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

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***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. To solve this problem, we optimize user scheduling for a typical maritime ship-to-ship/shore communication system, where ship-to-ship 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 much slowly and can be obtained through the positional information of each vessel based on its specific shipping lane and timetable. We formulate an optimization problem to minimize the total energy consumption, while guaranteeing the quality of service (QoS). The problem is uncovered to be NP-hard. To solve it, we simplify the original problem into three sub-problems and propose an efficient algorithm for each sub-problem. The algorithms 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 81% over the existing ones in certain cases.**

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

I. Introduction

With the rapid development of marine activities such as marine tourism, offshore aquaculture and oceanic mineral exploration, the demand for reliable and high-speed ship-to-shore maritime communication services increases sharply. In order to meet the increasing demand, several maritime communication network (MCN) projects have been developed in recent years, 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 base station (BS) sites. In order to cover a vast area with limited BSs, the system usually adopts high-powered BSs, which 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.

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 [19]. The second one exploited statistical and outdated CSI, as studied in [20] and [21]. 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 [22]-[26]. In [22], a joint antenna-subcarrier-power allocation scheme was proposed for distributed antenna systems with limited backhaul capacity to maximize the energy efficiency while providing min-rate guaranteed services. In [23], a matching algorithm of joint sub-channel assignment and power allocation was developed for non-orthogonal multiple access networks to maximize the total sum-rate with user fairness taken into consideration. In [24], 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 [25], 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. More recently in [26], a user scheduling and pilot assignment scheme was proposed for massive MIMO systems to serve the maximum number of users with guaranteed QoS.

As for maritime user scheduling, few work concentrated on energy efficiency has been done. In [**?**], an efficient user scheduling algorithm aiming to optimize the pilot power under the average power constraint was proposed. In [**?**], scheduling transmission of MAC control messages and data packets within 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 [**?**]. With respect to maritime ship-to-ship/shore communication, the conflict between the limitation in power and spectrum (limited BSs covering vast area) and heavy overhead for full CSI becomes more intense, on account of the dynamic of maritime channel.

Aside from heavy overhead for full CSI, the introduction of ship-to-ship communication [**?**][**?**] makes it even more difficult for user scheduling. We consider ship-to-ship communications in our system since the direct communication between neighboring ships may greatly reduce the system energy consumption. Unfortunately, more transmitters (BS/relays) to choose from brings more difficulties in user scheduling.

Given the difficulties for obtaining perfect CSI as well as choosing from transmitters 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 [**?**]. Hence, we can use the position information of vessels to exploit long-term large-scale CSI instead of the complete instantaneous CSI. Through large-scale CSI, we avoid the heavy overhead for full CSI;

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

In this paper, we formulate an optimization problem for user scheduling in maritime ship-to-ship/shore communication systems, aiming to minimize the energy consumption. The problem is proved to be NP-hard (see Appendix A). To overcome the difficulties of solving the NP-hard problem, we decompose the problem into three simpler subproblems. We further propose efficient algorithms to solve the subproblems in an iterative way with a polynomial time complexity.

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 decomposed into three subproblems and solved in an iterative way. 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

As shown in Figure 1, the following sections focus on the 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.

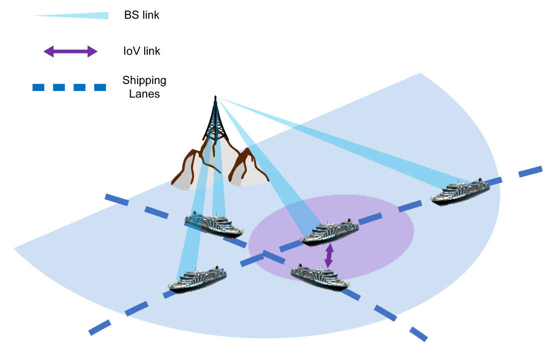

Fig. 1. Maritime ship-to-ship/shore communication system for data distribution service.

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 user during a certain time period. We further assume that 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 C_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.

We further assume a modified 2-ray propagation model, since the sea surface is relatively flat [33]–[35]. 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.

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 (ship j holds still during time slot t). 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)-(2d). We justify our replacement by simulations in Section IV. SIMULATION RESULTS. Denote $\gamma_{i,j,\tau} = {P_{i,j,\tau}\beta_{i,j,\tau}}/{\sigma^2}$ for simplicity, the channel capacity or transmission speed in this paper can therefore be simplified as

$$\begin{aligned} r_{i,j,t} &= \mathbb{E}\left[B_s \log_2\left(1+\frac{P_{i,j,\tau}\beta_{i,j,\tau}|h_{i,j,\tau}|^2}{\sigma^2}\right)\right], && \text{(2a)}\\ &= \mathbb{E}\left[B_s \log_2\left(1+\gamma_{i,j,\tau}|h_{i,j,\tau}|^2\right)\right], && \text{(2b)}\\ &= \mathbb{E}\left[(\log_2 e)\, e^{\frac{1}{\gamma_{i,j,\tau}}}\int_1^\infty \frac{1}{u}e^{-\frac{u}{\gamma_{i,j,\tau}}}du\right], && \text{(2c)}\\ &\approx (\log_2 e)\, e^{\frac{1}{\gamma_{i,j,t}}}\int_1^\infty \frac{1}{u}e^{-\frac{u}{\gamma_{i,j,t}}}du, && \text{(2d)} \end{aligned}$$

where $\tau \in [(t-1), t]\,\Delta\tau$ represents all time τ within time slot t. The transmission speed in (2c) is derived based on current study [36]. We take one step further and complete our long-term large-scale CSI replacement of full CSI in (2d) by assuming that $\beta_{i,j,\tau}$ remains constant (ship j stays in the same position) in each time slot t and taking out the expectation operator. Any further denotation of CSI in this paper refer to the 'long-term large-scale CSI in (2d)' 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. SIMULATION RESULTS.

The total energy consumption of the system consists of ship-to-shore transmission part and ship-to-ship transmission part. The energy consumption in this system is

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

where $P_{i,j,t}$ represents the average power consumed by the transmission from BS/relay i to user j during time slot t.

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 further 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 $i \to j@t$. For the link $i \to j@t$, we denote the ratio of used transmission power to max transmission power by

$$\eta_{i,j,t} = \frac{P_{i,j,t}}{P_i^{\max}}, \eta_{i,j,t} \in [0, 1]. \tag{4}$$

$\eta_{i,j,t} = 0$ means there is no transmission from BS/relay i to user j at time slot t, while $\eta_{i,j,t} \in (0, 1]$ means a subcarrier is scheduled at time slot t for the link and the transmission uses $\eta_{i,j,t}$ of the transmitter's max transmission power. $P_i^{\max} = \left\{P_0^{\max}, \left\{P_j^{\max}\right\}\right\}$ represents the maximum transmission power of BS or relays (ships).

By $C_{j,t}$ we denote the total data volume user j currently has at time slot t. Since the system has no ship-to-ship link data reuse, user j must have enough data $C_{j,t}$ in order to act as relay and transmit to another user j' at t

Thus, we formulate the energy consumption optimization problem as

$$\min_{\mathrm{H}\in[0,1]^{(J+1)\times J\times T}} \left\{\sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=0}^{J} P_{i,j,t}\Delta\tau\right\}, \tag{5a}$$

$$s.t. \;\; \sum_{i\neq j}(\eta_{i,j,t} > 0) + \sum_{j'\neq j}(\eta_{j,j',t} > 0) \le 1, \tag{5b}$$

$$\sum_{j}\sum_{i}(\eta_{i,j,t} > 0) \le N, \tag{5c}$$

$$C_{j,t}\big|_{t=0} = 0, C_{j,t}\big|_{t=T} \ge C_j^{QoS}, \tag{5d}$$

$$C_{j,t} = \sum_{\tau=1}^{t}\left(\sum_{i} r_{i,j,\tau} - \sum_{j'} r_{j,j',\tau}\right)\Delta\tau,\ C_{j,t} \ge 0. \tag{5e}$$

H = $\{\eta_{i,j,t}\}^{(J+1)\times J\times T}$ since we have to consider transmissions from $J+1$ transmitters (BS/relays) to J receivers (users) at T time slots. 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. Constraint in (5c) guarantees that at most N users can be severed simultaneously in the system, by BS or relays, since there is only N subcarriers. (5d) and (5e) make sure that the QoS constraint is met and relays cannot transmit more than they have currently.

Theorem 1: The problem in (5) is NP-hard.

Proof: See Appendix A.

III. User Scheduling for Maritime Ship-to-Ship/Shore Communication

In this section, we focus on the reduction of system energy consumption while ensuring the users' service requirements (QoS). We decompose the optimization problem in (5) into 3 subproblems. Moreover, we proposed an efficient algorithm for each of the subproblems with polynomial time complexity to solve the NP-hard problem.

A. Problem Decomposition

The problem in (5) is a discrete non-convex optimization problem and is NP-hard. Therefore, conventional methods for solving linear or convex optimization problems are no longer applicable, and achieving the optimal solution for the NP-hard problem in (5) is not practical. In order to achieve a suboptimal solution, we decompose the problem into three simpler subproblems, each based on its predecessor subproblem. Eventually, after solving three subproblems, we achieve a suboptimal solution for the original problem in (5).

First, in **Subproblem 1: BT (BS Transmission)**, we consider the BS transmission and ignore the subcarrier constraint.

Second, in **Subproblem 2: NBT (N-Subcarrier BS Transmission)**, we use an iterative algorithm to make sure the

BS transmission uses no more than N subcarriers and get a suboptimal solution for the BS-only system.

Last, in **Subproblem 3: IoV-NBT (IoV-Aided N-Subcarrier BS Transmission)**, we consider the maritime communication system with IoV. We use another iterative algorithm to substitute part of the BS-only links for BS-&-IoV links for less energy consumption. Each of the substitution BS-&-IoV links consists of exact a BS part $0 \rightarrow i'@t_1$ for BS to transmit data to relay i' and an IoV relay transmission part $i' \rightarrow j@t_2$ for relay i' to transmit to receiver user j. The BS-&-IoV link $[0 \rightarrow i'@t_1, i' \rightarrow j@t_2]$ (one BS and one IoV) in the substitution link set must use less energy combined than the original BS-only link $0 \rightarrow j@t_0$ for improvement energy-wise.

*B. Solution to **Subproblem 1: BT***

For the first two subproblems, we consider a BS-only system. We fix $i = 0$ since users can only receive data from BS.

$$\min_{\mathrm{H}_{\mathbf{0}} \in [0,1]^{(J+1)\times J\times T}} \left\{ \sum_{t=1}^{T} \sum_{j=1}^{J} P_{0,j,t} \Delta\tau \right\}, \tag{6a}$$

$$s.t. \ \sum_{j} (\eta_{0,j,t} > 0) \leq N, \tag{6b}$$

$$C_{j,t}\big|_{t=0} = 0, C_{j,t}\big|_{t=T} \geq C_j^{QoS}, \tag{6c}$$

$$C_{j,t} = \sum_{\tau=1}^{t} r_{0,j,\tau} \Delta\tau, \ C_{j,t} \geq 0. \tag{6d}$$

$\mathrm{H}_{\mathbf{0}} = \{\eta_{0,j,t}\}^{J\times T}$ since in the first two BS-only sub problems, there is only one transmitter. Constraint in (5b) is not necessary here since users can only receive data from BS.

In the first subproblem, we optimize $\mathrm{H}_{\mathbf{0}}$ with constraint (6c) and (6d), ignoring the subcarrier constraint in (6b). This means we assume that the BS can serve infinite number of users, and we ignore the subcarrier constraint. In this case, the optimization variables of different users in no longer correlated, and the optimal solution of this problem can be obtained by scheduling each user separately. The problem can be reduced to $\min\limits_{\mathrm{H}_{\mathbf{0}} \in [0,1]^{T}} \left\{ \sum\limits_{t=1}^{T} P_{0,j,t} \Delta\tau \right\}$. Note that $r_{0,j,t}$ is a monotone increasing function of $\beta_{0,j,t}$, therefore we can obtain the optimal solution for each user by assigning time slots with best CSI.

We further define $\mathbf{S_1}$ as the set of chosen BS-only link at a specific time slot in **Subproblem 1: BT**, i.e., $(0, j, t) \in \mathbf{S_1}$ if $\eta_{i,j,t} \in (0, 1]$. We propose Algorithm 1 to solve the first subproblem. For each user, we find link $0 \rightarrow j@t$ with best $\beta_{0,j,t}$ and set the ratio of the used transmission power $\eta_{0,j,t} = 1$ until the QoS constraint is met.

*C. Solution to **Subproblem 2: NBT***

The solution $\mathbf{S_1}$ returned by Algorithm 1 is not a feasible one for the BS-only system in (6a)-(6d) since (6b) has not been taken into account. We design an effective method to

Algorithm 1 Optimal User Scheduling for BS-only System Regardless of Subcarrier Count

```
Initialize S_1 = φ
for each user j do
    while C_{j,T} ≥ C_{j,QoS} not met do
        Find (0, j, t) = arg max {r^max_{0,j,t}}.
        Set η_{0,j,t} = 1.
        Update C_{j,t}, P_{0,j,t}, S_1 = S_1 ∪ {(0, j, t)}.
    end while
end for
```

approach the suboptimal feasible solution $\mathbf{S_2}$ for constraints in (6) iteratively.

As $\mathbf{S_1}$ is the optimal solution for (6c) and (6d), the original problem in (6) is equivalent to minimizing the energy consumption gap between $\mathbf{S_1}$ and the result $\mathbf{S_2}$ in subproblem 2, and the second subproblem can be expressed as

$$\min_{\mathrm{H}_{\mathbf{0}} \in [0,1]^{J\times T}} \left\{ \sum_{t=1}^{T} \sum_{j=1}^{J} \left(\underset{(0,j,t)\in \mathbf{S_2}}{P_{0,j,t}} - \underset{(0,j,t)\in \mathbf{S_1}}{P_{0,j,t}} \right) \Delta\tau \right\}, \tag{7a}$$

$$s.t. \ \sum_{j} (\eta_{0,j,t} > 0) \leq N, \tag{7b}$$

$$C_{j,t}\big|_{t=0} = 0, C_{j,t}\big|_{t=T} \geq C_j^{QoS}, \tag{7c}$$

$$C_{j,t} = \sum_{\tau=1}^{t} r_{0,j,\tau} \Delta\tau, \ C_{j,t} \geq 0. \tag{7d}$$

Note that solving this subproblem is a process of adjusting the user scheduling result in $\mathbf{S_1}$.

If the constraint (7b) isn't met in time slot t, we have to use alternative links like $0 \rightarrow j@t'$ for replacement. These replacements will satisfy the N-subcarrier constraint at the cost of more energy consumption.

To acquire the suboptimal solution $\mathbf{S_2}$, we find links in $\mathbf{S_1}$ that have least impact on system capacity if substituted. We drop those links out of $\mathbf{S_2}$ and find substitution links to satisfy the QoS need under the N-subcarrier constraint in (7b) with minimal energy addition.

The proposed iterative method is shown in Algorithm 2.

*D. Solution to **Subproblem 3: IoV-NBT***

After solving the first two subproblems, we have already claimed an approximation of the optimal solution for the BS-only system. In subproblem 3, we change part of the BS-only links into BS-&-IoV links for better energy efficiency. The optimization in subproblem 3 derives the final solution $\mathbf{S_3}$. $\mathbf{S_3}$ contains both BS-only links like $0 \rightarrow j@t'$ and BS-&-IoV links like $[0 \rightarrow i'@t_1, i' \rightarrow j@t_2]$.

Given that $\mathbf{S_2}$ is only based on constraint (6a)-(6d), the original problem in (5a)-(5e) is equivalent to maximizing the energy consumption reduction between $\mathbf{S_3}$ and the result $\mathbf{S_2}$ in subproblem 2, and the third subproblem can be expressed as

Algorithm 2 Suboptimal User Scheduling for BS-only System

Initialize $\mathbf{S_2} = \mathbf{S_1}$
while $\forall t, \sum_j \eta_{0,j,t} \leq N$ not met **do**
  Find $(0,j,t) = \arg \min_{\substack{(0,j,t)\in \mathbf{S_1} \\ (0,j,t')\notin \mathbf{S_2}}} \{r_{0,j,t} - r_{0,j,t'}\}$, where $\sum_j \eta_{0,j,t'} \leq N-1$, $\sum_j \eta_{0,j,t} > N$.
  Set $\mathbf{S_2} = \mathbf{S_2} \backslash \{(0,j,t)\}$, $\eta_{0,j,t} = 0$.
  while $C_{j,T} \geq C_{j,QoS}$ not met **do**
    Find $(0,j,t) = \arg \max_{(0,j,t)\notin \mathbf{S_2}} \{r_{0,j,t}\}$, where $\sum_j \eta_{0,j,t} \leq N-1$.
    Set $\eta_{0,j,t} = 1$.
    Update $C_{j,t}$, $P_{0,j,t}$, $\mathbf{S_2} = \mathbf{S_2} \cup \{(0,j,t)\}$.
  end while
end while

$$\max_{\mathrm{H}\in[0,1]^{(J+1)\times J\times T}} \left\{ \sum_{t=1}^{T}\sum_{j=1}^{J} \left(\underset{(0,j,t)\in\mathbf{S_2}}{P_{0,j,t}} - \sum_{i=0}^{J} \underset{(i,j,t)\in\mathbf{S_3}}{P_{i,j,t}} \right) \Delta\tau \right\}, \tag{8a}$$

$$s.t. \ \sum_{i\neq j} (\eta_{i,j,t} > 0) + \sum_{j'\neq j} (\eta_{j,j',t} > 0) \leq 1, \tag{8b}$$

$$\sum_j \sum_i (\eta_{i,j,t} > 0) \leq N, \tag{8c}$$

$$C_{j,t}\big|_{t=0} = 0, C_{j,t}\big|_{t=T} \geq C_j^{QoS}, \tag{8d}$$

$$C_{j,t} = \sum_{\tau=1}^{t} \left(\sum_i r_{i,j,\tau} - \sum_{j'} r_{j,j',\tau} \right) \Delta\tau, \ C_{j,t} \geq 0, \tag{8e}$$

where H = $\{\eta_{i,j,t}\}^{(J+1)\times J\times T}$ since there are $(J+1)$ transmitters (BS/relays), J receivers (users) and T time slots. For simplicity, by $0 \to j@t_0$ we denote the BS-only link in $\mathbf{S_2}$ that is to be replaced by a BS-&-IoV link $[0 \to i'@t_1, i' \to j@t_2]$ in subproblem 3. Whereas the BS-&-IoV substitution link $[0 \to i'@t_1, i' \to j@t_2]$ in this paper consist of exact a BS part $0 \to i'@t_1$ and an IoV relay transmission part $i' \to j@t_2$. Two parts (one BS and one IoV) in the substitution link must use less energy combined than the original BS one.

We propose another iterative method as shown in Algorithm 3.

For each user j, we first record all plausible BS-&-IoV links like $[0 \to i'@t_1, i' \to j@t_2]$ in a temporary set $\mathbf{R}$. Here 'plausible' means that the constraint in (8b) and the N-subcarrier constraint in (8c) are satisfied and both parts of the links are at speed greater than the that of the original links. Further exploration will be conducted in the plausible BS-&-IoV link set $\mathbf{R}$.

Once we have the plausible set $\mathbf{R}$, we check the BS part and the IoV part in each BS-&-IoV link to see if they are capable of substitution, i.e., whether there are enough power unused in those link to complete the transmission in the original BS-only link $0 \to j@t_0$. Of all the BS-&-IoV links that pass the test, we find the combination of link $[0 \to i'@t_1, i' \to j@t_2]$ and original link $0 \to j@t_0$ that save most power, remove $0 \to j@t_0$ from $\mathbf{S_3}$ and move $[0 \to i'@t_1, i' \to j@t_2]$ from $\mathbf{R}$ to $\mathbf{S_3}$. Continue those steps until the plausible link set $\mathbf{R}$ become empty or there are no power gain from substitution.

Algorithm 3 Suboptimal User Scheduling for Maritime Communication System with IoV

Initialize $\mathbf{S_3} = \mathbf{S_2}$
for all user j **do**
  Initialize $\mathbf{R} = \phi$ as group for all plausible BS-&-IoV links.
  $r_0^{\min} = \min_{(0,j,t)\in\mathbf{S_2}} \left\{ r_{0,j,t}^{\max} \eta_{0,j,t} \right\}$.
  for all relays $i' \neq j$ **do**
    for all time slot t_2 where $r_{i',j,t_2}^{\max} \geqslant r_0^{\min}$ **do**
      if i' & j & SYSTEM are FREE at t_2 **then**
        for all time slot t_1 where $r_{0,i',t_1}^{\max} \geqslant r_0^{\min}$ and i' & SYSTEM are FREE at t_1 and $t_1 \neq t_2$ **do**
          if C_{i',t_2} is ENOUGH **then**
            Set $\mathbf{R} = \mathbf{R} \cup \{[(0,i',t_1), (i',j,t_2)]\}$.
          end if
        end for
      end if
    end for
  end for
  while $\mathbf{R} \neq \phi$ **do**
    Find P_{0,i',t_1}^{temp}, P_{i',j,t_2}^{temp}.
    Find $[(0,j,t_0), (0,i',t_1), (i',j,t_2)] = \arg\max\{\Delta P\}$, where $\{\Delta P\}$ is group for substitution power gains $\Delta P = P_{0,j,t_0} - \left(P_{0,i',t_1}^{temp} + P_{i',j,t_2}^{temp} \right)$.
    if $\max\{\Delta P\} \leq 0$ **then**
      Break.
    end if
    Set $\eta_{0,j,t_0} = 0$, $\eta_{0,i',t_1} += \frac{P_{0,i',t_1}^{\text{temp}}}{P_{i'}^{\max}}$, $\eta_{i',j,t_2} += \frac{P_{i',j,t_2}^{\text{temp}}}{P_0^{\max}}$.
    Update $\mathbf{S_3} \leftarrow (\mathbf{S_3} \backslash \{(0,j,t_1)\}) \cup \{[(0,i',t_1), (i',j,t_2)]\}$ and $C_{j,t}, C_{i',t}$ and $P_{0,j,t_0}, P_{0,i',t_1}, P_{i',j,t_2}$.
    Set $\mathbf{R} \leftarrow \mathbf{R} \backslash \{[(0,i',t_1), (i',j,t_2)]\}$.
  end while
end for

Here in Algorithm 3 P_{0,i',t_1}^{temp} and P_{i',j,t_2}^{temp} represent the **sufficient power for the BS-&-IoV links** $[0 \to i'@t_1, i' \to j@t_2]$ to substitute the original BS-only link $0 \to j@t_0$. We find P_{0,i',t_1}^{temp} and P_{i',j,t_2}^{temp} based on (2d), by setting $r_{i,j,t} = r_0^{\min}$. "i'

& j & SYSTEM are FREE at t_2" means that

$$\begin{cases} \sum\limits_{i^* \neq j} (\eta_{i^*,j,t_2} > 0) + \sum\limits_{j^* \neq j} (\eta_{j,j^*,t_2} > 0) \leq 1, & \text{(9a)} \\ \sum\limits_{i^* \neq i'} (\eta_{i^*,i',t_2} > 0) + \sum\limits_{j^* \neq i'} (\eta_{i',j^*,t_2} > 0) \leq 1, & \text{(9b)} \\ \sum\limits_{j^*} \sum\limits_{i^*} (\eta_{i^*,j^*,t_2}) \leq N. & \text{(9c)} \end{cases}$$

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

$$\begin{cases} \sum\limits_{i^* \neq i'} (\eta_{i^*,i',t_1} > 0) + \sum\limits_{j^* \neq i'} (\eta_{i',j^*,t_1} > 0) \leq 1, & \text{(10a)} \\ \sum\limits_{j^*} \left(\sum\limits_{i^*} (\eta_{i^*,j^*,t_1} > 0) \right) \leq N. & \text{(10b)} \end{cases}$$

And the system constraints in (8b) and (8c) are met. "C_{i',t_2} is ENOUGH" means that

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

Therefore the system constraint in (8e) is met.

IV. Simulation Results

In this section, we provide numerical results for the BS-only method in the first two subproblems and the proposed IoV method in the third subproblem, as well as a reference greedy BS-only method, which based on current CSI only. For the reference BS-only method, in each time slot, we find and choose N ships that have the highest transmission speed under given BS broadcast power and current CSI.

We compare the large-scale CSI replacement in (2d) with the complete channel in the following simulations. Moreover, we take one step further by taking the expectation operator out from the original channel in (2a) and replace $h_{i,j,t} \sim \mathcal{CN}(0, \mathbf{I})$ with $|h_0|^2 = 1$. Based on a low SNR assumption, we get

$$r_{i,j,t} \approx B_s \log_2 \left(1 + \frac{P_{i,j,t} \beta_{i,j,t} |h_0|^2}{\sigma^2} \right). \tag{12}$$

We further discuss the performance of this estimation and the large-scale CSI replacement in (2d) in this section.

As for the simulation parameters, the BS is located in the central position at the plane, 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 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 BS power for BS-only transmission is set to be 10W whereas the ships' IoV transmission power are 1W, 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 -174dBm/Hz.

First, we study the impact of only acquiring part of the lone-term large-scale CSI.

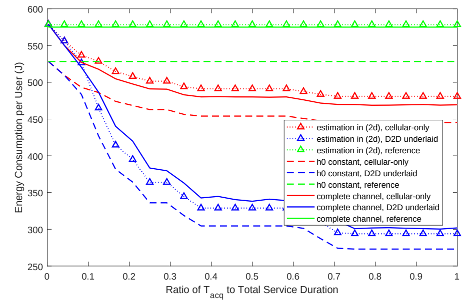

Fig. 2. Average energy consumption per user versus the ratio of T_{acq} to total service time duration.

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. The QoS constraint here is 1Gbits/user.

As we can see, our proposed IoV method outmatches the BS-only method and the reference method, especially in ideal conditions (which means we can acquire all CSI, T_{acq} = total service time). When we can acquire all CSI, i.e. T_{acq} approximate the total service time duration, we have maximum benefit from the long-term CSI. The IoV method consummates 40% less energy than the BS-only method, 50% less than the reference method, since the introduction of IoV transmission brings forward more transmitters (relays) to choose from. As the ratio of T_{acq} to total service time decreases, energy consumption increases, 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 any long-term CSI and the proposed methods become greedy with no 'future information' about the CSI. Since the BS-&-IoV link are even more difficult to find in such short time period, the energy consumption gap between BS-only and IoV underlaid shrinks.

As shown in Figure 2 - Figure 4, the difference between h_0 constant approximation and the actual channel is around 10% under simulation settings. On the other hand, the gap between the large-scale CSI replacement we proposed in (2d) and the complete channel is only a mere 3% worst case, where the error comes from assuming that ship j stays in the same position and $\beta_{i,j,\tau}$ remains constant in each time slot t and taking out the expectation operator in (2c). This as well as other simulations show that the large-scale CSI replacement in (2d) is quite explicit and acceptable. If we are less strict with the approximation, the h_0 constant estimation may be acceptable since the estimation in (12) shares similarity in trend and shape with the actual channel.

Next, we investigate the impact of different service needs in Figure 3 and 4.

Figure 3 shows the bit-wise average energy consumption under different QoS constraint. When there is a smaller QoS constraint, which is more often the case in the simulations, our proposed IoV method outmatches the BS-only method and the

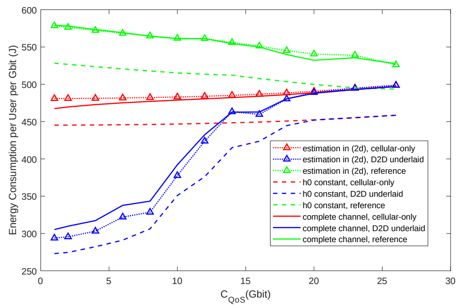

Fig. 3. Average energy consumption per user E_{avg} versus the QoS constraint C_{QoS}.

reference method. When the QoS constraint is 1Gbits/user, the IoV method consummates 40% less energy than the BS-only method, 50% less than the reference method. The proposed IoV method's energy consumption approaches proposed the BS-only method as the QoS constraint gets larger. This is because the large QoS demands might take up too many time slots in first two subproblems, and left the IoV optimization in the third subproblem few time slots with feasible IoV links to choose from.

The reference method's bit-wise energy consumption decreases as the QoS constraint get larger, while the proposed methods' energy consumptions increase. The reference method's energy consumption decreases since the reference method is a greedy one, and it aims to meet the QoS constraint as soon as possible. When the QoS constraint is smaller, the reference method may end up choosing many time slots with relatively lower $\beta_{0,j,t}$ and can still satisfy the QoS constraint. When the QoS constraint gets larger, the reference method has to choose more time slots, and there are likely to be more time slots with relatively higher $\beta_{0,j,t}$ and higher transmission speed $r_{0,j,t}$. Under higher overall transmission speed, the reference method's energy consumption per Gbit decreases. The rise in proposed methods' energy consumption is because we end up choosing the time slots with low transmission speed in order to meet the increasing QoS constrain. This results in a larger energy consumption per user per Gbit.

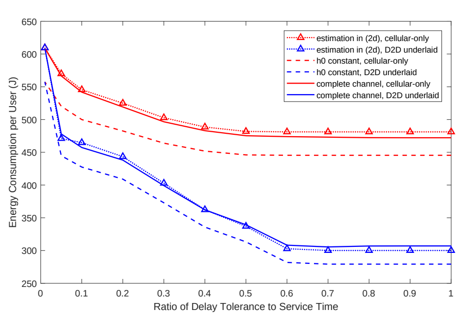

Fig. 4. Average energy consumption per user versus the ratio of delay tolerance.

Figure 4 shows the relationship between average energy consumption and the ratio of delay tolerance to service time duration. In this paper, we assumed delay-tolerant service for maximum benefit from the long-term CSI. Here we further checked the performance of our method under different delay tolerance.

When the delay tolerance ratio $= 1$, the system is fully delay-tolerant, and we once again see the 40% percent improvement from the introduced transmitters (relays) in optimization. As the delay tolerance gets smaller, the energy consumption of both BS-only method and IoV-aided method gets larger, and the gap between them shrinks. Similar to what happened in Figure 2, the delay tolerance decrease directly result in the energy consumption rise since there are less time slots for the links to choose from and the system has to schedule the service in a shorter time period. For the same reason, the BS-&-IoV links are even more difficult to find in such short time period since they requires two links for one BS-&-IoV link. Thus the gap between the BS-only and IoV-aided optimizations shrinks as the delay tolerance gets smaller.

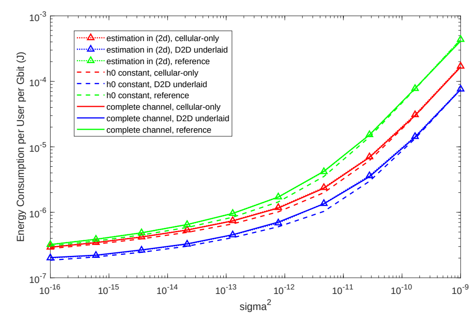

Fig. 5. Average energy consumption per user E_{avg} per Gbit versus the noise function σ^2.

Last, we investigate the impact of system status in Figure 5.

Figure 5 shows average energy consumption versus noise σ^2. As we can see, the energy consumption increases as the noise rises. The gap between large-scale CSI approximation (2d) and the actual channel remains minimal, whereas the gap between the h_0 constant estimation and the actual channel shrinks as the noise rises. The worsening in SNR also result in the increase in energy consumption, while making our proposed methods more benefitial as the gap in energy consumption between reference method and proposed IoV-aided method increases. The relationship between SNR and the gaps are explored below.

We estimate $r_{i,j,t}$ in (2d) and in (12) both through taking out the expectation operator. Since $x \geq \log_2(1+x)$ when $x \geq 0$, the transmission speed or channel capacity $r_{i,j,t}$ is smaller in estimation (12) than the actual channel or large-scale CSI replacement in (2d). Therefore, the energy consumptions with the h_0 constant estimation are smaller than the others, just as showed in Figure 5. Since the h_0 constant approximation is based on a low SNR assumption, as the noise function σ^2 increases, the h_0 constant estimations approximate the large-scale CSI replacement in (2d) and the complete channel energy-wise.

As the SNR decreases, the channel capacity worsen and the greedy reference method end up with more low-speed links. Thus we can see an improvement of over **81%** in energy consumption from the proposed IoV method when $\sigma^2 \leq 10^{-10}$.

V. Conclusion

In this paper, we focused on the reduction of energy consumption through user scheduling in maritime communication system with IoV. We reduce the energy consumption by using long-term large-scale CSI and implementing IoV transmission. By utilizing each users' positional information acquired from their specific shipping lanes, we repalce the complete channel with large-scale CSI during the whole service process. Further, we decompose the NP-hard energy consumption optimization problem into 3 subproblems. By solving the first two subproblems (BS transmission without or with N-subcarrier constraint) we acquire a sub-optimal solution for BS-only system.Proceeding to the 3rd subproblem (IoV-aided N-subcarrier BS transmission), we further benefit from more transmitters (relays) with IoV-aided transmission and achieved an improvement up to 81% in certain cases.The iterative algorithms we proposed can solve the three subproblems with polynomial time complexity. Simulation results justify our large-scale CSI replacement and show that the schemes significantly enhances the system performance in terms of energy consumption.

Appendix A
Proof of Theorem 1

For simplicity, we transform the variables in (5) into functions of $r_{i,j,t}$. Express (2d) as $r_{i,j,t} = f(P)$ and we have

$$P_{i,j,t} = g(r_{i,j,t}) = f^{-1}(r_{i,j,t}), \tag{13a}$$

$$\eta_{i,j,t} = \frac{P_{i,j,t}}{P_i^{\max}} = \frac{g(r_{i,j,t})}{P_i^{\max}}. \tag{13b}$$

Thus, the original problem in (5) is equivalent to

$$\min_{\{r_{i,j,t}\}^{(J+1)\times J\times T}} \left\{ \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=0}^{J} g(r_{i,j,t})\,\Delta\tau \right\}, \tag{14a}$$

$$s.t.\ \sum_{i\neq j}\left(\frac{g(r_{i,j,t})}{P_i^{\max}} > 0\right) + \sum_{j'\neq j}\left(\frac{g(r_{j,j',t})}{P_j^{\max}} > 0\right) \leq 1, \tag{14b}$$

$$\sum_j \sum_i \left(\frac{g(r_{i,j,t})}{P_i^{\max}} > 0\right) \leq N, \tag{14c}$$

$$C_{j,t}\big|_{t=0} = 0, C_{j,t}\big|_{t=T} \geq C_j^{QoS}, \tag{14d}$$

$$C_{j,t} = \sum_{\tau=1}^{t}\left(\sum_i r_{i,j,\tau} - \sum_{j'} r_{j,j',\tau}\right)\Delta\tau,\ C_{j,t} \geq 0, \tag{14e}$$

where the objective function (14a) and optimization constraints (14b) and (14c) are all nonlinear functions of $r_{i,j,t}$.

The problem in (14) is a Nonlinear Integer Programming problem, which has been proved to be NP-hard [**?**]. Therefore, the equivalent problem (5) is NP-hard.

Acknowledgement

This work was partially supported by the National Science Foundation of China under grant No. 61771286 and grant No. 91638205 and grant No. 61621091. The authors Yunzhong Hou and Te Wei contributed equally to this work.

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