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SUD 수신기의 획득가능한 전송률 분석: 상관 정보원 비직교 다중 접속의 강 채널 사용자에 대한 응용

정규혁*

Analyses on Achievable Data Rate for Single-User Decoding(SUD) Receiver: with Application to CIS NOMA Strong Channel User

Kyu-Hyuk Chung*

요 약

본 논문은 표준 SIC NOMA와는 대조적으로, SIC를 수행하지 않는 SUD 수신기의 최대 전송률을 고찰한다. 먼저, 강 채널 사용자에 대해 상관 정보원의 SUD NOMA에 대한 최대 전송률의 폐쇄형 표현식을 유도한다. 다음, 강 채널 사용자에 대해서는, 독립 정보원의 SIC NOMA의 최대 전송률과 비교하여, 상관 정보원의 SUD NOMA의 최대 전송률은 일반적으로 감소하는 것을 보여준다. 그러나, 아주 강한 상관 정보원에 대해서는, 독립 정보원의 SIC NOMA의 최대 전송률과 비교하여, 상관 정보원의 SUD NOMA의 최대 전송률은 아주 우수하다는 것을 입증한다. 추가로, 상관 정보원이 SUD 수신기의 최대 전송률에 미치는 영향을 고찰하기 위해, 다양한 상관 관계 계수에 대해, SUD NOMA의 최대 전송률과 SIC NOMA의 최대 전송률을 폭넓게 비교한다.

ABSTRACT

This paper investigates the achievable data rate for the single-user decoding(SUD) receiver, which does not perform successive interference cancellation(SIC), in contrast to the conventional SIC non-orthogonal multiple access(NOMA) scheme. First, the closed-form expression for the achievable data rate of SUD NOMA with correlated information sources(CIS) is derived, for the stronger channel user. Then it is shown that for the stronger channel user, the achievable data rate of SUD NOMA with independent information sources(IIS) is generally inferior to that of conventional SIC NOMA with IIS. However, for especially highly CIS, we show that the achievable data rate of SUD NOMA is greatly superior to that of conventional SIC NOMA. In addition, to verify the impact of CIS on the achievable data rate of SUD, the extensive comparisons of the achievable data rates for the SUD receiver and the SIC receiver are compared for various correlation coefficients.

키워드

NOMA, Superposition Coding, Successive Interference Cancellation, Power Allocation, Correlation Coefficient
비직교 다중 접속, 중첩 코딩, 순차적 간섭 제거, 전력 할당, 상관 관계 계수

* 교신저자 : 단국대학교 소프트웨어학과
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• Corresponding Author : Kyu-Hyuk Chung
Dept. Software Science, Dankook University,
Email : khchung@dankook.ac.kr

Ⅰ. Introduction

In the fifth-generation(5G) wireless mobile communications, non-orthogonal multiple access(NOMA) has emerged as a promising multiple access(MA), owing to high spectral efficiency and low transmission latency[1, 2], compared to orthogonal multiple access(OMA)[3-5]. The power-domain NOMA has been studied extensively[6, 7]. The users with better channel conditions can remove other users′ signals by successive interference cancellation(SIC)[8].

Lately, the bit-error rate(BER) performance of NOMA was investigated[9]. The impacts of local oscillator imperfection were studied in NOMA[10]. The BER expression with randomly generated signals was derived[11]. The BER expression was studied for Nakagami-m fading channels[12]. The average symbol error rate(SER) expressions were derived[13]. The optimal power control was investigated based on individual QoS constraints[14], whereas the energy harvesting NOMA was proposed for machine-to-machine(M2M) communications[15].

In addition, single-user decoding(SUD) has been studied for discrete-input Lattice-based NOMA, and a single-user decoder, which treats other users' signals as interference, was proposed, instead of the conventional SIC decoder[16-19].

The most of the above-mentioned literature in NOMA assume independent information sources(IIS). Recently, the BER performance has been investigated for correlated information sources(CIS)[20].

In this paper, we investigate the achievable data rate of the stronger channel user in NOMA for CIS, especially under the SUD receiver, in contrast to most of the existing NOMA using the SIC receiver. Fist, we derive the analytical expression for the achievable data rate of the stronger channel user with the SUD receiver for CIS NOMA. Then it is shown that the achievable data rate of the SUD receiver is larger than that of the conventional SIC receiver, for highly CIS.

The remainder of this paper is organized as follows. In Section Ⅱ, the system and channel model are described. The analytical expression for the achievable data rate of the SUD receiver is derived in Section Ⅲ. The results are presented and discussed in Section Ⅳ. Finally, the conclusions are presented in Section Ⅴ.

Ⅱ. System and Channel Model

In a cellular downlink NOMA transmission system, all the users are assumed to be experiencing block fading, in a narrow band of frequencies. For wideband systems, orthogonal frequency division multiplexing(OFDM) can transform a frequency-selective channel into slow fading ones. A base station and paired users are within the cell. The complex channel coefficient between the mth user and the base station is denoted by h_m, $m=1,2$. The channels are sorted as $|h_1| > |h_2|$. The base station sends the superimposed signal $x=\sqrt{\alpha P_A}\,s_1+\sqrt{(1-\alpha)P_A}\,s_2$, where s_m is the message for the mth user with unit power, $E[|s_1|^2]=E[|s_2|^2]=1$, where $E[u]$ represents the expectation of a random variable(RV) u, α is the power allocation factor, with $0 \le \alpha \le 1$, and P_A is the total allocated power. The correlation coefficient is $\rho_{1,2}=E[s_1 s_2^*]$. Owing to correlation, the power of the superimposed signal x is not equal to P_A. Therefore, for the constant total transmitted power P at the base station, P_A is effectively scaled by [21].

$$P_A = \frac{P}{1+2Re\{\rho_{1,2}\}\sqrt{\alpha}\,\sqrt{1-\alpha}} \tag{1}$$

where $Re\{z\}$ is the real part of a complex number

z. It should be noted that for IIS, $P_A = P$. The observation at the mth user is given by

$$\begin{aligned} r_m &= |h_m| x + n_m \\ &= |h_m| \sqrt{\alpha P_A} s_1 + |h_m| \sqrt{(1-\alpha) P_A} s_2 + n_m, \end{aligned} \tag{2}$$

where $n_m \sim N(0, N_0/2)$ is additive white Gaussian noise(AWGN). The notation $N(\mu, \Sigma)$ represents the distribution of Gaussian RV with mean μ and variance Σ. Two uniform sources are given by

$$\begin{cases} P(b_1 = 0) = p_1 = 1/2 \\ P(b_1 = 1) = 1 - p_1 = 1/2 \end{cases} \tag{3}$$
$$\begin{cases} P(b_2 = 0) = p_2 = 1/2 \\ P(b_2 = 1) = 1 - p_2 = 1/2 \end{cases}.$$

For IIS, the joint probability mass function (PMF) is given by

$$\begin{cases} P(b_1 = 0, b_2 = 0) = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4} \\ P(b_1 = 0, b_2 = 1) = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4} \\ P(b_1 = 1, b_2 = 0) = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4} \\ P(b_1 = 1, b_2 = 1) = \frac{1}{2} \times \frac{1}{2} = \frac{1}{4}. \end{cases} \tag{4}$$

For CIS, the joint PMF is given by

$$\begin{cases} P(b_1 = 0, b_2 = 0) = q_{0,0} \\ P(b_1 = 0, b_2 = 1) = q_{0,1} = \frac{1}{2} - q_{0,0} \\ P(b_1 = 1, b_2 = 0) = q_{1,0} = \frac{1}{2} - q_{0,0} \\ P(b_1 = 1, b_2 = 1) = q_{1,1} = q_{0,0}. \end{cases} \tag{5}$$

In this paper, we assume that CIS has the positive correlation, $\rho_{1,2} > 0$, which corresponds to $\frac{1}{4} < q_{0,0} < \frac{1}{2}$. Then the correlation coefficient is calculated as[20]

$$\rho_{1,2} = E[s_1 s_2^*] = 4q_{0,0} - 1. \tag{6}$$

In this paper, we consider the BPSK modulation, $s_m \in \{+1, -1\}$. It is also assumed that the conventional bit-to-symbol mapping:

$$\begin{cases} s_1(b_1 = 0) = +1 \\ s_1(b_1 = 1) = -1 \end{cases} \quad \begin{cases} s_2(b_2 = 0) = +1 \\ s_2(b_2 = 1) = -1. \end{cases} \tag{7}$$

Additionally, to ensure the user fairness, the power allocation range, $\alpha \le 0.5$, is usually assumed. However, in this paper, to have the broader perspective and understanding, we consider the entire power allocation range, $0 \le \alpha \le 1$.

III. Derivation for Achievable Data Rate of SUD Receiver

We consider mainly the first user, i.e. the stronger channel user. It should be noted that SUD is already used for the weakest channel gain user in the conventional SIC NOMA, because in the conventional SIC NOMA, the user with the weakest channel gain dose not perform SIC generally.

Shannon Capacity is defined as the mutual information $I(y;x) = h(y) - h(y \mid x)$, where $h(y) = -E[\log_2 p_Y(y)]$ is the differential entropy, and $p_Y(y)$ is the probability density function(PDF). For the SUD receiver, since SIC is not performed, we have the received signal

$$y_1 = r_1. \tag{8}$$

Based on the definition of the mutual information, the achievable data rate $R_1^{(SUD)}$ is given by

$$\begin{aligned} R_1^{(SUD)} &= I(y_1; b_1) \\ &= h(y_1) - h(y_1 \mid b_1). \end{aligned} \tag{9}$$

Now, the PDF of y_1 is represented by

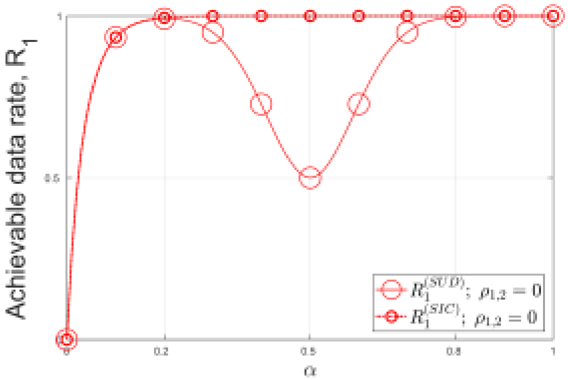

Fig. 1 Achievable data rates $R_1^{(SUD)}$ and $R_1^{(SIC)}$ for $\rho_{1,2}=0$

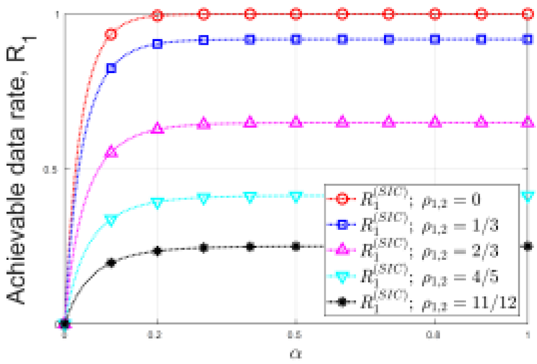

Fig. 2 Achievable data rate $R_1^{(SIC)}$ for $\rho_{1,2}=0, \frac{1}{3}, \frac{2}{3}, \frac{4}{5}$ and $\frac{11}{12}$

$$\begin{aligned} P_{Y_1}(y_1) = & q_{0,0}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{(r_1-|h_1|(+\sqrt{P_A(1-\alpha)}+\sqrt{P_A\alpha}))^2}{2N_0/2}} \\ & + q_{0,1}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{(r_1-|h_1|(-\sqrt{P_A(1-\alpha)}+\sqrt{P_A\alpha}))^2}{2N_0/2}} \\ & + q_{1,0}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{(r_1-|h_1|(+\sqrt{P_A(1-\alpha)}-\sqrt{P_A\alpha}))^2}{2N_0/2}} \\ & + q_{1,1}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{(r_1-|h_1|(-\sqrt{P_A(1-\alpha)}-\sqrt{P_A\alpha}))^2}{2N}} \end{aligned} \tag{10}$$

Then, the differential entropy is calculated by

$$\begin{aligned} h(y_1) &= -E[\log_2 P_{Y_1}(y_1)] \\ &= -\int_{-\infty}^{+\infty} P_{Y_1}(y_1)\log_2 P_{Y_1}(y_1)dy_1. \end{aligned} \tag{11}$$

And the conditional differential entropy is calculated by

$$\begin{aligned} & h(y_1 \mid b_1) \\ &= -E[\log_2 P_{Y_1 \mid B_1}(y_1 \mid b_1)] \\ &= -\sum_{b_1=0}^{1} P(b_1)\int_{-\infty}^{+\infty} P_{Y_1 \mid B_1}(y_1 \mid b_1)\log_2 P_{Y_1 \mid B_1}(y_1 \mid b_1)dy_1. \end{aligned} \tag{12}$$

where the conditional PDF is given by

$$\begin{aligned} & P_{Y_1 \mid B_1}(y_1 \mid b_1) = \\ & + \frac{q_{b_1,0}}{P(b_1)}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{(r_1-|h_1|(+\sqrt{P_A(1-\alpha)}+(-1)^{b_1}\sqrt{P_A\alpha}))^2}{2N_0/2}} \\ & + \frac{q_{b_1,1}}{P(b_1)}\frac{1}{\sqrt{2\pi N_0/2}}e^{-\frac{(r_1-|h_1|(-\sqrt{P_A(1-\alpha)}+(-1)^{b_1}\sqrt{P_A\alpha}))^2}{2N_0/2}}. \end{aligned} \tag{13}$$

Then we derive the achievable data rate $R_1^{(SUD)}$ with the SUD receiver for the first user

$$\begin{aligned} R_1 &= h(y_1) - h(y_1 \mid b_1) \\ &= h(y_1) + \sum_{b_1=0}^{1} P(b_1)\int_{-\infty}^{+\infty} P_{Y_1 \mid B_1}(y_1 \mid b_1)\log_2 P_{Y_1 \mid B_1}(y_1 \mid b_1)dy_1 \\ &= h(y_1) + \int_{-\infty}^{+\infty} P_{Y_1 \mid B_1}(y_1 \mid b_1=0)\log_2 P_{Y_1 \mid B_1}(y_1 \mid b_1=0)dy_1, \end{aligned} \tag{14}$$

where the translation property of the differential entropy is used. Now, we simplify $R_1^{(SUD)}$ more by the total probability theorem

$$\begin{aligned} & P_{Y_1}(y_1) = \\ & P_{Y_1 \mid B_1}(y_1 \mid b_1=0)P(b_1=0) + P_{Y_1 \mid B_1}(y_1 \mid b_1=1)P(b_1=1). \end{aligned} \tag{15}$$

Then $R_1^{(SUD)}$ is simplified as

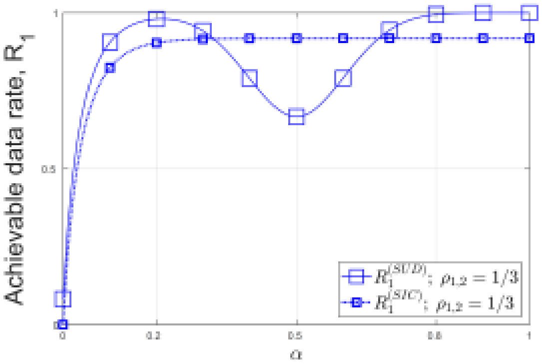

Fig. 3 Achievable data rates $R_1^{(SUD)}$ and $R_1^{(SIC)}$ for $\rho_{1,2}=\dfrac{1}{3}$

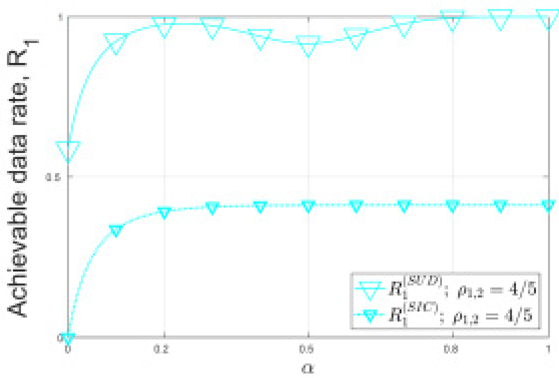

Fig. 5 Achievable data rates $R_1^{(SUD)}$ and $R_1^{(SIC)}$ for $\rho_{1,2}=\dfrac{4}{5}$

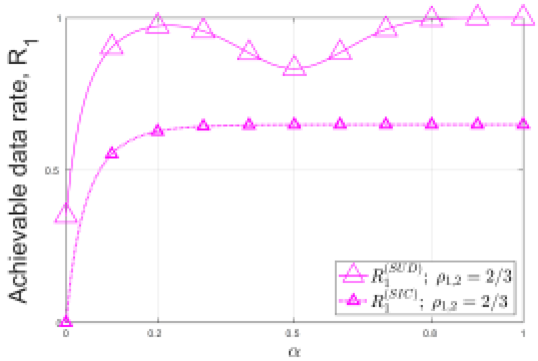

Fig. 4 Achievable data rates $R_1^{(SUD)}$ and $R_1^{(SIC)}$ for $\rho_{1,2}=\dfrac{2}{3}$

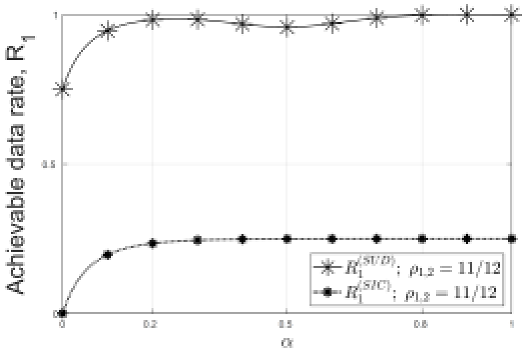

Fig. 6 Achievable data rates $R_1^{(SUD)}$ and $R_1^{(SIC)}$ for $\rho_{1,2}=\dfrac{11}{12}$

$$R_1= \tag{16}$$
$$-\int_{-\infty}^{+\infty}\begin{pmatrix}P_{Y_1\mid B_1}(y_1\mid b_1=0)P(b_1=0)\\+P_{Y_1\mid B_1}(y_1\mid b_1=1)P(b_1=1)\end{pmatrix}\log_2 P_{Y_1}(y_1)dy_1$$
$$+\int_{-\infty}^{+\infty}P_{Y_1\mid B_1}(y_1\mid b_1=0)\log_2 P_{Y_1\mid B_1}(y_1\mid b_1=0)dy_1,$$
$$=-\int_{-\infty}^{+\infty}P_{Y_1\mid B_1}(y_1\mid b_1=0)\log_2 P_{Y_1}(y_1)dy_1$$
$$+\int_{-\infty}^{+\infty}P_{Y_1\mid B_1}(y_1\mid b_1=0)\log_2 P_{Y_1\mid B_1}(y_1$$

where we use again the translation property of the differential entropy. Finally $R_1^{(SUD)}$ is derived as

$$R_1=\int_{-\infty}^{+\infty}P_{Y_1\mid B_1}(y_1\mid b_1=0)\log_2\frac{P_{Y_1\mid B_1}(y_1\mid b_1=0)}{P_{Y_1}(y_1)}dy_1. \tag{17}$$

Ⅳ. Results and Discussions

We compare the achievable data rate $R_1^{(SUD)}$ of the SUD receiver to the achievable date rate $R_1^{(SIC)}$ of the ideal perfect SIC receiver, which is given by

$$\begin{aligned} & R_1^{(SIC)} \\ & = I(r_1; b_1 \mid b_2) \\ & = h(r_1 \mid b_2) - h(r_1 \mid b_1, b_2) \\ & = -\int_{-\infty}^{+\infty} P_{Y_1 \mid B_2}(y_1 \mid b_2 = 0) \log_2 P_{Y_1 \mid B_2}(y_1 \mid b_2 = 0) dy_2 \\ & - \frac{1}{2} log_2 (2\pi e N_0 / 2). \end{aligned} \tag{18}$$

where

$$\begin{aligned} & P_{Y_1 \mid B_2}(y_1 \mid b_2) = \\ & \frac{q_{0,b_2}}{P(b_2)} \frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{(r_1 - |h_1| \sqrt{P_A \alpha})^2}{2N_0/2}} \\ & + \frac{q_{1,b_2}}{P(b_2)} \frac{1}{\sqrt{2\pi N_0/2}} e^{-\frac{(r_1 + |h_1| \sqrt{P_A \alpha})^2}{2N_0/2}}. \end{aligned} \tag{19}$$

It is assumed that $|h_1| = \sqrt{1.5}$ and $|h_2| = \sqrt{0.5}$. We consider the constant total transmitted signal power to noise power ratio (SNR) $P/N_0 = 15$.

In Fig. 1, for IIS, i.e., $\rho_{1,2} = 0$, we depict the achievable data rate $R_1^{(SUD)}$, compared to the achievable date rate $R_1^{(SIC)}$, over the entire power allocation range $0 \le \alpha \le 1$, for better understanding. As shown in Fig.1, for IIS, $R_1^{(SUD)}$ is generally inferior to $R_1^{(SUD)}$, especially at the vicinity of $\alpha = 0.5$. And in Fig. 2, we plot only $R_1^{(SIC)}$ for the various correlation coefficient, $\rho_{1,2} = 0, \frac{1}{3}, \frac{2}{3}, \frac{4}{5}$ and $\frac{11}{12}$, which correspond to $q_{0,0} = \frac{1}{4}, \frac{2}{6}, \frac{5}{12}, \frac{11}{24}$ and $\frac{23}{48}$, respectively. As shown in Fig. 2 when the correlation coefficient $\rho_{1,2}$ increases, $R_1^{(SIC)}$ decreases severely.

However, for the SUD receiver, as the correlation coefficient $\rho_{1,2}$ increases, $R_1^{(SUD)}$ increases greatly, as shown in Fig. 3, 4, 5, and 6. First, as shown in Fig. 3, for $\rho_{1,2} = \frac{1}{3}$, except the vicinity of $\alpha = 0.5$, $R_1^{(SUD)}$ is superior to $R_1^{(SIC)}$. Second, as shown in Fig. 4, for $\rho_{1,2} = \frac{2}{3}$, $R_1^{(SUD)}$ is superior to $R_1^{(SIC)}$, over the entire power allocation range $0 \le \alpha \le 1$. Third, as shown in Fig. 5 and 6, the superiority of $R_1^{(SUD)}$ over $R_1^{(SIC)}$ increases more and more, for $\rho_{1,2} = \frac{4}{5}$ and $\frac{11}{12}$.

Lastly, we should mention that the results for the SIC receiver and the SUD receiver are different. First, for the SIC receiver, the reason for the reduced achievable rate is that the correlated sources reduce the entropy, because the maximum entropy is obtained by the uniform sources. Now, the same reasoning is also applied to the SUD receiver. However, for the SUD recever, the reduction of the entropy due to the correlation is applied to noise, not signal. Therefore, the achievable rate of the SUD receiver increases, as the correlation of sources increases.

Ⅴ. Conclusion

This paper investigated the achievable data rate of the SUD receiver for NOMA with CIS. First, the analytical expression for the achievable data rate of SUD NOMA with CIS, for the stronger channel user. Then it was shown that for the stronger channel user, the achievable data rate of SUD NOMA with IIS is generally inferior to that of conventional SIC NOMA with IIS, whereas for especially highly CIS, the achievable data rate of SUD NOMA is greatly superior to that of conventional SIC NOMA. In addition, to verify the superiority of the SUD receiver over the SIC receiver, the extensive comparisons of the achievable data rates for the SUD receiver and the SIC receiver were presented for various correlation coefficients.

As a direction of the future research, it would be interesting to investigate the criterion of the correlation coefficient, for which the SUD receiver is generally superior to the SIC receiver over the entire operating power allocation range.

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저자 소개

정규혁(Kyu-Hyuk Chung)

1997년 성균관대학교 전자공학과 졸업(공학사)

1998년 Univ. of Southern California 전기공학과 졸업(공학석사)

2003년 Univ. of Southern California 전기공학과 졸업(공학박사)

2005년 ~현재 단국대학교 SW융합대학 소프트웨어학과 교수

※ 관심분야 : 5G이동통신시스템, 비직교다중접속