User Scheduling for Maritime Ship-to-Ship/Shore Communications

Yunzhong Hou, Te Wei, Wei Feng, Ning Ge, and Yunfei Chen
Tsinghua National Laboratory for Information Science and Technology, Beijing 100084, China
School of Engineering, University of Warwick, Coventry CV4 7AL, U.K.
E-mail: {houyz14, wei-t14}@mails.tsinghua.edu.cn, {fengwei, gening}@tsinghua.edu.cn,

***Abstract*—The maritime ship-to-shore communication system has to cover a vast area with limited base stations (BSs) due to the restriction of geographically available BS sites. Therefore, its energy consumption is usually much larger than terrestrial cellular networks. In order to reduce the energy consumption, we optimize user scheduling for a typical maritime ship-to-ship/shore on-shore data distribution system. Ship-to-ship communication allows ships to act like relays and enables direct communication between neighboring vessels, so as to reduce the energy consumption. In general, the channel state information (CSI) is crucial for user scheduling. However, it is difficult to acquire perfect CSI in practical applications due to the time-varying channel fading. Different from traditional studies, we use only the large-scale CSI, which varies gradually and can be obtained through the positional information of each vessel based on its specific shipping lane and timetable. We formulate a user scheduling optimization problem whose objective is to minimize the total energy consumption while guaranteeing the quality of service (QoS). To solve it, we develop a progressive approach for the original-problem and propose a 3-step greedy algorithm for the approximation. The algorithm we proposed only require polynomial computational complexity. Simulation results reveal that the user scheduling scheme we provided significantly reduces the energy consumption by up to 60% over the existing ones in certain cases.**

***Index Terms*—Maritime ship-to-ship/shore communication, user scheduling, large-scale channel status information (CSI), progressive approach, greedy method**

I. Introduction

In recent years, the demand for reliable and high-speed ship-to-shore maritime communication services increases sharply on account of the rapid development of marine activities such as marine tourism, offshore aquaculture, and oceanic mineral exploration. Several maritime communication network (MCN) projects have been developed, e.g., the BLUECOM+ project, the MarCom project, and the TRITON project [1]–[3], in order to meet the increasing demand. Unlike terrestrial cellular networks, a maritime ship-to-shore communication system has quite limited geographically available base station (BS) sites. The maritime communication system usually adopts 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. User scheduling, as an important perspective for saving energy, has attracted increasingly worldwide attention. In this paper, we introduce the idea of ship-to-ship communications, which may reduce the total energy consumption by exploiting direct communications between neighboring users. With proximate communication opportunities, ship-to-ship communication may increase spectral efficiency, improve BS coverage, as well as reduce energy consumption, while ensuring the quality of service (QoS). Unfortunately, the introduction of ship-to-ship communications greatly increases the difficulties for user scheduling.

A. Related work

So far, the majority of energy-efficient user scheduling techniques focused on terrestrial cellular networks, and CSI is a crucial factor therein. 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 in a minuscule time scale, i.e., in each coherence time [8]-[12]. In [8], the authors proposed a joint antenna-subcarrier-power allocation scheme for distributed antenna systems with limited backhaul capacity to maximize the energy efficiency for min-rate guaranteed services. In [9], a matching algorithm of joint sub-channel assignment and power allocation was developed for NOMA networks to optimize both total sum-rate and user fairness. A joint power allocation and user scheduling algorithm based on dynamic programming (DP) was proposed for multi-user MIMO systems to minimize the total energy consumption under hard delay constraints in [10]. In [11], a cross-layer cooperative user scheduling and power allocation scheme was developed for hybrid-delay services, and the fundamental tradeoff between delay and energy consumption was illustrated. Lately, a user scheduling and pilot assignment scheme for massive MIMO systems was proposed in [12] to serve the maximum number of users with guaranteed QoS.

As for maritime user scheduling, limited works have concentrated on energy efficiency. Both [13] and [14] focused on monitoring videos uploading via maritime communication networks. They both focus on user scheduling of ship-to-shore communication with the store-carry-and-forward mechanism. In [15], the authors studied the performance of a multipath

TCP controller and demonstrated how path diversity can be implicitly utilized to spread flows across available paths. In [16], 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. In [17], an efficient user scheduling algorithm aiming to optimize the pilot power under the average power constraint was proposed. In [18], transmission of MAC control messages and data packets within the three-hop neighborhood is investigated for the purpose of minimizing interference.

All of the mentioned energy-efficient user scheduling heavily depend on CSI. However, it is rather costly to acquire perfect CSI, due to the excessive system overhead including pilot overhead and feedback overhead [19]-[21]. With respect to maritime ship-to-ship/shore communication, the conflict between the limitation in power and spectrum (limited BSs covering the vast area) and heavy overhead for full CSI becomes more intense, on account of the dynamic of the maritime channel.

B. Contributions

Given the difficulties in obtaining perfect CSI in ship-to-ship/shore maritime communication systems, current studies on user scheduling for terrestrial scenarios require systematic redesign for the following reasons.

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 [19]. Hence, we can use the position information of vessels to exploit large-scale CSI instead of the complete instantaneous CSI. Through large-scale CSI, we avoid the heavy overhead for full CSI;

2. Different from the random trails of human beings in terrestrial scenarios where the previous studies focused on, most vessels have specific fixed shipping-lanes and timetables that can be acquired beforehand, thus their positional information can be easily predicted. From the positional information, we can obtain large-scale CSI for the whole service duration. With long-term large-scale CSI, we can have extensive gain by considering the whole service process instead of the short timescale in terrestrial scenarios.

Therefore, we focus on large-scale CSI rather than full CSI in this paper, and further use large-scale CSI to help us design user scheduling algorithms.

To reduce system energy consumption, we introduce the idea of ship-to-ship communications, where vessels act like relays in the data distribution network. In previous works, like [1], [3], and [22], ship-to-ship communications have been considered in the maritime network system. Nevertheless, to the best of authors' knowledge, the area still remains undiscovered where we consider ship relay transmission to reduce energy consumption. Maritime ship relay transmission may bring forward great improvements energy-wise since direct relay transmission between neighboring ships can significantly reduce the system transmission energy. Moreover, maritime users focus more on the data volume and validity rather than transmission delay, the BS can transmit data to a ship relay, which then store-carry-and-forward the data to the target user. We can further use large-scale CSI to provide channel information for the whole service duration and help us with user scheduling for relay transmission.

Thus, the ship relay transmission enabled by ship-to-ship communication is promising in reducing system energy consumption.

In this paper, with the help of large-scale CSI, we formulate an optimization problem for user scheduling in maritime ship-to-ship/shore communication systems, aiming to minimize the energy consumption. Unfortunately, ship-to-ship relay transmission introduces more transmitters (BS/relays), which brings more difficulties in user scheduling and make the problem incomputable. To overcome the difficulties of solving the incomputable problem, we progressively approach the original-problem. We further propose three efficient algorithms for our progressive approach by taking advantages of large-scale CSI. The progressive algorithms we proposed all have polynomial time complexity.

C. Organization and Notation

The rest of the paper is organized as follows.

Section II introduces the system model, where a multi-user maritime ship-to-ship/shore communication system is considered, and the formulation of the optimization problem for user scheduling is presented. In Section III, the problem is progressively approached by three progressive algorithms. Section IV presents simulation results along with further discussions. Finally, Section V gives the concluding remarks.

Throughout this paper, lightface symbols represent scalars, while boldface symbols denote vectors, matrices or sets. $\mathbf{I}$ represents an identity matrix, $\mathbb{E}[x]$ denote the expectation of x, and $\mathcal{CN}(0, \sigma^2)$ denotes the complex Gaussian distribution with zero mean and σ^2 variance.

II. System Model

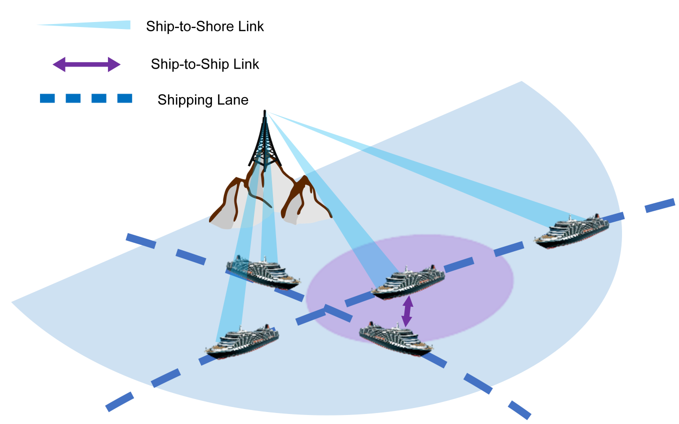

Fig. 1. Maritime ship-to-ship/shore communication system for data distribution service.

A. System Parameters

As shown in Figure 1, the following sections focus on the user scheduling of an FDMA downlink transmission of a single-BS maritime ship-to-ship/shore communication system. In the system, there are one on-shore BS and J single-antenna users (ships) in the sea. We assume that there are N subcarriers, and the subcarrier bandwidth is B_s. In this paper, we only consider two-hop half-duplex 'ship-to-ship/shore communications' for simplicity.

In the studied 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. At any given time, each ship-to-ship or ship-to-shore links will use distinct subcarrier. Here in this paper by 'link' we mean the transmission from BS/relay to a user during a certain time period. Given that we only consider half-duplex transmission, the J single-antenna users can either receive data from one transmitter (BS/relay) or send data to another user (act as a relay) at any given time.

Without loss of generality, we assume the on-shore BS coverage shape to be a semicircle. Each user sails into and out of the semicircle according to its shipping lane and timetable. For each user, delay-torrent service is assumed, and the total amount of the data required by the j^{th} user is denoted by V_j^{QoS}. Together with long-term large-scale CSI, the delay-tolerant assumption in QoS can bring forward great potential in long-term user scheduling. In order to simplify the problem, we only consider ship-to-ship and ship-to-shore transmissions of the ships in the semicircle. We also assume all the users request different data and the system has no ship-to-ship link data reuse.

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

B. Large-Scale CSI

In terrestrial scenarios, according to multipath effect, signals are well scattered and the small-scale fading factor has a significant impact on the channel. Whereas 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 [23]–[25]. 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 $h_{i,j,\tau}$ follows 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

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

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. $P_i = \{P_0, \{P_j\}\}$ represents the fixed transmission power of BS or ship relays (ships) on any subcarrier.

To fully utilize the slowly-varying characteristic of the large-scale channel fading, we divide the total service time into T time slots, each lasts $\Delta\tau$. The value $\Delta\tau$ is carefully chosen so that $\beta_{i,j,\tau}$ remains constant in each time slot t (ignore ship movement during time slot). Thus, we make it possible to acquire $\beta_{i,j,t} = \mathbb{E}\left[\beta_{i,j,\tau}\right]$ for $\forall t \in \{1, ..., T\}$ from positional information based on shipping-lanes and timetable. In this paper we replace the perfect CSI with long-term large-scale CSI as shown in (2a)-(2c). We justify our replacement by simulations in Section IV. Denote $\gamma_{i,j,t} = {P_i\beta_{i,j,t}}/{\sigma^2}$ for simplicity, where P_i represents the transmission power from BS/relay i to receivers. The channel capacity or transmission speed in this paper can therefore be simplified as

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

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

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

The transmission speed in (2c) is derived based on current study [26]. Any further denotation of CSI in this paper refer to the 'large-scale CSI' in (2c) for the whole service duration unless specified. The impact of this replacement (assuming that ship j stays in the same position and $\beta_{i,j,\tau}$ remains constant in each time slot t) is further discussed in Section IV.

C. Problem Formulation

The total energy consumption of the system consists of a ship-to-shore transmission part and a ship-to-ship transmission part. For each user, they receive transmission from different transmitter i in each time slot t. Therefore the energy consumption in this system is

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

By $\delta_{i,j,t} \in \{0, 1\}$ we denote if a subcarrier is scheduled for the link $i \to j@t$. $\delta_{i,j,t} = 0$ 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 $i \to j@t$ and a subcarrier is scheduled for the link. Moreover, $\forall j, \forall t, \delta_{j,j,t} \equiv 0$, since we don't allow receiving transmissions from oneself. Our objective is to minimize the system energy consumption by means of user scheduling in ship-to-shore transmissions and ship-to-ship transmissions.

We denote the total data volume 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 minus relayed data volume in each time slot.

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

The time slot user j enter and leave the BS coverage is denoted by $t_j^{\mathrm{B}}, t_j^{\mathrm{E}}$, respectively. In the considered system, based on delay-tolerant assumption, $t_j^{\mathrm{B}}, t_j^{\mathrm{E}}$ equal the service begin time slot and end time slot for user j. Since the system has no ship-to-ship link 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 ship-to-ship/shore links we chosen in a link set $\mathbf{S}$. $\mathbf{S}$ can be acquired before ships enter the BS coverage based on our proposed algorithm. 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 to each user at any given time slot.

Thus, we formulate the energy consumption optimization problem as

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

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

$$\sum_{i}\sum_{j} \delta_{i,j,t} \leq N, \tag{5c}$$

$$V_{j,t}|_{t=t_j^{\mathrm{B}}} = 0,\, V_{j,t}|_{t=t_j^{\mathrm{E}}} \geq V_j^{QoS}, V_{j,t} \geq 0. \tag{5d}$$

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 severed simultaneously in the system, by BS or relays, since there are only N subcarriers. (5d) and (5e) make sure that the QoS constraint is met and relays cannot transmit more than they have currently.

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

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 efficient algorithm with polynomial time complexity.

A. Progressive Approach of the Original-Problem

The original-problem in (5) involves various factors, and achieving the optimal solution for it is not practical. In order to approximate the optimal solution, we first loosen some constraints in (5), and then gradually add them back to approach the original-problem through a 3-step progressive algorithm, with each step based on its predecessor's result.

First, we focus on long-term user scheduling enabled by large-scale CSI, since the key factor of our long-term scheduling is the utilization of large-scale CSI that we can know in advance. We simply consider the ship-to-shore transmission and ignore the subcarrier constraint. We can get a greedy result from this simple problem by choosing links with best CSI.

Second, we consider the maritime ship-to-ship/shore communication system. Benefiting from large-scale CSI between ships, we substitute part of the ship-to-shore links we get in step-1 for two-hop ship-to-ship/shore links $[0 \to i'@t_1, i' \to j@t_2]$ 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, we use a progressive 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 for ship-to-shore links. Since this constraint hasn't 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 three algorithms, we approximate the optimal solution for the original-problem in (5). In Section IV we prove the validity of our progressive approach by comparing the energy consumptions.

B. Step-1

For the first algorithm, 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.

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

$$s.t. \quad V_{j,t}|_{t=t_j^{\mathrm{B}}} = 0,\, V_{j,t}|_{t=t_j^{\mathrm{E}}} \geq V_j^{QoS}, V_{j,t} \geq 0. \tag{6b}$$

We only optimize $\{\delta_{0,j,t}\}^{J\times T}$ since in step-1, there is only one transmitter. Half-duplex constraint in (5b) is 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 algorithm, 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 a easy greedy solution for each user by choosing links with best CSI (transmission speed).

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 $\delta_{i,j,t} = 1$.

For each user, we find link $0 \to j@t$ with best $\beta_{0,j,t}$ and set the ratio of the used transmission power $\delta_{0,j,t} = 1$ until the QoS constraint is met.

C. Step-2

In step-2 of the progressive approach, we greedily change many ship-to-shore links into fewer ship-to-ship/shore links with higher transmission speed for lower energy consumption and record the link set 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 $0 \to j@t'$, while $\mathbf{S_2}$ also contains ship-to-ship/shore links like $[0 \to i'@t_1, i' \to j@t_2]$.

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

$$\max_{\{\delta_{i,j,t}\}} \left\{ \sum_{j=1}^{J} \sum_{t=1}^{T} \left(\underset{(0,j,t)\in\mathbf{S_1}}{P_0 \delta_{0,j,t}} - \sum_{i=0}^{J} \underset{(i,j,t)\in\mathbf{S_2}}{P_i \delta_{i,j,t}} \right) \Delta\tau \right\}. \quad (7)$$

We maximize the difference term to approximate the optimal solution.

Aiming to maximize the system energy reduction, for each user, we greedily choose ship-to-ship/shore links 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 the ship-to-ship/shore links 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 ship-to-ship/shore links (one link from BS to relay, the other from relay to user). We do this to maximize the difference term 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 algorithm in step-2 is carried out as follows.

For each user j, we first record all plausible ship-to-ship/shore links like $[0 \to i'@t_1, i' \to j@t_2]$ in a temporary set $\mathbf{R}$. Here 'plausible' means that the half-duplex constraint in (5b) and the N-subcarrier constraint in (5c) are satisfied, plus both parts of the links have higher transmission speed than the original links. Further exploration will be conducted in the plausible ship-to-ship/shore link set $\mathbf{R}$. We assume that in each ship-to-ship/shore links, the BS to relay part and relay to user part transmit same volume of data.

Once we have the substitution set $\mathbf{R}$, we add ship-to-ship/shore links to the system until we can meet the QoS constraint only with ship-to-ship/shore links, i.e., $V_{j,t}|_{t=T} \geq 2V^{QoS}$. Continue those steps until the plausible link set $\mathbf{R}$ become empty or there is no gain energy-wise from substitution, i.e., there are no ship-to-ship/shore links that have lower composite power to rate ratio $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$ than the original links. After this, we complete our substitution by removing original links with relatively higher power to rate ratio $\frac{P_0}{r_{0,j,t_0}}$.

In order to make sure that system constraint in (5d) is met, and relays do not transmit more than they have currently, we

Algorithm 1 Suboptimal User Scheduling for Maritime Ship-to-Ship/Shore Communication System

Initialize $\mathbf{S_2} = \mathbf{S_1}$
Initialize $\mathbf{R} = \phi$ as group for all plausible ship-to-ship/shore links.
Find all ship-to-ship/shore links combination that have higher transmission speed than the original ship-to-shore only links. Store them in $\mathbf{R}$.
for all user j **do**
  while $V_{j,t}|_{t=T} < 2V^{QoS}$ **do**
    if there is no relay link with j as target in $\mathbf{R}$ **then**
      Break.
    end if
    Find ship-to-ship/shore links in $\mathbf{R}$ with lowest (best) composite power to rate ratio $\frac{P_0}{r_{0,i',t_1}} + \frac{P_{i'}}{r_{i',j,t_2}}$.
    if 'V_{i',t_2} is ENOUGH' AND 'i' & j & SYSTEM are FREE at t_2' AND 'i' & SYSTEM are FREE at t_1' **then**
      Add them from $\mathbf{R}$ to $\mathbf{S_2}$.
    end if
  end while
end for
while $V_{j,t}|_{t=T} \geq V^{QoS}$ **do**
  Find original ship-to-shore link in $\mathbf{S_2}$ with highest (worst) power to rate ratio $\frac{P_0}{r_{0,j,t_0}}$.
  Remove it from $\mathbf{S_2}$ for the substitution.
end while

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

$$\begin{cases} V_{j',t_2-1} \geq r_0^{\min}\Delta\tau, \textit{if}\, t_1 > t_2, & (9a) \\ V_{j',t_2-1} + r_{0,j',t_1}\Delta\tau \geq r_0^{\min}\Delta\tau, \textit{else}. & (9b) \end{cases}$$

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

$$\begin{cases} \sum_{i^*\neq j} (\eta_{i^*,j,t_2} > 0) + \sum_{j^*\neq j} (\eta_{j,j^*,t_2} > 0) \leq 1, & (10a) \\ \sum_{i^*\neq i'} (\eta_{i^*,i',t_2} > 0) + \sum_{j^*\neq i'} (\eta_{i',j^*,t_2} > 0) \leq 1, & (10b) \\ \sum_{j^*} \sum_{i^*} (\eta_{i^*,j^*,t_2}) \leq N. & (10c) \end{cases}$$

And "i' & SYSTEM are FREE at t_1" means that

$$\begin{cases} \sum_{i^*\neq i'} (\eta_{i^*,i',t_1} > 0) + \sum_{j^*\neq i'} (\eta_{i',j^*,t_1} > 0) \leq 1, & (11a) \\ \sum_{j^*} \left(\sum_{i^*} (\eta_{i^*,j^*,t_1} > 0) \right) \leq N. & (11b) \end{cases}$$

Through (10) and (11) the half-duplex constraint (5b) and N-subcarrier constraint (5c) are met, at least for the ship-to-ship/shore substitution links.

D. Step-3

After step-1, we achieved the optimal solution for probelm (6), though we haven't take the subcarrier constraint into the ship-to-shore only system. Thus, we might end up with some ship-to-shore links that don't satisfy the subcarrier constraint in (5c). Through step-2, we change part of the original links into ship-to-ship/shore links. This may relieve the conflict after step-1 since the system now have fewer links. In step-3, we deal with the remaining links that don't satisfy the subcarrier constraint.

Since the ship-to-shore links returned by step-1 are the optimal choice, any changes in step-3 will result in higher energy consumption. 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 $\mathbf{S_3}$. In step-2, we considered the subcarrier constraint when making substitutions. Thus only the original links introduced by step-1 will violate the subcarrier constraint in (5c). Therefore we propose the following algorithm in step-3.

In step-3, we minimize the energy consumption gap

$$\min_{\{\delta_{i,j,t}\}} \left\{ \sum_{i=0}^{J} \sum_{j=1}^{J} \sum_{t=1}^{T} \left(\delta_{\substack{i,j,t \\ (i,j,t)\in\mathbf{S_3}}} - \delta_{\substack{i,j,t \\ (i,j,t)\in\mathbf{S_2}}} \right) P_i \Delta\tau \right\}. \quad (12)$$

If the constraint (5c) isn't met in time slot t, we find links in $\mathbf{S_2}$ that have the highest (worst) power to rate ratio $\frac{P_0}{r_{0,j,t_0}}$. We drop those links out of $\mathbf{S_2}$ and find substitution links to satisfy the QoS need under the N-subcarrier constraint in (5b) with minimal energy addition.

Algorithm 2 Subcarrier Constraint Adjustments

```
Initialize S_3 = S_2
for all t do
    if Σ_j η_{0,j,t} ≤ N not met then
        Find original link in S_3 that have the highest (worst)
        power to rate ratio P_0 / r_{0,j,t_0}.
        Remove it from S_3.
        while V_{j,T} ≥ V_{j,QoS} not met do
            Find ship-to-shore only link or ship-to-ship/shore
            links with lowest (best) composite power to rate
            ratio.
            Add it/them to S_3.
        end while
    end if
end for
```

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 reference round-robin method. For the reference 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 & Denotation

As for the system settings, the on-shore BS is located in the center of the plane and have a semicircle coverage shape in the sea, while the ships traverse along two intersecting shipping-lanes. Ships (user) 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, which have identical bandwidth 2MHz. The on-shore BS's transmission power is 10W on any subcarrier, whereas the vessels' relay transmission power is 1W on any subcarrier since they are arguably smaller in size. The antenna height of the BS and the ships is 100m and 10m respectively. The power density of the additive white Gaussian noise is -140dBm/Hz.

Of all the following simulations in Figure 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 long-term 'full CSI' is around 5%. 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% error in ship-to-ship/shore systems shows that the large-scale CSI replacement in (2d) is quite acceptable.

B. Figures

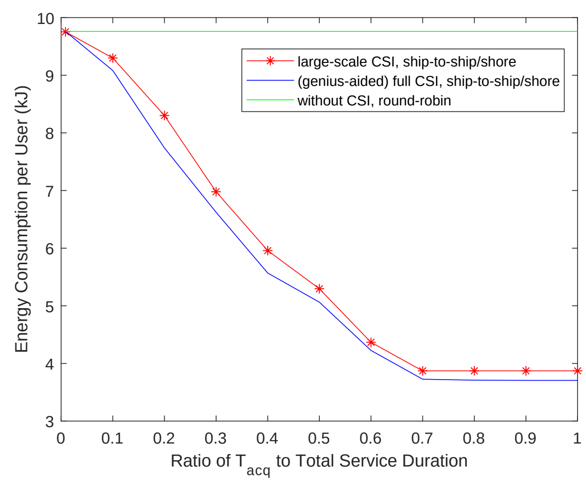

Fig. 2. Average energy consumption per user versus the ratio of T_{acq} to total service time duration.

First, we study the impact of only acquiring large-scale CSI for a part of the whole service duration.

Figure 2 demonstrates the relationship between average energy consumption and the ratio of T_{acq} to total service time duration. Here T_{acq} represents the time duration whose CSI we can acquire in advance.

As we can see, our proposed ship-to-ship/shore method outmatches the reference method, especially in ideal conditions (which means we can acquire all CSI, T_{acq} = total service time). The genius-aided full CSI curves are better than our large-scale CSI replacement energy-wise generally. However, the long-term (larger T_{acq}) large-scale CSI result we get is still better than getting full CSI for a shorter period (smaller T_{acq}), which justifies our large-scale replacement, since the long-term large-scale CSI can be easily predicted based on shipping lanes and timetables.

When T_{acq} approximate the total service time duration, we have maximum benefit from the long-term CSI. The large-scale CSI ship-to-ship/shore method consummates 60% less energy than the round-robin method. Energy consumption rises as the ratio of T_{acq} to total service time decreases, mainly because we aim to satisfy as much as possible in fewer time slots. When we can only acquire present CSI, i.e. $T_{acq} = 1$, our proposed method retrogresses to the reference method since we no longer have any long-term CSI and the proposed methods become greedy with no 'future information' about the CSI.

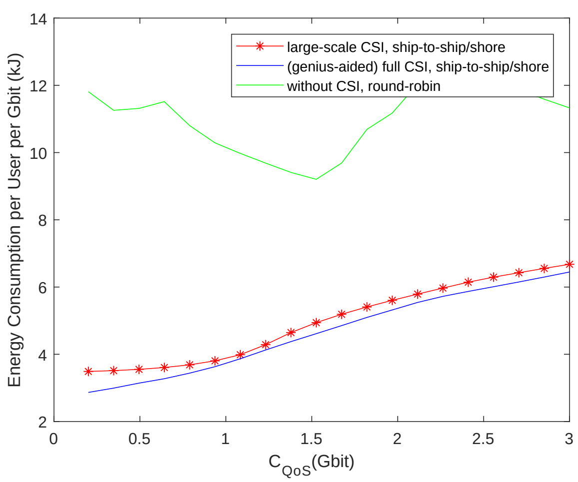

Fig. 3. Average energy consumption per user E_{avg} versus the QoS constraint V_{QoS}.

Next, we investigate the impact of different service needs in Figure 3.

Figure 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 reference method. When the QoS constraint is 1Gbits/user, the ship-to-ship/shore method consummates 60% less energy than the reference method.

The reference 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 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.

Last, we investigate the impact of different transmission power, since our algorithms mainly focus on user scheduling with fixed transmission power.

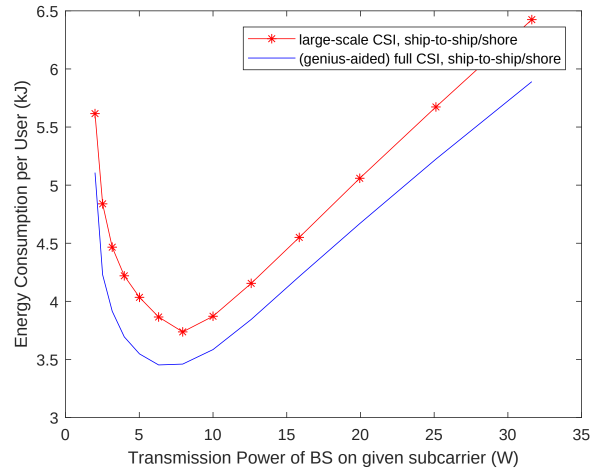

Fig. 4. Average energy consumption per user E_{avg} per Gbit versus the transmission power of BS.

Figure 4 shows average energy consumption versus BS's transmission power. The transmission power ratio of BS and ship relays remain 10 during the change, i.e. the transmission powers of ship relays also change in direct proportion to the BS's change. As we can see, the energy consumption first decreases then increases. The energy consumption first increases since the increase in transmission power results in the increase 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 transmission powers, we can find the optimal transmission power in any specific scenario. In this case, the optimal transmission power is around 8W for the BS (0.8W for the ship relays), smaller than the 10W BS assumption we first made.

To sum up, the total energy improvement is around 60% as shown by simulations in Figure 2 - 4. The approximate optimal solution we deduced from step 1 - 3 with polynomial time complexity show its potential as well as its simplicity. Therefore, the progressive approach through 3-step algorithm in Section III is justified.

V. Conclusion

In this paper, we focused on user scheduling in maritime ship-to-ship/shore communication system, aiming to reduce the system energy consumption. By exploiting large-scale CSI for the whole service duration, we proposed a user scheduling algorithm. We replace the complete channel with large-scale CSI during the whole service process, by utilizing each users' positional information acquired from the specific shipping-lanes and timetables. Further, we progressively approach the user scheduling problem through a 3-step algorithm. The 3-step algorithm we proposed can return an approximation of the optimal solution with polynomial time complexity. Simulation results justify our large-scale CSI replacement and show that the schemes significantly enhance the system performance by 60% in terms of energy consumption.

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REFERENCES

[1] R. Campos, T. Oliveira, N. Cruz, A. Matos, and J. M. Almeida, “BLUECOM+: Cost-effective broadband communications in remote ocean areas,” in *Proc. OCEANS*, Apr. 2016, pp. 1–6.

[2] F. Bekkadal, “Innovative maritime communications technologies,” in *Proc. Intern. Conf. Microwaves, Rader, & Wireless Commun.*, June 2010, pp. 1–6.

[3] M. Zhou, et al., “TRITON: high-speed maritime wireless mesh network,” *IEEE Wireless Commun.*, vol. 20, no. 5, pp. 134–142, 2013.

[4] S. Buzzi, et al., “A survey of energy-efficient techniques for 5G networks and challenges ahead,” *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 697–709, 2016.

[5] M. Shreedhar and G. Varghese, “Efficient fair queuing using deficit round-robin,” *IEEE/ACM Trans. Networking*, vol. 4, no. 3, pp. 375–385, 1996.

[6] Q. Cao, Y. Sun, Q. Ni, S. Li, and Z. Tan, “Statistical CSIT aided user scheduling for broadcast MU-MISO system,” *IEEE Trans. Veh. Tech.*, vol. 66, no. 7, pp. 6102–6114, 2017.

[7] J. Wang, M. Matthaiou, S. Jin, and X. Gao, “Precoder design for multiuser MISO systems exploiting statistical and outdated CSIT,” *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4551–4564, 2013.

[8] X. Li, et al., “Energy efficiency optimization: joint antenna-subcarrier-power allocation in OFDM-DASs,” *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7470–7483, 2016.

[9] B. Di, L. Song, and Y. Li, “Sub-channel assignment, power allocation, and user scheduling for non-orthogonal multiple access networks,” *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7686–7698, 2016.

[10] L. Shan and R. Miura, “Energy-efficient scheduling under hard delay constraints for multi-user MIMO System,” in *Proc. Intern. Symp. Wireless Personal Multimedia Commun.*, Sept. 2014, pp. 696–699.

[11] S. Cao, Q. Cui, Y. Shi, H. Wang, and X. Ma, “Cross-layer cooperative delay-energy tradeoff scheme for hybrid services in cellular networks,” in *Proc. IEEE Veh. Tech. Conf.*, May 2014, pp. 1–5.

[12] X. Xiong, B. Jiang, X. Gao and X. You, “QoS-guaranteed user scheduling and pilot assignment for large-scale MIMO-OFDM systems,” *IEEE Trans. Veh. Tech.*, vol. 65, no. 8, pp. 6275–6289, 2016.

[13] T. Yang, H. Liang, N. Cheng, and X. Shen, “Towards video packets store-carry-and-forward scheduling in maritime wideband communication,” in *IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2013, pp. 4032–4037.

[14] T. Yang, H. Liang, N. Cheng, R. Deng, and X. Shen, “Efficient scheduling for video transmissions in maritime wireless communication networks,” *IEEE Trans. Veh. Tech.*, vol. 64, no. 9, pp. 4215–4229, 2015.

[15] A. Bejan, R. Gibbens, Y. Lim, and D. Towsley, “A performance analysis study of multipath routing in a hybrid network with mobile users,” in *Proc. of the 2013 25th International Teletraffic Congress (ITC)*, Sept. 2013, pp. 1–9.

[16] Y. Bai, Y. Zhai, and D. Wang, “Research on optimum cooperative relay model for moving targets based on ant colony algorithm,” in *4th International Conference on Information, Cybernetics and Computational Social Systems (ICCSS)*, Nov. 2017, pp. 539–543.

[17] T. Wei, W. Feng, N. Ge, and J. Lu, “Optimized time-shifted pilots for maritime massive MIMO communication systems,” in *Proc. 26th Wireless & Optical Commun. Conf.*, Apr. 2017, pp. 1–5.

[18] M. T. Zhou, H. Harada, P. Y. Kong, and J. S. Pathmasuntharama, “Interference range analysis and scheduling among three-hop neighborhood in maritime WiMAX mesh networks,” in *Proc. IEEE Wireless Commun. & Networking Conf.*, Apr. 2010, pp. 1–6.

[19] W. Feng, Y. Wang, D. Lin, N. Ge, J. Lu, and S. Li, “When mmWave communications meet network densification: a scalable interference coordination perspective,” *IEEE J. Sel. Areas Commun.* , vol. 35, no. 7, pp. 1459–1471, 2017.

[20] W. Feng, Y. Chen, N. Ge, and J. Lu, “Optimal energy-efficient power allocation for distributed antenna systems with imperfect CSI,” *IEEE Trans. Veh. Tech.*, vol. 65, no. 9, pp. 7759-7763, 2016.

[21] W. Feng, Y. Wang, N. Ge, J. Lu, and J. Zhang, “Virtual MIMO in Multi-Cell Distributed Antenna Systems: Coordinated Transmissions with Large-Scale CSIT,” *IEEE J. Sel. Areas in Commun.*, vol. 31, no. 10, pp. 2067-2081, 2013.

[22] J. S. Pathmasuntharam, J. Jurianto, P. Y. Kong, Y. Ge, M. Zhou, and R. Miura, “High speed maritime ship-to-ship/shore mesh networks,” in *Proc. 7th Intern. Conf. ITS Telecommun.*, June 2007, pp. 1–6.

[23] S. Balkees P A, K. Sasidhar, and S. Rao, “A survey based analysis of propagation models over the sea,” in *Proc. Intern. Conf. Advances in Computing, Commun. & Informatics*, Aug. 2015, pp. 69–75.

[24] Y. Zhao, J. Ren, and X. Chi, “Maritime mobile channel transmission model based on ITM,” *Proc. Intern. Symp. Computer Commun. Control & Automation*, vol. 68, no. 3, pp. 378–383, 2013.

[25] J. C. Reyes-Guerrero, M. Bruno, L. A. Mariscal, and A. Medouri, “Buoy-to-ship experimental measurements over sea at 5.8 GHz near urban environments,” in *Proc. Mediterranean Microwave Symp.*, Sept. 2011, pp. 320–324.

[26] H. Shin and J. H. Lee, “Capacity of multiple-antenna fading channels: spatial fading correlation, double scattering, and keyhole”, *IEEE Trans. Info. Theory*, vol. 49, no. 10, pp. 2636–2647, 2003.