Block Coding Techniques with Cyclic Delay Diversity for OFDM Systems

Ting Du*, Bing Hui** ***Associate Members***, KyungHi Chang** ***Lifelong Member***

ABSTRACT

Cyclic delay diversity (CDD) is considered as a simple approach to exploit the frequency diversity in OFDM system. In this paper, we apply CDD to the conventional STBC/SFBC/STFBC-OFDM transmit diversity schemes for Rayleigh fading channels. We compare the performances of STBC/SFBC/STFBC with and without CDD schemes. Simulation results show that the combination of block coding with CDD works well when using the ITU-R M. 1225 channel for both Pedestrian A (Ped A) channel with the mobility of 3 km/h, and Vehicular A (Veh A) channel with the mobility of 120 km/h. For a BER of 10^{-3}, compared to the conventional block coding schemes, a gain of 2 dB, 4 dB, and 5 dB is obtained under the Ped A channel environment by STBC-OFDM, SFBC-OFDM and STFBC-OFDM with CDD, respectively. Under the Veh A channel, gains by the combined schemes are 6 dB, 2 dB, and 4 dB, respectively.

Key Words : Cyclic delay diversity, Spatial diversity, STBC/SFBC/STFBC, OFDM

Ⅰ. Introduction

Orthogonal frequency division multiplexing (OFDM) is a multicarrier transmission scheme that can potentially attain high-rate transmission and combat the multipath fading channel. However, OFDM suffers from the lack of built-in diversity. Therefore, some forms of diversity schemes can be used to improve the bit error rate (BER) performance. One of these techniques is the CDD. CDD is a simple approach to introduce spatial diversity to an OFDM transmission scheme. It can effectively increase the frequency selectivity of equivalent channel, therefore resulting in the improvement of frequency diversity gain with the assistance of the channel coding and bit interleaving. Furthermore, to implement CDD, only some simple additional signal processing is required at the transmitter and no modification is required for the existing receiver [1].

Transmitter diversity has received significant interest in recent years driven in part by the strong demand to provide reliable voice and data services. A number of space-time coding techniques have been proposed for transmit diversity. Unfortunately, the large delay spread in frequency-selective channel destroys the orthogonality among sub-carriers which is crucial to these techniques. A well-known transmit diversity approach is space-time block coding (STBC), which has been applied to OFDM as an attractive solution for a high bit rate data transmission in a multipath fading environment [2]. The use of OFDM also offers the possibility of coding in the frequency dimension in a form of space-frequency block coded OFDM (SFBC-OFDM) transmitter diversity, which has also been studied in [3]. In [4], a space-time-frequency coded OFDM (STFBC-OFDM) is proposed to achieve diversity gain with low decoding flexibility.

In order to exploit full diversity gain and to improve performance, we consider the joint application of the diversity schemes STBC, SFBC and STFBC with CDD in OFDM system over Rayleigh fading channels. In the above combined transmission

* 중국 중경우전대학교 정보통신대학원 이동통신연구실 (tingduswjtu@sina.com)
** 인하대학교 정보통신대학원 이동통신연구실 (huibing_zxo@163.com, khchang@inha.ac.kr)
논문번호 : KICS2008-06-275, 접수일자 : 2008년 6월 17일, 최종논문접수일자 : 2008년 8월 21일

schemes, both spatial diversity and frequency diversity gain can be achieved under the Ped A and Veh A channel environments as defined in [5].

The remainder of this paper is organized as follows. At first, we introduce the frequency diversity gain by CDD technology in section Ⅱ, and in section Ⅲ, spatial diversity gain by block coding is presented. Section Ⅳ presents the combination of block coding with CDD in details. In section Ⅴ, the simulation results are shown and discussed. Finally, conclusions are addressed in section VI.

Ⅱ. Frequency Diversity Gain by CDD Technology

Figure 1 shows the principle of CDD for N transmit antennas. First, data is encoded by a forward error correction (FEC) encoder. The coded bits are mapped, for example, on PSK symbols. OFDM is implemented by using the inverse fast fourier transform (IFFT) of size N_c, where N_c is the number of sub-carriers. After the IFFT, the signal is split into N antenna branches. The cyclic shift of the first antenna is set to zero, while in other branches the signals are cyclically shifted by specific cyclic shift values $\delta_{cyc,n}$, $n=1,....,N-1$. The cyclic delays denote cyclic shifts of the OFDM symbol in time domain, which can be chosen according to the modulation alphabet and the number of transmit antennas. In [6], the choice of the cyclic delay size is analyzed in details. The equivalent representation of cyclic delay in the time domain, which is called phase delay (PD) in the frequency domain, is denoted as follows,

$$s(l) = \frac{1}{\sqrt{N_c}} \sum_{k=1}^{N_c} S(k) e^{j\frac{2\pi}{N_c}kl} \tag{1}$$

$$s(l-\delta_n) = \frac{1}{\sqrt{N_c}} \sum_{k=1}^{N_c} e^{-j\frac{2\pi}{N_c}k\delta_n} S(k) e^{j\frac{2\pi}{N_c}kl} \tag{2}$$

where $s(l)$, $S(k)$ denote the complex valued signals in time domain and frequency domain, respectively. l and k denote the index of the discrete time and the discrete frequency, respectively. After cyclic delay, a cyclic prefix is inserted to avoid inter symbol interference for multipath channel.

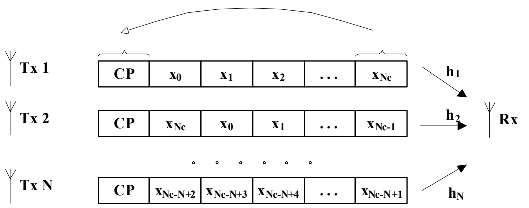

Fig. 1. The CDD scheme

At the receiver, the cyclic shifts appear as multipath which increase the frequency selectivity of equivalent channel, therefore resulting in the improvement of frequency diversity gain when applying FEC and interleaving. There is no additional complexity and the superimposed signals are just processed by simply removing the cyclic prefix and performing the fast fourier transformation (FFT), decoding, and de-interleaving.

Ⅲ. Spatial Diversity Gain by Block Coding

Orthogonal 4-antenna Alamouti code is obtained by grouping four symbols into two Alamouti blocks and disposing them diagonally for 4-antenna transmission systems, which has been regarded as an effective transmit diversity scheme in existing and/or upcoming wireless communication systems for its simplicity and its compatibility with orthogonal 2-antenna Alamouti code [7]. The orthogonal 2-antenna Alamouti code [8] and 4-antenna Alamouti code are defined in (3) and (4) respectively,

$$S_{2\times 1} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{3}$$

$$S_{4\times 1} = \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix} \tag{4}$$

where

$$A = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \text{ and } B = \begin{bmatrix} s_3 & s_4 \\ -s_4^* & s_3^* \end{bmatrix}.$$

The 4-by-1 STBC/SFBC/STFBC coding schemes for OFDM system is shown in Fig. 2. In STBC-OFDM, all four successive symbols are formed in one sub-carrier. While in SFBC-OFDM, all four successive symbols are located in four sub-carriers. In STFBC-OFDM, two successive OFDM symbols are

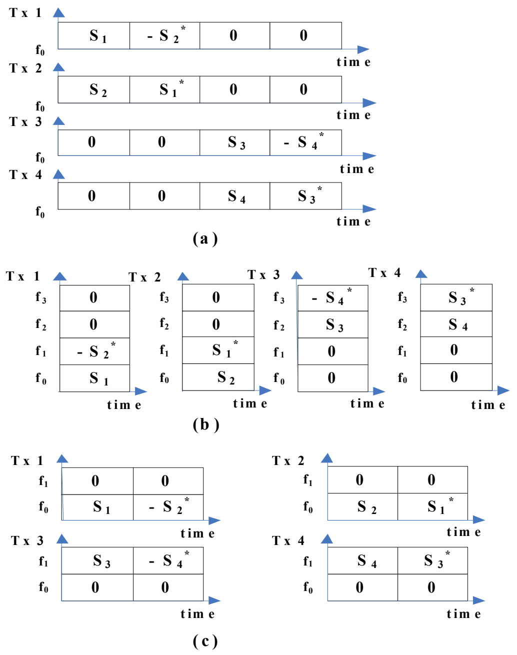

Fig. 2. 4-by-1 STBC/SFBC/STFBC-OFDM schemes (a) STBC-OFDM; (b) SFBC-OFDM; (c) STFBC-OFDM

considered in two sub-carriers, which will be used for transmission in first time slot. Other two successive symbols are considered in the same sub-carriers, but they will be used for transmission in second time slot.

Ⅳ. Combination of Block Coding Techniques with Cyclic Delay Diversity

To exploit the spatial and frequency diversity gain, we introduce CDD into the conventional STBC/SFBC/STFBC-OFDM systems. For comparison, we apply $S_{4\times 1}$ to the 4-by-1 conventional STBC/SFBC/STFBC-OFDM systems, while we apply $S_{2\times 1}$ to the block coding technique with CDD. The combined scheme is presented in Fig. 3.

Figure 4 shows the different coding methodologies for the combined scheme. At first, the signals which have been encoded by the STBC/SFBC/STFBC part are split into two branches. Then, we add another antenna as a cyclic delay antenna for each branch. We consider the original two branches as one group and the other additional two branches with CDD as another group. Both of the two groups follow the same principle of the coding schemes. In STBC-OFDM with CDD, all two successive symbols are formed in one sub-carrier. While in SFBC-OFDM with CDD, all two successive symbols are located in two sub-carriers. In STFBC-OFDM with CDD, one OFDM symbol is considered in one sub-carrier, which will be used for transmission in first time slot. The other symbol is considered in the same sub-carrier, but it will be used for transmission in second time slot.

Assuming that the original data is encoded by a FEC encoder, after interleaving and mapping we get the signal vector $X=(x_1,x_2,\ldots x_m)^T$ in the frequency domain, where m denotes the number of the mapped symbols. The signal vector X is used to implement STBC/SFBC/STFBC schemes. After the STBC/SFBC/STFBC encoding, the coded signal vector $S_{BC}=(S_1,S_2,\ldots S_m)^T$ is split into 2 branches and

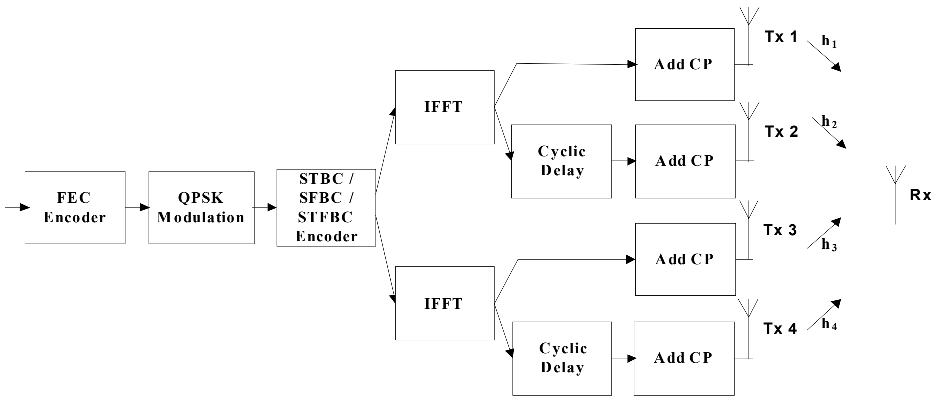

Fig. 3. Block coding technique combined with CDD

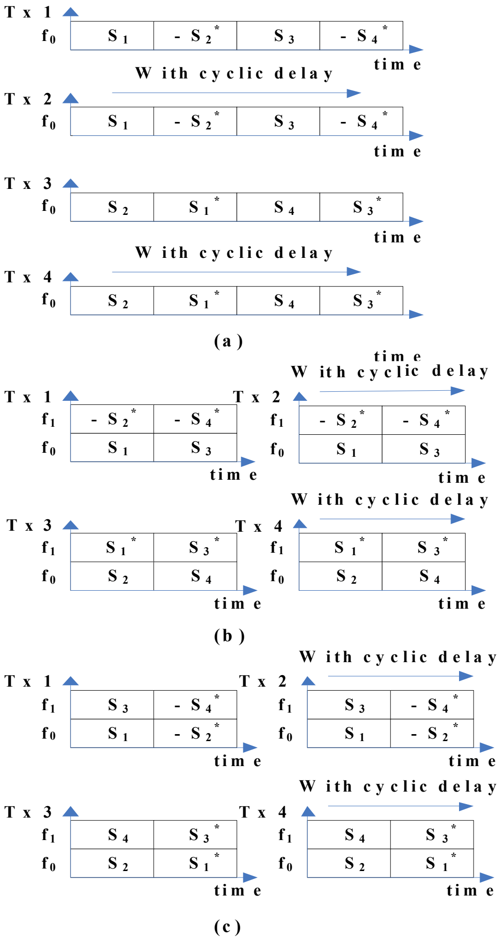

Fig. 4. 4-by-1 STBC/SFBC/STFBC-OFDM schemes with CDD (a) STBC-OFDM w. CDD; (b) SFBC-OFDM w. CDD; (c) STFBC-OFDM w. CDD

then IFFT is implemented. The transmit symbol from antenna i at time t is given by (5).

$$s_{BC_i}(l) = \frac{1}{\sqrt{N_c}} \sum_{k=1}^{N_c} S_{BC_i}(k) e^{j\frac{2\pi}{N_c}kl} \quad (5)$$

In CDD, the signal vector from each branch, cyclically delayed respectively with an antenna specific shift $\delta_{cyc,i}$, $i=1,2,\ldots,n_T$, i. e. equation (5) can be rewritten as (6).

$$s_{BC_i}((l-\delta_{cyc,i}) \mathrm{mod} N_c) = \frac{1}{\sqrt{N_c}} \sum_{k=1}^{N_c} e^{-j\frac{2\pi}{N_c}k\delta_{cyc,k}} S_{BC_i}(k) e^{j\frac{2\pi}{N_c}kl} \quad (6)$$

Using (5) and (6), the S_{BC}^{CDD} including CDD in frequency domain yields

$$S_{BC,k,l}^{CDD} = S_{BC,k,l} e^{-j\frac{2\pi}{N_c}\delta_{cyc,k}}. \quad (7)$$

Before transmission, a cyclic guard interval is included at each transmit antenna. The signals from different transmit antennas superimpose on the channel, and then are processed by the receiver via the guard interval removal and the OFDM demodulation, which contains the FFT, followed by the STBC/SFBC/STFBC decoding, the QPSK demodulation, the de-interleaving, and the FEC decoding.

The equivalent channel frequency response at the k^{th} sub-carrier is now given by

$$H_{eq,k} = \frac{1}{\sqrt{2n_T}} \sum_{i=1}^{2n_T} H_{i,k,v} e^{-j\frac{2\pi}{N_c}k\delta_{cyc,k}}, \quad (8)$$

where $H_{i,k,v}$ is the channel transfer function between the v^{th} receive antenna, and the i^{th} transmit antenna at the k^{th} sub-carrier. Mathematical model can be deduced as follows.

$$y_v^{CDD}(l) = \sum_{i=1}^{2n_T} H_{eq,v,i}(l) S_{BC}^{CDD}(l) + n_v(l) \quad (9)$$

At the receiver side, the combined algorithm is equivalent to increase the diversity gain both in frequency domain and spatial domain.

V. Simulation Results

In this section, we provide simulation results for the combined scheme and compare with the conventional STBC/SFBC/STFBC-OFDM systems. Four transmit antennas and one receive antenna are considered for the combined scheme. Table 1 shows the principal simulation parameters.

Figure 5 shows the performances of the conventional STBC-OFDM scheme with and without CDD. For STBC-OFDM without CDD, the performance under Ped A channel is 3.5 dB better than that under Veh A channel at BER of 10^{-3}. It is due to the lose of orthogonality of STBC-OFDM in highly time-selective channel, which degrades the performance of the

Table 1. System parameters

Item	Value
Carrier Frequency	2 GHz
Bandwidth	800 KHz
Number of FFT	64
Length of Guard Interval	16
Length of Cyclic Delay	0, 16
Channel Coding	1/2 Convolutional Code
Interleaving	Random Interleaving
Modulation	QPSK
Detection	Maximum Likelihood
Mobility	3 km/h for Ped A 120 km/h for Veh A
Fading Channel	Ped A / Veh A

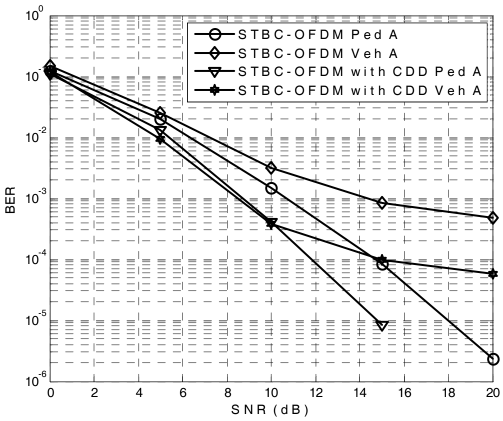

Fig. 5. STBC-OFDM vs. STBC-OFDM w. CDD

STBC-OFDM. When applying CDD to STBC-OFDM, for a BER of 10^{-3}, a gain of 2 dB and 6 dB is obtained for Ped A channel and Veh A channel, respectively. On one hand, the precondition of applying STBC is that the channel should keep constant during 2 consecutive symbol intervals in time-domain. Moreover, compared with Ped A channel, the Veh A channel provides a higher time selectivity caused by higher mobility, and a higher frequency selectivity caused by more propagation delays. This higher time selectivity makes the channel change fast in time-domain, and degrades the performance of STBC seriously. It makes the error flow happen in the high SNR range. On the other hand, the system can get more benefits in the channel with higher frequency selectivity by using the CDD technique to exploit frequency diversity gain. As a consequence, in Veh A channel, a huge additional frequency diversity gain is obtained due to the above reasons and the error flow at a BER of 10^{-4} when applying CDD to the conventional STBC-OFDM system.

Figure 6 shows the performances of the conventional SFBC-OFDM scheme with and without CDD. For SFBC-OFDM without CDD, the performance under Ped A channel is 4.2 dB worse than that under Veh A channel at BER of 10^{-3}. It is due to the higher frequency selectivity of the channel in case of Veh A compared to the case of Ped A. As a consequence, transmitting each data symbol over 2 uncorrelated sub-carriers leads to exploiting frequency diversity gain at the receiver side. When applying CDD to SFBC-OFDM, for a BER of 10^{-3}, a gain of 4 dB and 2 dB is obtained for Ped A channel and Veh A channel, respectively. The main reason behind the obtained performance improvement is that additional frequency diversity is achieved by applying the CDD technique.

Figure 7 shows the performance of the conventional STFBC-OFDM without CDD, the performance under Ped A channel is worse than that under Veh A channel for SNR<10.5 dB. However, for SNR>10.5 dB, the performance under Ped A channel is better than that under Veh A channel. It is because that STFBC-OFDM have a better performance than STBC-OFDM in time-selective fading channel environment and also have a better tolerance in frequency-selective fading channel environment compare to SFBC-OFDM. When applying CDD to STFBC-OFDM, for a BER of 10^{-3}, a gain of 3 dB and

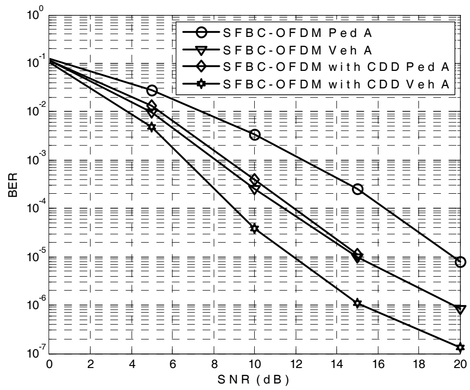

Fig. 6. SFBC-OFDM vs. SFBC-OFDM w. CDD

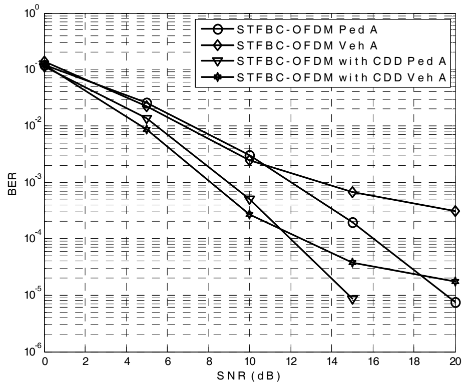

Fig. 7. STFBC-OFDM vs. STFBC-OFDM w. CDD

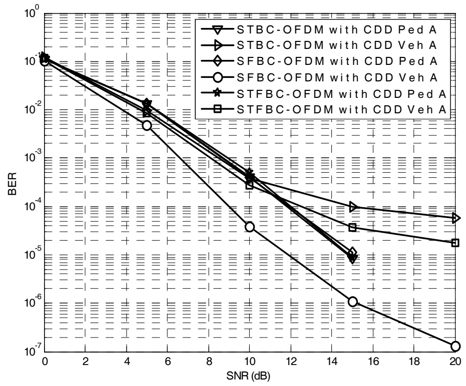

Fig. 8. STBC/SFBC/STFBC-OFDM w. CDD

5 dB is obtained for Ped A channel and Veh A channel, respectively.

Figure 8 shows the performance of the combined STBC/SFBC/STFBC-OFDM with CDD under Ped A channel and Veh A channel, respectively. In Ped A channel environment, STBC-OFDM, SFBC-OFDM and STFBC-OFDM with CDD show the similar performances. However, In Veh A channel environment, for a BER of 10^{-3}, a gain of 1.5 dB and 2 dB is attained for SFBC-OFDM with CDD compare to STFBC-OFDM with CDD and STBC-OFDM with CDD, respectively. It is because that the highly time selectivity degrades the performance in STBC/STFBC-OFDM with CDD, while highly frequency selectivity increase the frequency diversity in SFBC-OFDM with CDD.

Ⅵ. Conclusions

CDD is a simple approach used to exploit the frequency diversity without increasing the complexity of the original communication system. In this paper, we apply the CDD technique to the conventional STBC-OFDM, SFBC-OFDM and STFBC-OFDM schemes to achieve additional diversity gain. It is found that the combination of block coding technique with cyclic delay diversity can achieve significant diversity gain compared with conventional schemes under both the Ped A and Veh A channel environments.

References

〔1〕 M. Bossert, A. Huebner, F. Schuehlein, H. Hass, and E. Costa, "On cyclic delay diversity in OFDM based transmission schemes," *OFDM Workshop*, Sep. 2002.

〔2〕 K.F. Lee and D.B. Williams, "A space-time coded transmitter diversity technique for frequency selective fading channel," in *Proc. IEEE SAM*, Mar. 2000, pp.149-152.

〔3〕 K.F. Lee and D.B. Williams, "A space-frequency transmitter diversity technique for OFDM systems," in *Proc. IEEE GLOBECOM*, Vol.3, Nov. 2000, pp.1437-1477.

〔4〕 K. Suto and T. Ohtsuki, "Space-Time-Frequency Block Codes over Frequency Selective Fading Channels," *IEICE Trans. Commun.,* Vol.E87-B, no. 7, pp.1939-1954, July 2004.

〔5〕 International Telecommunications Union, Recommendation section (ITU-R), Recommendation M.1225, Guidelines for evolution of radio transmission technologies for IMT-2000, pp.28, 1997.

〔6〕 G. Bauch and J. Malik, "Parameter optimization, interleaving and multiple access in OFDM with cyclic delay diversity," in *Proc. VTC*, Vol.1, May 2004, pp.505-509.

〔7〕 Y. Kim, "A full diversity full rate 4-antenna Alamouti code," in *Proc. IEEE 16th PIMRC*, Vol.1, Sep. 2005, pp.72-76.

〔8〕 S. Alamouti, "A simple transmitter diversity scheme for wireless communications," *IEEE J-SAC*, Vol.16, pp.1451-1458, Oct. 1998.

두 정 (Ting Du) 준회원

2006년 7월 중국 서남교통대학교 정보통신공학과 (공학사)

2006년 9월~현재 중국 중경우전대학교 정보통신 대학원 석사과정

<관심분야> OFDM / MIMO Systems, MIMO detection algorithm, WiMAX, 3GPP LTE

회 빙 (Bing Hui) 준회원

2005년 7월 중국 동북대학교 정보통신공학과 (공학사)

2007년 9월~현재 인하대학교 정보통신 대학원 석사과정

<관심분야> OFDM / MIMO Systems, MIMO detection algorithm, WiMAX, 3GPP LTE

장 경 희 (KyungHi Chang) 종신회원

1985년 2월 연세대학교 전자공학과 (공학사)

1987년 2월 연세대학교 전자공학과 (공학석사)

1992년 8월 Texas A & M Univ., EE Dept. (Ph.D.)

1989년~1990년 삼성종합기술원 주임연구원

1992년~2003년 한국전자통신연구원, 이동통신연구소 무선전송방식연구팀장 (책임연구원)

2003년~현재 인하대학교 정보통신대학원 부교수

<관심분야> 4세대 이동통신 및 3GPP LTE 무선전송방식, WMAN 및 DMB 시스템 무선전송기술, Cognitive Radio, Cross-layer Design, Cooperative Relaying System, RFID / USN Systems