

# MIMO-aided Efficient Communication Resource Scheduling Scheme in VDES

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## 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.

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

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## 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.

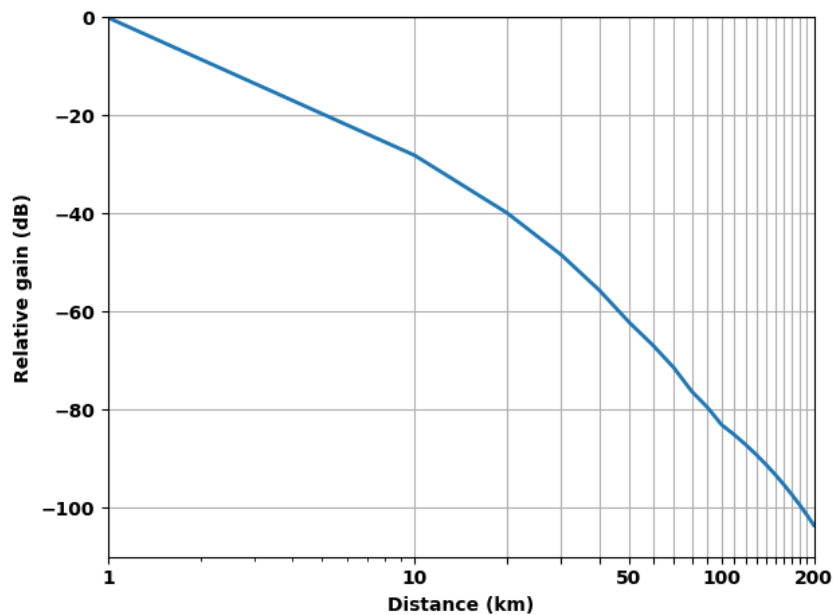
**Table 1.** Center frequency and application in each VDES channel

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:

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

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

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \quad (2)$$

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  $\alpha$  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 additive white gaussian noise (AWGN) with a variance  $\sigma_n^2$ . 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:

$$\mathbf{r} = \mathbf{W}^H \mathbf{y} = \mathbf{W}^H \mathbf{H} \mathbf{F} \mathbf{s} + \mathbf{W}^H \mathbf{n}, \quad (3)$$

where  $\mathbf{r}$  is the  $N_r \times 1$  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  $\mathbf{s}$  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  $\eta^{SE}$  can be calculated as follows [14-16]:

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

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  $\|\mathbf{F}\|_F^2 = N_L$ ,  $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \frac{P_t}{N_L} \mathbf{I}_{N_L}$  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  $\eta^{EE}$  can be calculated as follows:

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

where  $\xi$  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  $\mathbf{H}$  can be written as

$$\mathbf{H} = \sqrt{\frac{K_R}{1 + K_R}} \sqrt{N_t N_r} \beta_0 \mathbf{a}_r(\psi_0^r) \mathbf{a}_t(\psi_0^t)^H + \sqrt{\frac{1}{1 + K_R}} \sqrt{\frac{N_t N_r}{N_{sc}}} \sum_{i=1}^{N_{sc}} \beta_i \mathbf{a}_r(\psi_i^r) \mathbf{a}_t(\psi_i^t)^H, \quad (6)$$

where  $K_R$  is the Rician K-factor and  $N_{sc}$  is the number of scattering clusters and  $\beta_i$  is the complex gain of the  $l^{th}$  path. The angular variables  $\psi_i^r$  and  $\psi_i^t$  are angle of arrival (AoA) and angle of departure (AoD) of the  $l^{th}$  path, respectively. Additionally,  $\mathbf{a}_r(\psi_i^r)$  and  $\mathbf{a}_t(\psi_i^t)$  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:

$$\mathbf{a}(\psi) = \frac{1}{\sqrt{N}} [1, e^{jk d \psi}, \dots, e^{jk(N-1)d\psi}]^T, \quad (7)$$

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  $\mathbf{F}$  and combining matrix  $\mathbf{W}$  as the precoding vector  $\mathbf{f}$  and combining vector  $\mathbf{w}$ ,

respectively. Then, the spectral efficiency described in (4) is reformulated as follows:

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

### 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  $N_r \times \text{rank}(\mathbf{H})$  unitary matrix and  $\mathbf{\Sigma}$  is a diagonal matrix of dimension  $\text{rank}(\mathbf{H}) \times \text{rank}(\mathbf{H})$  and  $\mathbf{V}$  is an  $N_t \times \text{rank}(\mathbf{H})$  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:

$$\mathbf{H} = \begin{bmatrix} \mathbf{u}_* & \tilde{\mathbf{U}} \end{bmatrix} \begin{bmatrix} \sigma_* & \mathbf{0} \\ \mathbf{0} & \tilde{\mathbf{\Sigma}} \end{bmatrix} \begin{bmatrix} \mathbf{v}_*^H \\ \tilde{\mathbf{V}}^H \end{bmatrix}, \quad (9)$$

where  $\sigma_*$  is the maximum singular value and  $\mathbf{u}_*$  and  $\mathbf{v}_*$  are corresponding  $N_r \times 1$  and  $N_t \times 1$  vectors. Furthermore,  $\tilde{\mathbf{\Sigma}}$  is a diagonal matrix of dimension  $(\text{rank}(\mathbf{H}) - 1) \times (\text{rank}(\mathbf{H}) - 1)$  and  $\tilde{\mathbf{U}}$  and  $\tilde{\mathbf{V}}$  are corresponding unitary matrices whose dimensions are  $N_r \times (\text{rank}(\mathbf{H}) - 1)$  and  $N_t \times (\text{rank}(\mathbf{H}) - 1)$ , 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

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**Algorithm 1** Proposed resource scheduling algorithm
 

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**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  $\mathbf{H}$  according 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**  $P_t, B$

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**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  $\xi$ , 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-noise 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.

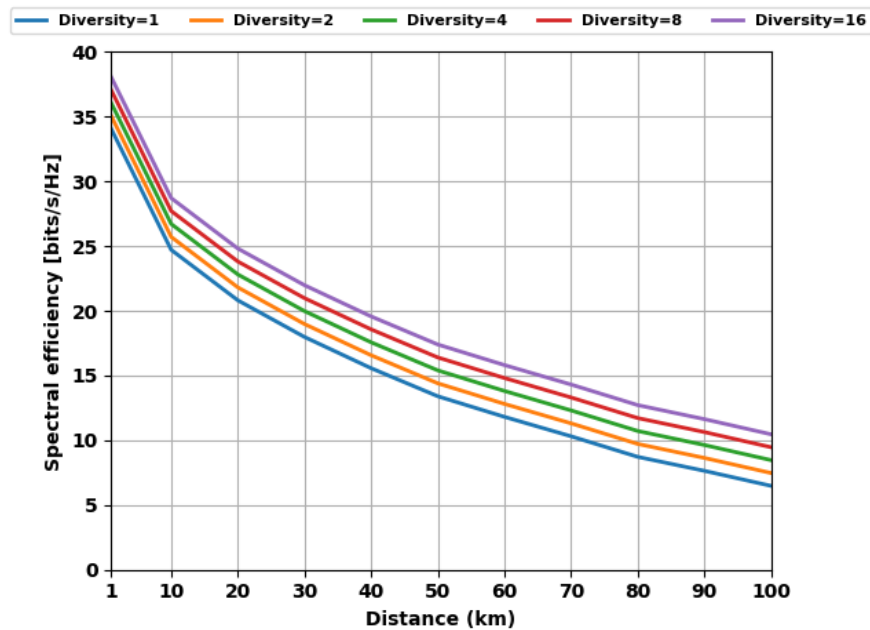


Fig. 3. Simulation result of spectral efficiency vs. distance

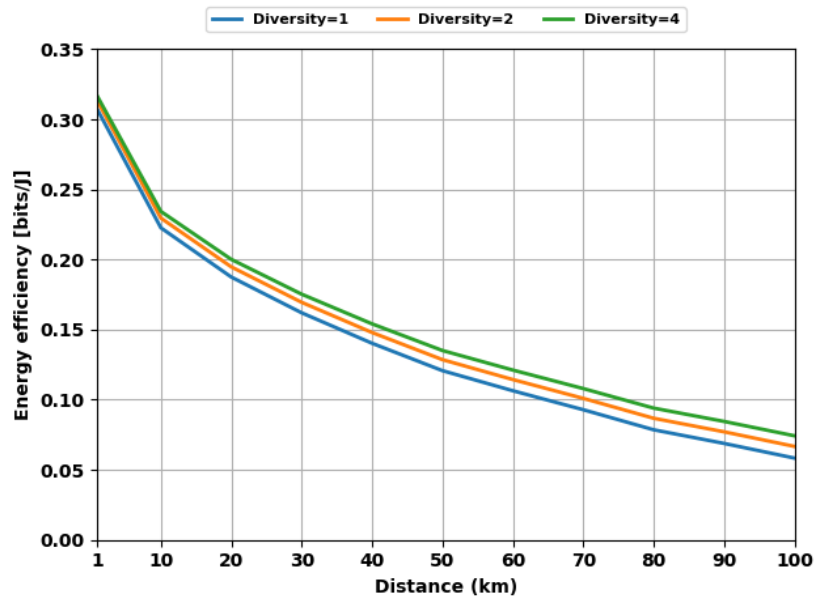


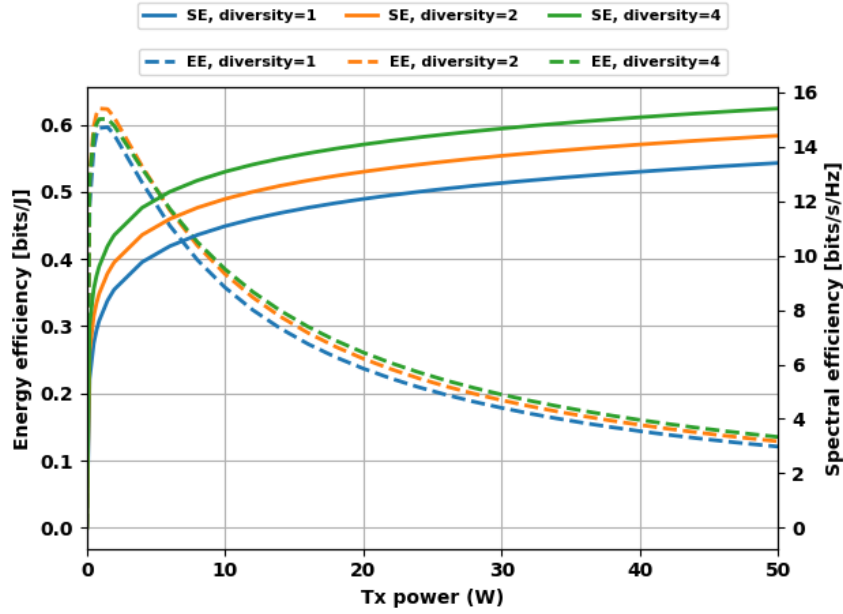
Fig. 4. Simulation result of energy efficiency vs. distance

## 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 is 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 the distance between Tx and Rx to 50 km while varying the Tx power from 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 the 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]:

$$\hat{\mathbf{H}} = \rho \mathbf{H} + \sqrt{1 - \rho^2} \mathbf{E}, \quad (10)$$

where  $\hat{\mathbf{H}}$  represents the estimated channel, the correlation coefficient  $\rho$  denotes the constant with a value  $0 \leq \rho \leq 1$  meaning the average accuracy of the channel estimation and  $\mathbf{E} \sim \mathcal{CN}(0, \|\mathbf{H}\|^2)$  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  $\rho$ . 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

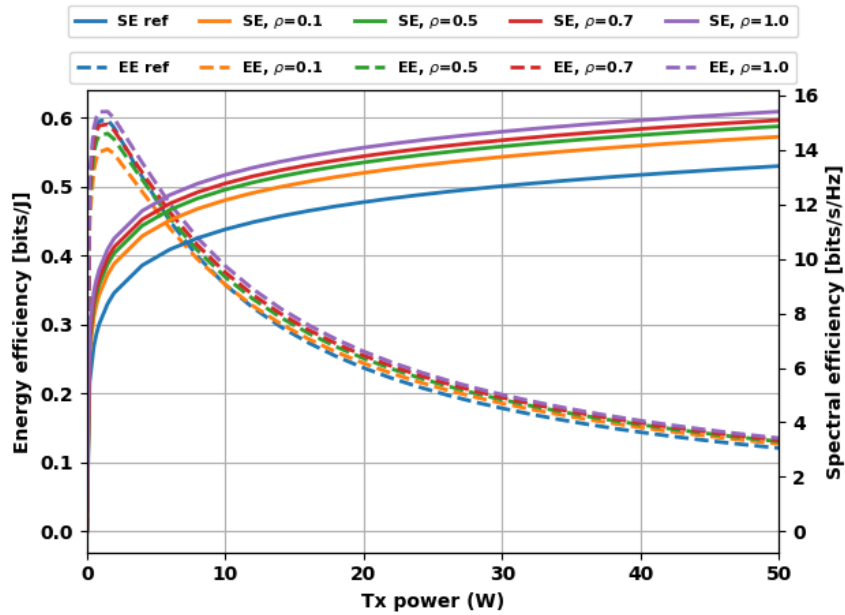


Fig. 6. Resource efficiencies comparison according to the channel estimation performance

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.

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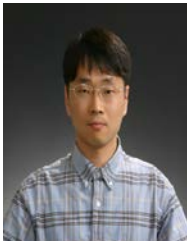
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