Virtual MIMO Transmissions for Underwater Acoustic Communications with Moving Platforms

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ABSTRACT

Underwater acoustic communications with multiple autonomous underwater vehicles (AUVs) is critically important because it supports the coordinated team mission in the ocean. AUVs, as compact mobile platforms, have limited computing resources and physical space, thus impeding the adoption of spectrally-efficient acoustic communication strategies including multi-antennas transmissions. For example, only a single transmitter is installed on an AUV. Allocation of limited communication resources is also a critical issue when multiple vehicles are involved in the mission. Here, we propose a virtual multiple-input/multiple-output (MIMO) strategy for communications with multiple AUVs. The virtual MIMO strategy selects the transmitters from a subset of AUVs to form a virtual transmit array. The objective is to increase spectral efficiency for the uplink, referring to the transmission connection from the AUVs to moored communication base stations. A user selection algorithm is used to determine the active AUV subset for data transmissions, to ensure the fairness in access to the time slots. Adaptive modulation is combined to improve the throughput further. The user selection and modulation choice are decided by predicted data rates derived from the communication range rather than the channel state information, thus avoiding the high overhead. The performance of the underwater virtual MIMO scheme has been examined in computer simulations, where the vehicle-specific mission tracks, simulated acoustic communication channels from BELLHOP, and time reversal communication receivers were used. The simulation results showed that the proposed algorithm achieved a high overall throughput in a scenario with five AUVs. Further, the assignment fairness of time slots was considered while maximizing the overall throughput.

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KEYWORDS

Underwater acoustic communications, autonomous underwater vehicles, adaptive modulation, resource allocation, user selection

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1 INTRODUCTION

Reliable underwater acoustic communications with multiple autonomous underwater vehicles (AUVs) is critically important. It supports communications among multiple AUVs, which in turn enables AUVs to coordinate for complicated tasks. For example, in [17], multiple AUVs moved along parallel paths to inspect underwater oil pipeline. During the mission, the AUVs needed to exchange the location and assignment information. In [9], a team of AUVs was dynamically assigned to sub-areas to complete the mine countermeasures mission of a large area. Communications with the individual AUVs was necessary for track optimization. Here, we focus on how to achieve high throughput in acoustic communications with multiple AUVs.

Underwater acoustic communications among multiple AUVs have a number of challenges. As well known, acoustic communications is often associated with difficulties such as limited bandwidth, low and variable data rates, large communication latency, etc. The compact mobile platform introduces additional constraints. First of all, the AUVs have limited physical space, computing resources, and power. These characteristics make difficult the adoption of spectral-efficient acoustic communication strategies including multi-antennas systems. For example, only a single transmitter is often installed on an AUV. Another problem is how to allocate communication resources among the multiple AUVs communications in a fair way in light of limited communications assets in terms of bandwidth and time. Here we apply the concept of adaptive modulation and virtual multiple-input/multiple-output (MIMO) to address the challenges.

Adaptive modulation has been discussed in underwater acoustic communications [8][15]. In [10], the performance of adaptive transmission with mobile marine platform was investigated. Both communication reliability and spectral efficiency can be improved in the time-varying underwater acoustic channel through adaptation of modulation schemes. Often a feedback loop is required. Before transmissions, the transmitter needs the channel state information or transmission directives from the receiver to adjust to the channel condition.

MIMO communications have long been investigated in underwater acoustic communications for single and multi-carrier systems. Instead of using one antenna, the MIMO system employs multiple antennas at both the transmitter and receiver units. The effectiveness of MIMO has been demonstrated with achieved data rates of several tens of kbps. So far, limited efforts have been directed to apply the MIMO techniques to compact platforms like AUVs.

As an alternative scheme, virtual MIMO technique groups multiple users to form a virtual antenna array to achieve MIMO communications. Therefore, it does not require either the transmitter or receiver units to be equipped with multiple antennas. The theoretical gains of MIMO transmissions are still available for distributed antennas on different users [5].

Most efforts on virtual MIMO techniques have so far been confined to the area of wireless radio-frequency communications. In [3], a virtual MIMO communication structure has been proposed for LTE uplink transmission. In the underwater environment, a two-user multi-user receiver was investigated in [2]. The developed receiver separated data packets in the scenario where one user was moving while the other was stationary.

In the virtual MIMO transmissions with multiple AUVs, allocation of the communication resources, including bandwidth and time slots, is an important research issue. The overall objective is to maximize the overall efficiency while ensuring the fairness. The resource allocation is formulated into an optimization problem of user selection. Suitable users can be selected based on different optimization goals, such as maximized throughput. In the time-division mode, the task is to determine the subset of the AUVs for transmissions. The subset of active AUVs are treated as a multi-transmit-antenna system. So far, resource allocation in the virtual MIMO framework has not been addressed in the underwater environment.

The combination of the virtual MIMO strategy and adaptive modulation provides new opportunities in underwater acoustic communication. The virtual MIMO strategy allows multiple users to transmit data simultaneously. This leads to an increase of throughput. The throughput can be further improved by dynamically allocating more communication resources to users with better channel condition. Each of the selected users can fine-tune their modulation schemes to achieve a trade-off between the reliability and high data rates.

The combination of virtual MIMO transmissions and adaptive modulation requires more feedback. First of all, a subset of AUV users needs to be selected. Further, modulation orders need to be determined. If the channel state information is used as the feedback, transmissions of the channel state information would introduce a large amount of overhead, since there are multiple AUVs in the missions. Thus, a low-overhead strategy is needed.

In this paper, we study the virtual MIMO techniques with multiple AUVs in the ocean environment. The application scenario is that multiple AUVs performs their subsea missions where a control center is present. We select a subset of active users to form a virtual transmitter array. Each active user also adjusts its modulation order. Our proposed method selects the active users and their modulation orders based on data rates predictions from the AUV range information. The method avoids the large overhead, which comes the method that uses the channel state information as the feedback.

The user selection maximizes the overall throughput while ensuring fairness to each AUV [3]. The fairness is controlled by a variable weighting factor. The weighting factor of a user is adjusted based on the user's average data rate. Users with higher average data rate is assigned with small weighting factors. So this user is allocated less communication time resources. The users with low average rates may be assigned with more time slots for the sake of the fairness. We predict the data rate of the AUVs of next time slots based on an acoustic model and the environmental parameters. A subset of AUVs that maximizes the weighted throughput is selected to transmit during the next time slot. Note that a comprehensive version of the model-based method was developed in [11]. However, it was not used in the virtual MIMO setting. To support virtual MIMO transmissions, a time reversal equalizer is adopted for signal separation and inter-symbol interference cancellation. A serial interference cancellation scheme is employed to suppress co-channel interference in the virtual MIMO framework.

The major efforts of this paper are summarized as follows. First, we proposed to apply the virtual MIMO concept to the scenario where multiple AUVs communicate underwater. Adaptive modulation was combined with Virtual MIMO transmissions to achieve a high throughput for the mobile underwater network. Second, the user selection problem in the virtual underwater MIMO framework has been addressed. Third, we simulated a scenario with five AUVs to examine the performance of the proposed algorithms.

The paper is organized as follows. In Section 2, we describe an application scenario that involves multiple AUVs. In Section 3, we introduce the virtual MIMO transceiver structure. In Section 4, we describe the proposed user selection algorithm. In Section 5, we demonstrate the performance of the proposed virtual MIMO underwater acoustic communications with computer simulations. In Section 6, we provide concluding remarks.

2 APPLICATION SCENARIO

Cooperation of multiple AUVs supports execution of complicated missions in ocean sampling[4]. In this scenario, the sampling mission is divided into multiple sub-tasks. Each AUV is often allocated with one sub-task. In [1], three AUVs were considered to navigate in parallel tracks to survey the ocean temperature. By utilizing the AUV team, the sampling cost in terms of energy and time was minimized. In [4], a fleet of AUVs were deployed for ocean sampling mission in the Monterey Bay, California. The prescribed fleet formation was maintained despite periods of strong currents.

Coordination among a group of AUVs requires communication support. We consider the case where a control center is used to support the coordination of the AUVs. Communication between the AUVs and the control center has two directions, uplinks and downlinks. Via the uplinks, the AUVs send signals to the control center. Via the downlinks, the control center transmits instructions to the AUVs. In this paper, we focused on the communication issues related to the uplinks.

The two main issues with the uplinks are the overall throughput and fairness. The communication resource need to be allocated among AUVs to maximize the system throughput. Further, each AUV should have their fair share of opportunities for data transmissions. We propose an user selection algorithm to ensure both objectives.

In the application scenario, the following assumptions are used. First, the control center has reliable downlink communications with the AUVs. The control commands, to select active AUV users and the related modulation schemes, are sent to the AUVs by the downlinks. Second, the locations of the AUVs are known by the control center. Third, the user selection commands can be directed to the AUVs in a timely fashion. One way is to use the downlinks at a different frequency band to send the AUV transmission directives. In addition, it is assumed that the control center knows the error rates of the uplinks from all the AUVs.

3 VIRTUAL MIMO UNDERWATER ACOUSTIC COMMUNICATIONS

We consider uplink communications in the application scenario stated in Section 2. We assume the total number of AUVs in the mission is N_V. We select a total of N_T active users for each time slot. Each AUV is equipped with a single transducer for data communications. In the virtual MIMO scheme, a subset of the AUVs are selected to form a transmitter array. The transceiver structure is shown in Fig. 1. At the transmitter side, the information bits are modulated and then transmitted via acoustic waves. The modulations order is adjusted based on the commands from the control center. Note that these selected AUVs transmit asynchronously, i.e., sending out their packets in a un-synchronized way.

The transmitted signal propagates through the underwater acoustic channel, where multipath is one of the limiting feature for high data communication. At the receiver side, multiple data streams that are emitted from the underway AUVs are received by an receiving array. Assume N_R hydrophones are used in the receiver array. The received signal on the m-th hydrophone at the discrete baseband is:

$$y_m(n) = \sum_{i=1}^{N_T} x_{i,m}(n) * h_{i,m}(n) + v(n) \tag{1}$$

where $h_{i,m}(n)$ is the impulse response, $v(n)$ is complex noise, and $x_{i,m}$ is the symbol transmitted from the i-th AUV.

We use a time-reversal-based MIMO receiver that combines the time reversal processing, decision feedback equalizer (DFE), and serial interference cancellation for demodulation [12]. The receiver consists of five function blocks: channel estimation, time-reversal combining, channel-estimated-based DFE (CE-DFE), PSK demodulation, and interference cancellation. Time reversal combining, CE-DFE equalizer, and serial interference cancellation all require channel estimates. The lease squares (LS) algorithm is used to estimate the channel impulse responses.

In the time reversal combining block, the received signals are convolved with time-reversed and conjugated channel estimates and then the results are combined. The CE-DFE is applied at the output of the time reversal block to compensate for the residual inter-symbol interference. The channel estimates are used to calculate the DFE filter coefficients. The equations for the CE-DFE feed-forward and feedback filters can be found in Ref. [7].

The strongest data stream is processed and demodulated first. When processing weaker data streams, we use the serial interference cancellation to remove the co-channel interference, resulted from the strongest data stream. The co-channel interference is calculated using estimated channel impulse responses and demodulated data stream.

4 USER SELECTION

Channel allocation needs to be considered when multiple AUVs communicate with the control center during a undersea mission. In this section, we formulate the resource allocation issue into a user selection problem. Both fairness among AUVs and high throughput are considered when selecting suitable users for active transmissions,

In a conventional strategy, the acoustic channel can be shared based on non-contentious schemes, for example time-division, frequency-division, or code-division multiple access. In a time-division scheme, the acoustic channel is divided into discrete time slots. Each AUV only transmits at its own time slot. The time-division scheme can be carried out in a round-robin fashion. Therefore, each AUV is assigned with the same amount of time resources for communications, regardless the channel conditions.

Our proposed algorithm dynamically selected multiple AUVs to transmit simultaneously in each time slot. The proposed algorithm maximizes the overall throughput and the fairness among the AUVs. At the beginning, N_T AUVs with better channel conditions are selected for data transmissions. This strategy maximizes the overall throughput. As the time goes on, the AUVs with bad channel conditions have limited opportunities for transmissions. To ensure the fairness, the user selection algorithm intentionally selects these users that do not get their fair share of time slots. In this way, the proposed algorithm strikes a balance between maximizing the overall throughput and ensuring the fairness.

Before detailing the user selection algorithm, we define several metrics, the data rate, average data rate, weighting function, and overall weighted throughput. The data rate here is defined as successfully received bits per unit time,

$$r_i(k) = \frac{b_i(k)}{T} \tag{2}$$

where b_i is the number of successfully received bits for the i-th AUV in the k-th time slot and T is the length of each time slot.

The average data rate of the i-th AUV, $R_i(k)$, is defined as the average data rate over a time duration t_c:

$$R_i(k) = \begin{cases} \left(1 - \frac{1}{t_c}\right) R_i(k-1) + \frac{1}{t_c} r_i(k) & \text{if the } i\text{-th user is selected} \\ \left(1 - \frac{1}{t_c}\right) R_i(k-1) & \text{otherwise.} \end{cases} \tag{3}$$

A weighting function is used to ensure the fairness to access the channel. It is the inverse value of the average data rate,

$$\rho_i(k) = \frac{1}{R_i(k-1)}. \tag{4}$$

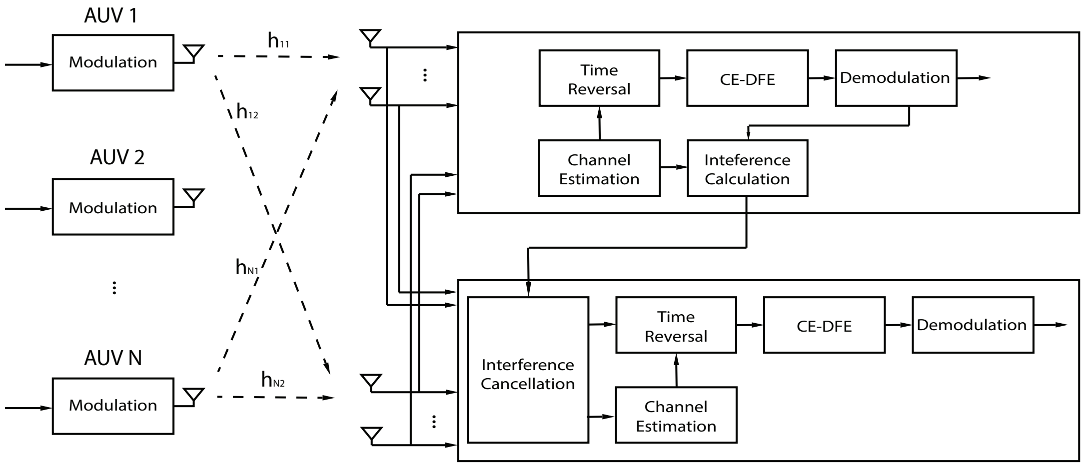

Figure 1: Virtual MIMO acoustic communication transceiver among multiple AUVs and a receiver array. The receiver consists of five function blocks: time-reversal combining, CE-DFE, channel estimation, PSK demodulation, and interference cancellation block.

When one AUV has a higher average data rate than other AUVs, its weighting factor decreases, thus discouraging future transmissions. Conversely, when an AUV has a lower average data rate than others, the weighting factor increases to encourage future transmissions.

The overall weighted throughput is the summation of the weighted throughput from all AUVs, defined as,

$$\psi = \sum_{k=1}^{K} \sum_{i=1}^{N_V} \tau_i(k)\phi_i(k) \tag{5}$$

where $\tau_i(k)$ is an indicator function for active transmissions, and $\phi_i(k)$ is the weighted data rate at the k-th time slot for the i-th user,

$$\phi_i(k) = \rho_i(k)\, r_i(k)\,. \tag{6}$$

$\tau_i(k)$ is defined as:

$$\tau_i(k) = \begin{cases} 1 & \text{if the } i\text{-th user is selected in } k\text{-th time slot} \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

The optimization objective is to maximize the overall weighted throughput. We formulated the optimization objective as:

$$\arg\max \psi = \arg\max \sum_{k=1}^{K} \sum_{i=1}^{N_V} \tau_i(k)\phi_i(k) \tag{8}$$

Maximizing the overall weighted throughput is equivalent to maximizing the weighted throughput at each time slot. Define a $N_V \times 1$ user selection vector and an $N_V \times 1$ data rate vector as:

$$\tau(k) = \begin{bmatrix} \tau_1(k) & \tau_2(k) & \cdots & \tau_{N_V}(k) \end{bmatrix}^{\mathrm{T}} \tag{9}$$

and

$$\Phi(k) = \begin{bmatrix} \phi_1(k) & \phi_2(k) & \cdots & \phi_{N_V}(k) \end{bmatrix}^{\mathrm{T}} \tag{10}$$

respectively. Then we can rewrite the optimization problem in one time slot as:

$$\arg\max_{\tau(\mathbf{k})} \left\{ \tau^{\mathrm{T}}(k)\Phi(k) \right\} \tag{11}$$

Eq. (11) can be solved as a combination problem. There are $\frac{N_V!}{N_T! \times (N_V - N_T)!}$ different ways to select N_T users from N_V AUVs. For each possible combination of N_T users, we first need to know their data rates. With the data rates, the weighted data rates can be obtained. In turn, the weighted throughput is calculated using Eq. (5). The user selection algorithm calculates the weighted throughput of every possible combination. It selects the combination with a maximum weighted throughput.

4.1 Prediction of data rates

The core issue is how to obtain the data rate estimation for a candidate combination of N_T users, that is each of possible virtual MIMO transmissions. Since there are multiple AUVs, sending probing packets from each of the candidate combination to achieve closed-loop feedback is not practical. The reason is that there are a large number of combinations, even for a small number of AUVs in the mission. Therefore the probing strategy introduces a large overhead.

We propose a low-overhead prediction strategy to estimate the data rates based on the communication range. Adaptive modulation is also implemented. This method does not involve the process of closed-loop information exchange. Instead, we use the locations of the AUVs. For simplicity, we only consider the situation when $N_T = 2$.

The proposed strategy first estimates the data rates for individual users at their present locations. When considering a candidate combination, we derive the virtual MIMO performance from the performances of individual users. Note that the virtual MIMO performance is affected by the co-channel interference, which in turn is decided by the relative strength of each data stream from the considered AUVs. The AUV location relative to the control center determines the signal strength. Therefore, we consider the user separation distance when predicting the data rates of the users in a candidate combination, which corresponds to the virtual MIMO transmissions.

To estimate the data rates of individual users, we first establish the relationship between the data rate and communication range at the mission site offline. Acoustic channel impulse responses can be modeled with historical environmental data, using acoustic toolboxes such as BELLHOP, for different communication ranges. With a known source level, ambient noise level, and simulated impulse responses, acoustic communication performance is simulated. Note here only one transmitter is used for transmissions. An receiver array is used for reception and demodulation. This constitutes a scenario for single-input and multiple-output (SIMO) communications. This way, the bit-error-rate (BER) performance of different modulation orders is obtained for all range points in SIMO communications. Based on the BER requirement, we can identify the achieved data rates of specific modulation orders over different ranges.

In the next step, we use the data rate estimates of individual users, or the SIMO data rate, to generate the data rates of a candidate combination. Clearly, due to the co-channel interference, the data rates of a candidate combination, referred to as the virtual MIMO data rate, should be less than the summation of the data rates of the individual user in the combination. A conversion factor is introduced to account for the difference.

In the $N_T = 2$ case, we obtain an empirical equation for this conversion factor. By comparing the data rates of individual users and the data rate of virtual MIMO transmissions, we obtain the conversion factor as a function of the separation distance,

$$\alpha_{i,j} = a_1 d_{i,j}^3 + a_2 d_{i,j}^2 + a_3 d_{i,j} + a_4 \tag{12}$$

where $d_{i,j}$ is the distance between two AUVs, $a_1 = 2.89 \times 10^{-11}$, $a_2 = -1.91 \times 10^{-7}$, $a_3 = 4.034 \times 10^{-4}$, $a_4 = 0.7512$.

We use the conversion factor to generate adjusted data rates,

$$\begin{aligned} r_i(k) &= \alpha_{i,j} r_{i,SIMO}(k), \\ r_j(k) &= \alpha_{i,j} r_{j,SIMO}(k) \end{aligned} \tag{13}$$

where $r_{i,SIMO}(k)$ and $r_{j,SIMO}(k)$ are the indexed data rates for the i-th and j-th AUV users, based on their locations relative to the control center, in SIMO transmissions. The conversion factor is small when the distance of two users is short. Therefore the adjusted data rates are low. This conversion factor, therefore, discourages the selection of two AUVs that are closely located.

During the AUV fleet mission, we assume the location information of AUVs is known at the center center. This is often the case since the trajectories are pre-programmed. Further, frequent communications with navigating AUVs can help to track the locations. Based on the established relationship between the data rate and communication range, each AUV can be associated multiple data rates for allowed modulation orders. We select the highest data rate from allowed modulation schemes, which is $r_i(k)$ in Eq. (2).

5 SIMULATION RESULTS

We created a multi-AUV cooperation scenario to demonstrate the performance of the proposed algorithm. The water depth was 100 m. We used historical sound speed profiles from Ref. [13] in the acoustic simulations. In the mission, five AUVs and a control center was simulated, as in Fig. 2. Five AUVs were deployed at different depths, 30, 40, 60, 70, and 80 m, respectively. AUVs at the depth of 30 and 40 m traveled away from the control center while the AUVs at the depth of 60 m and 70 m navigated toward to the control center. The remaining AUV stayed around the distance of 1 km from the control center. The speed of all the AUVs was set to 4 knots. The control center provided the communication coverage.

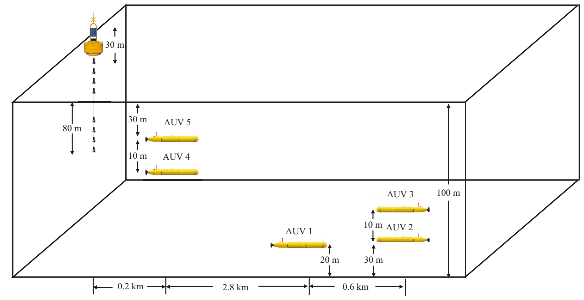

Figure 2: Simulation setup. Five AUVs had their respective tracks. AUV-1 was roughly stationary around 3 km away. AUV-2 and AUV-3 moved toward to the receiver array while AUV-4 and AUV-5 moved away from the receiver array.

The tracks of the AUVs were simulated by a dynamic model of YSI EcoMapper [6]. The dynamic model of EcoMapper was recently developed in [16]. Parameters of the model were identified from theoretical calculations, computational fluid dynamics (CFD) simulations, and field experiments. The vehicle dynamic model was then validated by a series of field tests. The vehicle simulation emulated the motion by steering the AUVs to the desired heading. The depths of the AUVs were assumed constant. Thus we only considered the 2D motion of the AUVs.

The initial vehicle positions were all set to $[x, y] = [0, 0]^\top$ with heading towards positive Y axis. The initial velocity of the AUVs was set to zero. To demonstrate the steering maneuver, the desired heading was set to positive X axis. Thus, the AUV turned 90 degrees clockwise. A feedback controller commanded the angles of the vertical fins to reduce the error between the current heading and the desired heading of the AUV. Fig. 3 demonstrates the trajectory and velocity of the simulated steering maneuver.

The single transmitter on the AUVs used the carrier frequency of 28 kHz and the symbol rate of 10 kHz. Every packet had a duration time of 10 seconds. The source level was set to 170 dB. The wind speed was set to 2 m/s. We used the model in [14] to model the ambient noise. The calculated noise level was 81 dB for the transmission band. The control center had an eight-element receiving array. Eight elements were deployed at the depth of 30 m with 5 m element spacing and 35 m array aperture.

The BELLHOP model was used to simulate the channel impulse responses. Fig. 4 shows the channel impulse response when a AUV moved away from the control center. When the AUV traveled away, the number of channel taps increased. The time span of the channel decreased.

Based on the environmental setup and sound-speed profile, we simulated the BER performances of different modulation schemes, including BPSK, QPSK, 8-PSK and 16-PSK, for SIMO communications. The results are shown in Fig. 5. Next we calculated the

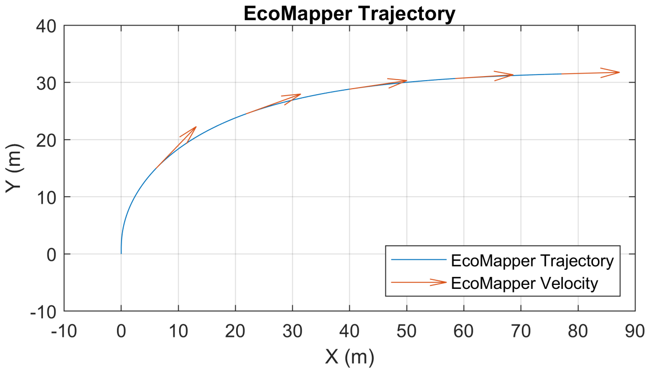

Figure 3: Simulated vehicle trajectory and velocity in the 2D plane.

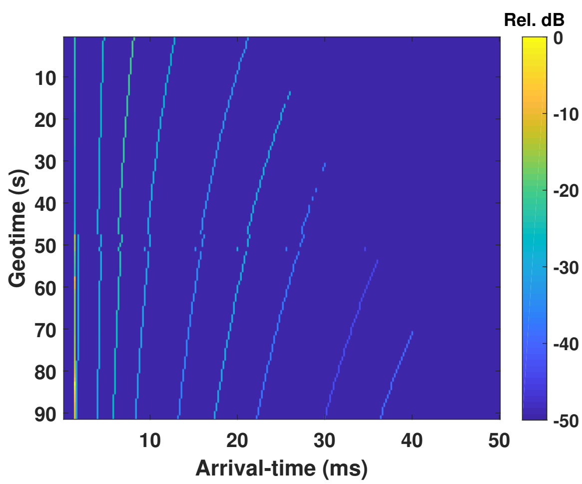

Figure 4: Channel impulse responses simulated by the BELLHOP model when AUV moved toward the control center.

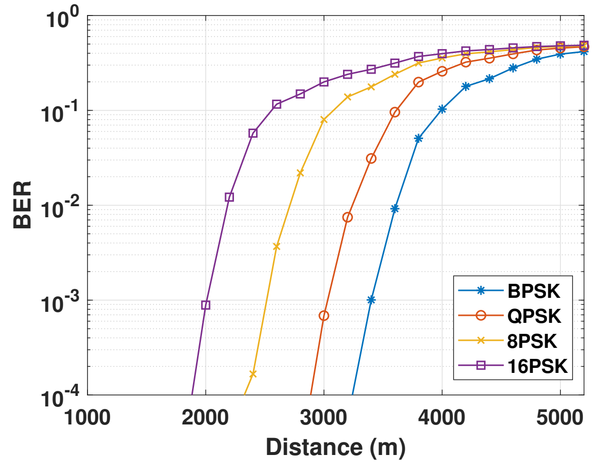

Figure 5: The BER performance of four modulation schemes over different communication ranges in SIMO communications.

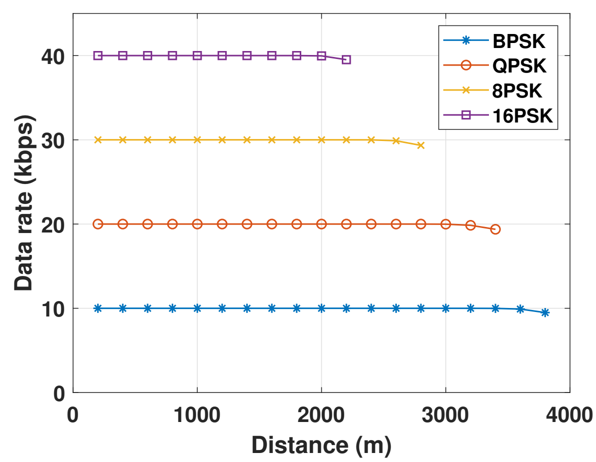

Figure 6: Data rates of four modulation orders over different ranges for SIMO communications.

data rate of each modulation scheme over different ranges. We assumed that the maximum tolerable BER was 10^{-2}. Fig. 6 shows data rates versus the communication range for four modulation schemes. 16-PSK had the highest data rate over shortest communication ranges. Conversely, BPSK had the lowest data rate over longest communication ranges.

Based on Fig. 6, we constructed a look-up table for data rates for SIMO communications, with the communication range as the input. For a certain range, the highest modulation order permitted was selected. We also considered a 100 m protection margin. So, between the distance between 200 and 2000 m, 16-PSK was selected and the predicted data rate was 40 kbps. Between the distance between 2000 to 2500 m, 8-PSK was selected and the predicted data rate was 30 kbps. Between the distance of 2500 to 3200 m, QPSK was selected and the predicted data rate was 20 kbps. Between the distance of 3200 to 3600 m, BPSK was selected and the predicted data rate was 10 kbps. When the communication distance was large than 3600 m, the transmission would stop, generating a data rate of 0 kbps.

Using the data rate look-up table, we obtained the predicted data rate for SIMO transmissions, $r_{i,SIMO}(k)$. The virtual MIMO data rate was obtained based on Eq. 13. With the predicted data rates, suitable N_T AUVs were selected based on Eq. (11). To demonstrate the effects of the conversion factor, we also conducted simulations where we forced the conversion factor as one. This way, we treated the virtual MIMO data rate as the summation of the predicted SIMO data rates from N_T users.

The simulation results for the virtual MIMO acoustic communications over 1700 seconds are presented in Fig. 7 and Fig. **??**. Achieved data rates of the individual AUVs, as well as the overall throughput, are shown. The overall throughput was summation of the data rates from all five AUVs. Fig. 7 shows the results when the

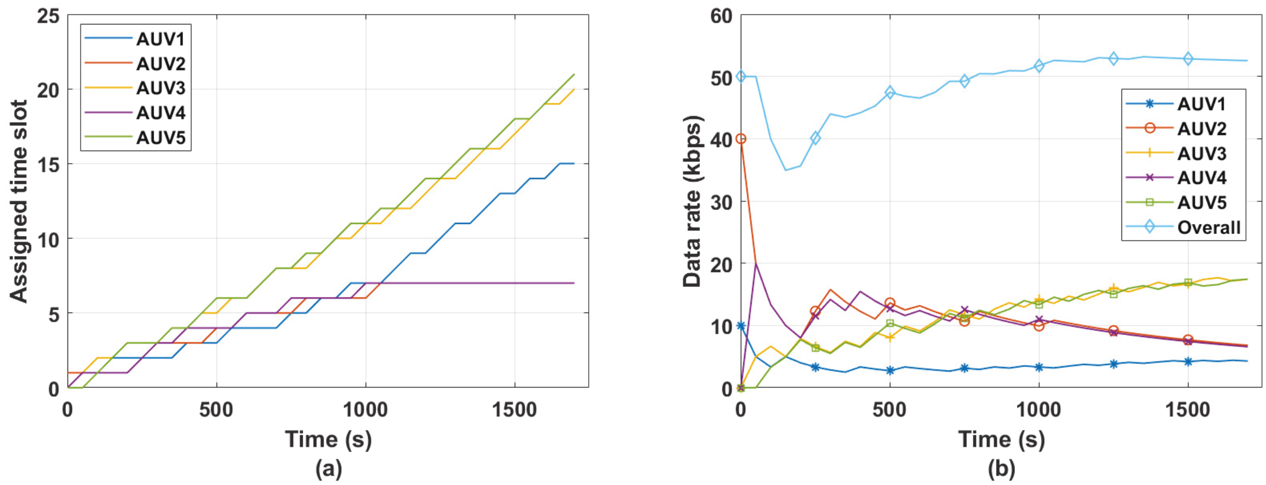

Figure 7: Time slot allocation and achieved data for five AUVs when the conversion factor was forced to one. The overall throughput is shown. (a) Assigned time slots. (b) Achieved data rates.

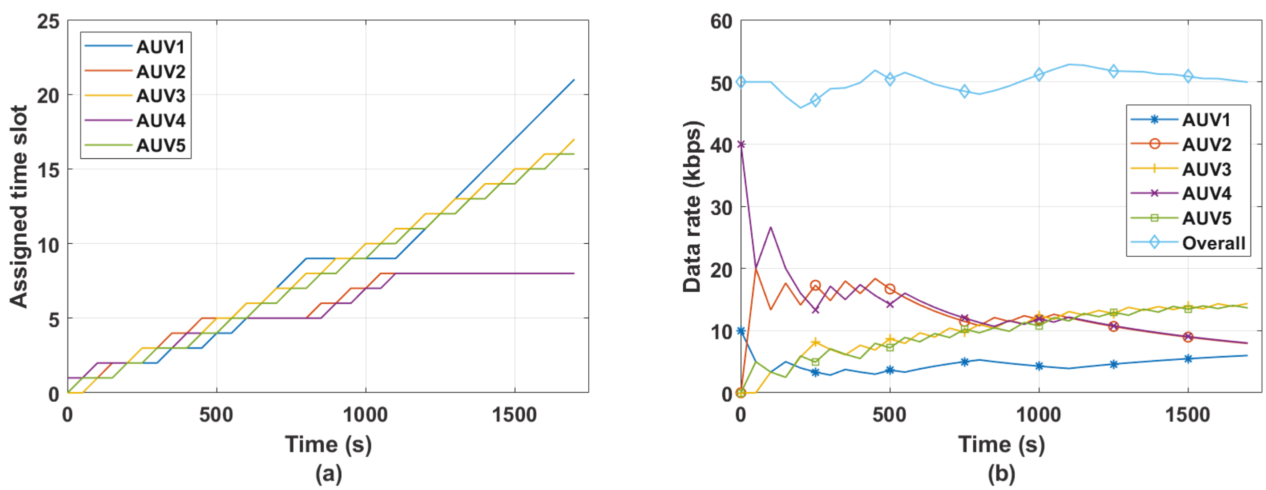

Figure 8: Time slot allocation and achieved data for five AUVs when the empirical conversion factor in Eq. 12 was used. (a) Assigned time slots. (b) Achieved data rates.

conversion factor was forced to one. Fig. 7 shows the results with a conversion factor from Eq. 12.

Fig. 7(a) shows that the user selection algorithm assigned more time slots to the AUVs with better channel conditions, but still assigned some transmission opportunities to the AUVs with worst channel conditions. This balanced the fairness with a maximized throughput. For example, at the first 900 seconds, AUV-3 and AUV-5 had the worse channel conditions but still were assigned time slots to transmit.

As shown in Fig. 7(b), AUV-2 and AUV-4, which moved away from the control center, had highest data rates at the beginning. In contrast, AUV-3 and AUV-5, which moved toward the control center, had lowest data rate at the beginning. AUV-1 that was stationary had lowest data rates all the time. The data rates of AUV-3 and AUV-5 increased as the channel conditions improved when they moved toward the control center.

In Fig. 7, the conversion factor was used. As shown in Fig. 8(a), the AUVs with short separation distances were less possible to pair up for the MIMO transmissions since a small separation led to a small factor $\alpha_{i,j}$, leading to a low predicted data rate. This happened to the pair of AUV-3 and AUV-5, which had the parallel tracks. This was also true for the pair of AUV-2 and AUV-4.

Fig. 8(b) shows an improved overall throughput, compared with that in Fig. 7(b). For example, during 100 to 300 s, a decrease of the overall throughput did not exist in Fig. 8(b) while it was there in

Fig. 7(b). Particularly at 240 s, the overall throughput was 47 kbps in Fig. 8(b) while it was 35 kbps in Fig. 7(b).

In both simulations (Fig. 7 and Fig. 8), the overall throughput of the proposed scheme was about 40 to 50 kbps. The achieved overall throughput was much higher than the traditional time-division strategy. In the traditional time-division strategy, time slots are equally allocated among all the users. Only one user is allowed to transmit signal in each time slot. If all the AUVs used the BPSK modulation, the reliability would be guaranteed. But the maximum overall throughput would be 10 kbps. If the AUVs went for the 16-PSK modulation, clearly communications failures would occur when the AUVs moved away from the high data rate zones.

We acknowledge that several factors were not examined in the simulations. For example, the time delay was not considered for the AUVs to receive the directives from the control center. About 2 seconds were needed before the AUVs' transmission, considering the dimensions of the operation site. In addition, guard time that was needed between the time slots to avoid collision was not included either. Both the virtual MIMO and traditional time-division schemes needed such guard intervals. Therefore, the proposed MIMO strategy would still maintain an advantage in terms of the overall throughput, if both factors were considered.

6 CONCLUSION

In this paper, we proposed a virtual MIMO underwater acoustic communications systems with multiple AUVs. The core idea was to select multiple AUV users and to select proper modulation schemes for concurrent transmissions to maximize spectral efficiency. We applied the model-based method to predict allowable data rates for each AUV. To achieve low overhead, we used the modeled SIMO data rates to predict virtual MIMO data rates as a basis to select proper AUV users and to adjust modulation orders. We demonstrated the performance advantage of the proposed algorithm in a multi-AUVs communications scenario with five AUVs. The proposed algorithm was able to dynamically select different users to maximize the overall weighted throughput, striking a balance between the maximized throughput and user fairness.

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