0, A \geq 0 \\
0 & \text{otherwise}
\end{cases}
\]

(2.18)

The variable \( \sigma^2 \) is the predicted detection result of the multipath signal. Parameter \( A \) here stands for the peak magnitude of the component without fading, and \( I_0 \) is the modified Bessel function. If \( A \) is close to zero, the Rician probability distribution function will change to a Rayleigh probability distribution function, which is expressed as [25]

\[
p(r_0) = \begin{cases} 
\frac{r_0}{\sigma^2} \exp \left[ -\frac{r_0^2}{2\sigma^2} \right] & r_0 \geq 0 \\
0 & \text{otherwise}
\end{cases}
\]

(2.19)

In conclusion, small scale fading may happen because of time spreading of signal or time variant behavior of the signal.
Figure 2: small scale fading classification [28]
3 MIMO-OFDM

3.1 MIMO

MIMO is an import act part of the IEEE802.11n standard and is also widely used in today’s wireless communication. By using multiple antennas at the transmitter and the receiver, both the throughput and the range of the reception can be improved. MIMO can also provide better capacity and potential of improved reliability compared to single antenna channels. And the combination of MIMO and OFDM is a very effectual way to achieve high efficiency spectral wideband systems.

![Diagram of MIMO wireless communication system](image)

**Figure 3: Overview of a MIMO wireless communication system [3]**

Multipath propagation can lead to fading problems. Components with the same phase will be added constructively, while components with opposite phase will be added destructively. For MIMO, Generally there are two ways to solve the problem, Spatial Diversity and Spatial Multiplexing.

Spatial Diversity is the idea that, in case the antennas are spaced apart enough, the fading problem will occur independently. By always selecting the antenna with the best channel, or (better) combining the one with appropriate weights, the probability of a poor reception (signal outage) is dramatically reduced[3]. The communication will be more stable, but the data rate can’t be increased so much this way. In this case, Spatial Diversity is usually used in lower signal to noise ratio situations. To get a redundant signal, space- time code can be used.

Spatial multiplexing, on the contrary, increases the data rate but do not make the transmission system more robust. The data will be separated into several streams, and then these streams will be transmitted independently through separate antennas. Because they share the same channel, it is possible that during the
transmission they will mutually affect each other. To solve the problem, the receiver can either make channel estimation or broadcast the channel performance through a special feedback loop. Since there are several parallel channels transmitting independent streams at the same time, the capacity can be increased several times.

\[
H = \begin{bmatrix}
    h_{11} & h_{12} \\
    h_{21} & h_{22}
\end{bmatrix}
\]

**Figure 4:** MIMO 2x2 antenna configuration [2]

### 3.2 MIMO-OFDM

MIMO systems can utilize multipath components during transmission to solve the multipath fading. MIMO and OFDM combination can not only solve frequency selective fading, but also increase bandwidth efficiency. At the same time, it can provide high transfer rate, and increase system capacity. Here is an example of a 2*2 MIMO system model, which is showed in the figure below:

**Figure 5:** Block diagram of the proposed MIMO system [1]

The block diagram includes the basic functions that a MIMO system should consist of. As mentioned above, it contains both spatial multiplexing and space time coding.

Space-time coding has three main methods: STBC, space-time trellis coding (STTC) and layered space-time (LST). [1]Because STBC is easy to apply and can have low BER,
it is chosen here. Later, in the IEEE 802.11n block diagram, the system will be updated to satisfy the requirements of the standard.

Assuming GI is longer than the multipath delay, for a MIMO-OFDM system with $N_T$ transmit antennas and $N_R$ receiving antennas, let $r_q[k,j]$ denote the received signal from receiving antenna $q$, subcarrier $k$ of OFDM symbol $j$. Then

$$r_q[k,j] = \sum_{p=1}^{N_T} h_{p,q}[k,j] s_p[k,j] + n_q[k,j]$$  \hspace{1cm} (3.1)

In the formula above, $h_{p,q}[k,j]$ denote the frequency domain channel coefficient between transmit antenna $p$ and receive antenna $q$. $s_p[k,j]$ denotes the signal from transmitting antenna $p$ and $n_q[k,j]$ denotes the noise caused by the receiving antenna $q$. We can translate it into matrix

$$R[k,j] = H[k,j] S[k,j] + N[k,j]$$ \hspace{1cm} (3.2)

in which

$$R[k,j] = \{r_1[k,j], r_2[k,j], ..., r_{N_T}[k,j]\}^T$$ \hspace{1cm} (3.3)

$$S[k,j] = \{s_1[k,j], s_2[k,j], ..., s_{N_T}[k,j]\}^T$$ \hspace{1cm} (3.4)

$$H[k,j] = \begin{pmatrix}
h_{1,1}[k,j] & h_{1,2}[k,j] & \cdots & h_{1,N_T}[k,j] \\
h_{2,1}[k,j] & h_{2,2}[k,j] & \cdots & h_{2,N_T}[k,j] \\
\vdots & \vdots & \ddots & \vdots \\
h_{N_T,1}[k,j] & h_{N_T,2}[k,j] & \cdots & h_{N_T,N_T}[k,j]
\end{pmatrix}$$ \hspace{1cm} (3.5)

Formulas above can be simplified to

$$R = HS + N$$ \hspace{1cm} (3.6)

$$R = \{r_1, r_2, ..., r_{N_T}\}^T$$ \hspace{1cm} (3.7)

$$S = \{s_1, s_2, ..., s_{N_T}\}^T$$ \hspace{1cm} (3.8)
4 IEEE 802.11N STANDARD

Even though the IEEE802.11a,g peak value of average speed is up to 54Mbps, the speed is still not enough for multimedia service in WLAN. In January 2004, IEEE established a new workgroup to make a higher speed standard, which is IEEE 802.1n [5]. In January 2007, IEEE 802.11 workgroup held the 101st meeting in London, to vote for the amendment IEEE 802.11n, version 1.10 [5]. In October 2009, the IEEE 802.11n was published to public. Most importantly, the MAC of IEEE802.11n brought in MIMO-OFDM technique. By implementing spatial diversity using array antennas in the OFDM system, the signal quality is improved and the multipath capacity is increased. The effective transmission speed is dramatically increased with carrier frequencies of 2.4GHz and 5GHz.

The IEEE802.11n amendment clearly describes MIMO-OFDM in High throughput (HT) mode. In order to raise throughput of the entire network, IEEE802.11n optimizes MAC protocol, with some improvements.

IEEE802.11n supports a modified OFDM technique. By using higher maximum code rate and wider bandwidth, the OFDM of 802.11a/g is expanded.

IEEE802.11n improves throughputs and transmission rate. The protocol applies 2.4GHz and 5GHz frequency bands, as well as the bandwidth of 20MHz and 40MHz.

Utilizing the improvement of MIMO technique, IEEE 802.11n supports Space-time Block Coding and Beam Forming. The protocol supports 4*4:4 antennas layout, which means the maximum number of transmitting antennas is 4, the maximum number of receiving antennas is 4, and there are up to 4 data streams. MIMO not only enhances the capability of receivers to extract useful information from transmitting signals with exploiting the multipath signals diversity. Moreover, Spatial Division Multiplexing (SDM) used in MIMO can realize transporting multipath independent signals on the same frequency.

Apart from these above-mentioned properties, IEEE 802.11n has very good backward compatibility. It offers a kind of mixed mode, and allows IEEE 802.11a or IEEE 802.11g to be embedded in the transmission frame.
### Table 2: Main parameters of IEEE 802.11n protocol

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>2.4GHz/5GHz</td>
</tr>
<tr>
<td>Modulation Type</td>
<td>BPSK, QPSK, 16QAM, 64QAM</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20MHz/40 MHz</td>
</tr>
<tr>
<td>Coding Technique</td>
<td>LDPC/Convolution Code</td>
</tr>
<tr>
<td>Number of Antennas</td>
<td>1Tx, 2Tx, 3Tx, 4Tx</td>
</tr>
<tr>
<td>Spatial Streams</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>Peak Data Rate</td>
<td>600Mbps (4 spatial streams, 40MHz bandwidth)</td>
</tr>
<tr>
<td>IFFT</td>
<td>64 points IFFT, 56 subcarriers (52 data subcarriers and 4 pilot subcarriers)</td>
</tr>
<tr>
<td>IFFT/FFT period</td>
<td>0.3125MHz</td>
</tr>
<tr>
<td>Subcarrier Interval</td>
<td>3.2ns</td>
</tr>
<tr>
<td>GI</td>
<td>0.8ns</td>
</tr>
<tr>
<td>OFDM Symbol Period</td>
<td>4us</td>
</tr>
<tr>
<td>Training Sequence Length</td>
<td>1.6us</td>
</tr>
</tbody>
</table>

#### 4.1 BLOCK DIAGRAM OF IEEE 802.11n TRANSMITTER

This is the basic IEEE 802.11n transmitter model. Compared to the proposed MIMO system above, it does not include the STBC part. In order to increase the stability, it is preferred to be added later to the simulation model.

![Block Diagram of IEEE 802.11n Transmitter](image)

*Figure 6: Block Diagram of IEEE 802.11n Transmitter*
4.2 BLOCK DIAGRAM OF IEEE 802.11n RECEIVER

![Block Diagram of IEEE 802.11n Receiver]

Figure 7: Block Diagram of IEEE 802.11n Receiver

4.3 IEEE 802.11n simulation model

An IEEE 802.11n simulation model was found on the internet, which is created by Tokunbo Ogunfunmi [7]. As the IEEE 802.11n standard mentioned, some PHY features that distinguish a high throughput (HT) STA from a non-HT STA are referred to as MIMO operation; spatial multiplexing (SM); spatial mapping (including transmit beamforming); STBC; low-density parity check (LDPC) encoding; and antenna selection (ASEL) [5]. In this simulation model, it contains MIMO, SM, and STBC. These features make sure that this is a model satisfy the requirements of 802.11n standard. In this case, the existing model is used as a Matlab simulation model. Next, a brief explanation of each part in the simulation is made.
Figure 8: IEEE 802.11n simulation model [7]
### 4.3.1. Variable-Rate Data source

The model uses random generator to get random binary (bit 0 and bit 1), and then there is a buffer that gathers these bits into packets. The random generator frequency has to be paid attention, because it depends on the data rate of the system. Mode is the input control. There are 8 modes operations in total which are correlated with 8 kinds of M_QAM with different code rate.

### 4.3.2. Legacy/HT preamble

Since this model is HT STA, its frame which uses L-SIG TXOP protection, consists of two main parts, which are preamble and data symbol. Training sequence is included in the preamble part, which is usually used for receiver system synchronization, channel estimation and automatic gain control.

The IEEE 802.11n WLAN system consists of three types of MAC frames. One is Non-HT, which uses a legacy preamble. The second is HT mixed mode, which applies the HT Mixed Format preamble. This kind of preamble keeps the preamble of IEEE 802.11a, but the training sequence which is aiming at the high throughput of MIMO is added in the preamble. Thereby it can be applied in a system environment where IEEE802.11n and IEEE 802.11a coexist. The third one is the HT Green Field Mode, which is used in pure IEEE802.11n system environment. In this mode, the preamble is called Greenfield Format.

![PPDU format](image)

**Figure 9: PPDU format [5]**
In Non-HT mode, the format includes L-STF, L-LTF, and L-SIG. In HT-Greenfield format, HT-GF-STF can be used for AGC, and the synchronization between time capture and frequency. HT-GF-STF is made up of 10 same sequences, and each of the sequence includes 16 samples. HT-LTF1 is made up of two long sequences and the guard intervals.

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-STF</td>
<td>Non-HT short Training field</td>
</tr>
<tr>
<td>L-LTF</td>
<td>Non-HT long Training field</td>
</tr>
<tr>
<td>L-SIG</td>
<td>Non-HT SIGNAL field</td>
</tr>
<tr>
<td>HT-SIG</td>
<td>HT SIGNAL field</td>
</tr>
<tr>
<td>HT-STF</td>
<td>HT Short Training field</td>
</tr>
<tr>
<td>HT-GF-STF</td>
<td>HT-Greenfield Short Training field</td>
</tr>
<tr>
<td>HT-LTF1</td>
<td>First HT long Training field(Data)</td>
</tr>
<tr>
<td>HT-LTFs</td>
<td>Additional HT Long Training fields(Data and Extension)</td>
</tr>
<tr>
<td>Data</td>
<td>The Data field includes the PSDU</td>
</tr>
</tbody>
</table>

**Table 3: Elements of the HT PLCP packet [5]**

Here HT Mixed Mode as seen in Figure 9 is chosen. HT-SIG provides the information to analyze HT, including modulation type, bandwidth choice, data length, STBC, channel estimation, spatial spreading and so on. HT-LTF is used for channel estimation, and it can also be used for synchronization of the receiving system. Each long OFDM symbol includes 64 samples. In MIMO systems, data HT-LTFs is essential for data modulation, but the Extension HT-LTFs is optional.

When the system bandwidth is 20MHz,

\[
HTLTFT_{28,28} = \{1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1\} 
\]

When the system bandwidth is 40MHz,

\[
HTLTFT_{58,58} = \{1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1\} 
\]

4.3.3. Modulator bank

The modulator bank includes the interleaving, and the FEC function which consists of convolution encoding with puncturing. Also, it creates the OFDM symbols, which means reshaping and adding pilot zeros.
The FEC encoder may include a binary convolution encoder or an LDPC encoder followed by a puncturing device. There are some advantages of the LDPC encoder compared to the binary convolution coding (BCC). But BCC is already existing in the Simulink model, so BCC is chosen here.

The BCC will add some extra bits that are used to check and correct errors at the receivers, which will increase the length of bit streams, and decrease the data rate. The puncturing block which can reduce the length of bit stream added by BCC, is used to solve the problem. Since there are 8 modes, there are 8 Convolution & puncture blocks.

The Stream Parser divides the outputs of the encoders into blocks which are sent to different Interleavers and mapping devices. Each sequence of the bits sent to the Interleaver is called a spatial stream.

The Interleaver changes the order of bits of each spatial stream to prevent long sequences of neighboring noisy bits coming from BCC decoder. Basically, there are two kinds of Interleavers: Bit Interleaver and Block Interleaver.

The Constellation mapper maps the sequence bits of each spatial stream to the constellation points (complex).

The Pilot sequence is inserted here in each OFDM frame where the training sequence is used for data frame synchronization and channel estimation, the Pilot sequence is helpful to estimate the residual phase error.

**4.3.4. Assemble OFDM frames**

As wireless communication develops, the increasing data rates require wide bandwidth. OFDM can dramatically increase the efficiency of bandwidth, which is very important when we face the limited bandwidth resources. It has good performance of preventing multipath interference and fading. Adopting subcarrier allocation makes the system get highest bit rate. It can also reduce the complexity of the receiver by decoupling the intersymbol interference. This part takes responsibility of connecting the modulated signal and preamble together, so that the 802.11n OFDM frames is created.

**4.3.5. STBC**

The purpose of space time block code is to achieve the largest spatial diversity increase, the largest coding gain, and the possibly largest throughput. It transports variety copies of data stream through different antennas and to use different received versions of data to increase the reliability of data communication. STBC
codes offer advantages versus the other main coding scheme, STTC, in that it can achieve full diversity gain with low complexity, whereas STTC codes increase in decoding complexity as the constellation size, state number, and code length increases.\[18\]

In this thesis, Alamouti coding which is STBC is used. By applying linear processing, every symbol can be decoded individually, and the rank criterion is still fulfilled, so that it can provide maximum diversity. When the transmitted subcarrier modulation symbol from the first antenna of the system between time \(t\) and \((t + T)\) is \(s_1\) and \(s_2\), that \(T\) is the OFDM frame period, and the symbol from the second antenna of the system between time \(t\) and \((t + T)\) is \(-s_2^*\) and \(s_1^*\), the matrix coding can be written as can be written as:

\[
s = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}
\]  \tag{4.3}

Assuming that all the transmitted symbol energy is normalized, which means the transmitted symbol signal energy of each antenna is half of the total energy. Therefore the inputs \(s_1\) and \(s_2\) will be expressed as two space time streams \(y_1\) and \(y_2\).

\[
y_1 = \begin{bmatrix} s_1 \\ -s_2^* \end{bmatrix}, \quad y_2 = \begin{bmatrix} s_2 \\ s_1^* \end{bmatrix}
\]  \tag{4.4}

The received symbols are

\[
r_1 = [h_1 \ h_2] \begin{bmatrix} s_1 \\ -s_2^* \end{bmatrix} + n_1
\]

\[
r_2 = [h_1 \ h_2] \begin{bmatrix} s_2 \\ s_1^* \end{bmatrix} + n_2
\]  \tag{4.5}

In the receiver, the transmitted data can be recovered from the received data by forming the vector \(\{r_1, r_2\}\) using one receive antenna \[7\].

\[
\begin{bmatrix} r_1^* \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_1 & -h_2 \\ h_2^* & h_1^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2^* \end{bmatrix} + \begin{bmatrix} n_1^* \\ n_2 \end{bmatrix}
\]  \tag{4.6}

Since the noises are independent Gaussian white noise, after transmission, they remain white. \(E[nn^*] = N_0 I\). After applying the matched filter

\[
\begin{bmatrix} x_1 \\ x_2^* \end{bmatrix} = H_{\text{eff}}^H H_{\text{eff}} \begin{bmatrix} s_1 \\ s_2^* \end{bmatrix} + H_{\text{eff}}^H \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}
\]

\[
= \|H\|^2 \begin{bmatrix} s_1 \\ s_2^* \end{bmatrix} + H_{\text{eff}}^H \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix}
\]  \tag{4.7}

Where \(H^H H\) can be seen to be \(|H|^2 I\), \(|H|^2 = |h_1|^2 + |h_2|^2\). After applying equalization, the noise still remain white, because that \[7\]
Thus, the ML detection for $s_1, s_2$ is simplified, since applying a simple slicer to each symbol may be used to obtain the ML solution, when there is no interference between $s_1, s_2^*$, and the noise is white[7].

For 802.11n standard, with the combination of SDM and STBC, there may exists several antenna sets. Here is an example of the STBC coding mapping two spatial streams to four space time streams.

The two-spatial stream input vectors are:

$$s_{2n} = \begin{pmatrix} s_{1,2n} \\ s_{2,2n} \end{pmatrix} \quad s_{2n+1} = \begin{pmatrix} s_{1,2n+1} \\ s_{2,2n+1} \end{pmatrix}$$

(4.9)

The space time coding outputs are:

$$y_1 = \begin{pmatrix} s_{1,2n} \\ -s_{1,2n+1} \\ s_{2,2n} \\ -s_{2,2n+1} \end{pmatrix} \quad y_2 = \begin{pmatrix} s_{1,2n+1} \\ s_{1,2n} \\ s_{2,2n+1} \\ s_{2,2n} \end{pmatrix}$$

(4.10)

In this way, the two input spatial streams are changed into four spatial steams after STBC. While there are only 2 receiving antennas, the received symbols for Rx antenna 1 of the 4*2 MIMO system are like:

$$r_{1,2n} = \begin{pmatrix} h_{1,1} & h_{1,2} & h_{1,3} & h_{1,4} \end{pmatrix} \begin{pmatrix} s_{1,2n} \\ -s_{1,2n+1} \\ s_{2,2n} \\ -s_{2,2n+1} \end{pmatrix} + n_{1,2n}$$

(4.11)

$$r_{1,2n+1} = \begin{pmatrix} h_{1,1} & h_{1,2} & h_{1,3} & h_{1,4} \end{pmatrix} \begin{pmatrix} s_{1,2n+1} \\ s_{1,2n} \\ s_{2,2n+1} \\ s_{2,2n} \end{pmatrix} + n_{1,2n+1}$$

(4.12)

For Rx antenna 2

$$r_{2,2n} = \begin{pmatrix} h_{2,1} & h_{2,2} & h_{2,3} & h_{2,4} \end{pmatrix} \begin{pmatrix} s_{1,2n} \\ -s_{1,2n+1} \\ s_{2,2n} \\ -s_{2,2n+1} \end{pmatrix} + n_{2,2n}$$

(4.13)
In order to recover the transmitted data, the decoding procedure can be expressed as

$$r_{2,2n+1} = (h_{2,1} h_{2,2} h_{2,3} h_{2,4}) \begin{pmatrix} s_{1,2n+1} \\ s_{1,2n}^* \\ s_{2,2n+1} \\ s_{2,2n}^* \end{pmatrix} + n_{2,2n+1}$$

(4.14)

The channel matrix above can be used to recover spatial streams through MIMO detection.

4.3.6. SDM

SDM is technique used to obtain higher throughputs using multiple antennas. Multiplexing of multiple data streams is applied across spatial dimensions. With suitable antennas spacing, independent data streams can be transmit through individual antenna. Also each data stream will be demodulated respectively.

4.3.7. Beamforming

In WLAN, the transmission distance of signal, channel quality and interference are the essential problems to overcome. IEEE802.11n standard improved PHY and MAC to increase the throughput of WLAN. At this moment, beamforming becomes very useful.

Beamforming is a technique which uses several antenna elements to spatially shape the emitted electromagnetic wave in order to beam the energy into the receiver by changing the magnitude and phase from every transmit antenna. Beamforming requires the transmitting and receiving stations to perform channel sounding so that it can optimize both the shape and direction of the beam. Beamforming can be applied together with spatial multiplexing or by itself if there is only one path available between the radios.

4.3.8. IFFT

OFDM uses Inverse Fast Fourier Transform (IFFT) and FFT, which is used in OFDM for modulation and demodulation, in order to increase the calculation speed. Since IFFT and FFT are based on Discrete Fourier Transform (DFT), it is easily realized in DSP.
4.3.9. CSD and Cyclic prefix

Cyclic Shift Diversity (CSD) is a type of transmit diversity. It is a signal shaping technique combined with the 802.11n specification that spreads the spatial streams across multiple antennas by sending the same signal with various phase shifts. CSD stands for insert cyclic shifts in time domain grouping. When the usage space is extended, the number of antennas can be increased. At the same time, cyclic shifts can be used in frequency domain. When the input signal is $s(t)$. The cyclic shifts is $T_{cs}$. After CSD, the signal is changed into

$$s_{cs}(t, T_{cs})|_{t < 0} = \begin{cases} s(t - T_{cs}) & 0 \leq T < T + T_{cs} \\ s(t - T_{cs} - T) & T + T_{cs} \leq t \leq T \end{cases}$$

(4.16)

In the equation above, $T$ is the length of DFT, and the value of $T_{cs}$ is less than zero.

Cyclic prefix, prefixing a symbol with repetition of the end used in OFDM, is for the purpose of combating multipath by making channel estimation easy. As a guard interval, it can avoid the interface of inter symbol caused by previous symbol. Also, the linear convolution of a frequency-selective multipath channel is allowed to be modeled as circular convolution, which can be changed into the frequency domain using DFT. Consider an OFDM system which has $N$ subcarriers and prefixing it with a prefix of length $N-1$, the OFDM symbol obtained is

$$X_v = [x[0], x[1], \ldots, x[N-1]]^T$$

(4.17)

$$X = [x[N - L + 1], \ldots, x[N - 2], x[N - 1], x[0], x[1], \ldots, x[N - 1]]^T$$

(4.18)

4.3.10. Multiplex OFDM frames

Reshape the OFDM frames from $x*y$ to $(x*y)*1$, in order to be prepared to transmit them through the channels.

4.3.11. TGn channels

This is the channel model to be used for the High Throughput Task Group (TGn). TGn channels are available for 2GHz and 5GHz frequency bands, and it has wide application range. Different application environment corresponds with different channel model.
Table 4: TGn models and its corresponding environment

<table>
<thead>
<tr>
<th>Environment</th>
<th>Condition</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>LOS</td>
<td>B-LOS</td>
</tr>
<tr>
<td></td>
<td>NLOS</td>
<td>B-NLOS</td>
</tr>
<tr>
<td>Residential/Small Office</td>
<td>LOS</td>
<td>B-LOS</td>
</tr>
<tr>
<td></td>
<td>NLOS</td>
<td>C-NLOS</td>
</tr>
<tr>
<td>Typical Office</td>
<td>LOS</td>
<td>C-LOS</td>
</tr>
<tr>
<td></td>
<td>NLOS</td>
<td>D-NLOS</td>
</tr>
<tr>
<td>Large Office</td>
<td>LOS</td>
<td>D-LOS</td>
</tr>
<tr>
<td></td>
<td>NLOS</td>
<td>E-NLOS</td>
</tr>
<tr>
<td>Large Space(Indoors and Outdoors)</td>
<td>LOS</td>
<td>E-LOS</td>
</tr>
<tr>
<td></td>
<td>NLOS</td>
<td>F-NLOS</td>
</tr>
</tbody>
</table>

Its path loss can be expressed as

$$L(d) = \begin{cases} L_{FS}(d) & d \leq d_{BP} \\ L_{FS}(d_{BP}) + 3.5 \log_{10}(d/d_{BP}) & d \leq d_{BP} \end{cases}$$

(4.19)

where $L_{FS}$ is the free space loss. $d_{BP}$ is the breakpoint distance, which is used to determine if there exists LOS. The path loss parameters for different TGn channels are shown below. Models A to C mean time delay spread 0 to 30ns, which represents small environments. Models D to F means time delay spread 50 to 150ns, which represents larger environments.

Table 5: Parameters of Path Loss Models [10]
5 MATLAB SIMULATION

5.1. Before the simulation

Because the simulation model was created in 2008, at first it could not be simulated in Matlab 2010b correctly. After replacing some models with their new version, there were still something wrong with the SS functions. It took a long time to fix these problems individually. However, once a problem was fixed, there were always some new problems coming up. At last, some other Matlab versions were tested to be used. Luckily, Matlab7.0 works, and the model can finally be simulated. Later on, after some adjustment, the MIMO model can be simulated under the Matlab 2009b version, which is the same environment as DSP builder works.

5.2. Simulation tools

Lots of engineers around the world choose Simulink to model and solve real problems in variety of industries, including [13]:

- Aerospace and Defense
- Automotive
- Communications
- Electronics and Signal Processing
- Medical Instrumentation

Simulink has a graphical model interface, so users can save lots of time for programming, and devote more energy to build the model system. Lots of basic communication models have already been offered by Simulink. For some functions not found among the existing models, users can create their own models by writing them in MATLAB languages themselves.

5.3. Simulation settings

The proposed model offered some basic settings adjustments.

- **Number of TX Antennas:** the value is from 1 to 4, and it depends on the number of Space Time Streams.
- **Number of Rx Antennas:** the value is from 1 to 4, and it depends on the MCS value.
- **Modulation/Coding Scheme (MCS):** the value is from 0 to 31.
- **Space-Time Block Coding:** the value is from 0 to 2, and it depends on MCS value.
- **Beamforming:** the value is 0 or 1, and value 0 means applying without beamforming while value 1 means applying beamforming.
- **Number of Packets/SNR value:** number of packets of each SNR that will be transmitted.
- **Vector of SNR values:** SNR values specified for simulation.
MCS is a value determines the modulation, coding and the number of spatial channels. The value of MCS is from 0 to 127.

- **MCS value 0 to 7 and 32**: single spatial stream (compatible with IEEE802.11a/b/g).
- **MCS value 8 to 31**: multiple spatial streams using equal modulation on all streams (EQM).
- **MCS value 33 to 76**: multiple spatial streams using unequal modulation on the spatial streams (UEQM).
- **MCS value 77 to 127**: reserved.

Table 6 shows how to set the simulation parameters correctly.

<table>
<thead>
<tr>
<th>MCS</th>
<th>Number of Spatial Streams</th>
<th>STBC Fields</th>
<th>Number of Space Time Streams</th>
<th>Number of TX Antennas</th>
<th>Number of RX antennas</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-&gt;7</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>8-&gt;15</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>16-&gt;23</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>14-&gt;31</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 6: MCS, STBC fields, number of Tx and Rx antennas

The data rate can increase n times with n spatial steams. Table 7 show the data rates of the same modulation with different number of spatial streams when the system works in bandwidth 20MHz and the guard interval is 800ns. Note that if the system works in bandwidth 40MHz and the guard interval is 400ns, the maximum data rate can reach 600MBps.
Table 7: Data rates of different spatial streams [20MHz]

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK[1/2]</td>
<td>6.5</td>
<td>13</td>
<td>19.5</td>
<td>26</td>
</tr>
<tr>
<td>QPSK[1/2]</td>
<td>13</td>
<td>26</td>
<td>39</td>
<td>52</td>
</tr>
<tr>
<td>QPSK[3/4]</td>
<td>19.5</td>
<td>39</td>
<td>58.5</td>
<td>78</td>
</tr>
<tr>
<td>16-QAM[1/2]</td>
<td>26</td>
<td>52</td>
<td>78</td>
<td>104</td>
</tr>
<tr>
<td>64-QAM[2/3]</td>
<td>52</td>
<td>104</td>
<td>156</td>
<td>208</td>
</tr>
<tr>
<td>64-QAM[3/4]</td>
<td>58.5</td>
<td>117</td>
<td>175.5</td>
<td>234</td>
</tr>
<tr>
<td>64-QAM[5/6]</td>
<td>65</td>
<td>130</td>
<td>195</td>
<td>260</td>
</tr>
</tbody>
</table>

5.4. Simulation results

5.4.1. TGn channel

- Simulation result of two spatial streams without beamforming.

The TGn channel models assumed minimum tap spacing of 10 nsec and were employed for system Bandwidth of up to 40 MHz. [10]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{SS}$</td>
<td>Number of spatial streams</td>
</tr>
<tr>
<td>$R$</td>
<td>Coding rate</td>
</tr>
<tr>
<td>$N_{BPCS}$</td>
<td>Number of coded bits per single carrier (total across spatial streams)</td>
</tr>
<tr>
<td>$N_{BPCS}(i_{SS})$</td>
<td>Number of coded bits per single carrier for each spatial stream, $i_{SS} = 1, ..., N_{SS}$</td>
</tr>
<tr>
<td>$N_{SD}$</td>
<td>Number of complex data number per spatial stream per OFDM symbol</td>
</tr>
<tr>
<td>$N_{SP}$</td>
<td>Number of pilot values per OFDM symbol</td>
</tr>
<tr>
<td>$N_{CBPS}$</td>
<td>Number of coded bits per OFDM symbol</td>
</tr>
<tr>
<td>$N_{DBPS}$</td>
<td>Number of data bits per OFDM symbol</td>
</tr>
<tr>
<td>$N_{ES}$</td>
<td>Number of BCC encoders for the DATA field</td>
</tr>
</tbody>
</table>

Table 8: Symbols used in MCS parameter tables [5]

The rate-dependent parameters for optional 20MHz, $N_{SS}=2$ MCSs with $N_{ES}=1$ and EQM of spatial streams is as shown in Table 9. [5]
<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Modulation</th>
<th>R</th>
<th>$N_{BPFC S} (t_{SS})$</th>
<th>$N_{SD}$</th>
<th>$N_{SP}$</th>
<th>$N_{CBPS}$</th>
<th>$N_{DBPS}$</th>
<th>Data rate(Mb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>52</td>
<td>4</td>
<td>104</td>
<td>52</td>
<td>13.0</td>
</tr>
<tr>
<td>9</td>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>52</td>
<td>4</td>
<td>208</td>
<td>104</td>
<td>26.0</td>
</tr>
<tr>
<td>10</td>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>52</td>
<td>4</td>
<td>208</td>
<td>156</td>
<td>39.0</td>
</tr>
<tr>
<td>11</td>
<td>16-QAM</td>
<td>1/2</td>
<td>4</td>
<td>52</td>
<td>4</td>
<td>416</td>
<td>208</td>
<td>52.0</td>
</tr>
<tr>
<td>12</td>
<td>16-QAM</td>
<td>3/4</td>
<td>4</td>
<td>52</td>
<td>4</td>
<td>416</td>
<td>312</td>
<td>78.0</td>
</tr>
<tr>
<td>13</td>
<td>64-QAM</td>
<td>2/3</td>
<td>6</td>
<td>52</td>
<td>4</td>
<td>624</td>
<td>416</td>
<td>104.0</td>
</tr>
<tr>
<td>14</td>
<td>64-QAM</td>
<td>3/4</td>
<td>6</td>
<td>52</td>
<td>4</td>
<td>624</td>
<td>468</td>
<td>117.0</td>
</tr>
<tr>
<td>15</td>
<td>64-QAM</td>
<td>5/6</td>
<td>6</td>
<td>52</td>
<td>4</td>
<td>624</td>
<td>520</td>
<td>130.0</td>
</tr>
</tbody>
</table>

Table 9: MCS parameters for optional 20MHz, $N_{SS}$=2, $N_{ES}$=1, EQM [5]

<table>
<thead>
<tr>
<th>Tx</th>
<th>Rx</th>
<th>MCS</th>
<th>STBC</th>
<th>Beamforming</th>
<th>Packets per SNR</th>
<th>SNR</th>
<th>Bits/Packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>42:-3:18</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 10: Settings of MCS15 TGn channel direct map performance

Based on the settings shown in Table 10, it can be seen now the BER depends on SNR.
The bit-error-rate (BER) performance of a transmission system is a very important figure of merit that allows different designs to be compared in a fair manner [14]. BER performance is usually represented as a two dimensional graph. The ordinate is the normalized signal-to-noise ratio (SNR) expressed as $E_b/N_0$, the energy-per-bit divided by the one-sided power spectral density of the noise, expressed in decibels (dB).

Many bits will be in error if the BER is high. The worst case BER is 50%, and the modem is useless then. Most communications systems require BER several orders of magnitude lower [14]. Even a BER of 1% is considered as very high.

Figure 10: MCS15 TGn channel direct map performance
To calculate BER in the IEEE802.11n system, it is needed to get the sum of error bits of each SNR. And then divide it by the number of total transmitted bits, which is the multiplication of data number in each packets and the number of packets.

Getting accurate result at high SNRs is time consuming. For example, a BER of $10^{-6}$ means there is only one error bit in every million bits. So if BER result under $10^{-5}$ is required, it will require long simulations. The X-axis vector will contain SNR as dB values, while the Y-axis vector will contain bit-error-rates. [14] The Y-axis should be plotted on a logarithmic scale, whereas the X-axis should be plotted on a linear scale. [14] We use Matlab to plot:

```
semilogy(SNR, BER).
```

When enough simulation data is collected to reach reasonable results at all SNRs, the curve of BER as a function of SNR can be plotted.

In order to save time of simulation, here the parameter Packets per SNR is set with 10. Even though the figure may not be that smooth, the trend can still be told.

<table>
<thead>
<tr>
<th>Tx</th>
<th>Rx</th>
<th>MCS</th>
<th>STBC</th>
<th>Beamforming</th>
<th>Packets per SNR</th>
<th>SNR</th>
<th>Bits/Packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>8-15</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>42-3:3</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 11: Settings of MCS 8-15 direct map BER

![Figure 11: MCS 8-15 direct map BER](image-url)
The packet error rate (PER) is the number of incorrect received data packets which is divided by the total number of received packets. Even if there is only one error bit in a packet, the received packet is considered incorrect. However, no matter how many error bits existed in a packet, it is only treated as one error packet. So here it is only needed to calculate the sum of error packets in each SNR, and then divided it by the total number of received packets in each SNR.

For the purpose of getting accurate PER result, Packets per SNR here is 442. As a result, the simulation time is very long.

<table>
<thead>
<tr>
<th>Tx</th>
<th>Rx</th>
<th>MCS</th>
<th>STBC</th>
<th>Beamforming</th>
<th>Packets per SNR</th>
<th>SNR</th>
<th>Bits/Packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>13-&gt;15</td>
<td>0</td>
<td>0</td>
<td>1*442</td>
<td>42:-3:18</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 12: Settings of MCS13-15 direct map PER

From SNR of 18 dB to SNR of 42 dB, with 3 dB step, the PER result of MCS13, 14 and 15 are presented above. The system control PER is lower than acceptable value.
Simulation result of two spatial streams with beamforming.

<table>
<thead>
<tr>
<th>Tx</th>
<th>Rx</th>
<th>MCS</th>
<th>STBC</th>
<th>Beamforming</th>
<th>Packets per SNR</th>
<th>SNR</th>
<th>Bits/Packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>15</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>42::3:18</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 13: Settings of MCS15 TGn channel with beamforming performance

Figure 13: MCS15 TGn channel with beamforming performance

<table>
<thead>
<tr>
<th>Tx</th>
<th>Rx</th>
<th>MCS</th>
<th>STBC</th>
<th>Beamforming</th>
<th>Packets per SNR</th>
<th>SNR</th>
<th>Bits/Packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>15</td>
<td>0</td>
<td>1</td>
<td>10</td>
<td>42::3:18</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 14: Settings of MCS15 TGn channel with beamforming BER
Figure 14: MCS15 TGn channel with beamforming BER result

Figure 15 is the PER result adding beamforming based with the settings below. It can be told that after using beamforming, PER result is a little improved.

<table>
<thead>
<tr>
<th>Tx</th>
<th>Rx</th>
<th>MCS</th>
<th>STBC</th>
<th>Beamforming</th>
<th>Packets per SNR</th>
<th>SNR</th>
<th>Bits/Packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>15</td>
<td>0</td>
<td>1</td>
<td>1*442</td>
<td>42:-3:18</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 15: Settings of MCS15 TGn channel with beamforming PER
5.4.2. AWGN channel

Additive white Gaussian noise (AWGN) is a channel model in which the only noise to communication is a linear addition of white Gaussian noise of which the spectral density and a Gaussian distribution of amplitude are constant. The model does not include frequency selectivity, interference, fading, nonlinearity or dispersion. The channel is considered as generating the signal by addition of white Gaussian noise, through which the received signal in the interval can be expressed as [17]

\[ r(t) = s_m(t) + n(t), \quad 0 \leq t \leq T \] (5.1)

Where \( n(t) \) stands for a sample function of the AWGN process, and its power spectral density is \( \frac{1}{2} N_0 \).

<table>
<thead>
<tr>
<th>Tx</th>
<th>Rx</th>
<th>MCS</th>
<th>STBC</th>
<th>Beamforming</th>
<th>Packets per SNR</th>
<th>SNR</th>
<th>Bits/Packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>42:3:18</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 16: Settings of MCS31 AWGN channel performance
Figure 16: MCS31 AWGN channel performance

<table>
<thead>
<tr>
<th>Tx</th>
<th>Rx</th>
<th>MCS</th>
<th>STBC</th>
<th>Beamforming</th>
<th>Packets per SNR</th>
<th>SNR</th>
<th>Bits/Packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>42:3:3</td>
<td>1000</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>15</td>
<td>2</td>
<td>0</td>
<td>400</td>
<td>42:3:3</td>
<td>1000</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>400</td>
<td>42:3:3</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 17: Settings of AWGN channel PER&BER
Figure 17: AWGN channel BER result

Figure 18: AWGN channel PER result
5.4.3. Conclusion

Based on above settings, most possible functions on the model are tested. It can be seen that if MCS is changed to higher data rate with the same transmitting antennas, both PER and BER performance will be influenced. Modulation together with beamforming can improve the BER and PER performance. Because AWGN channel does not contain fading, frequency selectivity, interference and so on, the PER and BER performance is better than TGn channel.

STBC functions for TGn channel was also intended to be tested, but different TGn channel-D mat file had to be required at first. This part of work can be extended in future.
IEEE 802.11N MIMO DETECTION

6.1 MIMO Detection

MIMO detection refers to the process of determining the transmitted data symbols, sent using SDM, from the received signal vector. In this part, transmitted streams will be separated; meanwhile, channel equalization is going to be performed. Due to the use of OFDM, the reception of MIMO OFDM needs to be implemented individually. There are three main methods to realize MIMO detection: Minimum Mean Squared Error (MMSE) linear detector, Zero-Forcing (ZF) linear detector, and Maximum Likelihood (ML) detector. For introducing MIMO detection, basic form of a memoryless MIMO system should be first provided:

\[ r = H a + n \]  

(6.1)

Where \( r \) is the N-dimensional received signal vector, \( H \) is the \( N \times M \) matrix of channel estimates, \( a \) is the M-dimensional transmitted signal, and \( n \) is a complex additive white Gaussian noise vector. Symbol \( a \) is chosen from the constellation set.

After channel estimation, \( H \) is known at the receiver, and then the main three methods can be depicted.

6.1.1 MMSE detector

For MMSE linear detector, if the additional constraint \( CH=I \) is ignored, \( C \) is able to be minimized as

\[ MSE = E[|| S' - S ||^2] \]  

(6.2)

Equivalently,

\[ S' = W^H R \]  

(6.3)

Assuming signals from each antenna are independent and noise from each path are independent.

\[ E[SS^H] = I \]  

(6.4)

\[ E[SN^H] = 0 \]  

(6.5)

\[ E[NN^H] = \sigma^2 I \]  

(6.6)

Here \( \sigma^2 \) is noise variance.

\[ \frac{\partial MSE}{\partial W} = \frac{\partial}{\partial W} E[(S - W^H R)^H (S - W^H R)] \]

\[ = E[R^H (S - W^H R)] - E[(S - W^H R)^H R] \]

\[ = 2E[R^H W^H R] - 2E[R^H S] \]

(6.7)
\[ \frac{\partial \text{MSE}}{\partial W} = 2E[(HS + S)^H W^H (HS + N)] - 2E[(HS + N)^H S] \]
\[ = 2H^H HW^H R(SS^H) + 2W^H E(NN^H) - 2H^H E(SS^H) \]
\[ = 2(H^H H + \sigma^2 I)W - 2H^H \]

Let the equation above be equal to zero, then
\[ W^H = (H^H H + \sigma^2 I)^{-1} H^H \] (6.9)

In that case C can be written either
\[ C = H^H (HH^H + N_o I)^{-1} \] (6.10)

or
\[ C = (H^H H + N_o I)^{-1} H^H \] (6.11)

In the formula above, \( N_0 \) means noise power, which can be measured by using the received signal.

This kind of method can decrease the error caused by noise and the same spectrum signal interference, without increasing noise. In this design, MMSE detector was chosen as the receiver type.

### 6.1.2 Zero-forcing detector

The zero-forcing liner detector selects the liner detector matrix C in order to eliminate interference completely. [8] Assuming that the columns of H are linearly independent, \( CH = I \) will always exist. If the channel has the same number of inputs as outputs, H is a square matrix and the ZF linear detector has a unique solution: \( C = H^{-1} \). [7] In the other case, for the situation that the channel consists more outputs than inputs, which means there are more RX antennas than TX antennas, there will be an infinite number of solutions for \( CH = I \). Then C is chosen in the situation that it can minimize \( \text{MSE} = E[\|cr - a\|^2] \). The form of ZF linear detector is
\[ C = (H^H H)^{-1} H^H \] (6.12)

or
\[ C = H^{-1} \] (6.13)

when H is invertible.

A drawback with the ZF linear detector is that it focuses solely on interference cancellation. [7] In this process, it can also remove signal energy that projects onto the interference subspace, even when the interference is significantly lower than the desired signal. [7]
6.1.3 ML detector

The Maximum likelihood method is widely used in statistic estimation. Here, all effectual transmitted sequences of symbols should be checked elaborately based on the rule below.

\[ s = \arg \min_{x \in S} \| r - Hs \|^2 \]  \hspace{1cm} (6.14)

It is easy to understand that the performance of the ML detector is better than ZF and MMSE which are mentioned previously, since if the mean square error is \( \text{MSE} = N_0 \), the detect symbol must be ideal. However, most systems can’t cope with the complexity of optimal ML decoding. Suppose modulation constellation size is \( q \), the number of transmitter antennas is \( M \), \( q^M \) comparisons need to be performed, which is \( q^M(2N + NM^2) \) multiplications. Time for detecting using ML is extremely long and the computation requirement for hardware is very high.

6.1.4 MIMO detection model

A whole MIMO detection model used in the Simulink simulation part is showed below [4]. The key point of the model is the channel estimation. Moreover, since the channel estimation has to be done individually but in the same way, single path estimation is needed to be explained.
Figure 19: MIMO detection Simulink model [4]

6.2 MIMO channel estimation

As explained above, the general MIMO channel estimation focuses mostly on frequency-domain techniques. [7] By using OFDM as well as cyclic prefix, in the frequency domain the channel can be written as

$$R(k) = H(k)S(k) + N(k)$$ \hspace{1cm} (6.15)

In a MIMO channel, \(H(k,j)\) is

$$H[k,j] = \begin{bmatrix} h_{11}[k,j] & \cdots & h_{1,N_T}[k,j] \\ \vdots & \ddots & \vdots \\ h_{N_R,1}[k,j] & \cdots & h_{N_R,N_T}[k,j] \end{bmatrix}$$ \hspace{1cm} (6.16)

Though it is a MIMO system, when running the MIMO detection, each path has to be done individually, so the problem can still be treated as a SISO case. Then the received signal \(r_k\) can be represented as

$$r_k = H_k s_k + N_k$$ \hspace{1cm} (6.17)
With SISO, obtaining a least-square channel estimates for sub-carrier k only requires multiplying the received symbol by the conjugate of the transmitted symbol (since all training symbols \( s_k \) are constrained to unit magnitude). [7]

\[
\hat{H}_k = r_k s_k^* \\
= (H_k s_k + n_k) \cdot s_k^* \\
= H_k [s_k] + n_k s_k^* 
\]

(6.18)

The HT-LTF sequence is transmitted in the case of 20MHz operation. [7]

\[
\text{HTLTF}_{28,28} = \{1,1,1,1,-1,1,1,1,1,1,1,1,1,1,1,-1,1,1,1,1,1,0,1,-1,-1,1,1,-1,1,-1,1,-1,-1,-1,-1,-1,1,1,-1,-1,1,-1,1,1,1,1,-1,-1\} 
\]

(6.19)

Based on IEEE 802.11n draft, the long training field (HT-LTF) frame can be described as the orthogonal matrix

\[
H_{\text{HTLTF}} = \begin{bmatrix} 1 & -1 & 1 & 1 \\
1 & 1 & -1 & 1 \\
1 & 1 & 1 & -1 \\
-1 & 1 & 1 & 1 \\
\end{bmatrix} 
\]

(6.20)

Therefore, the received sequence can be represented in matrix as

\[
R_{\text{HTLTF},k} = H_k (S_k P_{\text{HTLTF}}) + N_k 
\]

(6.21)

To obtain a least squares estimation of the MIMO channel, [7] it can be written as

\[
R_{\text{HTLTF},k} W_{\text{HTLTF}} = H_k (S_k P_{\text{HTLTF}} W_{\text{HTLTF}} + N_k W_{\text{HTLTF}} \\
= H_k + N_k W_{\text{HTLTF}} 
\]

(6.22)

Where

\[
W_{\text{HTLTF}} = U^H (U U^H)^{-1} 
\]

(6.23)

\[
U = S_k P_{\text{HTLTF}} 
\]

(6.24)

Since

\[
S_k = 1/-1 
\]

(6.25)

\[
W_{\text{HTLTF}} = S_k P_{\text{HTLTF}}^H (P_{\text{HTLTF}}^H P_{\text{HTLTF}})^{-1} 
\]

(6.26)

In the equation above, \( S_k \cdot P_{\text{HTLTF}} \) is the transmitted training sequence for sub-carrier, over all OFDM symbols. [7]
6.3 MIMO channel estimation model

Figure below is the key component of the MIMO channel estimation [4].

![MIMO channel estimation model diagram](image)

Figure 20: MIMO channel estimation model [4]

Since the procedure of realizing this model in DSP builder is going to be shown in the next chapter, a simple explanation of each model function should be given.

Remove DC component means removing the 29th row which is the DC component of the matrix. Select training data is to choose the 9th and 10th columns of the matrix.

It should be noticed that the product model in Simulink is not the regular matrix multiplication. Here the two inputs are the same dimensions matrices. Each element of the output will be the product of corresponding elements of the inputs.

![Product operation example](image)

Figure 21: example of product block
Figure 22: Channel estimates block [4]

Figure above is the detail of the block channel estimates [4] which is the second part of channel estimation.

\( u^T \) is transpose block which is easy to understand that it computes matrix transpose. \( N_{sts} \) here is equal to 2. It controls the multiport switch block to enable averaging. Finally, the averaging data in the bottom has to be divided by the averaging data in the top.
7 DSP MODEL OF MIMO CHANNEL ESTIMATION

7.1 DSP Builder

DSP Builder is a digital signal processing developing tool released by Altera. In the Quartus II FPGA environment, it integrates the developing software of Matlab and Simulink by MathWorks. Altera DSP system is an innovative solution to FPGA application. DSP builder help engineers to create DSP hardware design without generating VHDL all by typing, so that design cycle can be shorter. Developers can first do algorithm design in Matlab, and then do the system integration in Simulink. Finally generate hardware description language (HDL) files to be used in Quartus II.

![Design Flow Diagram]

Figure 23: Altera DSP design flow

7.2 Design tool

The working environment of this design is:
- DSP Builder 9.0
- Matlab R2009b
- Quartus II 9.0
- ModelSim-Altera 6.4a

7.3 Extract input data from Simulink model

In order to make sure that the DSP builder design works exactly as the Simulink design, as well as to easily get qualified input data to MIMO channel estimation for testing, a decision of using exactly the same data used in Simulink design as the input was made. It means the data format has to be easily applied in DSP builder.
The format used in the Simulink blocks is complex matrix frame which can’t be used in DSP Builder blocks, since DSP Builder could not handle either matrix or frame format. Doing the format conversion in DSP builder is very complicated, so this part of the work is executed in Simulink blocks. The frame data is transformed into single data transmitted one after another. The procedure of using Rxsig is going to be explained as an example. First, an Unbuffer is used to convert the format from 57*26 to a higher sample rate 1*26. Since it is already one dimensional matrix, and Reshape can only work with frame format data, Unbuffer is unable be used continuously. A frame conversion helps to convert the data from sample-based to frame-based. Then Reshape block change the 1*26 array to 26*1 array in order to do the next Unbuffer. After Unbuffer, the data finally is the single data one by one. However, in DSP environment, complex format is hard to be calculated. A Complex to Real-Imag is needed then.

![Figure 24: The process of extracting input data](image)

### 7.4 Detector model in DSP Builder

The most difficult part in the detector design is to realize a matrix calculation with sample-based data. The solution has been considered for a long time. It seems using a RAM is the only way to not only do calculation one by one but also give the output a chance to be transformed into matrix. In order to deal with exactly the same data as Simulink, a variable num is set which means the number of matrices in total to be detected.
Figure 26: Detector model in DSP Builder

7.4.1 Trainsig Valid and Trainsig Choose

For the purpose of generating proper signal to enable and disable the Dual-Port RAM block, Trainsig Data Valid is applied as the figure below shows.

Figure 26: Trainsig Data Valid
The Trainsig data is a 57*2 matrix. At first reading and writing RAM at the same time was tried, however, in return the output would be sometimes useful and sometimes meaningless, which would cause big difficulties in later calculation. So the model now first writes all useful data into memory, and after finishing the task, it begins to output continuously useful data for a period. That’s the reason why there are three valid control output.

Comparator and comparator1 are responsible for removing 29th row of the matrix. Comparator3 make sure RAM stop writing data after all supposed Trainsig data have been saved. Comparator2 take charge in enabling RAM to read data after the period Rxsig data have been saved in RAM.

Trainsig_read_valid is for Dual-port RAM enable input which determine if the Dual-port RAM is going to work or not. Trainsig_wriiten_valid determines if the RAM is writing data to its memory. Trainsig_read_address_valid decide when to start counting the read address.

Also, in order to synchronize Trainsig and Rxsig data, the enable counter1&2 should depend on larger size data Rxsig. Count modulo \((1482*\text{num}+112*\text{num}+10)\) is a safe region in the design to be large enough to give the RAM right time to write and read.

Figure 27: Trainsig Data Choose
In the Trainsig choose part, initially wren port was not applied. It then caused that RAM could not produce continues effective signals. After adjustment, Dual-Port RAM can write data without the 29\textsuperscript{th} row of the matrix. And it can read data after \((1482*\text{num}+5)\) time step. One delay adding in the data port of RAM is drastic revision compared to the first version design. Thereby the RAM can wait until the right data to come.

### 7.4.2 Rxsig Valid and Rxsig Choose

Rxsig valid and Rxsig choose are almost the same as Trainsig. The only difference is after removing the 29\textsuperscript{th} row of matrix, Rxsig needs to choose 9\textsuperscript{th} and 10\textsuperscript{th} columns of matrix then. Thus, in Rxsig valid, comparator and comparator 1 are responsible for removing 29\textsuperscript{th} row of matrix 57*26. Comparator2 and comparator3 control choosing 9\textsuperscript{th} and 10\textsuperscript{th} columns.

![Data Valid Circuit](image)

**Figure 28: Rxsig Data Valid**

Originally, there is no need to explain more about the Rxsig choose part, besides one more delay before the output of the whole model was added. That’s because when the simulations are run, correct result did not show up at all. After carefully examination, it is found out that even the enable reading signal for both Rxsig and
Trainsig RAM were exactly the same, the two outputs were still not synchronized. Even until now, the reason is still unclear, problems are solved.

Figure 29: Rxsig data Choose

### 7.4.3 Channel Estimates

Here both multiplications in the channel estimates model are applied, other than separating one outside the model as Simulink model. Because the complex signal has been separated into real part and imaginary part, simple multiplication in Simulink has to be complicated now.

\[(a + bi) \cdot (c + di) = (ac - bd) + (ad + bc)i\]  \hspace{1cm} (7.1)

Then the two multiplications can be written as

\[\text{Trainsig} \cdot \text{Trainsig} = (\text{trainsig Re} \cdot \text{trainsig Re} - \text{trainsig Im} \cdot \text{trainsig Im}) + (\text{trainsig Re} \cdot \text{trainsig Im} + \text{trainsig Im} \cdot \text{trainsig Re})i\]  \hspace{1cm} (7.2)

\[\text{Trainsig} \cdot \text{Rxsig} = (\text{trainsig Re} \cdot \text{rxsig Re} - \text{trainsig Im} \cdot \text{rxsig Im}) + (\text{trainsig Re} \cdot \text{rxsig Im} + \text{trainsig Im} \cdot \text{rxsig Re})i\]  \hspace{1cm} (7.3)

The implementation can be seen from the model below.
The next step is to calculate the mean of the multiplication result. Two ways are taken into account to fulfill the function. One is using RAM, which is the same way as the Trainsig valid choose part. Continues effective result can be calculated, but the model design will be complicated. The other way is to use a memory delay, but part of the results has to be ignored in later calculations. Here the second approach is chosen. Because the mean result is a 2*56 matrix in this design, and the sequence of data we get is the transpose of that matrix, which means every other result should be ignored later on.

Owing to the extraction data process, the supposed transpose process in this part can be totally ignored. The channel estimates in Simulink contains possibilities of applying different $N_{sts}$ values. In this DSP Builder channel estimates model, only situation $N_{sts}$ equals to 2 is considered. Since $N_{sts} = 2$, definitely only mean result of the matrix is going to be used.

In the Simulink model, accomplishing division of complex data is very easy, but in DSP Builder environment, things are much more complicated.

$$\frac{a + bi}{c + di} = \frac{a \cdot b + c \cdot d}{c^2 + d^2} + \frac{b \cdot c - a \cdot d}{c^2 + d^2}i$$  \hspace{1cm} (7.4)

A very troublesome thing is the divider in DSP Builder Blockset is not able to produce decimal value. It can only returns the quotient (q) and remainder (r) of dividing a by b.

$$a = b \cdot q + r$$  \hspace{1cm} (7.5)

What’s even worse, from the simulation result from Simulink Blockset, some data are quite small, like 0.0795. In order to get accuracy result which is able to compare to
Simulink result, data first is multiplied with $2^{14}$ before passing through the divider. In this way, the quotient will also be amplified $2^{14}$ times. So the result has to be right shifted 14 distances back at last.

The model design of divider in channel estimates shows below.

![Diagram](image)

**Figure 31: divider in channel estimates**

### 7.4.4 Adjustment of the result

As explained earlier, due to the matrix mean calculation method, the final result does not always make sense. Showing in Figure 25, some adjustment of the result executed after channel estimates.

The two final outputs of the channel estimates are just real part and imaginary part synchronized, so Re and Im valid control are exactly the same. Figure below shows how does Re valid work.

The comparator controls that every other data goes into the memory. Comparator1 is to be responsible for making sure the RAM begins writing data after Rxsig and Trainsig data choose RAM start to give the output. Comparator 3 controls RAM stop writing data after all effective data has been saved. Comparator 1 takes charge in conduct the RAM read data after all data have been saved. Here a little more intervals are provided before starting to read, which are $1482\times\text{num}+5+14+56\times\text{num}\times2+5$. 
At the end of the design, it is time to check the results. Of course the output of channel estimation in Simulink design has to be extracted first. And then it is essential to set the num variable before simulation. Also, based on the time period $1482*\text{num}+14+56*\text{num}*2+5$, suitable simulation time should be given. The num
value of sample below whose input Trainsig is a 57*2*2 matrix and Rxsig is a 57*26*2 matrix is 2. There is one important thing to be pointed out, the input data to DSP Builder needs to be added exact time values. Otherwise from work space model can’t work properly.

In the middle of Figure 34 is part of the result from Simulink. On its two sides, there are the simulation results from DSP Builder. Since num value here is 2, theoretically the result should start from 1482*2+5+14+56*2*2+5=3212. However, due to complicated model delay, it will be a little larger than that. Unluckily, it is not able to tell the exact delay slots. Some more samples were also tested; it seems the delay slots changes every time. The whole results were extracted to excel for comparing them, and the deviation is less than 0.1%. There were some test results from different samples, and the deviation is always less than 0.1%.

![Figure 34: Part of the simulation result](image)
8 CONCLUSIONS AND FUTURE WORK

In this thesis, an existing Simulink based IEEE802.11n system was simulated through both TGn channel and AWGN channel. The Simulink based 802.11n system focuses more on the physical layer. It supports up to 4*4 MIMO-OFDM and several MIMO schemes. Functionalities like STBC, beamforming and SDM were tested here.

From the simulation results it can be seen that with the application of SDM and STBC, special diversity as well as throughput is increased dramatically. And beamforming can improve the transmission quality, since both BER and PER are improved. Because the channel environment of the TGn channel is more complicated than the AWGN channel, the BER and PER result of the AWGN channel presented in this paper is much better.

Regarding the channel estimation part, there are mainly three kinds of detectors: zero-forcing detector, MMSE detector and ML detector. In this thesis, MMSE detector was chosen as the example of DSP builder based channel estimation system. By extracting both input and output data from Simulink model, the same input was offered to the DSP builder based system, and the output was compared to it from the Simulink model.

Though the Simulink based system supports most basic functionalities of the IEEE802.11n system in physical layer, there are several aspects can be improved in future. For example, the TGn channel model here only supports 2*2 antennas, so STBC function through TGn channel has not been tested yet. Also a figure of the throughput by the changes of SNR can be shown.

The DSP builder based channel estimation model only satisfies the situation that $N_{\text{sts}}$ equals to 2. For other situations, it should be modified in future. Moreover, implementing the model to real FPGA board may become the future work.
# LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>ACH</td>
<td>Access feedback Channel</td>
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<tr>
<td>AP</td>
<td>Access Point</td>
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<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
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<td>ASEL</td>
<td>Antenna Selection</td>
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<tr>
<td>BCH</td>
<td>Broadcast Channel</td>
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<tr>
<td>BER</td>
<td>Bit-Error Rate</td>
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<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
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<td>CKK</td>
<td>Complementary Code Keying</td>
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<td>CP</td>
<td>Cyclic-Delay Prefix</td>
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<td>CSD</td>
<td>Cyclic Shift Diversity</td>
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<td>CSI</td>
<td>Channel State Information</td>
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<td>Data Link Control</td>
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<td>Discrete Fourier Transform</td>
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<td>Direct Sequence Spread Spectrum</td>
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<td>Direct Mode</td>
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<td>Frequency-Hopping Spread Spectrum</td>
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<td>Guard Interval</td>
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<td>High Throughput</td>
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<td>Inverse Fast Fourier Transform</td>
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<td>Long transport Channel</td>
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<td>Low-density Parity Check</td>
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<td>Mobile Terminal</td>
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<td>Minimum Mean Squared Error</td>
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<td>Maximum Likelihood</td>
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<td>Orthogonal Frequency Division Multiplexing</td>
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<tr>
<td>PDU</td>
<td>Protocol Data Unit</td>
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<tr>
<td>PER</td>
<td>Packet Error Rate</td>
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<td>Physical Layer</td>
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<td>Quadrature Amplitude Modulation</td>
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<td>Quadrature Phase Shift Keying</td>
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<td>Single input Single output</td>
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<tr>
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<td>Spatial Division Multiplexing</td>
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<tr>
<td>SM</td>
<td>Spatial Multiplexing</td>
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SNR  Signal-to-Noise Ratio
STTC  space-time trellis coding
STBC  Space Time Block Coding
STA   Station
WLAN  Wireless Local Area Network
ZF    Zero Forcing
10 REFERENCES


