MIMO-aided Efficient Communication Resource Scheduling Scheme in VDES

Juhyoung Sung[1], Sungyoon Cho[1], Wongi Jeon[1], Kyungwon Park[1], Sang Jung Ahn[2*] and Kiwon Kwon[1*]
[1] Smart Network Research Center, Korea Electronics Technology Institute (KETI)
Seongnam-si, Gyeongi-Do, Republic of Korea
[e-mail: {jh.sung, sycho, jeonwg, kwpark, kwonkw}@keti.re.kr]
[2] R&D Planning Team, Korea Institute of Marine Science & Technology Promotion (KIMST)
Seoul, Republic of Korea
[e-mail: sjahn@kimst.re.kr]
[*]Corresponding authors: Sang Jung Ahn and Kiwon Kwon

Received March 17, 2022; revised May 20, 2022; accepted June 25, 2022;
published August 31, 2022

Abstract

As demands for the maritime communications increase, a variety of functions and information are required to exchange via elements of maritime systems, which leads communication traffic increases in maritime frequency bands, especially in VHF (Very High Frequency) band. Thus, effective resource management is crucial to the future maritime communication systems not only to the typical terrestrial communication systems. VHF data exchange system (VDES) enables to utilize more flexible configuration according to the communication condition.
This paper focuses on the VDES communication system among VDES terminals such as shore stations, ship stations and aids to navigation (AtoN) to address efficient resource allocation. We propose a resource management method considering a MIMO (Multiple Input Multiple Output) technique in VDES, which has been widely used for modern terrestrial wireless networks but not for marine environments by scheduling the essential communication resources. We introduce the general channel model in marine environment and give two metrics, spectral and the energy efficiencies to examine our resource scheduling algorithm. Based on the simulation results and analysis, the proposed method provides a possibility to enhance spectral and energy efficiencies. Additionally, we present a trade-off relationship between spectral and energy efficiencies. Furthermore, we examine the resource efficiencies related to the imperfect channel estimation.

Keywords: Energy efficiency, MIMO, Resource scheduling, Spectral efficiency, VDES

A preliminary version of this paper was presented at ICONI 2021, and was selected as an outstanding paper.
This version includes a concrete algorithm and a detailed mathematical implementation. This research was supported by the project No. 20210636 "The advancement of smart aids to navigation facilities," funded by the Ministry of Oceans and Fisheries, Republic of Korea.

http://doi.org/10.3837/tiis.2022.08.015 **ISSN : 1976-7277**

1. Introduction

International marine organization (IMO) introduced e-Navigation concept to maritime environments to support advanced information and communication technologies. The development and discussion of international communication standards have been proceeded to apply e-Navigation to marine systems [1]. The main purpose of e-Navigation is improving safety and security of the maritime environments. To support advanced features such as a robust electronic positioning and an agreed infrastructure of communications in the marine systems, various communication requirements should be considered. Moreover, due to the increases in maritime elements such as vessels and aids to navigation (AtoN), addressing communication link congestion is one of the crucial issues. Currently, many kinds of essential data exchanges of the marine systems are being operated in VHF (Very High Frequency) band. Especially, the automatic identification system (AIS) accounts for the VHF data link (VDL) overloading due to the exponentially increased number of vessels. This huge traffic often leads the quality of service (QoS) degradation, but it also causes a risk to navigational safety. Since e-Navigation also utilizes the VHF band to provide its services, the traffic issue should be considered.

VDES (VHF data exchange system) was proposed to enable VHF data exchange (VDE) in e-Navigation including safety relevant services and to manage the communication congestion caused by AIS in the VHF band. International association of marine aids to navigation and lighthouse authorities (IALA) has led the VDES specification and proposed a guideline for VDES [2]. VDES has been standardized by the international telecommunication union (ITU) based on the IALA guideline and the first specification was introduced in 2015. The latest document reflecting detailed packet structure was published in 2022 [3]. VDES composes not only the marine layer but also terrestrial and satellite layers, which could extend communication coverage [4]. VDES also covers AIS and application specific messages (ASM) to deliver information using VHF channels. VDES utilizes different channels according to the communication purpose and provides the highest priority to the transmission of safety-related information. As IMO determined to revise the international convention for the safety of life at sea (SOLAS) to make VDES mandatory, it is predicted that the related contents would be reflected in SOLAS from 2026.

So far, most of studies in the VHF maritime communication systems have focused on the characteristics of VHF band and vessel tracking. In [5], the protocol to reduce collision in VDES was introduced. A receiver sensitivity evaluation model of AIS terminals was proposed [6]. Deep learning architecture in [7] was introduced for vessel tracking prediction based on AIS data. Apart from the conventional research, we focus on the essential requirement to improve QoS under the limited VDES communication resources. In modern terrestrial wireless networks, MIMO (Multiple Input Multiple Output) using multiple antennas in both transmitter (Tx) and receiver (Rx) sides has been widely applied to improve overall communication performance. However, MIMO application in the marine systems has not been introduced yet, since the small amount of data exchanges compared to the terrestrial networks has been considered. As the use of VDES continues, a huge amount of data communication should be considered in marine environments [8-12], since demands for advanced functions and traffic congestion increase. This means efficient resource scheduling in VDES would be critical as the number of VDES users increases. We adopt MIMO in VDES to enhance communication resource efficiencies such as spectral and energy efficiencies. To the best of our knowledge, our work is the first attempt to consider communication resource management and MIMO application in VDES. We focus on the communication among shore stations, ship stations and

AtoN. The main contributions of our paper are as follows:

· We adopt the path loss model considering maritime VDES systems according to the distance between Tx and Rx. Moreover, we describe practical MIMO usages considering the frequency characteristics and maritime channel condition. Then, we propose a resource scheduling algorithm to increase the spectral efficiency and the energy efficiency.

· We illustrate several simulation results to show the performance of communication resource efficiencies. From the analysis of the results, we check the proposed MIMO-aided resource allocation method increases both the spectral and energy efficiencies in VDES. Moreover, we describe an imperfect channel model and analyze how channel estimation performance affects the spectral efficiency and the energy efficiency.

The remainder of this paper is organized as follows. In section 2, a system model for VDES is described including path loss derivation. The general MIMO system model and the proposed resource scheduling algorithm to enhance the resource efficiencies in VDES are illustrated in section 3. The analysis of the spectral efficiency and the energy efficiency based on simulation results is presented in section 4 before concluding this paper in section 5.

Notation: We indicate the following notation in the rest of this paper: Matrices and vectors by boldface capital letters and lower-case letters, respectively; $(\cdot)^T$ and $(\cdot)^H$ denote transpose and Hermitian conjugate transpose, respectively; $\mathbb{E}[\cdot]$ and $||\cdot||_F$ represent the statistical expectation and the Frobenius norm, respectively; $\mathbf{I}_N$ is the identity matrix whose size is $N \times N$.

2. A system model of VDES

2.1 General considerations

VDES utilizes a time-division multiple access (TDMA) technique. Operating channels of VDES are located around 160 MHz which belongs to the VHF band. Then, the wavelength in free space can be calculated as approximately 1.9 m.

VDES covers not only VDE for the general communication but also AIS and ASM. Globally allocated frequency bands for VDE are defined as channels 24, 84, 25, 85, 26 and 86 [2, 3]. Among them, channels 26 and 86 are only used for communicating with satellites. In addition, allocated frequency bands for AIS are channels 87 and 88 and those of ASM are channels 27 and 28. For long range AIS, VDES utilizes channels 75 and 76. All different VDES channels are separated in frequency domain, so that there is no interference between different channels. Compared to the terrestrial wideband communication systems, VDES utilizes narrowband. Each channel occupies 25 kHz bandwidth and can be combined up to 50 kHz or 100 kHz channels in case of VDE which enables high speed data transmission compared to using a single channel. Then, the noise power in VDES operating channel bandwidth 25 kHz, 50 kHz and 100 kHz can be calculated as -130 dBm, -127 dBm and -124 dBm, respectively with the noise power spectral density as -174 dBm/Hz. **Table 1** summarizes the detailed VDES channel information described in this section.

According to [3], Tx power range at a shore station is 12.5 to 50 W and that of a ship station is 1 to 12.5 W. Moreover, Tx power range of AtoN should be 1 to 12.5 W to support AIS and ASM in VDES [12]. Modulation orders are supported up to 16 QAM which enables high speed data transmission compared to the conventional VHF maritime communication system. A higher Rx sensitivity is required as the transmission bandwidth and the modulation order of VDES increase.

Table 1. Center frequency and application in each VDES channel

Channel number	Center frequency (MHz)	Application
87	161.975	AIS
88	162.025	
75	156.775	Long range AIS
76	156.825	
27	161.950	ASM
28	162.000	
24	157.200 (lower), 161.800 (upper)	VDE
84	157.225 (lower), 161.825 (upper)	
25	157.250 (lower), 161.850 (upper)	
85	157.275 (lower), 161.875 (upper)	
26	157.300 (lower), 161.900 (upper)	
86	157.325 (lower), 161.925 (upper)	

2.2 A propagation loss model

Generally, the strength of the transmitted power decreases in proportion to the square of the distance in free space. However, the propagated power is reduced more rapidly when external factors such as reflection loss and ionospheric loss etc. according to the communication environments are considered.

We consider the sea path propagation prediction with 50 % time variability described in [13] to apply into marine environments. The distance between Tx and Rx is up to 200 km. Frequency interpolation in [13] is used for operating VDES frequency range of approximately 160 MHz. **Fig. 1** shows a relative power gain in dB scales at the corresponding distances when the antenna height of Tx is 75 m and that of Rx is 10 m.

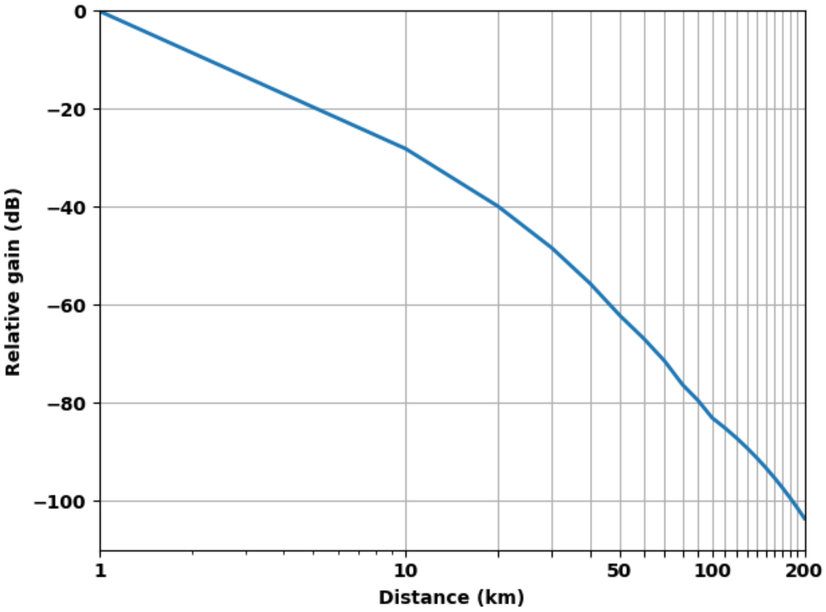


Fig. 1. A relative power gain in the VDES frequency band in the range from 1 to 200 km where antenna heights of Tx and Rx are 75 m and 10 m, respectively

We set the reference gain at 1 km as 0 dB in this figure. According to [13], transmission loss L on given electric field strength E is calculated as follows:

$$L = 139.3 - E + 20\log_{10} f + C, \tag{1}$$

where f is a frequency value in MHz and C is an electrical field compensation variable according to the Tx and Rx antenna heights. When antenna heights of Tx and Rx are 75 m and 10 m, respectively, C becomes to be 0. By using E of 106.9 at 1 km and plugging 160 MHz into f, then about 76.5 dB loss occurs at 1 km distance between Tx and Rx. From the **Fig. 1**, we can notice that the strength of transmission power decreases logarithmically as the distance increases.

3. Communication resource efficiency and proposed resource scheduling algorithm

3.1 The spectral and energy efficiencies in MIMO systems

We consider an $N_r \times N_t$ MIMO wireless network where a transmitter with N_t antennas communicates with a receiver with N_r antennas. Then, the $N_r \times 1$ received signal vector $\mathbf{y}$ is expressed as

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n}, \tag{2}$$

where $\mathbf{H}$ is an $N_r \times N_t$ channel matrix satisfying $\mathbb{E}[||\mathbf{H}||_F^2] = \alpha N_t N_r$ when the average pathloss coefficient is α derived from (1), $\mathbf{x}$ is an $N_t \times 1$ transmitted signal vector and $\mathbf{n} \sim CN(0, \sigma_n^2 \mathbf{1}_{N_r \times 1})$ denotes the $N_r \times 1$ complex addictive white gaussian noise (AWGN) with a variance σ_n^2. Herein, precoding and combining can be applied to the Tx side and Rx side, respectively. Then, the received signal in (2) is reconstructed as follows:

$$\mathbf{r} = \mathbf{W^H y} = \mathbf{W^H HFs} + \mathbf{W^H n}, \tag{3}$$

where $\mathbf{r}$ is the $N_L \times 1$ processed signal and $\mathbf{F}$ is an $N_t \times N_L$ precoding matrix and $\mathbf{W}$ is an $N_r \times N_L$ combining matrix and $\boldsymbol{s}$ represents an $N_L \times 1$ transmitted symbol vector. Here, N_L is the number of data streams which means N_L data streams are transmitted simultaneously.

One of the most important criteria in communication systems is the spectral efficiency in which unit is expressed as bits/s/Hz. Then, the achievable spectral efficiency η^{SE} can be calculated as follows [14-16]:

$$\eta^{SE} = \log_2 \left| \mathbf{I}_{N_L} + \frac{P_t}{N_L \sigma_n^2} (\mathbf{W}^H \mathbf{W})^{-1} \mathbf{W}^H \mathbf{HFF}^H \mathbf{H}^H \mathbf{W} \right|, \tag{4}$$

where P_t is the average Tx power. Without loss of generality and assuming equal power allocation among different layers, we use the Tx power constraint as $||\mathbf{F}||_F^2 = N_L$, $\mathbb{E}[\mathbf{ss}^H] = \frac{P_t}{N_L}\mathbf{I}_{N_L}$ and $P_t \leq P_{max}$ where P_{max} is the maximum transmit power. Accordingly, the achievable data rate can be obtained simply multiplying the spectral efficiency by the bandwidth size.

We adopt an additional metric, the energy efficiency, to achieve green or energy efficient usage during data transmission considering capital expenditures (CAPEX) and operating expenditures (OPEX) [17-19]. We consider an affine power consumption model [20, 21]. In the rest of this paper, we utilize a unit bandwidth analysis to express the unit of the energy efficiency as in bits/J. Then, the energy efficiency η^{EE} can be calculated as follows:

$$\eta^{EE} = \frac{\eta^{SE}}{\xi P_t + N_t \times P_c + P_s}, \tag{5}$$

where ξ stands for the transmit amplifier inefficiency, P_c represents the dynamic power per antenna and P_s describes the static circuit power. Here, the term $N_t \times P_c + P_s$ has no effect on the transmit power. From (5), we can notice that the energy efficiency is affected not only by the spectral efficiency but also by the total consumed power.

3.2 MIMO applications to VDES of AtoN

Using a large number of antennas for VDES is not feasible, considering the long wavelength described in section 2 since general antenna spacing is larger than or equal to one half wavelength to reduce mutual coupling effect [22-24]. Especially, installing many antennas would be more difficult for small vessel or buoying AtoN because of maintenance problems and calculation complexity. Therefore, in this paper, we consider a small number of antennas up to 4 in VDES terminals.

In a typical marine environment, a communication system has few sparse scattering clusters [25]. To incorporate this effect, we adopt the clustered geometrical channel model [15, 26, 27]. Using this model, the channel **H** can be written as

$$\mathbf{H} = \sqrt{\frac{K_R}{1+K_R}}\sqrt{N_t N_r}\beta_0 \mathbf{a}_\mathbf{r}(\psi_0^r)\mathbf{a}_\mathbf{t}(\psi_0^t)^H + \sqrt{\frac{1}{1+K_R}}\sqrt{\frac{N_t N_r}{N_{sc}}}\sum_{i=1}^{N_{sc}} \beta_l \mathbf{a}_\mathbf{r}(\psi_l^r)\mathbf{a}_\mathbf{t}(\psi_l^t)^H, \tag{6}$$

where K_R is the Rician K-factor and N_{sc} is the number of scattering clusters and β_l is the complex gain of the l^{th} path. The angular variables ψ_l^r and ψ_l^t are angle of arrival (AoA) and angle of departure (AoD) of the l^{th} path, respectively. Additionally, $\mathbf{a}_\mathbf{r}(\psi_l^r)$ and $\mathbf{a}_\mathbf{t}(\psi_l^t)$ are $N_r \times 1$ and $N_t \times 1$ normalized array response vectors at the Rx and Tx within the l^{th} scatter, respectively. The N-element array response vector can be represented as follows:

$$\mathrm{a}(\psi) = \frac{1}{\sqrt{N}}\left[1, e^{jkd\psi}, \dots, e^{jk(N-1)d\psi}\right]^T, \tag{7}$$

where k is a wave number having a value of $\frac{2\pi}{\lambda}$ and d is the inter-element spacing.

Moreover, most of non-line-of-sight (NLOS) signals are absorbed by the sea. This means that line-of-sight (LOS) paths would be prevalent on the VDES communication link. Then, the magnitude of the NLOS path gain is relatively very small rather than that of the LOS path gain. For this reason, it is better to obtain a diversity gain than to obtain a multiplexing gain in VDES when MIMO is applied [28, 29]. Also, the strategy for utilizing a diversity gain is applicable considering the reliable communication to extend coverage. Therefore, we consider the number of data streams N_L is fixed to 1 which leads to the interpretation of the precoding matrix **F** and combining matrix **W** as the precoding vector **f** and combining vector **w**, respectively. Then, the spectral efficiency described in (4) is reformulated as follows:

$$\eta^{SE} = \log_2\left(1 + \frac{P_t \mathbf{w}^H \mathbf{H}\mathbf{f}\mathbf{f}^H \mathbf{H}^H \mathbf{w}}{\sigma_n^2 \mathbf{w}^H \mathbf{w}}\right). \tag{8}$$

3.3 Proposed resource scheduling algorithm in VDES

In this subsection, we propose a simple and efficient resource scheduling method for VDES. From (8), we can boost the spectral efficiency dramatically by using a proper precoder $\mathbf{f}$ and a combiner $\mathbf{w}$ for MIMO. As we explained in the previous subsection, configuring the number of data streams to 1 is reasonable in VDES, which maximizes a diversity gain. Then, the spectral efficiency can be improved compared to SISO (Single Input Single Output) systems under the same power constraint. In addition, when a proper diversity gain is achieved, the wider VDES bandwidth can be allocated to the terminals when the received power with the diversity gain exceeds the Rx sensitivity of the increased bandwidth [3]. To find $\mathbf{f}$ and $\mathbf{w}$ to maximize (8), we simply adopt the singular value decomposition (SVD) leading the channel matrix $\mathbf{H}$ to be $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$ where $\mathbf{U}$ is an $N_r \times \mathrm{rank}(\mathbf{H})$ unitary matrix and $\mathbf{\Sigma}$ is a diagonal matrix of dimension $\mathrm{rank}(\mathbf{H}) \times \mathrm{rank}(\mathbf{H})$ and $\mathbf{V}$ is an $N_t \times \mathrm{rank}(\mathbf{H})$ unitary matrix. For utilizing the diversity gain using a single data stream, our interest is focused on the maximum singular value, so that we reconstruct the channel matrix with arranging singular values of $\mathbf{\Sigma}$ in decreasing order. Then, the channel matrix $\mathbf{H}$ is written as:

$$\mathbf{H} = \begin{bmatrix} \mathbf{u}_* & \widetilde{\mathbf{U}} \end{bmatrix} \begin{bmatrix} \sigma_* & \mathbf{0} \\ \mathbf{0} & \widetilde{\mathbf{\Sigma}} \end{bmatrix} \begin{bmatrix} \mathbf{v}_*^H \\ \widetilde{\mathbf{V}}^H \end{bmatrix}, \tag{9}$$

where σ_* is the maximum singular value and $\mathbf{u}_*$ and $\mathbf{v}_*$ are corresponding $N_r \times 1$ and $N_t \times 1$ vectors. Furthermore, $\widetilde{\mathbf{\Sigma}}$ is a diagonal matrix of dimension $(\mathrm{rank}(\mathbf{H}) - 1) \times (\mathrm{rank}(\mathbf{H}) - 1)$ and $\widetilde{\mathbf{U}}$ and $\widetilde{\mathbf{V}}$ are corresponding unitary matrices whose dimensions are $N_r \times (\mathrm{rank}(\mathbf{H}) - 1)$ and $N_t \times (\mathrm{rank}(\mathbf{H}) - 1)$, respectively. Then, we select the precoder $\mathbf{f}$ and combiner $\mathbf{w}$ optimizing (8) as $\mathbf{v}_*$ and $\mathbf{u}_*$, respectively. As the accuracy of the MIMO channel state information (CSI) estimation performance increases, the calculated precoder and combiner converge to the optimal results.

Obviously, the Tx shall transmit the maximum power in perspective of optimizing the spectral efficiency. However, this scheme is not always beneficial for balancing with the energy efficiency since the transmit power term is in the denominator of the energy efficiency as we explained in (5). Increasing the energy efficiency is beneficial when the power of the terminal is limited, especially in case of buoying AtoN. Thus, resources should be allocated considering a trade-off relationship between the spectral efficiency and the energy efficiency [18, 30-32].

We propose a simple but intuitive resource scheduling algorithm for improving both the spectral efficiency and the energy efficiency in two stages. Since (5) is a non-convex multi-variable function, the problem for maximizing the energy efficiency is an NP hard problem [33, 34]. To solve this problem, we firstly derive the precoder and combiner which optimizes the spectral efficiency within the fixed Tx power using (9). Then, only the Tx power is mitigated while maintaining the precoder and combiner for increasing the energy efficiency. The Tx power can be adjusted within the range that satisfies the received power exceeding Rx

```
Algorithm 1 Proposed resource scheudling algorithm
Input: Channel state information $\mathbf{H}$, Rx sensitivity $P_{th}$,
       VDES bandwidth candidate set $\mathcal{B}$
Output: Precoder $\mathbf{f}$, Combiner $\mathbf{w}$,
        Tx power $P_t$, Bandwidth $B$
Define: $f(\mathcal{B}|p)$ as bandwidth set under the Rx sensitivity
        condition of $p$
First stage: Find precoder and combiner
    Set $N_L = 1$
    Do SVD on $\mathbf{H}$ accoring to (9)
    $\mathbf{f} \leftarrow \mathbf{v}_*$
    $\mathbf{w} \leftarrow \mathbf{u}_*$
    return $\mathbf{f}, \mathbf{w}, \sigma_*$
Second stage: Find transmit power and bandwidth
    $P_t \leftarrow P_{max}$
    $P_r \leftarrow \sigma_*^2 P_t$
    if Increasing energy efficiency option is activated
        Select arbitrary value $\Delta \in \left(0, P_t - \frac{P_{th}}{\sigma_*^2}\right)$
        $P_t \leftarrow P_t - \Delta$
        $P_r \leftarrow \sigma_*^2 P_t$
    end if
    $B \leftarrow \max f(\mathcal{B}|P_r)$
    return $P_t, B$
```

Fig. 2. Resource scheduling algorithm for increasing resource efficiencies in VDES

sensitivity. This gives an advantage of maintaining the same MIMO gain regardless of the Tx power. Assuming the target Rx sensitivity is P_{th}, overall resource scheduling algorithm explained in this section is represented in **Fig. 2**. In the algorithm, we consider a narrowband block-fading channel and assume the channel has the same properties throughout the band, since VDES is the narrowband system.

4. Analysis of resource efficiencies based on simulation

In this section, we evaluate the resource efficiency of VDES based on the simulation. We assume there is no interference effect from other terminals since VDES uses TDMA schemes. The antenna gain of the VDES communication link is 8 dB. The Tx antenna height is 75 m and the Rx antenna height is 10 m. Then, approximately 68.5 dB loss occurs at 1 km distance referring the result in the section 2. Moreover, we use 2, 1 W and 10 W as the values of transmit amplifier inefficiency ξ, the dynamic power per antenna P_c and the static circuit power P_s, respectively. The simulation is conducted under the condition that the number of antennas on VDES terminals is 1, 2 or 4. Then, the number of obtainable combinations of the diversity gain is 1, 2, 4, 8 or 16. In the conventional SISO VDES environment, the value of the diversity gain is 1 which means there is no gain from MIMO. For multiple antenna cases, a half-wavelength inter-element spacing d is considered. In the system, the terminal candidates can be terrestrial shore stations, ship stations, AtoN, etc. We assume the propagation model as an $N_{sc} = 3$ scattering environment in the simulation. Also, the value of Rician K-factor is 10. In addition, Tx and Rx can obtain CSI, so that the precoder and combiner using (9) are applied to the Tx and Rx sides, respectively. Lastly, all simulation results are averaged over 1000 random channel iterations.

4.1 Spectral efficiency evaluation

We fix the Tx power to 50 W to evaluate the spectral efficiency. **Fig. 3** shows the spectral efficiency of VDES for different diversities while varying the distance between Tx and Rx from 1 to 100 km. As expected, the spectral efficiency decreases as the distance increases since the received power strength is reduced. However, we can also figure out that the diversity gain compensates for the decrease in the spectral efficiency. In other words, as the diversity gain increases, the spectral efficiency improves at the same distance, since overall received signal-to-nose ratio (SNR) is increased. For instance, the achievable spectral efficiency at 85 km when the diversity gain equals to 16 is the same as the spectral efficiency at 50 km when the value of the diversity gain is 1. In other words, the coverage can be expanded by 35 km while maintaining the same data rate. Furthermore, if the obtainable diversity gain is 16, the data rate can be increased up to approximately 30 % at the 50 km compared to the typical SISO case.

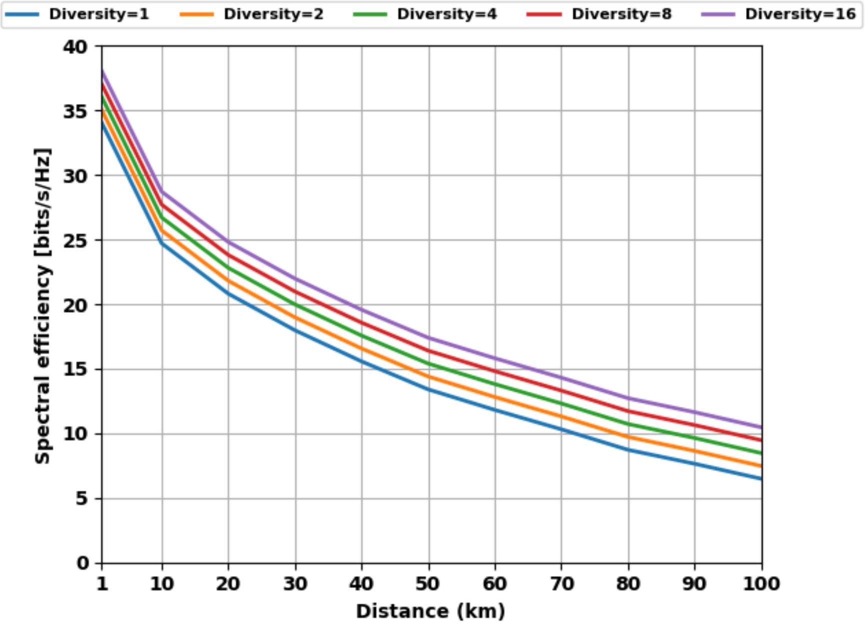


Fig. 3. Simulation result of spectral efficiency vs. distance

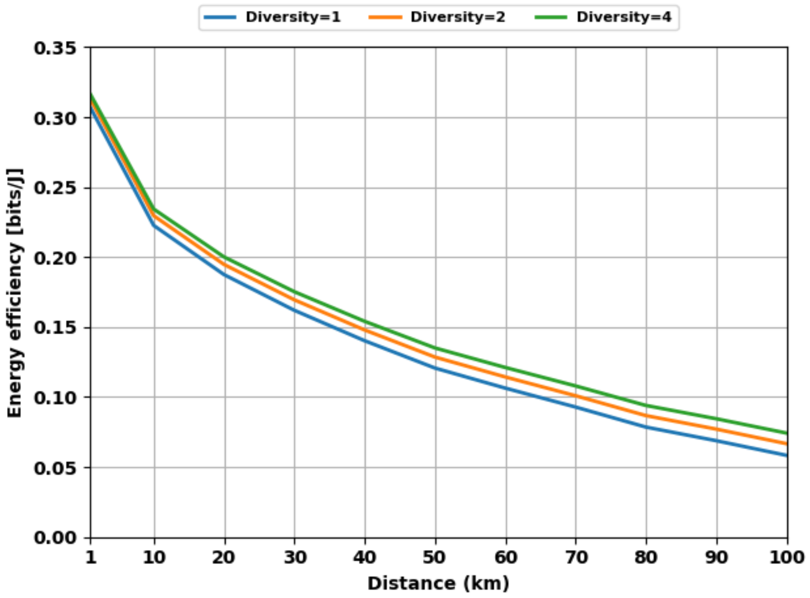


Fig. 4. Simulation result of energy efficiency vs. distance

4.2 Energy efficiency evaluation

In the same way as analyzing the spectral efficiency, we fix the Tx power to 50 W to evaluate the energy efficiency. Without loss of generality, the number of Rx antennas is fixed to 1, so that only the Tx diversity effect considered. **Fig. 4** shows the energy efficiency of VDES for different diversities while varying the distance between Tx and Rx from 1 to 100 km. Similar to the spectral efficiency, the energy efficiency decreases as the distance increases since the spectral efficiency is reduced. However, the diversity gain from multiple antennas enhances the spectral efficiency, so that we can check the diversity gain is also beneficial for improving the energy efficiency, too. Here, we only consider the Tx diversity effect, but the energy efficiency can be even improved as the number of Rx antennas increases, in the same way.

4.3 Trade-off relationship between spectral efficiency and energy efficiency

To analyze the trade-off relationship between the spectral efficiency and the energy efficiency, we fix to the distance between Tx and Rx to 50 km while varying the Tx power 0 to 50 W. The spectral efficiency and the energy efficiency according to the Tx power is illustrated in **Fig. 5**. The solid lines represent the spectral efficiency and the dashed lines describe the energy efficiency. As we explained in section 3, the spectral efficiency monotonically increases with the Tx power. However, we can check the different trend in case of the energy efficiency. In the range of very low Tx power lower than around 1 W, the energy efficiency increases as the Tx power increases. This is because the spectral efficiency is included in power-limited (low SNR) region in the very low Tx power range [15, 35]. Therefore, the energy efficiency also follows the trend of the spectral efficiency's curve, in the low Tx power region. On the other hand, in the outside of the power-limited region, the energy efficiency monotonically decreases with regard to the Tx power since the rate of increase of the spectral efficiency can no longer compensate for that of total consumed power. To be more specific, the spectral efficiency increases logarithmically while the consumed power increases linearly with respect

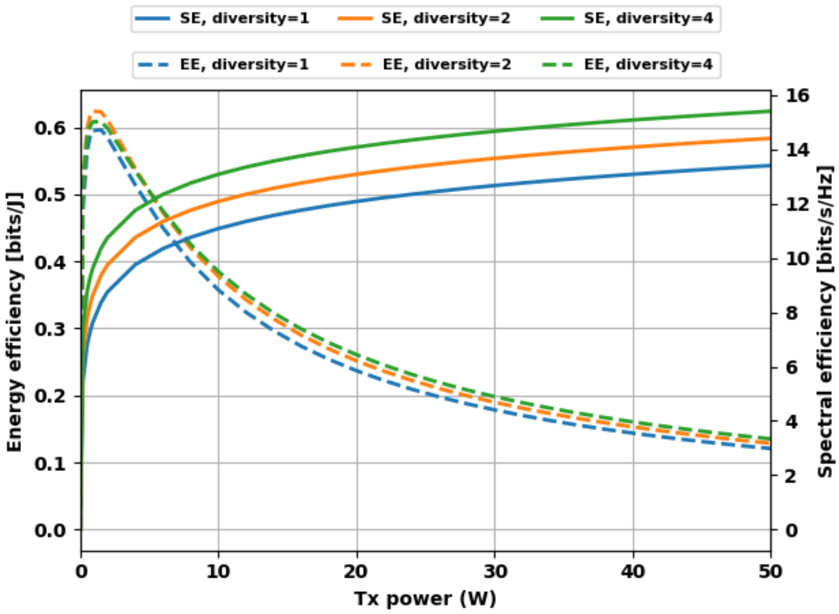


Fig. 5. Trade-off relationship between the spectral efficiency and the energy efficiency according to the Tx power at 50 km distance

to Tx power, which leads the decrease in the overall energy efficiency in the outside of the power-limited region. Incorporating with analysis of simulation results, we can check the following advantages using diversity in VDES.

· Utilizing a higher diversity gain improves both spectral and energy efficiencies under the same Tx power constraint.

· A higher diversity gain could give enhanced resource efficiencies even though Tx consumes the lower Tx power. Otherwise, it enables more effective Tx power allocation which can increase the energy efficiency.

4.4 Resource efficiencies according to the channel estimation accuracy

In previous subsections, we assumed the perfect CSI can be obtainable in both Tx and Rx sides. To analyze the resource efficiencies from channel estimation accuracy, we use the following equation to reflect imperfect CSI [36-38]:

$$\widehat{\mathbf{H}} = \rho\mathbf{H} + \sqrt{1-\rho^2}\mathbf{E}, \tag{10}$$

where $\widehat{\mathbf{H}}$ represents the estimated channel, the correlation coefficient ρ denotes the constant with a value $0 \le \rho \le 1$ meaning the average accuracy of the channel estimation and $\mathbf{E} \sim CN(0, ||\mathbf{H}||^2)$ is a complex Gaussian random matrix uncorrelated with $\mathbf{H}$.

We compare the trade-off curves between the spectral efficiency and the energy efficiency at the 50 km distance between Tx and Rx as covered in the previous subsection. **Fig. 6** illustrates the resource efficiencies with the diversity gain of 4 according to the different values of ρ. In addition, we use resource efficiency curves with the diversity gain of 1 for reference. The solid lines represent the spectral efficiency and the dashed lines describe the energy efficiency. As expected, overall resource efficiencies are improved as the average accuracy of the channel

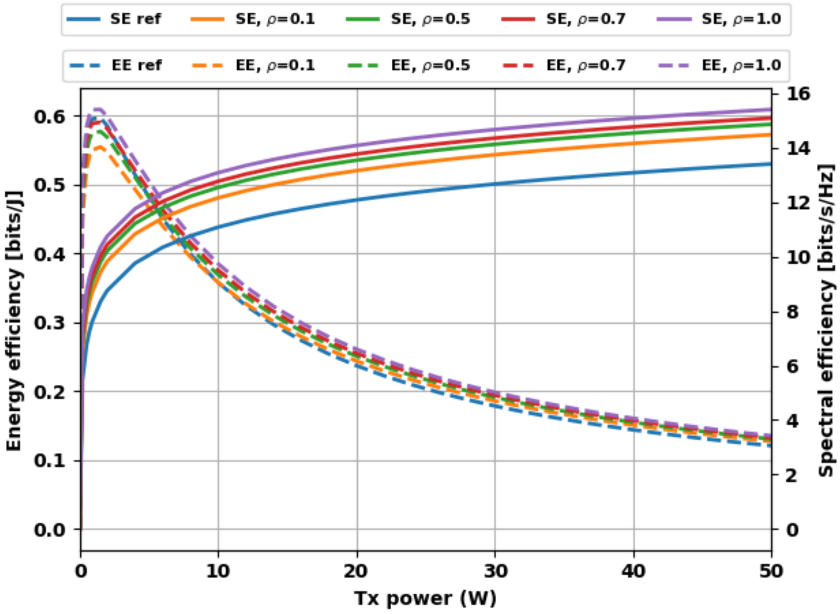


Fig. 6. Resource efficiencies comparison according to the channel estimation performance

estimation increases. Therefore, the channel estimation accuracy is also an important factor to improve the performance. Interestingly, even though the estimated CSI performance is degraded, the proposed MIMO-aided resource scheduling can improve the resource efficiencies to some extent. Moreover, the resource efficiencies with low CSI correlation coefficients (i.e., $\rho = 0.1$) are still superior to those of the conventional SISO reference condition.

5. Conclusion

In this paper, we presented the VDES system model and proposed the MIMO-aided resource scheduling method to increase the spectral efficiency and the energy efficiency. First, we described and analyzed the propagation loss model and the MIMO feasibility for VDES. We introduced two key metrics in communication systems which are the spectral efficiency and the energy efficiency. For the reliable communication and considering the LOS path prevalent maritime channel condition, maximizing the diversity gain is reasonable by introducing an MIMO on VDES. Second, installing a large number of antennas may not be feasible due to the large wave length of VDES, but we checked overall resource efficiencies can be improved the diversity gain from a small number of antennas based on the proposed resource scheduling algorithm compared to the typical SISO case. From the simulation results, we discussed that proposed scheduling algorithm allows to increase data rate or to expand the overall VDES coverage. Also, we checked the energy efficiency can be improved by adjusting the Tx power from the trade-off relationship. Lastly, we analyzed the resource efficiencies related to the channel estimation performance and the proposed method still performing well under the low channel precision.

References

[1] IALA, “Maritime radio communication plan,” Saint Germain en Laye, France, Dec. 2017. [Online] Available: https://www.iala-aism.org/product/maritime-radio-communications-plan/, Accessed: 2022-06-28.

[2] IALA Guideline G1139 Ed. 3, “The technical specification of VDES,” Jun. 2019.

[3] ITU-R M.2092.1, “Technical characteristics for a VHF data exchange system in the VHF maritime mobile band,” Feb. 2022.

[4] M. Wirsing, A. Dammann and R. Raulefs, “Positioning performance of VDES R-Mode,” in *Proc. of 94th IEEE Veh. Technol. Conf. (VTC)*, pp. 1-6, 2021. Article (CrossRef Link)

[5] X. Hu, B. Lin, P. Wang and Y. Yang, “A novel mac protocol for VDES in space-air-ground-sea integrated networks,” in *Proc. of Int. Conf. Space-Air-Ground Comput. (SAGC)*, pp. 60-61, 2020. Article (CrossRef Link)

[6] Q. Hu, J. Cao, G. Gao, L. Xu and M. Song, “Study of an evaluation model for AIS receiver sensitivity measurements,” *IEEE Trans. Instrum. Meas.*, vol. 69, no. 4, pp. 1118-1126, Apr. 2020. Article (CrossRef Link)

[7] N. Forti, L. M. Millefiori, P. Braca and P. Willett, “Prediction of vessel trajectories from AIS data via sequence-to-sequence recurrent neural networks,” in *Proc. of IEEE Int. Conf. Acoust. Speech Signal Process. (ICASSP)*, pp. 8936-8940, 2020. Article (CrossRef Link)

[8] R. W. Liu, J. Nie, S. Garg, Z. Xiong, Y. Zhang and M. S. Hossain, “Data-driven trajectory quality improvement for promoting intelligent vessel traffic services in 6G-enabled maritime IoT systems,” *IEEE Internet Things J.*, vol. 8, no. 7, pp. 5374-5385, Apr. 2021. Article (CrossRef Link)

[9] H. Guo, J. Li, J. Liu, Na. Tian and N. Kato, “A survey on space-air-ground-sea integrated network security in 6G,” *IEEE Commun. Surv. Tutor.*, vol. 24, no. 1, pp. 53-87, 1st Quart., 2022. Article (CrossRef Link)

[10] A. Zollch, D. Palma, K. Kansanen, K. Fjørtoft, J. Sousa, K. H. Johansson, Y. Jiang, H. Dong and T. A. Johansen, “Survey on communication and networks for autonomous marine systems,” *J. Intell. Robotic Syst.*, vol. 95, pp. 789-813, Sep. 2019. Article (CrossRef Link)

[11] F. Bekkadal, “Future maritime communications technologies,” in *Proc.* of *OCEANS*, *EUROPE*, Bremen, Germany, pp. 1-6, 2009. Article (CrossRef Link)

[12] ITU-R M.1371-5, “Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime frequency band,” Feb. 2014.

[13] ITU-R P.1546-6, “Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 4000 MHz,” Aug. 2019.

[14] A. Goldsmith, S. A. Jafar, N. Jindal and S. Vishwanath, “Capacity limits of MIMO channels,” *IEEE J. Sel. Areas. Commun.*, vol. 21, no. 5, pp. 684-702, Jun. 2003. Article (CrossRef Link)

[15] A. M. Sayeed and V. Raghavan, “Maximizing MIMO capacity in sparse multipath with reconfigurable antenna arrays,” *IEEE J. Sel. Top. Signal Process.*, vol. 1, no. 1, pp. 156-166, Jun. 2007. Article (CrossRef Link)

[16] A. Mishra, Y. Mao, O. Dizdar and B. Clerckx, “Rate-splitting multiple access for downlink multiuser MIMO: Precoder optimization and PHY-layer design,” *IEEE Trans. Commun.*, vol. 70, no. 2, pp. 874-890, Feb. 2022. Article (CrossRef Link)

[17] A. A. Abdulkafi, T. S. Kiong, I. K. Sileh, D. Chieng and A. Ghaleb, “A survey of energy efficiency optimization in heterogeneous cellular networks,” *KSII Transactions on Internet and Information Systems*, vol. 10, no. 2, pp. 462-483, Feb. 2016. Article (CrossRef Link)

[18] Y. Chen, S. Zhang, S. Xu and G. Y. Li, “Fundamental tradeoffs on green wireless networks,” *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 30-37, Jun. 2011. Article (CrossRef Link)

[19] O. Blume, D. Zeller and U. Barth, “Approaches to energy efficient wireless access networks,” in *Proc. of 4th Int. Symp. Commun. Control Signal Process. (ISCCSP)*, pp. 1-5, 2010. Article (CrossRef Link)

[20] J. Xu and L. Qiu, “Energy efficiency optimization for MIMO broadcast channels,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 690-701, Feb. 2013. Article (CrossRef Link)

[21] X. Song, L. Dong, X. Huang, L. Qin and X. Han, "Energy-efficient power allocation based on worst-case performance optimization under channel uncertainties," *KSII Transactions on Internet and Information Systems*, vol. 14, no. 11, pp. 4595-4610, Nov. 2020. Article (CrossRef Link)

[22] Y. Yang, R. Blum and S. Sfar, "Antenna selection for MIMO systems with closely spaced antennas," *EURASIP J. Wireless Commun. Netw.*, vol. 2009, Mar. 2009. Article (CrossRef Link)

[23] S. Sanayei and A. Nostratinia, "Antenna selection in MIMO systems," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 68-73, Oct. 2004. Article (CrossRef Link)

[24] W. Lee, H. Yang and B. Jang, "A high isolation 4 by 4 MIMO antenna for LTE mobile phones using coupling elements," *KSII Transactions on Internet and Information Systems*, vol. 11, no. 12, pp. 5745-5758, Dec. 2017. Article (CrossRef Link)

[25] X. Su, H. Yu, K. Chang, S. Kim and Y. Lim, "Case study for ship ad-hoc networks under a maritime channel model in coastline areas," *KSII Transactions on Internet and Information Systems*, vol. 9, no. 10, pp. 4002-4014, Oct. 2015. Article (CrossRef Link)

[26] W. U. Bajwa, J. Haupt, A. M. Sayeed and R. Nowak, "Compressed channel sensing: A new approach to estimating sparse multipath channels," *Proc. IEEE*, vol. 98, no. 6, pp. 1058-1076, Jun. 2010. Article (CrossRef Link)

[27] A. M. Sayeed, "Deconstructing multiantenna fading channels," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2563-2579, Oct. 2002. Article (CrossRef Link)

[28] L. Zheng and D. N. C. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Inf. Theory*, vol. 49, no. 5, pp. 1073-1096, May 2003. Article (CrossRef Link)

[29] D. N. C. Tse and P. Viswanath, *Fundamentals of Wireless Communications*, Cambridge, U.K.: Cambridge Univ. Press, 2005.

[30] C. Xiong, G. Y. Li, S. Zhang, Y. Chen and S. Xu, "Energy- and spectral-efficiency tradeoff in downlink OFDMA networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 11, pp. 3874-3886, Nov. 2011. Article (CrossRef Link)

[31] O. Amin, E. Bedeer, M. H. Ahmed and O. A. Dobre, "Energy efficiency-spectral efficiency tradeoff: A multiobjective optimization approach," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 1975-1981, Apr. 2016. Article (CrossRef Link)

[32] R. Aslani and M. Rasti, "A distributed power control algorithm for energy efficiency maximization in wireless cellular networks," *IEEE Wireless Commun. Lett.*, vo. 9, no. 11, pp.1975-1979, Nov. 2020. Article (CrossRef Link)

[33] S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambridge, U.K.: Cambridge Univ. Press, 2004.

[34] S. A. Cook, "The complexity of theorem-proving procedures," in *Proc. of 3rd Annu. ACM Symp. Theory Comput.*, New York, USA, pp. 151-158, 1971. Article (CrossRef Link)

[35] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wirel. Pers. Commun.*, vol. 6, pp. 311-335, 1998. Article (CrossRef Link)

[36] K. S. Ahn and R. W. Heath, "Performance analysis of maximum ratio combining with imperfect channel estimation in the presence of cochannel interference," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1080-1085, Mar. 2009. Article (CrossRef Link)

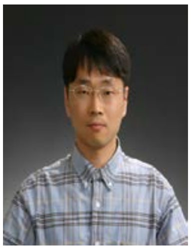
[37] H. A. Suraweera, P. J. Smith and M. Shafi, "Capacity limits and performance analysis of cognitive radio with imperfect channel knowledge," *IEEE Trans. Veh. Technol.*, vol. 59, no. 4, pp. 1811-1822, May 2010. Article (CrossRef Link)

[38] T. M. Hoang, X. N. Tran, B. C. Nguyen and L. T. Dung, "On the performance of MIMO full-duplex relaying system with SWIPT under outdated CSI," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 15580-15593, Dec. 2020. Article (CrossRef Link)

Juhyoung Sung received the B.S. degree (as a valedictorian) in Computer and Communication Engineering (currently Computer Science) from Korea University, Seoul, South Korea, in 2015; the M.S. degree in Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 2019. From 2015 to 2017, he was with the ROK Army as a lieutenant working on C4I systems and information security. He joined Samsung Electronics, Suwon, South Korea, in 2019, as a member of engineer in charge of LTE/NR MAC scheduling algorithm. Since 2021, he has been working as a senior researcher at Korea Electronics Technology Institute (KETI), Seoul, South Korea. His current research interests include wireless communication systems optimization, signal processing and reinforcement learning.

Sungyoon Cho received the B.S., M.S.and Ph.D. degrees in electrical and electronic engineering from Yonsei University, Seoul, Korea, in 2006, 2008, and 2013, respectively. From 2013 to 2020, he was with Samsung Electronics, Korea, as a Staff Engineer to research cellular communication systems and develop 4G and 5G modem chipset. Since 2020, he has been with Korea Electronics Technology Institute (KETI) as a Principal Researcher to develop the advanced technologies for embedded network. His research interests are in the fundamental aspects of wireless communication and signal processing, and learning algorithms for practical application.

Wongi Jeon received the B.S., M.S., and Ph.D. degrees in electronic engineering from Chung-Ang University, Seoul, Korea, in 1994, 1996, and 1999, respectively. In 1999, he was a BK contract professor at School of Electrical and Electronic Engineering in Chung-Ang University. In 2001, he joined the Korea Electronics Technology Institute (KETI), Korea, where he is presently a chief researcher. His research interests are in the area of intelligent signal processing and wireless digital communications, especially for multicarrier transmission systems.



Kyungwon Park received the B.S and M.S. degrees in electrical engineering from Chung-Ang University, Seoul, Korea, in 1999 and 2001, respectively, and Ph. D. degrees in the school of electrical and electronic Engineering from Chung-Ang University in 2005. Since 2005, he has been working at Korea Electronics Technology Institute (KETI), Korea, where he is presently a principal researcher of Smart Network Research Center. His research interests are in the areas of wireless/wired communications system design and multiple antenna systems including multiple-input multiple-output systems and smart antenna systems.

Sang Jung Ahn received Ph. D. degree in Biotechnology, Pukyong National University, Korea in 2005. He is working as a senior researcher in Technical Certification & Evaluation Team in Korea Institute of Marine Science & Technology Promotion (KIMST), Korea. He has authored or co-authored more than 28 articles in peer reviewed journals, and also published three Korean patents. His present research interest includes ICT-based digital convergence technologies in Maritime and Fisheries, Digital twins in personalize medicine, Big-data Analysis, Computational Intelligence Tools in Bioinformatics.

Kiwon Kwon received B.S. and M.S. degrees in computer engineering from Kwangwoon University, Korea, in 1997 and 1999, respectively. He also received the Ph.D. degree in the School of Electrical & Electronics Engineering from Chung-Ang University, Korea, in 2011. In 1999, he joined in Korea Electronics Technology Institute (KETI), Korea, where he is presently a chief researcher at the Smart Network Research Center. His research interests are in the area of wireless/mobile communications and ICT convergences.