

User Scheduling for Maritime Ship-to-Ship/Shore Communications Based on Large-Scale CSI

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Abstract—In this paper, we investigate user scheduling for a maritime communication system with both ship-to-ship and ship-to-shore links. Different from previous studies, we consider a more practical scenario that only the slowly-varying large-scale channel state information (CSI) is known at the transmitter. The large-scale CSI can be predicted through the positional information of each vessel based on its specific shipping lane and timetable. We formulate a user scheduling optimization problem, aiming to minimize the total energy consumption with guaranteed quality of service (QoS). To approximate the optimal solution to the user scheduling problem, we develop a 3-step progressive algorithm, which only requires polynomial computational complexity. Simulation results reveal that the proposed large-scale-CSI-based scheme significantly reduces the energy consumption by up to 71% over existing methods.

Index Terms—Maritime ship-to-ship/shore communication, user scheduling, large-scale channel state information (CSI), progressive approximation

I. INTRODUCTION

The rapid development of marine industries, as well as the economic and cultural exchanges between littoral states, has promoted the demand for reliable and high-speed ship-to-shore maritime communication services. In recent years, several maritime communication network projects have been developed in order to meet this increasing demand, e.g., the BLUECOM+ project, the MarCom project, and the TRITON project [1]–[3].

Unlike terrestrial cellular networks, a maritime ship-to-shore communication system has quite limited geographically available BS sites. Thus, maritime communication systems usually adopt high-powered BSs so as to cover a vast area with limited BSs. This high-powered BS strategy increases the operational costs of mobile network operators and poses a global threat to the environment [4]. Accordingly, reducing energy consumption becomes a critical issue for maritime communications. To reduce system energy consumption, we introduce the idea of ship-to-ship communications, where vessels act like relays in the on-shore data distribution network. Several previous maritime communication network projects [1]–[3] have already included ship-to-ship communications to extend the coverage of the systems. Nevertheless, to the best of the authors' knowledge, the area still remains undiscovered where ship-to-ship relay transmissions are introduced to reduce system energy consumption.

Undoubtedly, the ship-to-ship transmission will reduce system energy consumption with direct relay transmission

between neighboring vessels. However, it introduces more transmitters (BS/relays) and brings more challenges for user scheduling.

User scheduling, as an important perspective for energy saving, depends heavily on CSI. However, it is rather costly to acquire perfect CSI in maritime communication systems, due to the excessive system overhead including pilot overhead and feedback overhead [14]–[16]. Most of the previous user scheduling schemes overlook the difficulties in obtaining full CSI in maritime scenarios.

So far, the majority of energy-efficient user scheduling techniques focused on terrestrial cellular networks. Based on the utilization degree of CSI, terrestrial user scheduling schemes can be classified into three categories. The first one required no CSI, such as the simple but efficient round-robin scheme for fair queuing [5]. The second one exploited statistical and outdated CSI, as studied in [6] and [7]. The third one assumed full CSI, and utilized the instantaneous CSI for user scheduling on a minuscule time scale, i.e., in each coherence time [8]–[10]. In maritime scenarios, however, obtaining perfect CSI for user scheduling brings large overheads and is not cost-effective. Moreover, since the large-scale CSI can be predicted in maritime scenarios (which will be explained later), statistical and outdated CSI is not the best choice, either.

As for maritime user scheduling with ship relays, limited works have been done. Both [11] and [12] focused on monitoring videos uploading via maritime communication networks. They focus on user scheduling of ship-to-shore communication with the store-carry-and-forward relay mechanism. In [13], a scheduling model was developed to provide the communication path of the fewest routing times to the moving ships that are far apart, which has reduced the space link resources consumption. Nevertheless, these works were also based on the assumption that the channel capacity is known, and did not consider the real-world challenges in acquiring full CSI.

For the following reasons, current studies on user scheduling require systematic redesign, and should be based on large-scale CSI instead of full CSI.

1. As there are fewer scatterers on the sea than that in the terrestrial scenario, the large-scale channel fading becomes the dominant factor for the maritime channel [14]. Hence, we can use the position information of vessels to predict large-scale CSI and avoid the heavy overhead for full CSI;

2. Most vessels have specific fixed shipping-lanes and

timetables that can be acquired beforehand, and their position information can be easily predicted. From the position information, we can predict large-scale CSI for the whole service duration. We can have further gain by considering the whole service process instead of the short timescale as in terrestrial scenarios.

Therefore, we formulate a maritime user scheduling optimization problem based on large-scale CSI, aiming to minimize the system energy consumption. To overcome the difficulties in choosing transmitters brought forward by ship-to-ship transmission, we progressively simplify the optimization problem. We further design a 3-step algorithm for the approximate solution to the user scheduling problem.

II. SYSTEM MODEL

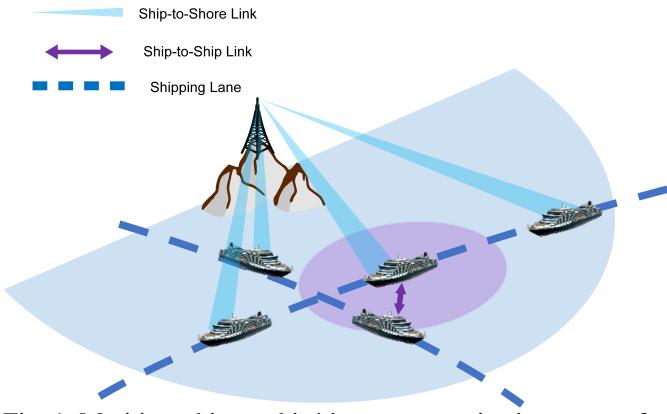


Fig. 1: Maritime ship-to-ship/shore communication system for data distribution service.

A. System Parameters

As shown in Fig. 1, the following sections focus on the user scheduling of an FDMA downlink transmission system. There are both ship-to-ship and ship-to-shore links in the considered system. The system has one on-shore BS and J single-antenna users that can either act like receivers or like transmitters (relays). In general, we denote the transmitters (BS/relays) as $i \in \{0, 1, \dots, J\}$, the receivers (users) as $j \in \{1, \dots, J\}$. $i = 0$ means the transmitter is BS, whereas $i > 0$ means the transmitter is one of the J ships that can act like relays. We assume that there are N subcarriers, and the subcarrier bandwidth is B_s . $P_i = \{P_0, \{P_j\}\}$ represents the fixed transmit power of BS ($i = 0$) or ship relays ($i > 0$) on any given subcarrier. In this paper, we only consider two-hop half-duplex ‘ship-to-ship/shore communications’ for simplicity.

In the considered system, ship-to-ship transmissions use the same licensed band of ship-to-shore transmissions (i.e. one of the N subcarriers), and the same air interface of the ship-to-shore transmissions. Based on the half-duplex assumption, the J single-antenna users can either receive data from one transmitter or transmit data to another user at any given time. Also, each transmission link uses distinct subcarrier. Here in this paper by ‘link’ we mean the transmission from BS/relay to a receiver during a certain time period.

Without loss of generality, we assume the on-shore BS coverage shape to be a semicircle. In order to simplify the problem, we only consider transmissions within the semicircle. We also assume that all the users request different data and the system has no data reuse. Each user sails into and out of the semicircle according to its shipping lane and timetable. Since maritime users focus more on data volume rather than transmission delay, we particularly focus on the delay-tolerant information distribution service, which is initiated and terminated when a marine user sails into and out of the BS’s coverage, respectively. The QoS constraint, i.e., the data volume required by the j^{th} user, is denoted by V_j^{QoS} .

B. Large-Scale CSI

In terrestrial scenarios, according to the multipath effect, signals are well scattered and the small-scale fading factor has a significant impact on the channel. However, in maritime scenarios, due to the scarcity of scatterers, the large-scale fading factor becomes dominant. Therefore, we focus on large-scale CSI in this paper.

We assume a modified 2-ray propagation model for the maritime channel, since the sea surface is relatively flat [18]–[20]. For a given subcarrier, we denote the composite channel gain from the BS/relay i to the user j at time τ by $\sqrt{\beta_{i,j,\tau}} h_{i,j,\tau}$. The small-scale fading vectors $h_{i,j,\tau}$ follow a complex Gaussian distribution with standard deviation $\sigma_s = 1$, i.e., $h_{i,j,\tau} \sim \mathcal{CN}(0, \mathbf{I})$. The large-scale fading coefficient $\beta_{i,j,\tau}$ is expressed as

$$\beta_{i,j,\tau} = \left(\frac{\lambda}{4\pi d_{i,j,\tau}} \right)^2 \left[2 \sin \left(\frac{2\pi h_t h_r}{\lambda d_{i,j,\tau}} \right) \right]^2, \quad (1)$$

where λ is the carrier wavelength, $d_{i,j,\tau}$ is the distance between the BS/relay i and the user j at time τ . The antenna height of the transmitter and the receiver are represented by h_t and h_r , respectively.

To fully utilize the slowly-varying characteristic of the large-scale channel fading, we divide the total system service time into T time slots, each lasting $\Delta\tau$. The value $\Delta\tau$ is carefully chosen so that $\beta_{i,j,\tau}$ remains constant in each time slot t (ignoring ship movements during each time slot). Thus, we make it possible to acquire large-scale CSI $\beta_{i,j,t} = \mathbb{E}[\beta_{i,j,\tau}]$ for $\forall t \in \{1, \dots, T\}$ from position information based on shipping-lanes and timetable. Any further denotation of CSI in this paper refers to the predicted ‘large-scale CSI’ for the whole service duration unless specified.

To avoid the heavy overhead, we replace the perfect CSI with large-scale CSI and use predicted slowly-varying large-scale CSI to predict transmission speed (capacity) as shown in (2a)-(2c). We justify our replacement by simulations in Section IV. Let us denote $\gamma_{i,j,t} = P_i \beta_{i,j,t} / \sigma^2$ for simplicity, where P_i represents the transmit power of BS/relay i . The transmission speed in this paper can therefore be simplified

as

$$r_{i,j,t} = B_s \log_2 \left(1 + \frac{P_i \beta_{i,j,t} |h_{i,j,t}|^2}{\sigma^2} \right), \quad (2a)$$

$$= B_s \log_2 \left(1 + \gamma_{i,j,t} |h_{i,j,t}|^2 \right), \quad (2b)$$

$$= (\log_2 e) e^{\frac{1}{\gamma_{i,j,t}}} \int_1^\infty \frac{1}{u} e^{-\frac{u}{\gamma_{i,j,t}}} du. \quad (2c)$$

The transmission speed in (2c) is derived based on previous study [21]. The impact of this replacement (assuming that ship j stays in the same position and $\beta_{i,j,t}$ remains constant in each time slot t) is further discussed in Section IV.

For simplicity, we denote the link from transmitter $i \in \{0, 1, \dots, J\}$ (BS/relay, $i = 0$ means BS, $i > 0$ means relay) to receiver j (user) at time slot t by $i \rightarrow j @ t$. Since we only consider two-hop link-pairs, a pair of the substitution ship-to-ship/shore links $[0 \rightarrow i' @ t_1, i' \rightarrow j @ t_2]$ consists of exact a ship-to-shore part $0 \rightarrow i' @ t_1$ for BS to transmit data to relay i' , and a ship-to-ship part $i' \rightarrow j @ t_2$ for relay i' to transmit to receiver user j .

C. Problem Formulation

The total energy consumption can be written as the sum of transmission energy to each user. Therefore the energy consumption of the whole system is

$$E_{\text{total}} = \sum_{j=1}^J E_j = \sum_{j=1}^J \left(\sum_{i=0}^J \sum_{t=1}^T P_i \delta_{i,j,t} \Delta \tau \right). \quad (3)$$

By $\delta_{i,j,t} \in \{0, 1\}$ we denote whether there is a link $i \rightarrow j @ t$ and a subcarrier is scheduled for the link. $\delta_{i,j,t} = 0$ means there is no transmission from BS/relay i to user j at time slot t , while $\delta_{i,j,t} = 1$ means there is a transmission link $i \rightarrow j @ t$ on a certain subcarrier. Moreover, $\forall j, \forall t, \delta_{j,j,t} \equiv 0$, since we do not allow receiving transmissions from oneself. Our objective is to minimize the system energy consumption by means of user scheduling in the ship-to-ship/shore communication system.

We denote the total data volume that user j currently has at time slot t by $V_{j,t}$. $V_{j,t}$ can be written as the sum of the received data volume in each time slot minus the sum of relayed data volume in each time slot.

$$V_{j,t} = \sum_{\tau=t_j^{\text{In}}}^t \left(\sum_i r_{i,j,\tau} \delta_{i,j,\tau} - \sum_{j'} r_{j,j',\tau} \delta_{j,j',\tau} \right) \Delta \tau. \quad (4)$$

The time slots when user j enters and leaves the BS's coverage are denoted by t_j^{In} , t_j^{Out} , respectively. In the considered system, based on delay-tolerant assumption, t_j^{In} , t_j^{Out} equal the service beginning time slot and ending time slot for user j . Since the system has no data reuse, user relay j must have enough data $V_{j,t}$ to relay and transmit, i.e., $V_{j,t} \geq 0$.

Although different users require different data in our system, it is possible to avoid keeping track of what BS/relays transmit to each user at any given time. To do this, we have to record all links we have chosen in a link set S . S can

be acquired before ships enter the BS coverage based on our proposed algorithm. The elements in S can be either ship-to-shore-only link $\{0 \rightarrow i' @ t_1\}$ or ship-to-ship/shore link-pair $\{[0 \rightarrow i' @ t_1, i' \rightarrow j @ t_2]\}$. With the link set known beforehand, we can get the transmission speed of each link in the set, and determine what and how much to transmit on each link at any given time. Thus we can avoid keeping track of what BS/relays transmit to each user at any given time slot.

Thus, we formulate the energy consumption optimization problem as

$$\min_{\{\delta_{i,j,t}\}^{(J+1) \times J \times T}} \left\{ \sum_{i=0}^J \sum_{j=1}^J \sum_{t=1}^T P_i \delta_{i,j,t} \Delta \tau \right\}, \quad (5a)$$

$$\text{s.t. } \sum_{i \neq j} \delta_{i,j,t} + \sum_{j' \neq j} \delta_{j,j',t} \leq 1, \quad (5b)$$

$$\sum_i \sum_j \delta_{i,j,t} \leq N, \quad (5c)$$

$$V_{j,t}|_{t=t_j^{\text{In}}} = 0, V_{j,t}|_{t=t_j^{\text{Out}}} \geq V_j^{\text{QoS}}, V_{j,t} \geq 0. \quad (5d)$$

We have to consider transmissions from $J + 1$ transmitters (BS/relays) to J receivers (users) at T time slots in problem (5). Half-duplex constraint (5b) guarantees that each user has access to at most one BS/user at a given time, and serves either as a transmitter or as a receiver. The constraint in (5c) guarantees that at most N users can be served simultaneously in the system, by BS or relays, since there are only N subcarriers. (5d) makes sure that the QoS constraint is met and relays cannot transmit more than what they have currently.

Given the difficulties in solving the Linear Integer Programming problem in (5), we propose the following progressive approximation.

III. USER SCHEDULING FOR MARITIME SHIP-TO-SHIP/SHORE COMMUNICATION

In this section, we focus on the user scheduling problem, which reduces system energy consumption while ensuring QoS. We progressively approach the optimization problem in (5) through a 3-step algorithm with polynomial time complexity.

A. Progressive Approximation of the Original-Problem

The original non-convex problem in (5) involves various factors, and achieving the optimal solution for it is not practical (exponential complexity). To avoid the difficulties introduced by more transmitters (BS/relays), we first loosen the subcarrier constraint in (5), and consider a ship-to-shore-only system. Then we replace the high-power part of ship-to-shore links with low-power ship-to-ship/shore link-pairs, and add back the loosen constraint. We propose a 3-step algorithm to achieve an approximation solution, with each step based on its predecessor's result.

In step-1, we simply consider the ship-to-shore transmission and ignore the subcarrier constraint, so as to focus solely on the simple scheduling based on large-scale CSI that we can

predict. We can get an optimal result for this simple problem by choosing links with best CSI.

In step-2, we consider the maritime ship-to-ship/shore communication system. We substitute part of the ship-to-shore links we get in step-1 for two-hop ship-to-ship/shore link-pairs $[0 \rightarrow i'@t_1, i' \rightarrow j@t_2]$ for less energy consumption. Since the introduction of relays brings forward great difficulties in user scheduling, we use a greedy method in step-2.

Last, in step-3, we use a greedy algorithm based on the result returned by step-2 to make sure that our user scheduling is applicable, i.e., the subcarrier constraint is met. Since this constraint has not been considered in step-1, we make adjustments in step-3 to get an approximation of the applicable solution for the ship-to-shore system.

Eventually, after all three steps, we approximate the optimal solution for the original problem in (5). Since the transmission speed for all $(J+1) \times J \times T$ links can be predicted based on large-scale CSI, the 3-step algorithm can be carried out using only large-scale CSI. In Section IV we prove the validity of our progressive approximation by comparing the energy consumptions.

B. Step-1

For the first step, we concentrate on large-scale CSI by considering the most simple scenario: a ship-to-shore-only system without subcarrier constraint. We fix transmitter $i = 0$ since users can only receive data from on-shore BS.

$$\min_{\{\delta_{0,j,t}\}} \left\{ \sum_{j=1}^J \sum_{t=1}^T P_0 \delta_{0,j,t} \Delta \tau \right\}, \quad (6a)$$

$$s.t. \quad V_{j,t}|_{t=t_j^{In}} = 0, \quad V_{j,t}|_{t=t_j^{Out}} \geq V_j^{\text{QoS}}. \quad (6b)$$

We only optimize $\{\delta_{0,j,t}\}^{J \times T}$ since in step-1, there is only one transmitter. Half-duplex constraint in (5b) and $V_{j,t} \geq 0$ in (5d) are not necessary here since users can only receive data from BS, and cannot act like relays. We also drop the N -subcarrier constraint in (5c) since we assume that the BS can serve infinite number of users.

In the first step, we optimize $\delta_{0,j,t}$ only with constraint (6b). In this case, the optimization variables of different users are no longer correlated, and the optimal solution here can be obtained by scheduling each user separately. The problem in (6) can be reduced to $\min_{\{\delta_{0,j,t}\}} \left\{ \sum_{t=1}^T P_0 \delta_{0,j,t} \Delta \tau \right\}$. Note that $r_{0,j,t}$ is a monotone increasing function of $\beta_{0,j,t}$, therefore we can obtain the optimal solution by choosing links with best CSI (transmission speed) for each user.

We further define \mathbf{S}_1 as the set of chosen ship-to-shore link at a specific time slot in problem (6), i.e., $(0, j, t) \in \mathbf{S}_1$ if $\delta_{0,j,t} = 1$.

For each user, we find link $0 \rightarrow j@t$ with best $r_{0,j,t}$ and set $\delta_{0,j,t} = 1$ until the QoS constraint is met.

C. Step-2

In step-2 of the progressive approximation, we greedily change many ship-to-shore links into fewer ship-to-ship/shore

Step-1: Algorithm for problem (6)

- 1: Initialize $\mathbf{S}_1 = \emptyset$
 - 2: **for** all user j **do**
 - 3: **while** $V_{j,t}|_{t=t_j^{Out}} < V_j^{\text{QoS}}$ **do**
 - 4: Find ship-to-shore link with highest transmission speed.
 - 5: Add them to \mathbf{S}_1 .
 - 6: **end while**
 - 7: **end for**
-

link-pairs with higher transmission speed for lower energy consumption. We record the result we get in step-2 as \mathbf{S}_2 . After step-1 we get \mathbf{S}_1 , which is an optimal solution for problem (6). \mathbf{S}_1 only contains ship-to-shore links like $0 \rightarrow j@t'$, while \mathbf{S}_2 also contains ship-to-ship/shore link-pairs like $[0 \rightarrow i'@t_1, i' \rightarrow j@t_2]$.

Since the introduction of ship-to-ship links brings forward energy reduction by reducing the number of ship-to-shore links, we can approximate the original problem in (5a)-(5d) by maximizing the energy consumption reduction between \mathbf{S}_2 and \mathbf{S}_1 by

$$\max_{\{\delta_{i,j,t}\}} \left\{ \sum_{j=1}^J \sum_{t=1}^T \left(P_0 \delta_{0,j,t} - \sum_{i=0}^J \sum_{(i,j,t) \in \mathbf{S}_2} P_i \delta_{i,j,t} \right) \Delta \tau \right\}. \quad (7)$$

In step-2, we maximize the difference term (7) to approximate the optimal solution. Still, we ignore the subcarrier constraint, only focusing on half-duplex constraint (5b) and QoS constraint (5d).

Aiming to maximize the system energy reduction, for each user, we greedily choose ship-to-ship/shore link-pair with lowest energy consumption under given transmission speed, i.e., the composite power-to-rate ratio $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$. If this ship-to-ship/shore link-pair have lower composite power-to-rate ratio, i.e., $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}} < \frac{P_0}{r_{0,j,t_0}}$, then we substitute the original link into this ship-to-ship/shore link-pair (one link from BS to relay, the other from relay to user). We do this to maximize the difference term (7) since

$$\Delta E = \left[P_0 - \left(\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}} \right) r_{0,j,t_0} \right] \Delta \tau. \quad (8)$$

The actual transmission speeds used in the link-pair are denoted by

$$r_{0,i',t_1}^{\text{desired}} = r_{i',j,t_2}^{\text{desired}} = \min \{r_{0,i',t_1}, r_{i',j,t_2}\}. \quad (9)$$

We also used $r_{i,j,t}^{\text{desired}}$ instead of $r_{i,j,t}$ in (4) to update the data volume. The remaining available transmission speed for any link $i \rightarrow j@t$ is expressed as

$$r_{i,j,t}^{(k+1),\text{remain}} = r_{i,j,t}^{(k),\text{remain}} - r_{i,j,t}^{\text{desired}}, \quad (10)$$

where (k) denotes the k^{th} update for link $i \rightarrow j@t$.

The algorithm in step-2 is carried out as follows.

For each user j , we first record all plausible ship-to-ship/shore link-pairs like $[0 \rightarrow i'@t_1, i' \rightarrow j@t_2]$ in a temporary set \mathbf{R} . Here ‘plausible’ means that the half-duplex

constraint in (5b) is satisfied, plus both parts of the link-pairs have higher transmission speed than the original links. Further exploration will be conducted in the plausible ship-to-ship/shore link-pair set \mathbf{R} . We assume that in each ship-to-ship/shore link-pair, the BS to relay part and relay to user part transmit the same volume of data.

Once we have the substitution set \mathbf{R} , while the half-duplex constraint in (5b) and $V_{j,t} \geq 0$ in (5d) are met, we add ship-to-ship/shore link-pairs with lowest (best) composite power-to-rate ratio $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$ to \mathbf{S}_2 . Preparing for substitution, we try to meet the QoS constraint only with ship-to-ship/shore link-pairs, i.e., $V_{j,t}|_{t=t_j^{\text{out}}} \geq 2V^{\text{QoS}}$ (we may substitute all the original links and only have ship-to-ship/shore link-pairs for user j). Continue those steps until there is no plausible link-pair to user j in \mathbf{R} .

After this, we complete our substitution by removing elements in \mathbf{S}_2 with relatively high (bad) power-to-rate ratio $\frac{P_0}{r_{0,j,t_0}}$ or $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$ while the QoS constraint is met. If the element we removed is a original link, then it means we substitute it with link-pairs. If else, the element we removed is a link-pair, then it suggests that this link-pair is no better than the original link, and we do not substitute.

Step-2: Algorithm for problem (7)

- 1: Initialize $\mathbf{S}_2 = \mathbf{S}_1$
- 2: Initialize $\mathbf{R} = \emptyset$ as group for all plausible ship-to-ship/shore link-pairs.
- 3: Find all ship-to-ship/shore link-pairs combination that have higher transmission speed than the original ship-to-shore-only links. Store them in \mathbf{R} .
- 4: **for** all user j **do**
- 5: **while** $V_{j,t}|_{t=t_j^{\text{out}}} < 2V^{\text{QoS}}$ **do**
- 6: **if** there is no relay link with j as target in \mathbf{R} **then**
- 7: Break.
- 8: **end if**
- 9: Find ship-to-ship/shore link-pair in \mathbf{R} with lowest (best) composite power-to-rate ratio $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$.
- 10: Update $r_{0,i',t_1}^{\text{desired}}, r_{i',j,t_2}^{\text{desired}}$.
- 11: **if** ' V_{i',t_2} is ENOUGH' AND ' i' & j are FREE at t_2 ' AND ' i' is FREE at t_1 ' **then**
- 12: Add them from \mathbf{R} to \mathbf{S}_2 .
- 13: Update $r_{0,i',t_1}^{\text{remain}}, r_{i',j,t_2}^{\text{remain}}$.
- 14: **else**
- 15: Drop them from \mathbf{R} .
- 16: **end if**
- 17: **end while**
- 18: **end for**
- 19: **while** $V_{j,t}|_{t=t_j^{\text{out}}} \geq V^{\text{QoS}}$ **do**
- 20: Find element in \mathbf{S}_2 with highest (worst) power-to-rate ratio $\frac{P_0}{r_{0,j,t_0}}$ or $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$.
- 21: Remove it from \mathbf{S}_2 to complete the substitution.
- 22: **end while**

In order to make sure that system constraint $V_{j,t} \geq 0$ in (5d) is met, and relays do not transmit more than they have

currently, we have " V_{i',t_2} is ENOUGH" in the algorithm, which means

$$\begin{cases} V_{j',t_2-1} \geq r_0^{\min} \Delta\tau, \text{if } t_1 > t_2, \\ V_{j',t_2-1} + r_{0,j',t_1}^{\text{desired}} \Delta\tau \geq r_0^{\min} \Delta\tau, \text{else}. \end{cases} \quad (11a)$$

$$V_{j',t_2-1} + r_{0,j',t_1}^{\text{desired}} \Delta\tau \geq r_0^{\min} \Delta\tau, \text{else}. \quad (11b)$$

In the above algorithm, " i' & j are FREE at t_2 " means that

$$\sum_{i^* \neq j} \delta_{i^*,j,t_2} + \sum_{j^* \neq j} \delta_{j,j^*,t_2} - \delta_{i',j,t_2} = 0, \quad (12a)$$

$$\sum_{i^* \neq i'} \delta_{i^*,i',t_2} + \sum_{j^* \neq i'} \delta_{i',j^*,t_2} - \delta_{i',j,t_2} = 0, \quad (12b)$$

$$r_{i',j,t_2}^{\text{remain}} \geq r_{i',j,t_2}^{\text{desired}}. \quad (12c)$$

And " i' is FREE at t_1 " means that

$$\sum_{i^* \neq i'} \delta_{i^*,i',t_1} + \sum_{j^* \neq i'} \delta_{i',j^*,t_1} - \delta_{0,i',t_1} = 0, \quad (13a)$$

$$r_{0,i',t_1}^{\text{remain}} \geq r_{0,i',t_1}^{\text{desired}}. \quad (13b)$$

Through (12) and (13) the half-duplex constraint (5b) and $V_{j,t} \geq 0$ in (5d) are met for the ship-to-ship/shore substitution link-pairs.

D. Step-3

After step-1, we achieved the optimal solution for problem (6), since we have not take the subcarrier constraint into consideration. Thus, we might end up with some ship-to-shore links that do not satisfy the subcarrier constraint in (5c). Through step-2, we change part of the original links into ship-to-ship/shore link-pairs. This may relieve the conflict after step-1 since the system now has fewer links. But still, we haven't considered the subcarrier constraint. In step-3, we deal with the links that do not satisfy the subcarrier constraint.

In step-3, we minimize the energy consumption gap

$$\min_{\{\delta_{i,j,t}\}} \left\{ \sum_{i=0}^J \sum_{j=1}^J \sum_{t=1}^T \left(\delta_{i,j,t} - \delta_{i,j,t} \right) P_i \Delta\tau \right\}. \quad (14)$$

Any changes in step-3 will result in higher energy consumption over \mathbf{S}_2 . Thus, we progressively approximate the optimal solution for the ship-to-ship/shore system by minimizing the energy consumption gap between \mathbf{S}_2 and the result \mathbf{S}_3 . We propose the following algorithm in step-3.

If the constraint (5c) is not satisfied in time slot t , we find element in \mathbf{S}_2 that have the highest (worst) power-to-rate ratio $\frac{P_0}{r_{0,j,t_0}}$ or $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$. We drop those elements out of \mathbf{S}_2 and find substitution to satisfy the QoS need under the N -subcarrier constraint in (5b) with minimal energy addition. The substitution process is similar to step-2, thus it is omitted here.

E. Complexity Analysis

When carrying out the 3-step algorithm, the transmission speed (capacity) is pre-calculated based on predicted large-scale CSI. Since we have to consider links from $J+1$ transmitters to J receivers in T time slots, it takes $(J+1) \times J \times T$

Step-3: Algorithm for problem (14)

```

1: Initialize  $S_3 = S_2$ 
2: for all  $t$  do
3:   if  $\sum_j \eta_{i,j,t} \leq N$  not met then
4:     Find element in  $S_3$  that have the highest (worst)
       power-to-rate ratio  $\frac{P_0}{r_{0,j,t_0}}$  or  $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$ .
5:     Remove it from  $S_3$ .
6:   while  $V_{j,T} \geq V_{j,QoS}$  not met do
7:     Find ship-to-shore-only link or ship-to-ship/shore
       link-pair (in the remaining  $R$ ) with lowest (best)
       composite power-to-rate ratio.
8:     Add it/them to  $S_3$  (similar to Step-2).
9:   end while
10:  end if
11: end for

```

calculations. The time complexity here is $O[(J+1)JT] = O(J^2T)$.

In step-1, we have to go through all J users. For each user $j \in \{1, \dots, J\}$, it takes T iterations worst case to get the optimal solution for (6). Finding a ship-to-shore-only link with highest transmission speed is an $O(\log(T))$ operation, whereas adding a link to S_1 is a cheap $O(1)$ operation. The total complexity of step-1 is $O(JT \log(T))$.

In step-2, first, we have to acquire the ‘plausible’ ship-to-ship/shore link set R . Then, we go through all J users, adding ship-to-ship/shore link-pairs trying to meet the QoS constraint only with ship-to-ship/shore link-pairs. There are at most $J \times T^2$ links in R for each user. Hence, finding the ship-to-ship/shore link with lowest (best) composite power-to-rate ratio for user j is an $O(\log(JT^2))$ operation. After the addition of ship-ship/shore link pairs there are at most $J \times T$ link-pairs (since the link-pairs have higher transmission speed than the original ship-to-shore-only links) and $J \times T$ ship-to-shore-only links. Among all $2JT$ elements we find element with highest (worst) composite power-to-rate ratio, and remove them from S_2 . After the removal there are at most $\frac{P_0}{P_0+P_i} JT$ links in S_2 (the energy consumption of S_2 is lower than that of S_1). The removal of links has an $O\left[\frac{P_0}{P_0+P_i} JT \log(2JT)\right]$ complexity. Thus, the overall complexity for step-2 is $O[JT \log(JT^2)]$.

In step-3, since there are at most $J \times T$ links inherit from S_2 , there are at most $J \times T$ links to remove from S_3 to satisfy the subcarrier constraint. This has an $O(JT \log(JT))$ worst case complexity. Similar to step-2, adding links so that the QoS constraint is satisfied takes at most $O(NT \log(JT^2))$ operations since there are at most NT links after step-3. Thus, the time complexity in step-3 is $O[JT \log(JT) + NT \log(JT^2)]$.

In total, the overall time complexity of the 3-step algorithm is

$$O[J^2T + (N + J)T \log(JT^2)]. \quad (15)$$

As can be seen from the above analysis, the pre-processing of the transmission speed and proposed 3-step algorithm all have polynomial complexity. The total complexity is also polynomial, which is much smaller than the $O[2^{(J+1)JT}]$ exponential complexity for the optimal solution.

IV. SIMULATION RESULTS

In this section, we provide numerical results for the proposed ship-to-ship/shore 3-step progressive method, as well as a referential round-robin method. For the referential ship-to-shore round-robin method, we have zero information about CSI, thus we find up to N ships in a round-robin method in each time slot.

A. Parameters Settings

As for the system settings, the on-shore BS is located in the center of the plane and have a semicircular coverage shape in the sea, while the ships traverse along two intersecting shipping-lanes. Ships (users) leave the harbors every 15 minutes, and all sail at the speed of 36km/h. The time slot duration here is $\Delta\tau = 60$ s. The QoS constraint is 1Gbits/ship if not specified. We assume that the system uses a carrier frequency of 1.9GHz, and has 32 subcarriers, each having a bandwidth of 2MHz. The on-shore BS’s transmit power is 10W on any subcarrier, whereas the vessels’ relay transmit power is 1W on any subcarrier since they are arguably smaller in size. The antenna height of the BS and the ships are 100m and 10m, respectively. The power density of the additive white Gaussian noise is -140 dBm/Hz.

Of all the following simulations in Fig. 2 - 4, the legend ‘genius-aided’ full CSI’ actually means the assumption that we can know full CSI for the whole service duration in advance. They are brought into the following simulations to examine the feasibility of our large-scale CSI method.

As shown later in simulations, having full CSI indeed will be most feasible. In ship-to-ship/shore systems, the difference in system energy consumption between large-scale CSI replacement and the genius-aided ‘full CSI’ is around 5% - 15%. These errors here come from assuming that ship j stays in the same position and $\beta_{i,j,\tau}$ remains constant during each time slot t , as well as not knowing the full CSI. This 5% - 15% error in ship-to-ship/shore systems shows that the large-scale CSI replacement in (2c) is quite acceptable.

B. Performance Evaluations

First, in Fig. 2, we study the impact of only considering a part of the service duration in user scheduling. Next, we investigate the impact of different service needs in Fig. 3. Last, in Fig. 4, we investigate the impact of different transmit powers, since our algorithm mainly focuses on user scheduling with fixed transmit power on given subcarrier.

Fig. 2 demonstrates the relationship between average energy consumption and the ratio of T^{US} to total service time duration. Here T^{US} represents the user scheduling time duration, i.e., we only consider at most T^{US} time slots in user scheduling.

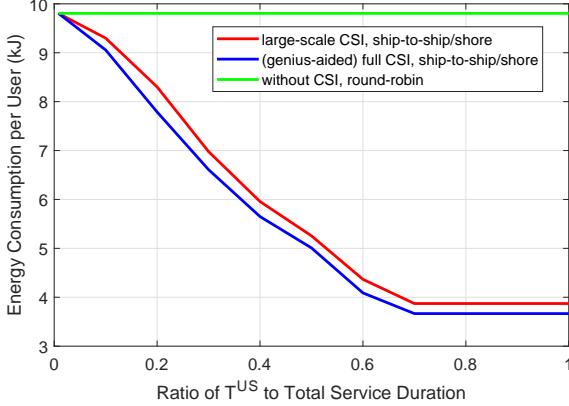


Fig. 2: System performance (energy consumption) when only considering a part of the system service duration in user scheduling algorithm

As we can see, the genius-aided full CSI curves are better than our large-scale CSI replacement energy-wise generally. Our proposed ship-to-ship/shore method outmatches the referential method, especially in ideal conditions (which means we consider full-service duration, $T^{\text{US}} = T$). Since we can take the cost of larger algorithm complexity (resulting from larger T^{US}), we can increase T^{US} in exchange for better performance energy-wise. The long-term (larger T^{US}) large-scale CSI result we get is better than the shorter-term (smaller T^{US}) genius-aided full CSI result, which justifies our large-scale replacement.

When T^{US} approximates the total service time duration, we have maximum benefit from user scheduling. The large-scale CSI ship-to-ship/shore method consummates 60% less energy than the round-robin method. Under simulation settings, due to geographical closeness and better CSI, users tend to finish their communications with BS or relays during the first 70% of their staying time inside the service zone (semicircle). The 60% improvement is steady until the ratio of T^{US} to total service time becomes less than 0.7. Thus we can set $T^{\text{US}} = 0.7T$ for relatively large improvements at a relatively small complexity cost. Energy consumption rises as the ratio of T^{US} to total service time shrinks, mainly because we aim to satisfy as much as possible in fewer time slots. When $T^{\text{US}} = 0$, i.e. having zero CSI, our proposed method retrogresses to the referential method.

Fig. 3 shows the bit-wise average energy consumption under different QoS constraint (desired data volume for each user). Our proposed ship-to-ship/shore method outmatches the referential method. We achieve the best performance improvement when the QoS constraint is 10Mbits/user. The ship-to-ship/shore method consummates 71% less energy than the referential method. When the QoS constraint is 1.5Gbits/user, we have the worst performance improvement, which is 46% over the referential method energy-wise.

The referential method's bit-wise energy consumption changes irregularly since it has zero information about CSI and chooses transmission links in a round-robin way. The

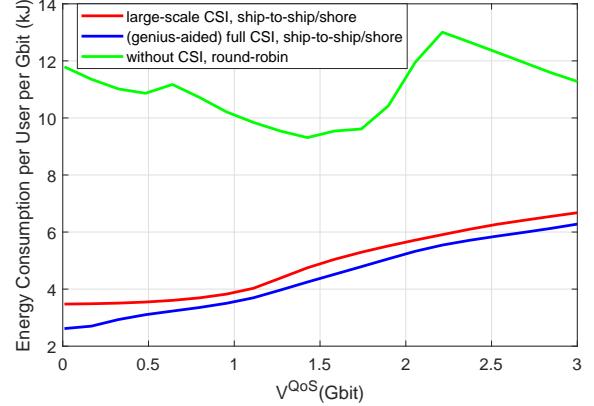


Fig. 3: System performance (energy consumption) under different QoS constraint (data volume constraint).

proposed method's energy consumptions, on the other hand, increase as the data volume desired becomes larger. The rise in proposed method's energy consumption is because we end up choosing the time slots with low transmission speed in order to meet the increasing QoS constraint. This results in a larger energy consumption per user per Gbit.

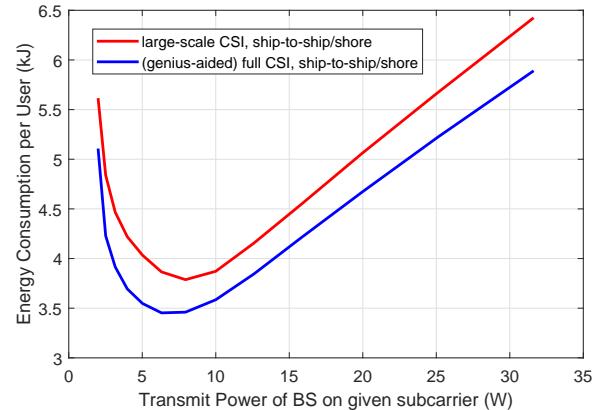


Fig. 4: System performance (energy consumption) under different BS's transmit power on given subcarrier.

Fig. 4 shows average energy consumption versus BS's transmit power under given QoS constraint. The transmit power ratio of BS and ship relays remains 10 during the change, i.e. the transmit powers of ship relays also change in direct proportion to the BS's transmit power. As we can see, the energy consumption first decreases then increases. The energy consumption increases first since the rise in transmit power results in the rise of transmission speed, and therefore the data distribution service can be done more quickly and in better CSI conditions. The overall energy consumption then increases since the $\log()$ operator in channel capacity (transmission speed) makes the increase in SNR less feasible when SNR is relatively large. Moreover, due to the greedy progressive methods for solving the user scheduling problem, the greedy choice we made focusing on links with best transmission speed also results in the increase energy-wise.

By going through different transmit powers, we can find the optimal transmit power in any specific scenario. In this case, the optimal transmit power is around 8W for the BS (0.8W for the ship relays), smaller than the 10W BS assumption we first made. The optimal transmit power is also slightly higher in large-scale CSI based user scheduling schemes than genius-aided perfect CSI scenario.

In section IV, we give the performance impact of different user scheduling time durations, as well as different QoS constraints. Besides, by going through different powers, we can choose the optimal transmit power for given QoS constraint.

As shown by simulations, the approximate solution shows its potential as well as its simplicity. The proposed large-scale-CSI-based scheme can improve the performance by up to 71% energy-wise, while only suffers a 5% - 15% rise in energy consumption over the genius-aided-full-CSI-based scheme. Thus the large-scale CSI replacement and the proposed 3-step progressive approximation are justified.

The main limitation of our progressive approximation comes from the inaccuracy in the large-scale CSI prediction. If there are any deviations in the ship routes and speeds, our large-scale CSI prediction will be inaccurate, and the performance of the proposed large-scale-CSI-based user scheduling algorithm will worsen.

V. CONCLUSION

In this paper, we have proposed a user scheduling algorithm in a maritime ship-to-ship/shore communication system, aiming to reduce the system energy consumption. In order to reduce the system energy consumption, we introduced ship-to-ship relay communication. Since large-scale CSI is the dominant factor in maritime scenarios, and the large-scale CSI can be easily predicted based on shipping lanes and timetables, we used large-scale CSI instead of full CSI to avoid the heavy overhead. Furthermore, we progressively approximated the user scheduling problem through a 3-step approximation, which has a polynomial time complexity. Simulations have shown that the proposed large-scale-CSI-based scheme significantly reduces the energy consumption by up to 71% over existing methods.

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