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Efficient Scheduling for Video Transmissions in Maritime Wireless Communication Networks

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***Abstract*—This paper develops a framework for vessel surveillance video uploading via maritime wideband communication networks. A broadband wireless network utilizing Time Division Multiple Access (TDMA) based media access control (MAC) protocol is employed to establish a shore-side network infrastructure, and a packet store-carry-and-forward routing mechanism is adopted to achieve the intermittent network connectivity in maritime communications. In order to provide high quality videos to the administrative authority, resource allocation problem is formulated as maximizing the throughput priority-based video transmissions problem, subject to the intermittent network connections and the time indices such as the release time and deadline of each video packet. To reduce computational complexity, time-capacity mapping is applied to transform the original resource allocation problem into a two-machine non-preemptive scheduling problem. Three offline scheduling algorithms are proposed, namely a time-capacity mapping based two phase (TMTP) algorithm for single machine, a TMTP algorithm for two machines, and an interval graph theory based job relay selection (IGTJRS) algorithm. It is mathematically proved that the IGTJRS algorithm has an approximation ratio (i.e., the ratio of the throughput of an optimal schedule to that of the IGTJRS algorithm) of 2, and a time complexity of $\mathcal{O}(n^2)$. Simulations results validate the performance of the proposed algorithms, based on real ship route traces obtained from navigation software BLM-Shipping.**

***Index Terms*—Job-machine scheduling, maritime wideband communication, time-capacity mapping, video transmission.**

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I. Introduction

It is envisioned that developing a maritime wideband communication system will greatly contribute to the maritime distress, urgency, safety, and general communications [1]. In particular, large capacity data such as surveillance videos collected from bridge, engine room or other critical regions of a vessel, can be efficiently delivered via such a system, which is crucial to maritime administrative authority on shore. Furthermore, safety related information and multimedia data could also be disseminated via this system. In other words, it extends wideband services from the land to the ocean.

The state-of-the-art maritime communication system, christened as Global Maritime Distress and Safety System, comprises of terrestrial and satellite systems [2]. For satellite maritime communication system, the advanced Fleet Broadband (FBB) system can be enabled to establish wideband transmissions with data rate up to 432 kbps. Nonetheless, high capital expenditure to launch satellites results in high service cost (e.g., voice service costs 13.75 U. S. dollars per minute). Consequently, the cost of conveying large capacity videos could be prohibitive. On the other hand, existing terrestrial maritime communication system cannot provide wideband services. Taking the legacy VHF communication system as an example, the maximum data rate is merely 9.6 kbps. Hence, it is an imperious demand to establish a maritime wideband communication system at a low service expenditure. It perfectly matches the emerging E-Navigation strategy initiated by International Maritime Organization (IMO), a led concept based on the harmonisation of marine navigation systems and supporting shore services driven by user needs [3].

The development of new maritime wideband networks has attracted significant attention recently. In [4], Zhou *et al.* devised a cognitive maritime mesh/ad hoc network. The US Navy ships have been getting advanced Fourth Generation Long-Term Evolution (4G LTE) broadband service since 2011 [5]. In Singapore, the project of wireless-broadband-access for Seaport (WISEPORT) achieves wireless broadband access rate up to 5 Mbps based on Worldwide Interoperability for Microwave Access (WiMAX) technology [6]. Due to its high data rate and large coverage area, WiMAX technology has been approved to be a candidate to satisfy the increasing demand of wideband data traffic at sea [7]. However, its coverage range is still limited (e.g., with a range of approximately 20 nautical miles from coastline). Moreover, the wireless channels are occasionally deteriorated due to the obstacles such as sea clutters, and the period of wireless connection is short

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because of a limited number of infostations deployed shore-side. Consequently, a continuous end-to-end path may not be available in maritime environment. An innovative complementary scheme is packet store-carry-and-forward routing in delay tolerant networks (DTNs) [8], which can efficiently utilize node mobility statistics and permit other nodes to store, carry, and forward data packets once a communication opportunity arises. Data delivery can be achieved via infostations shore-side, whereas the coverage provided by infostations might not be seamless due to long coastline and high deployment cost of infostations.

We design a broadband wireless network/store-carry-and-forward interworking maritime wideband communication system, which utilizes TDMA MAC protocol widely used in WiMAX and LTE technology, explicitly devised to overcome above limitations. We consider the Vessel Closed-circuit Television (CCTV) Systems which rigorously collect surveillance videos from bridge, engine room, deck, and/or other critical regions of the monitored vessel, under the control of elaborate intervalometer components [9]. Surveillance video clips are generated every fixed interval, which are further divided into packets. Each packet has a release time, a deadline, and a weight, which are known *a priori*, since the Electronic Chart Display and Information System (ECDIS) [10] combined with Radio Beacon-Differential Global Positioning System (RBN-DGPS) onboard, Automatic Identification System (AIS) and predefined WiMAX TDMA protocol could benefit the prediction of global information under the premise of the fixed routes scheduled in advance. For clarity, some terms used in this paper are defined as follows: Ship's route means the lane at sea that is a regularly used as the route for vessels; Sailing schedule is defined as the exact planning of vessel's travel between the origin port to destination port, according to the distance, speed, etc.; Actual trace represents the real-time ship locations, speed, course and other navigation data detected by GPS and AIS onboard. Weight is the quotient to value its contribution to the importance of video clips or the significance to the administrative authority. For instance, the packet with higher weight reflects the video information pertinent to the crucial sections of a vessel, such as bridge, engine room, chart room, and cargo hold, other than galley, mess, accommodation, and game room, etc. [11] When vessels pass by infostations deployed along the shore-side, i.e., the vessels are in the transmission coverage of infostations, the infostations will make an effort to upload video packets for vessels. The vessel speed, distance between vessel and infostation determine the contact period, which is defined as the *time window* within which a vessel can transmit video packets to infostations. Due to the mobility, a vessel can only communicate with an infostation in its transmission range during the available time window. Hence, the resource allocation issues, referring to allocating transmission time slots for video packets in the time windows of different infostations, are complicated and challenging as the link from vessel to infostation is highly dynamic and subject to periodic disconnections as a vessel sails en route. In order to transmit packets before respective deadline and gain better video quality which is determined by the weight of delivered packets, a cooperative transmission strategy can be exploited. However, the scheduling of data packets to be relayed by other vessels still needs to be investigated. It should be noted that the scenario of maritime wideband communications utterly distinguishes from that of the existing data service delivery studied in vehicular networks [12] and high-speed trains [13]. In vehicular networks, the traces of vehicles are nondeterministic and dynamically changing. In contrast, the traces of vessels are deterministic or predictable since ship routes[1] are relatively stable and known *a priori*. In terms of a high-speed train, the train schedule is deterministic and the trajectory is one-dimensional. However, the network topology in a maritime communication system could be either one-dimensional (without relay) or two-dimensional (with relay). How to schedule video packets in two-dimensional and intermittently connected maritime communication system with deterministic global knowledge is still an open issue.

In this paper, we are interested in transmitting critical video packets to the administrative authority, i.e., throughput maximization problem (TMP) based on the redefinition of throughput as the summation of weight of delivered packets. We first formulate the packet scheduling problem, by taking into account of the intermittent network connectivity and cooperative transmissions, and then mathematically transform this problem into a job-machine problem. To reduce computational complexity, a time-capacity mapping method is applied to transform the original resource allocation problem to a two-machine non-preemptive scheduling problem. Based on the knowledge of the schedules of vessels and the time indices of jobs, we propose three offline scheduling algorithms, namely a time-capacity mapping based two phase (TMTP) algorithm for single machine, a TMTP algorithm for two machines, and an interval graph theory based job relay selection (IGTJRS) algorithm. The performance of our proposed algorithms is demonstrated by simulations and comparisons with other classic scheduling algorithms and existing maritime communication algorithms, under the real ship routes data obtained from navigation software BLM-Ship. This work targets to investigate the scheduling issues in maritime communication system, which is featured by the two-dimensional network topology, intermittent network connection, and deterministic global knowledge. Specifically, the contribution of this paper is four-fold:

1) A time-capacity mapping technique is introduced to transform the original intermittent network connectivity scenario into a virtually continuous scenario. Thereby, the resource allocation issue could be converted from time based scheduling to capacity based scheduling over a continuous horizon to facilitate algorithm design;
2) Three offline scheduling algorithms, namely a time-capacity mapping based two phase (TMTP) algorithm for single machine, a TMTP algorithm for two machines, and an interval graph theory based job relay selection (IGTJRS) algorithm are proposed, respectively;
3) It is mathematically proved that the IGTJRS algorithm has an approximation ratio (i.e., the ratio of the throughput of an optimal schedule to that of the IGTJRS

[1] We use the term of vessel and ship interchangeably.

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algorithm) of 2, and a time complexity of $\mathcal{O}(n^2)$;

4) The simulations for the single-vessel, two-vessel, and multi-vessel scenarios are performed using real vessel traces obtained from BLM-Shipping navigation software.

The remainder of this paper is organized as follows. In Section II, we discuss some related works. System model and problem formulation are presented in Section III and Section IV, respectively. Three scheduling algorithms are proposed, as well as the performance analysis is corroborated in Section V. In Section VI, simulation results are given to demonstrate the performance of our approaches. We conclude this paper with future work in Section VII. As many symbols are used in this paper, some important notation definitions are tabulated in Table I.

II. Related work

In literature, there are several research works related to maritime communication networks. The project TRITON [14] investigates a wireless mesh network to support multi-hop data transmissions in maritime communications, and the performance of MAC protocol is simulated. The ship mobility model in terms of probability density function for ship speed is modeled in [15]. In [16], the performance comparison of three existing routing protocols, Optimized Link State Routing (OLSR), Ad hoc On-Demand Distance Vector Routing (AODV) and Ad-hoc On-demand Multipath Distance Vector (AOMDV) in maritime networks is shown. In [17], Lin *et al.* explored the WiMAX-based mesh technology for ship-to-ship communications with DTN features to provide less expensive wireless communication services at sea, and compared the performance between regular routing protocols and DTN routing protocols. In [18], a theoretical model is developed to analyze the ships encounter probability distribution, and the data delivery ratio from ships to the BS is derived. In [19], the performance of file delivery is investigated through maritime DTN networks. The proposed scheme integrates an existing oversea AIS to deal with mobility data of vessels, through which the inter-vessel connection can be accurately predicted. The transmission opportunities are introduced only when two vessels are direct within the communication range of each other, while in our work, we use DTN throw-box temporarily storing data to enhance the transmission opportunity. In [20], a distributed adaptive time slot allocation (DATSA) scheme for WiMAX mesh MAC protocol is proposed, considering the difference in monitoring reception quality of an allocated time slot. In [21], a novel approach is proposed by utilizing multi-hop WiMAX and mesh network to provide Internet access to the Mediterranean Sea without the assistance of satellite. The MAC and routing schemes suitable for such a scenario are investigated, with the network connectivity analysis. However, the Mediterranean Sea can be seen as a special scenario because the vessel density is high and Internet access is assumed available anytime via the multi-hop mesh network. In [22], the maritime mesh network based on IEEE 802.16 mesh standards is developed to provide maritime communications with high bandwidth and acceptable QoS. Different user requirements of oversea communications are investigated, followed by the analysis of connectivity and design of scheduling and routing schemes. In [23], the maximum network capacity with a minimum VoIP cost flow is dimensioned over multi-hop maritime networks. Also some other research issues are proposed for this special communication network application. They partially focus on ship-ship communication scenario through inter-vessel connectivity predictions and the evaluation of transmission performance in maritime DTNs [24]. Additionally, few literature with emphasis on data transmission scheduling problem in DTN maritime networks is presented.

With respect to data delivery, although there are very few research works in the literature for maritime scenario, vehicle-assisted data delivery has been extensively studied. In [12], Yan *et al.* developed a theoretical model to compute the achievable throughput of cooperative mobile content distribution in vehicular ad hoc networks. The IEEE 802.11p MAC protocol is proposed for video broadcasting in metro passenger communication system, which is specially designed for high-speed trains with a speed up to 360 km/h [25]. In [26], Maurice J. *et al.* provided the model and delay analysis of vehicular networks, investigating an information-delivery-delay minimization problem based on a probabilistic bundle release scheme and a greedy bundle release scheme. In [27], Gozupek *et al.* addressed a throughput satisfaction-based scheduling problem, which maximizes the number of satisfied users for cognitive radio networks. In [28], Liang *et al.* proposed a semi-Markov decision process based service model to manage interdomain resource allocation in mobile cloud networks. Cheng *et al.* proposed a vehicle-assisted data delivery method for smart grid applications. In [13], Liang and Zhuang investigated on-demand data services for high-speed trains. An online resource allocation algorithm based on Smith ratio and exponential capacity is proposed.

Regarding to job-machine scheduling problem, there exist related works that target maximizing the weight of jobs before their deadlines. Bar-Noy et al. [29] found combinatorial algorithms for diverse types of machines (identical vs. unrelated) and the weight of the jobs (identical vs. arbitrary). A $\frac{(1+1/k)^k}{(1+1/k)^k-1)}$ approximation algorithm is developed for the $R\,|r_\tau|\sum(1-U_\tau)$ problem with arbitrary job weight and k identical machines[2]. The *approximation ratio* of an approximation algorithm denotes the ratio of the throughput of an optimal schedule to that of the approximation algorithm for TMP. As $k \to \infty$, the approximation ratio bound tends to be $\frac{e}{e-1} \approx 1.58198$. A combinatorial algorithm labeled ADMISSION is presented for the $R\,|r_\tau|\sum w_\tau(1-U_\tau)$ problem with an approximation ratio bound of $3+2\sqrt{2} \approx 5.828$, where w_τ represents the weight of job τ. These are cases for nonpreemptive online scheduling algorithm. Nevertheless, the algorithms are complex and slow. Following the nomenclature of Lawler *et al.* [31], the special interval scheduling problem (ISP) problem for single machine is expressed as $1\,|r_\tau\,|\sum w_\tau(1-U_\tau\,)$ and is $\mathcal{NP}$-hard in general. Berman and

[2]According to standard notation of scheduling problems [30], R represents unrelated parallel machines; U_τ denotes the number of late jobs; $(1-U_\tau)$ indicates the number of finished jobs; r_τ is the time prior to which job τ cannot be processed.

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TABLE I. Notations and definitions.

Symbol	Definition
$A_{h,k}$	The capacity (the maximum number of bytes that could be delivered) of the kth frame of the hth infostation.
c_n	The marker point of the virtual period
H	The number of shoreside infostations
K_h	The number of frames within the hth infostation
S_i	The job instances of job i
t	The upper bound of all deadlines
T_F	Frame duration
$T_I(T_O)$	The starting (ending) time of the vessel
$T_h^i(T_h^o)$	The time for a vessel get into (come out of) the coverage of the hth infostation
$r_{jm}(d_{jm})(p_{jm})(b_{jm})(e_{jm})$	The release time(deadline)(processing time)(beginning time)(ending time)of video packet j proceeded on vessel m
$r_j^c(d_j^c)(p_j^c)$	The capacity of the release time(deadline)(processing time)
x_{jb_j}	Job j executed at the job interval$[b_j, b_j+p_j)$indicator
w_j	Weight of job j

Bhaskar [32] proposed a 2-approximation algorithm, which is remarkably close to the optimum value.

Abundant TMP algorithms recognize machine independent time indices. Subjects to time-window job availability and machine downtime constraints, mobile client may download within machine-dependent contact time window. In [33], Lee and Sherali studied the unrelated machines scheduling problem which is machine dependent for the first time. The release time, deadline and processing time are all machine dependent, with the goal of minimizing the total weighted flow times subject to time-window job and machine downtime constraints. Chen *et al.* [34] are the primary antecedent to one class of scheduling problems, in which jobs have machine-dependent time indices with the goal of throughput maximization, and propose offline and online algorithms to address the problems. However, the scenario is different from ours since the coverage areas of APs are assumed to be consecutive, and each client has only one job to convey. In [35], a two phase algorithm is leveraged in a joint timeslot, power control and rate assignment problem in mobile WSN. However, it is a parallel machine problem, without taking into account the cooperation.

In this paper, we focus on designing ship-shore data transmission scheduling schemes in DTN maritime communication networks, with the goal of throughput maximization through cooperation among different vessels.

III. System Model

We consider the scenario that a vessel generates surveillance videos periodically, within the duration of sailing. Video clips are segmented to packets and uploaded to authorities via infostations deployed along route line, or stored in a DTN throw-box (which is a small, stationary and inexpensive device equipped with wireless interfaces and storage, acting as a relay to create more connection opportunities [36]), and then carried and forwarded by other vessels.

A. Store-Carry-and-Forward Routing

Network topologies are shown in Fig. 1(a) and Fig. 1(b), for single-vessel scenario and multi-vessel scenario, respectively. A vessel sails from an origin port to a destination port within time duration $[T_I, T_O]$. H infostations playing the roles of base stations are deployed shore-side intermittently. And the vessels are regarded as subscriber stations. A broadband wireless network utilizing TDMA MAC protocol could provide seamless coverages within the communication range of infostations. Each infostation has a transmission range according to wireless propagation characteristics. A wireline/wireless network associates the infostations to content servers of administrative authorities via backbone network. Vessels communicate with infostations during the available time windows corresponding to the mobility characteristic. Several vessels might pass across the same rendezvous point, which is the cross point of routes with DTN throw-box, presumably not at the same time. Accordingly, vessels can participate in cooperative transmissions for data delivery via the DTN throw-boxes. All the channel between vessels and DTN throw-boxes are assumed to be with no obstacles. Meanwhile, there is no capacity constraints that all the data transmitted to DTN nodes could be stored. In this paper, we consider passenger vessels and cargo vessels which sail on predetermined and fixed route lines, such that schedules of vessels are relatively stable and known *a priori*. The analysis of vessels with lower tonnage (such as fishing boats) may involve stochastic modeling and/or optimization and is left for our future work.

B. Network Resources

The IEEE standard 802.16/TDMA MAC frame structure is utilized to provide high-bandwidth data services between the vessel and the infostations. The duration in which a vessel is within the coverage of the hth infostation is divided into frames with equal duration T_F, and correspondingly, the number of frames is given by $K_h = \left[\left(T_h^o - T_h^i\right)/T_F\right]$, where T_h^i and T_h^o are the times for a vessel to get into and come out of the coverage of the hth ($h \in [1, \cdots, H]$) infostation, respectively. The network resource is defined as frames, within which the video packets can be delivered[3]. Let capacity $A_{h,k}$ represent the maximum number of bytes that

[3]We use the term of frame and time slot interchangeably.

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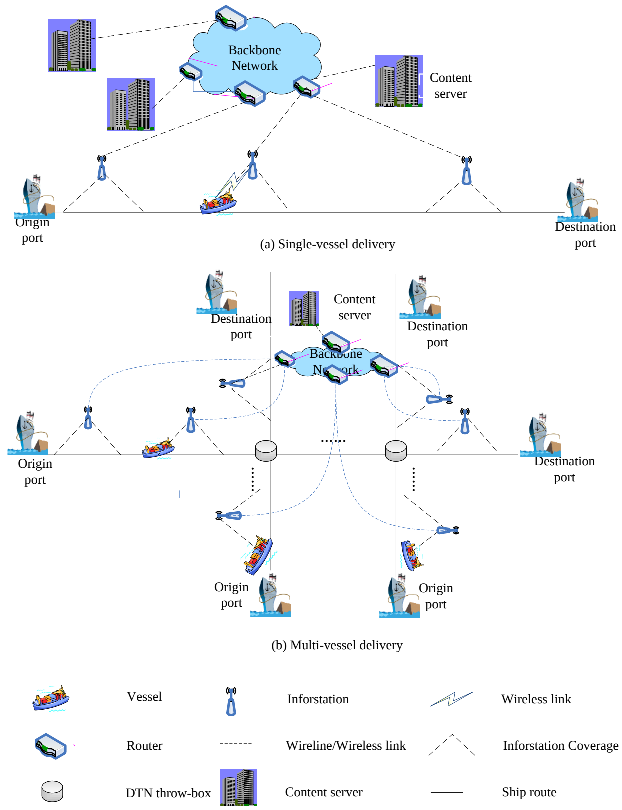

Fig. 1. An illustration of the network topologies.

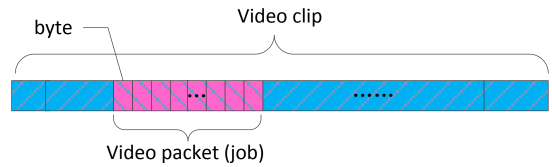

Fig. 2. Video service.

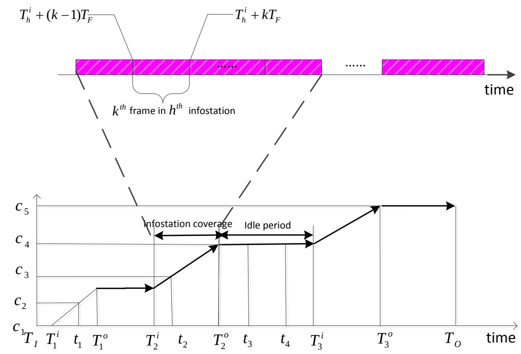

Fig. 3. Network resource and time-capacity mapping.

could be delivered within the kth frame of the hth infostation. We assume that the maritime wireless link connections are stable due to specially designed antenna systems that may overcome sea wave movement and occlusion, etc. And an omi-antenna that can receive/transmit in 360°direction is employed. The beginning and ending time of the kth frame during the hth infostation are $T_h^i + (k-1)T_F$ and $T_h^i + kT_F$, respectively. Fig. 2 shows network resource and time-capacity mapping.

C. Video Service

Video clips (e.g. 10 minutes video) are partitioned into packets, and each packet has its release time, deadline, and weight. Weight values its contribution to the importance to administrative authority. The profit of weight is obtained if the packet is delivered before its deadline. Denote r_j, d_j, b_j, e_j, w_j and p_j as the release time, deadline, beginning time, ending time, weight and processing time for job j, respectively. Let $i, j \in \{1, \cdots, n\}$ denote jobs, n the number of jobs, $b_j \in \{1, \cdots, t\}$ the beginning time of job j and $u \in \{1, \cdots, t\}$ the beginning time of another job which is defined to avoid multiple jobs being scheduled simultaneously on single machine. Obviously, the time indices should comply with $r_j \le b_j$ and $b_j + p_j \le d_j$. The time indices are approximated to integers. Fig. 3 shows video service.

D. Time-Capacity Mapping

A time-capacity mapping technique is used to transform the original scenario with intermittent network connectivity into a virtually continuous scenario [13]. We map the time indices into virtually cumulative capacity values, as shown in Fig. 2. The period $[T_h^o, T_{h+1}^i]$ is defined as the idle period, during which a vessel is not within the coverage of any infostation. For example, t_3 and t_4 moments are in an idle period during which no data is transmitted and thus, corresponding to the same cumulative capacity c_4. On the other hand, t_1 and t_2 are in the coverage of infostations, and are subsequently related to two different cumulative capacity values c_2 and c_3, respectively. The time-capacity mapping function $f(t)$: $[T_I, T_o] \rightarrow [0, 1, \cdots \sum_{h=1}^{H}\sum_{k=1}^{K} A_{h,k}]$ is given by

$$f(t) = \begin{cases} \sum_{m=1}^{(t-T_{h_t}^i)/T_F} A_{h_t,m} + \sum_{l=1}^{h_t-1}\sum_{m=1}^{K_l} A_{l,m}, \\ \text{if } h_t \ge 1 \text{ and } T_{h_t}^i \le t \le T_{h_t}^o \\ \sum_{l=1}^{h_t}\sum_{m=1}^{K_l} A_{l,m}, \quad \text{otherwise} \end{cases} \quad (1)$$

where $h_t = \arg\max_h \{T_h^i \le t\}$, if $T_{h_t}^i \le t \le T_{h_t}^o$, and $h_t = 0$ otherwise. Based on the time-capacity mapping, the resource allocation issue could be converted from time based scheduling to capacity based scheduling over a continuous horizon [13], such that the job-machine scheduling theory can be applied to solve the resource allocation problem at a low computational complexity, which will be discussed in the following section.

IV. Problem Formulation

In order to achieve high quality videos, i.e., maximizing the total weight of delivered packets, we focus on scheduling data delivery conducted by one vessel or cooperated vessels. Since ship routes are relatively stable, and the global information is known *a priori*, offline scheduling algorithms are considered. In this section, the problem of maximizing the total weight of delivered packets is formulated as a vessel throughput maximization problem (VTMP), which is a 0-1 integer programming problem. To solve the VTMP problem, a mathematic job-machine scheduling method is utilized to allocate resources (i.e., frames) to different video packets. In such job-machine scheduling method, vessels and video

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packets act as machines and jobs, respectively. The video packets transmitted by vessels resembles jobs could be executed on machines. We consider jobs $\mathcal{J} = \{J_1, \cdots, J_n\}$ that can be performed on machines $\mathcal{M} = \{M_1, \cdots, M_m\}$. For an arbitrary job, it corresponds to a family. A family is a set of job instances executed possibly within release time and deadline. No more than one job instance could be executed during this period [32]. Job instance S_i is represented as a quadruple of the following variables: (family, value, beginning, ending), i.e., (i, w_i, b_i, e_i), indicating integer time intervals during which a job may be executed. Each job instance in one family has the same weight w_i. At most one job instance of one family can be scheduled. Problem formulations are based on time-capacity mapping method, allowing multi-job being executed during the same period on one machine. (i.e., Regarding to time domain, the OFDMA technology could achieve multi-job transmission simultaneously. However, the jobs could not tolerate multi-job transmission at the same time in capacity domain.)

A. Formulation of Single-Vessel Delivery

In single-vessel delivery scenario, the data can be delivered when the vessel carrying the data is in the coverage of infostations, without cooperation among vessels. Through the time-capacity mapping, the single-vessel data delivery becomes a single-machine scheduling problem. Define binary variable x_{jb_j} which indicates whether job j is scheduled at interval $[b_j, b_j + p_j]$ as follows:

$$x_{jb_j} = \begin{cases} 1, & \text{if job } j \text{ is scheduled at interval } [b_j, b_j + p_j] \\ 0, & \text{otherwise.} \end{cases}$$

Then, the single-vessel VTMP is formulated as follows:

$$\max \quad \sum_{j=1}^{n} \sum_{b_j=r_j}^{d_j-p_j} w_j \cdot x_{jb_j} \tag{2}$$

$$s.t. \quad \sum_{j=1}^{n} \sum_{b_j=u-p_j+1}^{u} x_{jb_j} \leq 1, \forall u \tag{3}$$

$$\sum_{b_j=r_j}^{d_j-p_j} x_{jb_j} \leq 1, \forall j \tag{4}$$

$$x_{jb_j} \in \{0, 1\} \tag{5}$$

where n indicates the total number of jobs executed on single-machine. Constraint (3) is to avoid jobs to interfere with each other on a single machine, while constraint (4) indicates that each job can only be scheduled at most once. Therefore, the VTMP is a 0-1 integer programming problem.

To prove VTMP is $\mathcal{NP}$-complete, we first transform it into a decision problem (to be answered by "yes" or "no") by comparing the objective value with a threshold value. VTMP-DECISION is defined as

whether there exists $\{w_j, x_{jb_j}\}$ with

$$\begin{cases} \sum_{j=1}^{n} \sum_{b_j=r_j}^{d_j-p_j} w_j \cdot x_{jb_j} \geq \overline{x} & \text{(6a)} \\ \sum_{j=1}^{n} \sum_{b_j=u-p_j+1}^{u} x_{jb_j} \leq 1, \forall u & \text{(6b)} \\ \sum_{b_j=r_j}^{d_j-p_j} x_{jb_j} \leq 1, \forall j & \text{(6c)} \\ x_{jb_j} \in \{0, 1\} & \text{(6d)} \end{cases}$$

where $\overline{x}$ is a threshold value.

Lemma 1: VTMP $\in \mathcal{NP}$, i.e., VTMP-DECISION can be verified in polynomial time.

Proof: Consider that we are given coefficients w_j, x_{jb_j}, and a threshold value $\overline{x}$. We can verify in polynomial time whether

- $\sum_{j=1}^{n} \sum_{b_j=r_j}^{d_j-p_j} w_j \cdot x_{jb_j} \geq \bar{x}$
- $\sum_{j=1}^{n} \sum_{b_j=u-p_j+1}^{u} x_{jb_j} \leq 1$ and $\sum_{b_j=r_j}^{d_j-p_j} x_{jb_j} \leq 1$.

■

Lemma 2: VTMP is $\mathcal{NP}$-hard, i.e., VTMP-DECISION can be reduced from a known $\mathcal{NP}$-complete problem in polynomial time.

Proof: Knapsack problem (KP) is a known $\mathcal{NP}$-complete problem [37]. Define KP-DECISION as follows:

whether there exists x_i with

$$\begin{cases} \sum_{i=1}^{N} p_i x_i \geq \bar{p} & \text{(7a)} \\ \sum_{i=1}^{N} w_i x_i \leq c & \text{(7b)} \\ x_i \in \{0, 1\}. & \text{(7c)} \end{cases}$$

To show the $\mathcal{NP}$-hardness of VTMP, we reduce from KP-DECISION. Restrict VTMP-DECISION by allowing each job j to have a specific starting time b_j. We have

whether there exists $\{w_j, x_j\}$ with

$$\begin{cases} \max \sum_{j=1}^{n} w_j x_j \geq \bar{x} & \text{(8a)} \\ \sum_{j=1}^{n} x_j \leq 1 & \text{(8b)} \\ x_j \in \{0, 1\}. & \text{(8c)} \end{cases}$$

Note that KP-DECISION has a feasible solution if the corresponding VTMP-DECISION has a feasible solution. Therefore, VTMP can be reduced from KP, and the reduction runs in polynomial time. ■

Theorem 1: VTMP is $\mathcal{NP}$-complete.

Proof: Since VTMP belongs to the class $\mathcal{NP}$ and is $\mathcal{NP}$-hard, it is concluded that VTMP is $\mathcal{NP}$-complete [38]. ■

B. Formulation of Multi-Vessel Delivery

In multi-vessel delivery scenario, the cooperation among vessels can be utilized. A vessel, when passing by a DTN throw-box, can forward the data to it. When other vessels passing by, they can carry the data and try to deliver. Multi-vessel delivery, which corresponds to multi-machine scheduling, takes advantage of the different routes of vessels to enhance the chance of data delivery. Denote r_{jm}, d_{jm}, w_{jm}, p_{jm}, and b_{jm} as release time, deadline, weight, processing time, and beginning time for job j on machine m respectively, where $j \in \mathcal{J}$ represents jobs and $m \in \mathcal{M}$ represents machines. Apparently, we have $r_{jm} \leq b_{jm}$ and $b_{jm} + p_{jm} \leq d_{jm}$.

Let $x_{jmb_{jm}}$ be the decision variable on whether job j is performed at job interval $[b_{jm}, b_{jm} + p_{jm}]$, given by

$$x_{jmb_{jm}} = \begin{cases} 1, & \text{if job j is performed at interval } [b_{jm}, b_{jm} + p_{jm}] \\ 0, & \text{otherwise.} \end{cases}$$

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Then, the multi-vessel VTMP is formulated as follows:

$$\max \quad \sum_{j=1}^{n} \sum_{b_{jm}=r_{jm}}^{d_{jm}-p_{jm}} w_{jm} \cdot x_{jmb_{jm}} \tag{9}$$

$$s.t. \quad \sum_{j=1}^{n} \sum_{b_{jm}=u-p_{jm}+1}^{u} x_{jmb_{jm}} \leq 1, \forall m, u \tag{10}$$

$$\sum_{b_{jm}=r_{jm}}^{d_{jm}-p_{jm}} x_{jmb_{jm}} \leq 1, \forall j \tag{11}$$

$$x_{jmb_{jm}} \in \{0, 1\}. \tag{12}$$

where n indicates the total number of jobs executed on multi-machine.

Similar to *Theorem 1*, multi-vessel VMTP can be reduced from VMTP, and the reduction runs in polynomial time. Therefore, multi-vessel VMTP is also $\mathcal{NP}$-complete.

C. Capacity Based Formulation

To overcome the intermittent connectivity and achieve low computational complexity, time-capacity mapping is utilized to transform the original resource allocation problem to a single-machine non-preemptive scheduling problem and a two-machine non-preemptive scheduling problem, respectively. The time indices are required to be mapped into capacity horizon applying time-capacity mapping function $f(\cdot)$ in (1).

For single-vessel delivery scenario, the job instances are described as:

$$S_i = \{[b_i, b_i + p_i)|\ r_i < b_i \text{ and } \ b_i + p_i < d_i\}. \tag{13}$$

Time indices as b_i, e_i, r_i, d_i, p_i are all mapped by the time-capacity mapping to obtain capacity indices $b_i^{'}, e_i^{'}, r_i^{'}, d_i^{'}, p_i^{'}$, respectively, given by $b_i^{'} \xleftarrow{f} b_i$, $e_i^{'} \xleftarrow{f} e_i$, $b_i^{'} \xleftarrow{f} b_i$, $d_i^{'} \xleftarrow{f} d_i$, $p_i^{'} \xleftarrow{f} p_i$. Then the job instances are expressed as:

$$S_i^{'} = \{[b_i^{'}, b_i^{'} + p_i^{'})|\ r_i^{'} < b_i^{'} \text{ and } b_i^{'}+p_i^{'} < d_i^{'}\}. \tag{14}$$

For two-vessel delivery scenario, the capacity indices $b_i', e_i', r_i', d_i', p_{i,1}^{'}$ and $b_i'', e_i'', r_i'', d_i'', p_{i,2}^{''}$ are obtained by applying the mapping functions $f_1(\cdot)$ and $f_2(\cdot)$ on machine 1 and machine 2, respectively. All the video packets could be transmitted by either vessel 1 or vessel 2. Then, the job instances S_i indicate the families of intervals during which jobs may be executed:

$$S_i = \{[b_i, b_i + p_{i,m}) + (m-1)t|\ m \in [1, 2], \ \ r_i < b_i \text{ and } \ b_i + p_{i,m}^{'} < d_i\}. \tag{15}$$

Here, m indicates machine 1 or machine 2. Time indices $b_i^{'}, e_i^{'}, r_i^{'}, d_i^{'}, p_{i,1}^{'}$ are all mapped on machine 1, i.e., $b_i^{'} \xleftarrow{f_1} b_i$, $e_i^{'} \xleftarrow{f_1} e_i$, $r_i^{'} \xleftarrow{f_1} r_i$, $d_i^{'} \xleftarrow{f_1} d_i$, $p_{i,1}^{'} \xleftarrow{f_1} p_{i,1}$. The job instances are expressed as:

$$S_i^{'} = \{[b_i^{'}, b_i^{'} + p_{i,1}^{'})|\ r_i^{'} < b_i^{'} \text{ and } b_i^{'}+p_{i,1}^{'} < d_i^{'}\}. \tag{16}$$

The corresponding latest deadline is $t^{'}$ in capacity domain. Time indices $b_i^{''}, e_i^{''}, r_i^{''}, d_i^{''}, p_{i,2}^{''}$ are all mapped on machine 2, i.e., $b_i^{''} \xleftarrow{f_2} b_i$, $e_i^{''} \xleftarrow{f_2} e_i$, $r_i^{''} \xleftarrow{f_2} r_i$, $d_i^{''} \xleftarrow{f_2} d_i$, $p_{i,2}^{''} \xleftarrow{f_2} p_{i,2}$. Then the job instances can be expressed as:

$$S_i^{''} = \{[b_i^{''}, b_i^{''} + p_{i,2}^{''}) + t^{'}|r_i^{''} < b_i^{''} \text{ and } b_i^{''}+p_{i,2}^{''} < d_i^{''}\}. \tag{17}$$

Relatively, the latest deadline on machine 2 is $t^{''}$ in capacity domain. The job instances are expressed as:

$$S_i = \{\{[b_i^{'},\ b_i^{'} + p_{i,1}^{'})|r_i^{'} < b_i^{'} \text{ and } b_i^{'} + p_{i,1}^{'} \leq d_i^{'}\} \cup \{[b_i^{''},\ b_i^{''} + p_{i,2}^{''}) + t^{''}|r_i^{''} < b_i^{''} \text{ and } b_i^{''} + p_{i,2}^{''} \leq d_i^{''}\}\}. \tag{18}$$

Based on the time-capacity mapping transformation, time indices are virtually transformed into the cumulative capacity values, over which the packet transmissions could be continuously scheduled. The following three algorithms are based on the above capacity-based transformation.

V. Proposed Algorithms

Towards effective resource allocation with low computational complexity, we propose three offline algorithms to address VTMP, i.e., a TMTP algorithm for single machine, a TMTP algorithm for two machines, and an IGTJRS algorithm which leverages maximum weight 2-independent set algorithm.

A. Time-Capacity Mapping Based Two Phase Algorithm for Single Machine

The two phase algorithm is an offline algorithm [32], which reveals a stack based TMP algorithm with two phases, i.e., evaluation phase and selection phase. In phase one, the algorithm pushes job instances in sequence of non-decreasing ending time into a stack, and only those job instances which have large enough weight compared to overlapping instances already in the stack can enter the stack. In phase two, the algorithm pops job instances and arranges them into a non-conflicting schedule in inverted order. According to this rule, it could guarantee that the highest weight job instances with the earliest ending times are chosen. Therefore, the total weight of scheduled jobs is maximized.

Some useful definitions are given as follows. $\mathcal{S}$ is an initially empty stack that could store intervals, which is applied in the TMTP algorithm programming as described above; $\mathcal{L}$ is a sequence that contains an instance (i, w_i, b_i, e_i), for every integer $i \in [1, n]$; $TOTAL(i, b_i^{'})$ is the total sum of values of those instances other than i on the stack $\mathcal{S}$ that have $ending > b_i^{'}$, where *ending* indicates the ending time of job instance; $total(i, b_i^{'})$ is the total value of job instances that $ending < b_i^{'}$ of family i. The latest deadline on machine 1 is t and $t^{'}$ in time and capacity horizon, respectively. **Algorithm 1** shows a pseudo-polynomial algorithm.

B. Time-Capacity Mapping based Two Phase Algorithm for Two Machines

We first consider the two-vessel case which is a two-machine non-preemptive scheduling problem, and then generalize the results to the multi-vessel case.

1) Emergency Information Delivery Scenario: Consider an emergency information delivery case. In this case, vessel 1 has emergency data to transmit, e.g., surveillance videos in the warship. Vessel 2 is considered to have no data to deliver and acts a relay. On machine 1 (Vessel 1), let $TOTAL(i, b_i^{'})$ be the total sum of values of those instances other than i on the stack $\mathcal{S}$ that have $ending > b_i^{'}$, $total(i, b_i^{'})$ be the total value of job

Algorithm 1 : *Time-Capacity Mapping Based Two Phase Algorithm for Single Machine*

Phase one: Evaluation
$S \leftarrow$ an empty stack
for each $(i, w_i, b_i^{'}, e_i^{'})$ from $\mathcal{L}$ **do**
  $v \leftarrow w_i - total(i, b_i^{'}) - TOTAL(i, b_i^{'})$
  if $v > 0$ **then**
    push $((i, v, b_i^{'}, e_i^{'}), \mathcal{S})$
  end if
end for
Phase two: Selection
for each job instance i **do**
  $occupied[1] \leftarrow t^{'}$
  $done[i] = false$
end for
while S is not an empty **do**
  $(i, v, b_i^{'}, e_i^{'}) \leftarrow pop(\mathcal{S})$
  if $done[i] = false$ and $e_i^{'} \leq occupied[1]$ **then**
    insert $(i, w, b_i^{'}, e_i^{'})$ to solution
    $done[i] \leftarrow true$, $occupied[1] \leftarrow b_i^{'}$
  end if
end while

instances that $ending < b_i^{'}$ of family i. The latest deadline on machine 1 is $t^{'}$ in capacity horizon. On machine 2 (Vessel 2), $TOTAL(i, b_i^{''})$ and $total(i, b_i^{''})$ are the total sum of values of those instances other than i that have $ending > b_i^{''}$ and those instances of family i that have $ending < b_i^{''}$, respectively. The latest deadline on machine 2 is $t^{''}$ in capacity horizon.

Algorithm 2 shows a pseudo-polynomial algorithm for the two-machine case [32]. A job only has one instance scheduled on machines 1 and 2. When vessel 1 reaches the rendezvous point, it transmits the video packets which need to be delivered by machine 2, to the DTN throw-box.

Algorithm 2 : *Time-Capacity Mapping based Two Phase Algorithm for Two Machines*

Phase one: Evaluation
$S \leftarrow$ an empty stack
In machine 1
for each $(i, w_i, b_i^{'}, e_i^{'})$ from $\mathcal{L}$ **do**
  $v \leftarrow w_i - total(i, b_i^{'}) - TOTAL(i, b_i^{'})$
  if $v > 0$ **then**
    push $((i, v, b_i^{'}, e_i^{'}), S)$
  end if
end for
In machine 2 do
for each $(i, w_i, b_i^{''}, e_i^{''})$ from $\mathcal{L}$ **do**
  $v \leftarrow w_i - total(i, b_i^{''}) - TOTAL(i, b_i^{''})$
  if $v > 0$ **then**
    push $((i, v, b_i^{''}, e_i^{''}), S)$
  end if
end for
Phase two: Selection
for each job instance i **do**
  $occupied[2] \leftarrow t^{''}$
  $done[i] = false$
end for
while S is not an empty **do**
  In machine 2 do
  $(i, v, b_i^{''}, e_i^{''}) \leftarrow pop(S)$
  if $done[i] = false$ and $e_i^{''} \leq occupied[2]$ **then**
    insert $(i, w_i, b_i^{''}, e_i^{''})$ to solution
    $done[i] \leftarrow true$, $occupied[2] \leftarrow b_i^{''}$
  end if
  In machine 1 do
  $(i, v, b_i^{'}, e_i^{'}) \leftarrow pop(S)$
  if $done[i] = false$ and $e_i^{''} \leq occupied[1]$ **then**
    insert $(i, w_i, b_i^{'}, e_i^{'})$ to solution
    $done[i] \leftarrow true$, $occupied[1] \leftarrow b_i^{'}$
  end if
end while

2) Normal Information Delivery Scenario: We consider normal information delivery scenario in which both vessel 1 and vessel 2 have video packets with normal weight (rather than emergency information) to deliver. We focus on the scheduling after vessel 2 gets video packets from DTN throw-box. It can also be considered as a two-machine scheduling problem which is solved by Algorithm 2. The remarkable difference is that vessel 2 has its own videos to transfer. In this situation, with slight alteration, we use the TMTP algorithm of two machines firstly. Then, we check whether the packets relayed from vessel 1 conflict with the original packets on vessel 2. If they are conflicting, we propose the following feedback algorithm (**Algorithm 3**) to avoid transmitting the overlapping packets, i.e., those packets which cannot be relayed to vessel 2, from vessel 1 to DTN throw-box. In Algorithm 3, set A includes all the overlapping packets that cannot be scheduled by vessel 1; A_1 is the set of packets in A which are transmitted to vessel 2 from vessel 1 (determined by Algorithm 2); $t_{release}$ and $t_{deadline}$ denote the release time and deadline of the corresponding packets, respectively; B_1 is the set of packets that are in set A_1 and transmitted to vessel 2 by using Algorithm 2; B is the original packet set of vessel 2; $B^{'}$ is the set after B_1 merges into B, i.e., the whole packet set of vessel 2 after receiving packets from vessel 1; B_2 is the set of packets which cannot be scheduled on vessel 2; C is the intersection of B_1 and B_2.

Algorithm 3 : *Feedback Algorithm*

$B_1 \leftarrow A_1 : (t_{release},\ t_{deadline})$
$B^{'} \leftarrow B_1 \cup\ B$
Let B_2 be the set of packets which cannot be scheduled on vessel 2
$C \leftarrow B_1 \cap\ B_2$
$A_2 \leftarrow C : (t_{release},\ t_{deadline})$
$A_1 \leftarrow A_1 \backslash A_2$

In addition, since vessel 2 acts as a relay and vessel 1 cannot assist to deliver packets of vessel 2, we need to do some alterations to the original TMTP algorithm. When packets are reflected from vessel 2 to vessel 1, the ending time is set to $e^{'} > t^{'} + \delta,\ \ \delta > 0$. We have the following Lemma 3 with respect to Algorithm 2.

Lemma 3: Using time-capacity mapping based two phase algorithm to schedule the intersecting jobs, the job instances with the earliest beginning times are chosen.

Proof: We first show the case that three jobs intersect with each other, with $w_3 > w_2 > w_1$. In Fig. 4, two job instances are described, while the scheduling of more job instances could be easily extended. The calculation process is described in TABLE II. We judge whether the job instances should enter the stack in the left column, and display the calculation process in the right column, where $*$ means that the job instance is selected in phase two. It is found that the total weight of job instances which enter the stack is just the weight of the last one job instance (e.g., after the first job instance of job 3 enters the stack, the total weight of stack is $(w_3 - w_2) + (w_2 - w_1) + w_1 = w_3$. When evaluating whether

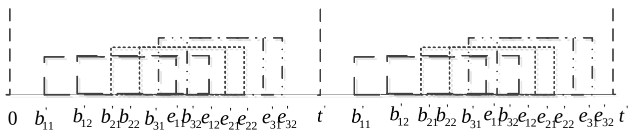

Fig. 4. Case of multi-job with multi-interval intersection.

TABLE II. The two phase process of TMTP algorithm.

Enter into stack	Calculate value
$(i_1, w_1, b_1^{'}, e_1^{'})$	$v = w_1 - 0 - w_1 = 0$
	$v = w_2 - w_1$, if $w_2 > w_1$
$(i_2, w_2 - w_1, b_2^{'}, e_2^{'})*$	$v = w_2 - (w_2 - w_1) - w_1 = 0$
	$v = w_3 - (w_2 - w_1) - w_1 = w_3 - w_2$, if $w_3 > w_2$
$(i_3, w_3 - w_2, b_3^{'}, e_3^{'})$	$v = w_3 - (w_3 - w_2) - (w_2 - w_1) - w_1 = 0$
	$v = w_1 - w_1 = 0$
	$v = w_2 - (w_2 - w_1) = w_1$
$(i_2, w_1, b_2^{''}, e_2^{''})$	$v = w_2 - (w_2 - w_1) - w_1 = 0$
	$v = w_3 - (w_3 - w_2) - w_1 = w_2 - w_1 > 0$
$(i_3, w_2 - w_1, b_3^{''}, e_3^{''})*$	$v = w_3 - (w_3 - w_2) - w_1 - (w_2 - w_1) = 0$

the second job instance of job 3 enter the stack, we have $(w_3 - w_3) = 0$. The rest of more job instances could be done in the same manner. The scheduling of more jobs and more job instances can be induced. Since the value of job n which enters the stack is $v = w_n - w_{n-1}$, the total weight of stack is $(w_n - w_{n-1}) + (w_{n-1} - w_{n-2}) + \cdots (w_3 - w_2) + (w_2 - w_1) + w_1 = w_n$. When evaluating whether the second job instance of job n enters the stack, we have $(w_n - w_n) = 0$. In other words, the job instances with the earliest beginning times are selected to enter the stack. It can be concluded that the job instances with the earliest beginning times are chosen. Likewise, the deductions of other intersecting cases with different weight values can obtain the same conclusion. ■

C. Interval Graph Theory Based Job Relay Selection Algorithm

Based on the observations in Lemma 3, we propose a more efficient interval graph theory based job relay selection (IGTJRS) algorithm (**Algorithm 4**) to choose packets to be delivered to vessel 2. First, time-capacity mapping is also implemented to mitigate the intermittent connectivity.

Step 3-7 is to judge whether jobs intersect with each other. When job instances ensure mutual exclusion, the algorithm can directly schedule the packets on vessel 1, while choosing the instances with earliest beginning times that guarantees non-overlapping with each other, as shown in step 12-13. However, we focus on packets with inevitable overlapping that could not be fully scheduled on vessel 1. In step 8-10, two sets of job instances are chosen, of which one is delivered by vessel 1 itself and the other is transmitted to the DTN throw-box. In each set, job instances are non-overlapping with each other.

In order to obtain the maximum total weight, we utilize the concept of maximum weight 2-independent set (MW2IS) in interval graph [39]. Interval graph is an intersection graph of a multi-set of intervals on the real line. It has one vertex for each interval in the set, and an edge between every pair of vertices

Algorithm 4 : *Interval Graph Theory Based Job Relay Selection Algorithm*

1: Definition: the same as Algorithm 1, and $M = \emptyset$
2: Detection two jobs whether intersect with each other:
3: **for** $\forall J_i \in \mathcal{J}$, $\forall J_j \in J \backslash J_i$ **do**
4: Let $b_i \leftarrow \{b_i^1, b_i^2, \cdots b_i^k\}$ express beginning time of job i intervals, $b_j \leftarrow \{b_j^1, b_j^2, \cdots b_j^k\}$ express beginning time of job j intervals
5: job instance $k_{\min}^i \leftarrow \min\{b_i^k\}$, $k_{\max}^j \leftarrow \max\{e_j^k\}$, $\alpha \leftarrow k_i^{b_{\min}}$, $\beta \leftarrow k_j^{e_{\max}}$
6: **if** $e_i^\alpha > b_j^\beta$ **then**
7: Job i and j mutually intersect, $J_j \leftarrow (j, w_j, b_{j\min}, e_{j\min})$, $J_i \leftarrow (i, w_i, b_{i\min}, e_{i\min})$
8: draw relative interval graph $G(V, E)$, then use Algorithm 5 to obtain two maximum weight interval sets $Q_u^{'}$ and $Q_v^{'}$ to be delivered in vessel 1 and vessel 2
9: $Q^{'} \leftarrow Q_m^{'}$, $Q_m^{'}$ has the latest ending time, and $m \in \{u, v\}$
10: vessel 2 $\leftarrow$ DTN throw-box $\leftarrow$ the set Q'
11: **else**
12: Job i and j not mutually intersect, Find $(j, w_j, \widetilde{b}_j, \widetilde{e}_j), (i, w_i, \widetilde{b}_i, \widetilde{e}_i) \to M$ with minimum $\widetilde{b}$
13: $M \leftarrow M \cup (j, w_j, \widetilde{b}_j, \widetilde{e}_j) \cup (i, w_i, \widetilde{b}_i, \widetilde{e}_i)$
14: **end if**
15: **end for**

corresponds to intervals that intersect [40]. According to the intersection between job instances, an interval graph $G(V, E)$ is obtained. Consequently, the job sets selection issue which is described in step 8-10 could be transformed to the collection selection issue in the interval graph. In [39], the MW2IS algorithm gives a collection of two sets with maximum weight. However, the elements contained in each set are not clear. We propose a modified MW2IS algorithm (**Algorithm 5**) to obtain the maximum 2 independent sets $Q_u^{'}$ and $Q_v^{'}$ as well as the elements in each set. For any 2-independent set Q of intervals I, $MWQ(u, v)$ indicates an MW2IS, and $w(u, v)$ denotes the weight of $MWQ(u, v)$, which is summation of the weight of all elements in the two sets. u and v are the largest indices of the intervals in the two sets, respectively. In step 2, the algorithm computes value of each $w(u, v)$ based on the equation $w(u, v) = w(i_j) + \max\{\{w(u, x)\,|b_j > e_x \ and \ u < x\} \cup \{w(x, v)\,|b_j > e_x \ and \ x < v\}\}$, if $v > u$, where the detailed algorithm *MWIS_IN_INTERVALS* is depicted in Algorithm 6; Step 3 gives the MW2IS $Q_{\max 2}$, without indicating the elements contained in each set; A backward interval selection procedure is described in step 4, in order to give $Q_u^{'}$ and $Q_v^{'}$. Between $Q_u^{'}$ and $Q_v^{'}$, the one with the latest deadline is chosen to be delivered to vessel 2.

Algorithm 6 is to find the maximum weight independent set (MWIS). Weight of $MWS(c)$ is given by

$$\chi(c) = wt(i_c) + \max\{\chi(x)\,|e_x < b_c\}, \quad \text{for any } 1 \leq c \leq n \quad (19)$$

$temp\_\max$ is a temporary variable which represents the weight of MWIS; $S_{\max 1}$ represents an MWIS of intervals I; $last\_interval$ represents the largest index of the intervals [39].

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Algorithm 5 : *Modified Maximum Weight 2-independent Set Algorithm*

Input: A set of weighted intervals $I \leftarrow \{i_1, i_2, \cdots i_n\}$ and the sorted endpoints list $L \leftarrow \{e_1, e_2, \cdots e_{2n}\}$.
Output: The MW2IS $Q_{\max 2}$ of I, two maximum weight interval sets $Q_u^{'}$, $Q_v^{'}$.
Step 1: $Q_{\max 2} \leftarrow \emptyset$; $Q_u \leftarrow \emptyset$; $Q_v \leftarrow \emptyset$; Set the initial value of $w(u, v)$,$0 \leq u,\ v \leq n$, to be 0.
Step 2: Compute each value of $w(u, v)$, $0 \leq u,\ v \leq n$, beginning from $w(0, v)$, $0 \leq v \leq n$, then $w(1, v)$, $0 \leq v \leq n, \cdots, w(n, v), 0 \leq v \leq n$, by algorithm MWIS_IN_INTERVALS and formula $w(u, v) = w(i_j) + \max\{\{w(u, x)\,|b_j > e_x \text{ and } u < x\} \cup \{w(x, v)\,|b_j > e_x \text{ and } x < v\}\}$, if $v > u$.
Step 3: Let $w(u_{n-1}, v_n) \leftarrow \psi(I)$; $Q_{\max 2} \leftarrow Q_{\max 2} \cup \{i_{u_{n-1}}, i_{v_n}\}$; $\psi(I) \leftarrow \psi(I) - (w(i_{u_{n-1}}) + w(i_{v_{n-1}}))$; $u_{n-1} \leftarrow u_1$; $v_n \leftarrow v_1$
while $\psi(I) > 0$ **do**
  Select a pair of intervals (i_{u2}, i_{v2}) with the constraints that $\max\{e_{u2}, e_{v2}\} < \max\{b_{u1}, b_{v1}\}$, $\min\{e_{u2}, e_{v2}\} < \min\{b_{u1}, b_{v1}\}$, and $w(u_2, v_2) = \psi(I)$.
  $Q_{\max 2} \leftarrow Q_{\max 2} \cup \{i_{u2},\ i_{v2}\}$;
  $\psi(I) \leftarrow \psi(I) - (w(i_{u_2}) + w(i_{v_2}))$;
  $u_1 \leftarrow u_2$; $v_1 \leftarrow v_2$;
  $Q_u \leftarrow Q_u \cup \{i_{u1}\}$; $Q_v \leftarrow Q_v \cup \{i_{v1}\}$;
end while
Step 4: Let $Q_u \leftarrow \{Q_{u1}, Q_{u2}, \cdots Q_{um}\}$; $Q_v \leftarrow \{Q_{v1}, Q_{v2}, \cdots Q_{vm}\}$; $Q_u^{'} \leftarrow \emptyset$; $Q_v^{'} \leftarrow \emptyset$
$Q_u^{'} \leftarrow Q_u^{'} \cup \{Q_{u_1}\}$; $Q_v^{'} \leftarrow Q_v^{'} \cup \{Q_{v_1}\}$
for $\leftarrow 1$ *to* m **do**
  if $b_{Q_{u_i}} > e_{Q'_{u_{(i-1)}}}$ and $b_{Q_{v_i}} > e_{Q'_{v_{(i-1)}}}$ **then**
    $Q_u^{'} \leftarrow Q_u^{'} \cup \{Q_{u_i}\}$; $Q_v^{'} \leftarrow Q_v^{'} \cup \{Q_{v_i}\}$,
  else
    $Q_v^{'} \leftarrow Q_v^{'} \cup \{Q_{u_i}\}$; $Q_u^{'} \leftarrow Q_u^{'} \cup \{Q_{v_i}\}$
  end if
end for

The above analysis focuses on the scenario in which each vessel only has one helper. The algorithm can be easily extended to multi-vessel scenario by repeating TMTP or IGTJRS algorithm multiple times.

D. Performance Analysis

In this section, we analyze the performance of the proposed algorithms, including the approximation ratio and time complexity. The approximation ratio is the ratio of the throughput of an optimal schedule to that of the approximation algorithms.

Theorem 2: The approximation ratio of the IGTJRS algorithm is 2.

Due to the page limitation, we omit the details of the proof.

In terms of time complexity, it can be observed from Algorithm 4 that the time complexity of IGTJRS algorithm constitutes of three components:

Insert families: Sort list $\mathcal{L}$ of all the families by the earliest ending time of the interval in this family. We adopt binary search method on $\mathcal{L}$ in $\mathcal{O}(\log n)$ time, where n is the number of jobs.

Algorithm 6 : *MWIS_IN_INTERVALS*

Input: A set of weighted intervals $I = \{i_1, i_2, \cdots i_n\}$ and the sorted endpoints list $L = \{e_1, e_2, \cdots e_{2n}\}$.
Output: The MWIS $S_{\max 1}$ of I.
Step 1: $temp\_\max \leftarrow 0$; $S_{\max 1} \leftarrow \emptyset$; $last\_interval \leftarrow 0$;
for $v \leftarrow 1$ to n **do**
  $\chi(v) \leftarrow 0$
end for
Step 2:
for $i \leftarrow 1$ to $2n$ **do**
  if e_i is a left endpoint of interval i_c **then**
    $\chi(c) \leftarrow temp\_\max$
    if e_i is a right endpoint of interval i_c **then**
      if $\chi(c) > temp\_\max$ **then**
        $temp\_\max \leftarrow \chi(c)$;
        $last\_interval \leftarrow c$;
      end if
    end if
  end if
end for
Step 3: $S_{\max 1} \leftarrow S_{\max 1} \cup \{i_{last\_interval}\}$; $temp\_\max \leftarrow temp\_\max - w\{i_{last\_interval}\}$
for $v \leftarrow last\_interval - 1$ to 1 **do**
  if $\chi(v) = temp\_\max$ and $e_v < a_{last\_interval}$ **then**
    $S_{\max 1} \leftarrow S_{\max 1} \cup \{i_v\}$;
    $temp\_\max \leftarrow temp\_\max - w\{i_v\}$;
    $last\_interval \leftarrow v$;
  end if
end for

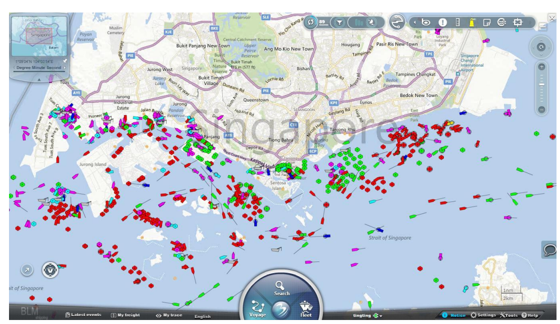

Fig. 5. The traces of vessel Rainbow1.

Judge intersection: Exploring linear search, time complexity $\mathcal{O}(n)$ for judgement is achieved.

Job relay selection: Maximum weight 2-independent set algorithm is adopted, solved in $\mathcal{O}(n^2)$ time [39].

Therefore, the IGTJRS algorithm runs in $\mathcal{O}(n^2)$ time. Comparatively, TMTP algorithm runs in $\mathcal{O}(2tn \log\log(2t))$ time, where t is the latest job deadline. Typically, one job occupies multiple timeslots, which indicates that $t \gg n$. Hence, the proposed IGTJRS algorithm has a more favorable time complexity performance than TMTP algorithm.

VI. Performance Evaluation

The proposed algorithms are verified using simulations, based on the traces of vessels in an area of Singapore Harbor obtained from BLM-Shipping navigation software [41].

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TABLE III. The time-position traces of vessels.

Time(1)	"Rainbow1" Position(1)	Time(2)	"Secret" Position(2)	Time(3)	"Gloden Rise" Position(3)	Time(4)	"Ayer" Position(4)	...
...	...	...	...	...	...	...	...	...
19 : 56	$1^o13^{'}54^{''}N103^o53^{'}32^{''}E$	19 : 37	$1^o05^{'}45^{''}N103^o44^{'}01^{''}E$	19 : 58	$1^o10^{'}30^{''}N103^o52^{'}20^{''}E$	20 : 16	$1^o07^{'}46^{''}N103^o47^{'}05^{''}E$	...
20 : 05	$1^o12^{'}20^{''}N103^o52^{'}16^{''}E$	19 : 52	$1^o08^{'}23^{''}N103^o46^{'}20^{''}E$	20 : 06	$1^o11^{'}43^{''}N103^o51^{'}52^{''}E$	20 : 31	$1^o08^{'}21^{''}N103^o46^{'}21^{''}E$	...
20 : 28	$1^o10^{'}31^{''}N103^o47^{'}57^{''}E$	19 : 58	$1^o08^{'}51^{''}N103^o46^{'}46^{''}E$	20 : 11	$1^o12^{'}20^{''}N103^o51^{'}19^{''}E$	20 : 42	$1^o09^{'}57^{''}N103^o46^{'}08^{''}E$	...
20 : 40	$1^o09^{'}10^{''}N103^o45^{'}34^{''}E$	20 : 03	$1^o09^{'}31^{''}N103^o47^{'}38^{''}E$	20 : 18	$1^o12^{'}54^{''}N103^o49^{'}51^{''}E$	20 : 48	$1^o10^{'}12^{''}N103^o45^{'}21^{''}E$	...
20 : 46	$1^o08^{'}51^{''}N103^o44^{'}27^{''}E$	20 : 19	$1^o10^{'}26^{''}N103^o49^{'}35^{''}E$	20 : 25	$1^o13^{'}12^{''}N103^o48^{'}15^{''}E$	20 : 56	$1^o10^{'}32^{''}N103^o44^{'}53^{''}E$	...
...	...	...	...	...	...	...	...	...

TABLE III lists the time-position information of some of the related vessels. Video compression standard is based on H.264, with compressed video bitrate of 0.47 Mbps [42]. The arrival process of jobs (packets) of any specific video is deterministic based on the video bitrate. Fig. 5 shows the trace of vessel "Rainbow1" as example. We consider that the infostations are uniformly deployed along the coastline. The DTN throw-boxes are deployed at the rendezvous points of vessels routes which is known *a priori*. To estimate the frame capacity $A_{h,k}$ for the offline scheduling, we utilize a two-ray propagation loss model to calculate the data transmission rate of vessels in different locations. The transmit power of vessel is denoted by P_{tx}. At the beginning of a specific frame (denoted by t_b), the distance between the vessel and the infostation is d. The receive power at the infostations can be calculated by:

$$\frac{P_{rv}}{P_{tx}} = (\frac{\lambda}{4\pi d})^2 \times \sin^2\left(\frac{2\pi h_{tx} h_{rv}}{\lambda d}\right), \tag{20}$$

where λ is the transmission wave length, h_{tx} and h_{rv} are the respective height of transmitting and receiving antennas [43]. Thus, the instant transmission rate at t_b can be estimated by

$$r = B * log_2(1 + \frac{P_{rv}}{N}), \tag{21}$$

where B is the bandwidth allocated to the vessel, and N is the noise power. Assume that the channel is stable within one frame duration, and the capacity of the frame is $A_{h,k} = \frac{r*T_f}{S_p}$, where T_F is the frame duration and S_p is the packet size. The simulation parameters are listed in Table IV [14].

Using the BLM-Shipping navigation software, we identify only the discrete locations of vessels, not the particular traces. We use lines that connect the locations as the approximate trace. In other words, we consider a synthetic vessel trace method, assuming that vessels sail in straight line between two adjacent position points. Curve fitting is implemented by undertaking the straight line hypothesis, based on the distance between any two contiguous locations. The following formulas calculate the great circle distance S in navigation science, due to the earth's geographic characteristics. We define the locations of two vessels as (φ_1, θ_1), (φ_2, θ_2), with φ and θ respectively expressing the latitude and longitude. Calculation formulas of the great circle distance are

$$\cos S = \sin\varphi_1 \cdot \sin\varphi_2 + \cos\varphi_1 \cdot \cos\varphi_2 \cdot \cos D\lambda \tag{22}$$
$$D\lambda = \theta_2 - \theta_1. \tag{23}$$

Consequently, we use $S = \arccos(\cos S)$ as the great circle distance [44], which is used to approximate the distance between two adjacent position points.

We compare the proposed algorithms with some other maritime communication algorithms [15], [19] and classic scheduling algorithms, i.e., Deadline (the job with the earliest deadline is scheduled first), First-input-first-output (FIFO) (the job with the earliest release time is scheduled first), Weight (the job with the largest weight is scheduled first), single (noncooperative between two-vessel, and only one vessel has packets to transmit) and Multi-single (noncooperative among multiple vessels). Here, the performance is evaluated by normalized throughput, indicating the ratio of the throughput of delivered packets to the throughput of total packets. In [15], vessels using the mesh network rather than DTN to transmit data. Thus, in the simulation, we assume a vessel can transmit only when it can directly communicate with an infostation, and uses Deadline scheduling. In [19], DTN scheme is utilized, where vessels can communicate with each other when possible, and deliver the stored packets when they meet an infostation. However, since there are no DTN-boxes, the chances that data can be successfully delivered may be less than our proposed framework.

TABLE IV. Simulation parameters.

Name	Value
Packet size S_p	100 bytes
System bandwidth	10 MHz
Noise spectral density	174 dBm/Hz
Transmit antenna height h_{tx}	10 m
Video bitrate	0.47 Mbps
Frame duration T_F	5 ms
UE transmit power P_{tx}	23 dBm
Receive antenna height h_{rv}	50 m

We first investigate the single-vessel scenario, i.e., no relays. Fig. 6(a) shows the normalized throughput versus the number of infostations, where the normalized throughput is defined as the ratio between the accomplished packets profits and the total weight of packets. Number of infostations varies from 2 to 16 of the whole route line. It can be observed that the normalized throughput of all four algorithms increases with the increment of the infostations. Furthermore, the throughput of the TMTP algorithm obviously outperforms the others, and hence the network performance is better. In Fig. 6(b), the normalized throughput versus the size of job (number of packets), for different schemes is presented. For larger job sizes, the total throughput becomes lower, because the number of overlapping jobs increases. In Fig. 6(c) shows the normalized throughput versus the job lifetime. The TMTP algorithm has a significantly better performance than other three algorithms. With a larger length of the job lifetime, the throughput of the TMTP algorithm becomes higher, since when the job lifetime increases, the probability of non-overlapping job instances increases, and therefore the performance of the TMTP algorithm

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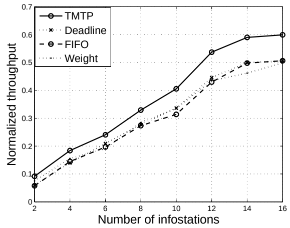
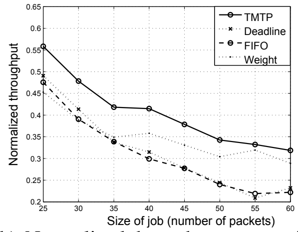
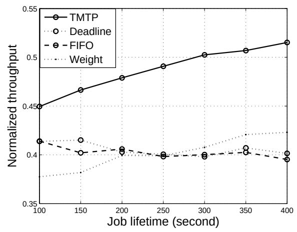


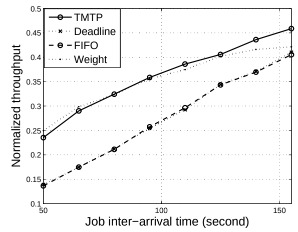
(a) Normalized throughput versus number of infostations for single-vessel



(b) Normalized throughput versus size of job for single-vessel

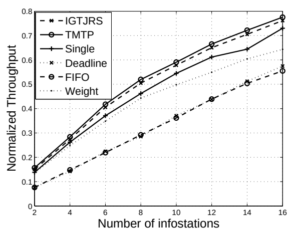


(c) Normalized throughput versus job lifetime for single-vessel

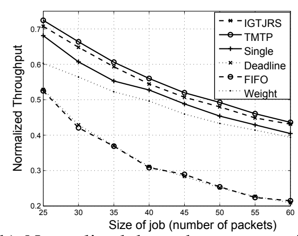


(d) Normalized throughput versus job inter-arrival time for single-vessel

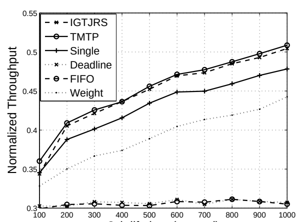
Fig. 6. Simulation results for single-vessel scenario.



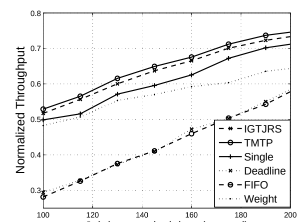
(a) Normalized throughput versus number of infostations for two-vessel



(b) Normalized throughput versus size of job for two-vessel



(c) Normalized throughput versus job lifetime for two-vessel



(d) Normalized throughput versus inter-arrival time for two-vessel

Fig. 7. Simulation results for two-vessel scenario.

is improved. In Fig. 6(d), the normalized throughput versus the job inter-arrival time is shown. With a longer inter-arrival time, i.e., the granularity of inter-arrival time increases, the number of overlapping packets decreases. As a consequence, the achieved total profits increase.

Then, we study the two-vessel scenario, assuming that only vessel “Rainbow1” has packets to transmit and vessel “Secret” acts as a relay. In TMTP algorithm, we assume that vessel “Secret” has all the packets that vessel “Rainbow1” may generate and transmit at the beginning of the simulation, which is not realistic. Thus, the performance of TMTP can be considered as the upper bound of all DTN algorithms. The Single algorithm corresponds to noncooperative scenario where TMTP algorithm is utilized for single machines. From Fig. 7, it is obvious that cooperative schemes IGTJRS and TMTP outperform noncooperative scheme Single. Moreover, the IGTJRS algorithm achieves nearly the same performance as the TMTP algorithm, and obviously outperforms the other three cooperative algorithms. The normalized throughput versus the number of infostations is shown in Fig. 7(a). As the number of infostations increases, the normalized throughput increases since there are more transmission opportunities. The impact of size of job is demonstrated in Fig. 7(b). A larger size of job indicates that one video packet needs more frame resource for transmission, which reduces the total weight of delivered packets. The normalized throughput versus job lifetime is described in Fig. 7(c). Longer job lifetime results in more non-overlapping job intervals and thus, higher normalized throughput. From Fig. 7(d), we can see that the normalized throughput increases as the job inter-arrival time increases, due to an increased number of non-overlapping jobs.

The simulation results of multi-vessel scenario are shown in Fig. 8. Each vessel has its own service, and acts as a relay to assist transmitting if possible. We compare our results with that in [19] and [15]. Similar to two-vessel scenario, in TMTP algorithm, the relaying vessels are assumed to carry all the packets generated by the vessel they assist at the beginning of the simulation. Thus, TMTP algorithm can still be considered to achieve the performance upper bound. The algorithm proposed in [15] does not perform as well as TMTP, IGTJRS and [19] because it does not apply DTN mechanism. The algorithm proposed in [19] achieves better performance than [15], however, it performs worse than TMTP and IGTJRS since it does not utilize the DTN throw-box. In Fig. 8(a), the normalized throughput versus number of infostations is shown. It can be seen that the normalized throughput increases with the increment of the number of infostations. The IGTJRS algorithm has nearly the same performance as the TMTP algorithm, and obviously outperforms the other four algorithms, which coincides with the performance analysis in Section V-D. Fig. 8(b) shows the normalized throughput versus the size of job (number of packets). Also the IGTJRS algorithm achieves almost the same performance as the TMTP algorithm. As the job size increases, the number of scheduled jobs decreases, and the throughput decreases accordingly. In Fig. 8(c), the normalized throughput versus job lifetime is plotted. As the job lifetime enlarges, the probability of non-overlapping job intervals increases and thus, the performance of IGTJRS and TMTP algorithms is improved. In Fig. 8(d), the normalized throughput versus the job inter-arrival time is shown, where the granularity of inter-arrival time varies from 100 to 200 seconds. The normalized throughput of the network increases with the increment of the granularity, since the number of non-overlapping jobs also increases.

Through the simulations, we can draw the following conclusions: 1) TMTP algorithm for single vessel offers improved performance than the other classic scheduling algorithms; 2) Compared with TMTP algorithm, IGTJRS algorithm can efficiently solve the target problem with almost the same performance; 3) Comparing with the existing maritime DTN/none-DTN algorithms besides some classic scheduling algorithms, the cooperative IGTJRS and TMTP algorithms outperform noncooperative algorithms; 4) The normalized throughput is increased with an increment in the number of infostations, job

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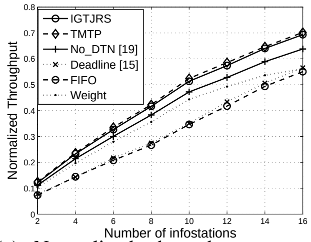
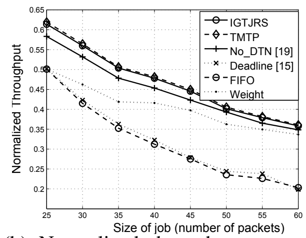
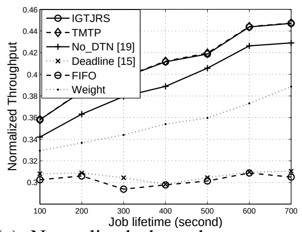


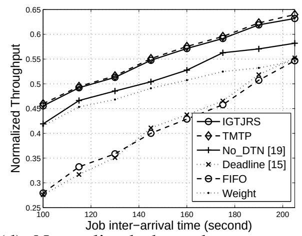
(a) Normalized throughput versus number of infostations for multi-vessel



(b) Normalized throughput versus size of job for multi-vessel



(c) Normalized throughput versus job lifetime for multi-vessel



(d) Normalized throughput versus inter-arrival time for multi-vessel

Fig. 8. Simulation results for multi-vessel scenario.

lifetime, and granularity between jobs; and 5) The normalized throughput decreases with the increased size of jobs.

VII. Conclusion

In this paper, we have shed light on the scheduling schemes in maritime wireless communication networks. In order to maximize the weighted throughput of the delivered video packets, we utilize the job-machine scheduling method to solve the VTMP. Three offline scheduling algorithms, namely TMTP algorithm for single machine, TMTP algorithm for two machines, and IGTJRS algorithm have been proposed. We show that the IGTJRS algorithm has a 2-approximation ratio, and runs in $\mathcal{O}(n^2)$ time. Simulation results indicate that our proposed algorithms can achieve better performance than several classic scheduling algorithms. For the future work, we will carry out the efficient scheduling for energy-constrained infostations and DTN throw-box with energy-harvesting technologies. Additionally, stochastic models will be developed to investigate the scheduling problems for vessels with lower tonnage such as fishing boats. Moreover, an interrelated throughput-delay-fairness (TDF) triplet will be also considered into the maritime network scheduling.

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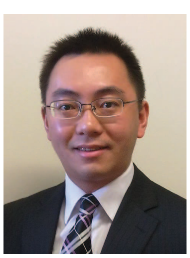

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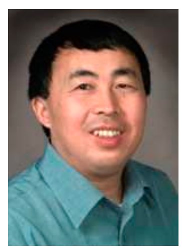

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