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A Non-linear Trellis Coding Scheme for Visible Light Communication Systems with Dimming Control

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A Non-linear Trellis Coding Scheme for Visible Light Communication Systems with Dimming Control

By

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A Thesis

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This thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science.

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Date

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Thesis Advisor: Tiffany Jing Li

_____
Chair of ECE Department: Chengshan Xiao

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Abstract

Visible light communication (VLC) is a short-range optical wireless communication system using white light-emitting diode (LED) lighting as a transmitter. Thus, dimming control is particularly important in VLC system. General dimming control methods by stuffing extra bits (zero or one) have an adverse effect on communication, e.g., limiting the achievable data rate or degrading the error performance, because the compensation bits do not contribute to error performance. In this thesis we propose a non-linear trellis coding scheme, which can achieve dimming control as well as improve error performance. The proposed finite-state machine is shown as an encoder. And the Viterbi algorithm is used in decoding to improve the error performance further. We analyze the communication performance among proposed scheme and two existing schemes. Analysis and simulation results both show that our proposed coding scheme keeps a good balance between illumination and communication where better error performance can be achieved especially. Therefore, the proposed non-linear trellis coding scheme can be regarded as an attractive alternative to achieve dimming control.

1. Introduction

Visible light communication (VLC) is a short-range optical wireless communication system using white light-emitting diode (LED) lighting as a transmitter ［1-3］. Taking advantages of VLC system, the first motivation of using it is to save energy. It carries information by modulating light in the visible spectrum (400-700nm) which can be also used to illumination. As a result, VLC system is efficient and green since it saves energy by achieving communication and illumination simultaneously. The second motivation is the convenience to build up VLC system using the existing infrastructure of lighting system. Moreover, taking advantages of modulation capability of visible spectrum, VLC has lots of notable advantages in comparison with radio frequency (RF) communication, such as huge bandwidth, high date rate, license-free operation, less interference and high efficiency of re-use. Some typical application that use VLC includes: 1) indoor communication where Wi-Fi and cellular wireless communication is not satisfied [4]; 2) communication wireless links for the Internet of Things (IOT) [5]; 3) wireless communication follows smart life concept [6]; 4) communication systems as part of intelligent transport systems (ITS) [7]; 5) provision dynamic information in museums, theme parks or hospitals [8-9]. 6) provision dynamic advertisement in supermarkets or malls.

More and more wireless devices are used in recent years, such as laptop, smart phone, tablet, smart watch and virtual reality (VR) glasses. Not only is the number of devices increasing, but also the data rate of each wireless devices is growing exponentially. As a result,

new wireless communication system is necessary where the existing wireless communication systems such as Wi-Fi, Bluetooth, cellular system are not satisfied. In this condition, VLC draws people's attention, especially about indoor system. It would be extremely convenient to add extra capacity to existing infrastructure by installing a VLC system in offices or residential rooms.

In the near future, billions of devices will have wireless connectivity, which is followed by the revolutionary concept of the Internet of Things. IOT makes it possible to have autonomous control and intelligent life which could adapt the environment to the requirements and demands of people. VLC could be a cheap, simple and immediate technology to contribute to IOT and it does not encroach on any electromagnetic spectrum. Also, VLC technology combined with positioning algorithms could provide location-based information, so people can enjoy a personal and multidimensional experience. This concept could be used in hospitals, museums and theme park. Because of the above advantages and application prospects, VLC has attracted more attentions in recent years [10-15]. The IEEE has defined a new standard, IEEE 802.15.7, which describes high data rate VLC, up to 96 Mb/s, by fast modulation of optical light sources.

Since VLC is an optical wireless communication using lighting as a transmitter, dimming control is a crucial factor to achieve energy savings and ecological benefits [16-24]. At the same time, controlling the brightness of lighting also meets people's needs. Therefore, the current challenges in dimming control is worth studying. So, we propose a non-linear trellis coding scheme, regarded as an attractive alternative to achieve dimming control.

The reminder of this thesis is organized as follows: In chapter 2, the motivation for this research is provided. Two existing schemes achieving dimming control, variable on-off keying (VOOK) modulation and weight threshold check coding (WTCC) are introduced. Chapter 3 introduces our proposed non-linear trellis coding scheme, which consists of encoding part and decoding algorithm. Chapter 4 deals with performance analysis of 3 mentioned dimming control schemes. The simulation results are shown in Chapter 5. Chapter 6 gives out the conclusion of the research.

2. Motivation for work

Since judging the brightness of lighting is not only a demand of people's life but also an effective method to save energy, dimming control becomes particularly important in VLC system. However, general dimming control schemes have an adverse effect on communication e.g., limiting the achievable data rate or degrading the error performance. In this chapter, we will show two existing schemes achieving dimming control as control groups in this study. They are variable on-off keying (VOOK) modulation and weight threshold check coding (WTCC) [25-26]:

2.1 Variable on-off keying (VOOK)

On-off keying (OOK) is the simplest form of amplitude-shift keying (ASK) modulation. In its simplest form (binary), the presence of a specific duration represents a binary one, while the absence for the duration represents a binary zero. Considering that light intensity is nonnegative, OOK-based modulation is a typical modulation in VLC system. But there might be some problems in OOK modulation. Since we carry data and information by on-off switching of light, there could be unexpected problems, flickering and dimming. We can avoid flickering problem by using run-length limited (RLL) coding technology because most people cannot perceive the flickering at a frequency over 100Hz. RLL coding bounds the length of stretches (runs) of repeated bits during which the signal does not change.

OOK can provide 50% brightness without control of adjustment if the inputs are equally probable. Variable on-off keying can achieve dimming control by stuffing extra bits of two level (one or zero) to the existing OOK Modulation. When zero is filler bit, VOOK provides lower brightness than 50%. When one is filler bit, VOOK provides high brightness than 50%. Comparing with other schemes, VOOK is most simple and convenient. However, the filler bits in VOOK do not carry information, which means they don't contribute to communication. As a result, VOOK may limit the achievable data rate or degrade the error performance on communication when it adjusts the brightness, especially extremely high brightness or extremely low brightness.

VOOK stuffs extra bits but these bits do not contribute to communication. We propose to come up with a trellis check coding scheme using filler bits as redundancy bits to enhance error performance. The following calculation will prove the above analysis. We consider binary entropy as the upper bound of data rate, which is given by

$$E_p = -P \, log_2 \, P - (1 - P) \, log_2(1 - P). \tag{1}$$

In this equation, P stands for the probability that one is sent at the transmit side. Respectively, $(1 - P)$ stands for probability that zero is sent.
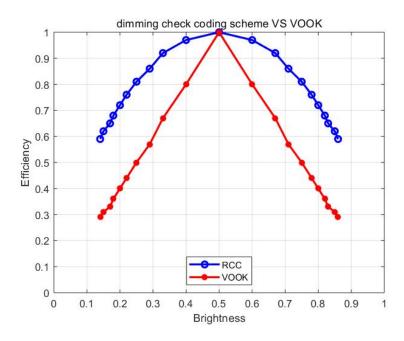
Fig.1 dimming check coding scheme VS VOOK, data bits length K=4, filler bits length M=1 to 10.

Table.1 dimming check coding scheme VS VOOK, data bits length K=2, filler bits length M=1 to 5.

Filler bit	Data bits length (K)	Filler bits length (M)	Brightness	Entropy	Bit stuffing (K/(K+M))	Coding gain
1	2	5	0.86	0.59	0.29	0.31
1	2	4	0.83	0.65	0.33	0.32
1	2	3	0.80	0.72	0.40	0.32
1	2	2	0.75	0.81	0.50	0.31
1	2	1	0.67	0.92	0.67	0.25
None	2	0	0.50	1.00	1.00	0.00
0	2	1	0.33	0.92	0.67	0.25
0	2	2	0.25	0.81	0.50	0.31
0	2	3	0.20	0.72	0.40	0.32
0	2	4	0.17	0.65	0.33	0.32
0	2	5	0.14	0.59	0.29	0.31

Here are two examples shown in Fig.1 and Table.1. In Table.1, the length of data bits is 2, the length of filler bits is from 0 to 5, this system could adjust 11 dimming levels from 0.14 to 0.86. Comparing with VOOK, theoretical trellis check coding scheme has coding gain from 0.25 to 0.32. In Fig.1, the length of data bits is 4, the length of filler bits is from 0 to 10, the system could adjust 21 dimming levels from 0.14 to 0.86. Theoretical trellis check coding scheme also has better performance than VOOK. These results inspire us to propose a trellis check coding scheme achieving dimming target as well as having better error performance than VOOK.

2.2 Weight Threshold Check Coding (WTCC)

Weight threshold check code (WTCC) is a code-based scheme to achieve dimming control. WTCC sets a threshold on code weight and has a low implementation complexity. The detection algorithm of WTCC is based on Maximum Likelihood (ML) detector, which also enhances efficiency and effectiveness.

The frame structure of WTCC consists of three parts: N_d data bits, 1 check bit and N_c compensation bits. Thus, the whole length of the codeword is $N = N_d + 1 + N_c$. WTCC can control the achievable dimming levels by changing the variable length of input data bits N_d and compensation bits N_c. In fact, the usual coded data consist almost the same number of 1 s and 0 s, which means the occurrence of 1 s and 0 s is equiprobable. Apparently, when not adding check bits and compensation bits, the dimming factor is 50%. If code weight of the input bit is

smaller than half of the input bit length, WTCC set the check bit as zero. Otherwise, if code weight of the input bit is bigger than half of the input bit length, WTCC set the check bit as one and flip all the input data bits. In a result, the occurrence of 0 s in WTCC codewords is always larger than 50%. Furthermore, WTCC could add compensation bits (0 s in this case) to achieve even larger occurrence of 0 s. In this way, WTCC could control dimming factor from 0% to 50%. Dimming factor from 50% to 100% is symmetrical to the above process.

The advantages of WTCC are structured design, low implementation complexity and Arbitrary dimming factor. The advantages of WTCC are similar to those of VOOK, but the difference is that WTCC uses a check bit to enhance the performance of signal transmission. Therefore, WTCC creates a balance between illumination and communication where better error performance can be achieved compared with VOOK. However, there are still some problems left for us to concern. Firstly, WTCC uses only one bit to enhance transmission performance. The compensation bits that play the role of brightness adjustment still do not carry the information, which is not helpful for error performance. Therefore, WTCC has a relatively small increase in error performance. Secondly, WTCC might lead to a disastrous code if the input signal has a long series of zero. According to the construction design of WTCC, if input signal is all zero, the check bit and the compensation bits will be also zero. Consequently, WTCC codeword makes a even longer series of zero than that of input signal. This could lead to flickering which is unacceptable for illumination. Table.2 shows an example of WTCC. The construction of length N =5 codeword with 4 data bit, 1 check bit and no compensation bit. As we were worried about before, the codeword of input '0000' is '00000'.

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Table.2 WTCC encoder, Codeword length N = 5, signal length Nd = 4, compensation bits length Nc = 0.

i	Input 4-bit	Codeword	i	Input 4-bit	Codeword
1	0000	00000	9	0110	00110
2	0001	00001	10	1010	01010
3	0010	00010	11	1100	01100
4	0100	00100	12	0111	11000
5	1000	01000	13	1011	10100
6	0011	00011	14	1101	10010
7	0101	00101	15	1110	10001
8	1001	01001	16	1111	10000

3. The proposed Non-linear Trellis Code

3.1 System Model

Since the light intensity should be restricted to be nonnegative, The VLC system uses OOK-based modulation, and the information is carried by light intensity emitted from the LED. Unlike radio frequency communications, the average power of the light is measured at the receiver rather than the amplitude of the light. Typically, we assume perfect symbol synchronization on the receiver side. The direct light is the main light, so we ignore reflected light in indoor VLC system. Therefore, line of sight (LOS) path is assumed. The received signal can be modeled as
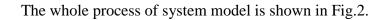
$$\boldsymbol{r} = h \cdot \boldsymbol{s} + \boldsymbol{n}. \tag{2}$$

where $\boldsymbol{s}$ denotes the transmitted signal and $\boldsymbol{n}$ denotes the additive white Gaussian noise (AWGN) with zero mean and variance σ^2. Without loss of generality, we assume channel gain $h = 1$.

Generally speaking, if the intensity changes more than 150 - 200 Hertz, the human eye usually perceives the average illumination rather than the instantaneous illumination. Set $\boldsymbol{P}$ to indicate the peak intensity, and $\overline{\boldsymbol{P}}$ means the average intensity of the received signal. The dimming factor can be given by

$$\gamma = \frac{\overline{\boldsymbol{P}}}{\boldsymbol{P}} \tag{3}$$

Where $0 < \gamma < 1.$

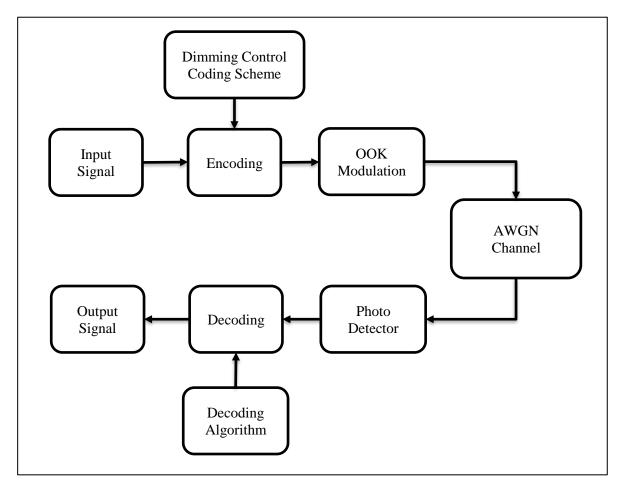The whole process of system model is shown in Fig.2.

Fig.2 block diagram of system model

3.2 Non-linear Trellis Code

As shown in Fig.2, dimming control of the whole system can be operated by two parts: Dimming Control Coding Scheme and Decoding Algorithm. The encoding part provides the ability to adjust brightness and the decoding part is also provided accordingly for efficiency and gain. The proposed non-linear trellis code consists of encoding part and decoding part. The

details of these two parts are discussed as follow:

3.2.1 Dimming encoder

The frame structure of the proposed non-linear trellis code consists of two parts, as shown in Fig.3, i.e. 3 primary bits and M compensation bits (all 0 s or 1 s). The length of compensation bits is variable, while the length of primary bits is fixed as 3. Thus, the whole length of the codeword is N =3 + M.
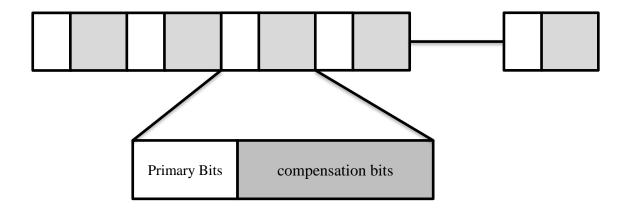

Fig.3 the frame structure of proposed encoded signal

The primary bits consist of a non-linear trellis code with a code rate of 1/3. The finite-state machine model of proposed code is shown as Fig.4. This is a non-linear code. In the proposed code, the occurrence of zero and one is not 50%, which means after encoding, the dimming factor γ will not equal to 0.5. We deliberately design this in purpose of achieving different dimming level and getting a better error performance at the same time.
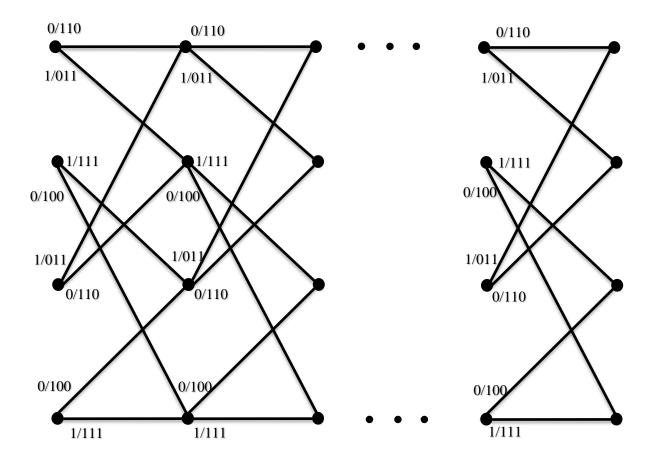
Fig.4 the finite-state machine model of proposed trellis code

From the above assumption in system model, the occurrence of 1 s and 0 s in input signal is equiprobable. Thus, it is equally probable to reach each state in the finite-state machine. Therefore, the dimming factor of this code can be given by:

$$\gamma = \frac{the\ occurrence\ of\ 1}{the\ occurrence\ of\ 0\ and\ 1} = \frac{16}{24} = \frac{2}{3} \tag{3}$$

Symmetrically, γ could be $\frac{1}{3}$ if we flip zero to one and one to zero. After trellis coding, we

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achieve dimming target $\gamma = \dfrac{1}{3}$ and $\gamma = \dfrac{2}{3}$. Since the compensation bits are variable, we can control dimming level via varying the number of compensation bits. In a result, we can achieve control dimming factor from 0 to 1. Analysis indicates that smaller and precise dimming levels can be obtained with the increase of compensation bits. However, overmuch compensation bits can degrade the performance of spectral efficiency

3.2.2 Trellis decoder

The decoder of the proposed scheme is a maximum likelihood (ML) decoder using the Viterbi algorithm. According to Viterbi algorithm, the final surviving path has minimum distance. We recover the estimated information sequence by inverting the final surviving path when the Viterbi algorithm finishes.

The Viterbi Algorithm

Step 1. Compute the partial metric for the single path entering each state. Store the path (the survivor) and its matric for each state.
```
metric( 1,ii)=norm([s2,s3]-[y(2*ii-1),y(2*ii)]);
......
metric(16,ii)=norm([s4,s4]-[y(2*ii-1),y(2*ii)]);
```
Step 2. Compute the partial metric for all 2 paths entering a state by adding the branch metric entering that state to the metric of the connecting survivor at the previous time unit. For each state, compare the metrics of all 2 paths entering that state, select the path with the largest metric, store it along with its metric, and eliminate all other paths.
```
a( 1,ii)=distance(1,ii)+metric( 1,ii);……
distance(1,ii+1)=min([a( 1,ii)  a( 2,ii)  a( 9,ii)
a(10,ii)]);…….
```
Step 3. Repeat step 2 until whole codeword are completed.

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4. Performance Analysis

As I mentioned before, VOOK stuffs extra bits to achieve dimming control. All the compensation bits do not contribute to error performance. It may limit the achievable data rate or degrade the error performance on communication. We use equation (1) to calculate binary entropy as the upper bound of data rate to see how VOOK performs. The data in Fig.1 and Table.1 verifies our analysis. In the case where data bits length is 2, there is about 0.3 coding gain between VOOK and the upper bound. Analysis and data both show that the error performance of VOOK has a lot of room for improvement.

WTCC uses a check bit to enhance the performance of signal transmission. Compared with VOOK, WTCC has found a better balance between signal transmission and brightness adjustment. The advantage of WTCC is low implementation complexity. WTCC does not need to sacrifice great implementation complexity to achieve error performance improvement. Unfortunately, the performance improvement of WTCC is not large enough.

Our proposed coding scheme mainly uses a non-linear trellis code with a code rate of 1/3. In other words, each input bit will be encoded into 3-bit codeword. This encoding method has higher coding gain compared with WTCC. In this way, we can achieve brightness adjustment at dimming level of 33% and 66%. Combined with compensation bits, we can achieve more dimming target from 0 to 1.

Efficient dimming schemes need to create a balance between illumination and communication. All of the above three schemes use compensation bits to achieve arbitrary

adjustment of brightness. However, overmuch compensation bits can degrade the performance of spectral efficiency. In reality, the proposed scheme can achieve brightness adjustment from 50% to 33% and 66% without using compensation bits. Therefore, our proposal has the best practicability and efficiency. And most importantly, our proposed scheme is the best in terms of error performance.

There are still some problems worth further studying. For example, WTCC and our proposal both may lead to disastrous code. We believe that combining existing schemes with Run-length Limited (RLL) code can solve this problem. This will be in future research of this thesis.

5. Simulation Results

For comparing the performance among the above-mentioned schemes, simulations have been carried out, and the results are depicted in Fig.5. Given dimming factor $\gamma = \frac{1}{3}$, our proposed code achieves 3.1 dB SNR gain compared with VOOK when BER $= 10^{-3}$. However, it can be seen that our proposed scheme behaves almost same error performance at low SNR as VOOK. Thus, high SNR is required to mention a reliable data transmission. In the case of high SNR, the advantage of our proposed scheme is obvious.
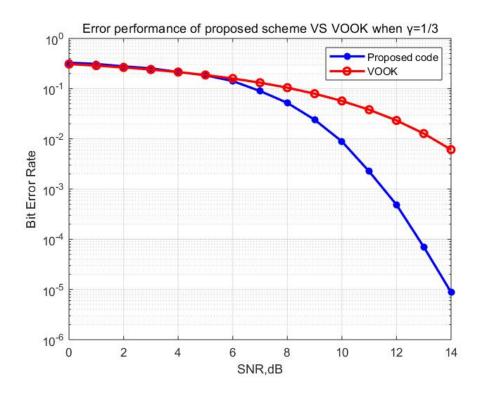

Fig.5 error performance of proposed code and VOOK when $\gamma = \frac{1}{3}$

The error performance of the proposed scheme with different dimming levels is shown in Fig.6, where different curves represent the different compensation bits. We can see that as we move near to 33% dimming level, better error performance appears. This result matches our analysis. When the compensation bits length is equal to 0, it has the best performance. In the Fig.6, we only consider dimming factor γ from 0 to 0.5, because the performance in $0 < \gamma < 0.5$ and in $0.5 < \gamma < 1$ are symmetrical when we flip all bits.
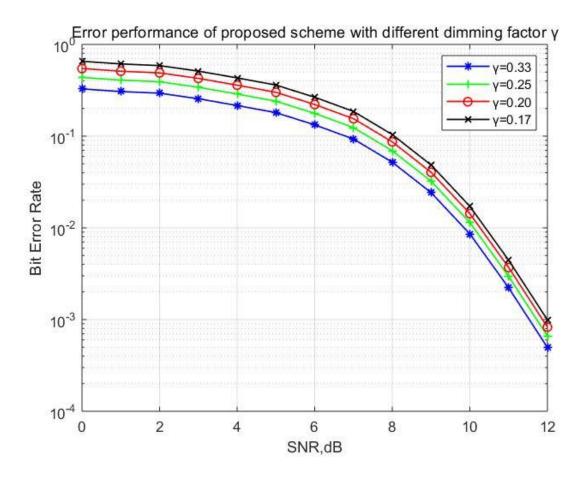

Fig.6 error performance of proposed scheme with different dimming factor γ

6. Conclusion

In this research, we propose a non-linear trellis coding scheme to achieve better error performance as well as dimming control function. If we don't use compensation bits, we can get a pretty good error performance and achieve practical dimming levels of 33% and 66%, which is 33% less or more than the default brightness. Furthermore, A wide range of dimming levels can be achieved via adding proper length of compensation bits. The proposed scheme uses finite-state machine as an encoder. And decoding algorithm is the Viterbi algorithm. Simulation results show that our proposed coding scheme keeps a good balance between illumination and communication where better error performance can be achieved especially. Therefore, the proposed non-linear trellis coding scheme can be regarded as an attractive alternative to achieve dimming control.

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Vitae

Yukang Xue was born on April 20th, 1993 to Qing Xue and Hongying Xu. In 2015 he got the admission from Lehigh for Master program in Electrical and Computer Engineering. After finishing his bachelor's degree of Information Engineering in Xi'an Jiaotong University, Xi'an China, he gapped one years to work in HuiLing new technology company to gain work experience during 2015 to 2016. In 2016 fall semester, Yukang went to Lehigh University for his Master degree. At the very beginning of the program, he had already made his mind that he was going to do a thesis for his Master of Science degree. After taking Prof. Tiffany Jing Li's course, he had a chance to discuss with Prof. Li, who gave him a lot of useful advices and help. Finally, Prof. Li became his advisor guiding his research. Under advisors' guidance, he was able to learn some skills he hadn't had a chance to know and to finish his master's thesis. After graduating from his master's degree, he decided to continue his doctorate degree under the guidance of Prof. Li.