Green Energy and Content-Aware Data Transmissions in Maritime Wireless Communication Networks

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***Abstract*—In this paper, we investigate the network throughput and energy sustainability of green-energy-powered maritime wireless communication networks. Specifically, we study how to optimize the schedule of data traffic tasks to maximize the network throughput with Worldwide Interoperability for Microwave Access technology. To this end, we formulate it as an optimization problem to maximize the weight of the total delivered data packets, while ensuring that harvested energy can successfully support transmission tasks. The formulated energy and content-aware vessel throughput maximize problem is proved to be $\mathcal{NP}$-complete. We propose a green energy and content-aware data transmission framework that incorporates the energy limitation of both infostations and delay-tolerant network throw boxes. The green energy buffer is modeled as a $G/G/1$ queue, and two heuristic algorithms are designed to optimize the transmission throughput and energy sustainability. Extensive simulations demonstrate that our proposed algorithms can provide simple yet efficient solutions in a maritime wireless communication network with sustainable energy.**

***Index Terms*—Diffusion approximation, leaky bucket, maritime wideband communication, sustainable energy.**

I. INTRODUCTION

WITH the advances of wireless technologies, maritime wireless communication network is emerging as one of the important information transmission systems. Generally, the transmissions in maritime wireless networks can be classified into two types: terrestrial and satellite communication [1]. By utilizing the legacy analog high-frequency/medium-frequency and very high frequency radios, long-range/medium-range or short-range ship-to-shore and ship-to-ship communications near port water can be enabled, respectively. However, such transmissions are not able to provide high rate services. With satellite communications, i.e., Fleet Broadband, the transmission can achieve a high data rate of up to 432 kb/s, but launching satellites into orbits leads to prohibitive service fees. Compared with land-based wireless communication, the maritime wireless networks suffer the much higher costs for devices deployment, energy consumption, and maintenance of maritime wireless networks. Therefore, it is essential to develop a novel cost-effective wideband maritime communication network by innovative communication technologies from land to sea.

Green energy refers to ecofriendly and sustainable energy sources, e.g., wind, solar, and modern biomass. Among a variety of green energy sources, wind power rapidly grows at the rate of 30% annually, which achieved 198 GW all over the world in 2010. Solar power is another popular green energy source, and cumulative global photovoltaic installations surpassed 40 GW at the end of 2010 [2]. Moreover, with the development of green energy technology, crystalline silicon devices can approach the theoretical limiting efficiency of 29%. Motivated by the relative high performance-cost ratio, solar and wind power are two of the most common energy sources that have been extensively used to power wireless networks, particularly the network infrastructure. For instance, the Green WiFi initiative has developed a low-cost solar-powered standardized WiFi solution for providing Internet access to developing areas [3]. The wind-powered wireless mesh networks are also applied for emergency network deployment after disasters [4].

The advances of green wireless networks have provided an alternative energy for maritime wireless networks, which can significantly decrease the cost of maritime wireless networks establishment and maintenance. For instance, due to the long coastline, some infostations may be constructed on the island or other remote areas, and thus, it might be prohibitive and inconvenient to use cable to connect electricity grid and access to the island for maintenance. By using green energy, the infostations can be easily constructed, and less maintenance is required, which can significantly reduce the cost. However, unlike

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TABLE I
NOTATIONS AND DEFINITIONS

Symbol	Definition
$r_{jk}(d_{jk})(p_{jk})(s_{jk})$	The release time(deadline)(processing time)(starting time)of video packet j on vessel k
w_{jk}	Weight of packet j on vessel k
$x_{jks_{jk}}$	Binary variable denote whether packet j on vessel k is implemented at the time interval $[s_{jk}, s_{jk} + p_{jk}]$
$A(t)(L(t))$	The cumulative number of arriving and leaving energy
$X(t)$	A continuous process to approximate buffer size $R(t)$
$\alpha(\beta)$	Diffusion and drift diffusion coefficient
μ_a (υ_a)	The mean (variance) of energy inter-charging interval
μ_l (υ_l)	The mean (variance) of energy inter-discharge interval
x_0	The initial queue length (energy level)
$p(x, t; x_0)$	The conditional probability density function of the energy buffer size $X(t)$ at time t
$p_D(x, t; x_0)$	The probability density function of the buffer depletion duration D
$\mathcal{P}(0; x_0)$	The energy buffer depletion probability from x_0
$M_D(s)$	The moment generation function of D
$E(D)$ $(Var(D))$	The mean(variance) of energy buffer depletion duration D
$\mathcal{P}(0; x_0)$	The energy buffer depletion probability from x_0
$F_D(T; x_0)$	The energy depletion probability before p_{jk} terminates

traditional electricity grid, green energy highly depends on its position, local weather, and time, which makes the green energy inherently variable or even intermittent with time. Thus, the fundamental design criterion and the main performance metric under the scenario of green-energy-powered maritime wireless networks are shifted from energy efficiency to energy sustainability. Combining with green energy supplies, the challenges of the maritime wireless communication networks are different with the applications of green-energy-based terrestrial wireless communication networks or maritime wireless communication networks with traditional energy [5]. In green-energy-powered maritime wireless networks, we have to consider not only the energy sustainability of each base station (BS) but also the distinctive challenges of maritime wireless networks, e.g., wireless coverage, various mobility patterns, and high-speed mobility, which are normally different from the concern of terrestrial wireless communication networks.

In this paper, we focus on optimizing the schedule of data traffic tasks to maximize the network throughput in maritime wireless networks powered with green energy. We redefine the throughput as the summation of weights of delivered data packets. In the following context, we take uploading surveillance video clips from seagoing vessel to authority on land as an application paradigm. Specifically, Worldwide Interoperability for Microwave Access (WiMAX)/store-carry-and-forward interworking maritime wireless network is devised to overcome the restrictions of long-distance traffic at sea and intermittent infostations deployment, where the infostations and delay-tolerant network (DTN) throw boxes [6] are powered by green energy. Under this network scenario, the data traffic scheduling should consider the energy sustainability to guarantee the successful data transmission. Aiming at maximizing network performance with stored and harvested energy, single-vessel transmission scheme and two-vessel cooperative transmission scheme, respectively, are designed to employ the available transmission opportunities, i.e., infostations and DTNs. In order to maximize the weight of data delivered, the proposed schemes study how to maximize the throughput of the delivered data packets, by scheduling the packets delivered through infostations or DTN, subject to the energy constraint. To the best of our knowledge, our work is the first to investigate such data packet scheduling issue in maritime wireless networks powered by renewable energy sources.

The main contributions of this work are shown as follows.

- We formulate the energy and content-aware vessel throughput maximization problem (EVTMP) and prove that the formulated problem is $\mathcal{NP}$-complete. Then, the energy buffer of infostations and DTN throw box is modeled as a $G/G/1$ queue, and a diffusion approximation method is engaged to investigate transient states, e.g., energy depletion duration and maximum carry delay.
- Based on energy buffer model, two algorithms are proposed, which are called leaky bucket energy buffer-based decentralized online algorithm and energy buffer-based combinatorial decentralized–centralized algorithm.
- Finally, we evaluate the performance of our proposed algorithms based on actual ship route trace data from dedicated navigation software. Extensive simulation results show that our proposed algorithms could provide simple yet efficient solutions in a maritime wireless communication network with sustainable energy.

The remainder of this paper is organized as follows. In Section II we review the related work. The system model is provided in Section III and the problem formulation is presented in Section IV. Section VI validates our approaches by simulations. Section VII concludes this paper. We summarize used symbols in Table I.

II. RELATED WORK

As a promising technology, there are many studies related to the maritime wideband network in both industry and academia [7]–[11]. The MarCom project [9] in Northern Europe shows how WiMAX technology can be applied in the maritime communication environment. The projects reported in [7] and [8] provide high-quality connectivity back to the Internet, voice services, and corporate networks to WiMAX users. In [10], the WiMAX-based mesh technology for ship-to-ship communications with DTN features is explored to provide low-cost wireless communication services at sea and compare the performance between regular routing protocols and DTN routing protocols. In [11], an architectural prototype is constructed by utilizing DTN overlay to achieve file delivery to the Internet, which integrates the function of Automatic Identification System. However, most works concern about research issues under the scenario of maritime wireless networks with traditional energy.

With respect to green wireless communication, many works have been studied in the literature in recent years. The authors of [12] identified that green-energy-powered access points (APs) provide a cost-effective solution for wireless local area networks. In [13], the throw box is assumed to be able to last for a certain period of time, which can calculate the average power from the capacity of the batteries or harvesting energy from solar panels. In [14], network deployment and resource management issues are investigated in the context of green mesh networks. A placement solution seeking paths with the minimum energy depletion probability is proposed to improve the network sustainability while ensuring that the energy and quality-of-service (QoS) demands of mobile users can be fulfilled. In [15], a network planning problem in green wireless communication network is studied. The relay nodes placement and subcarrier allocation issues are jointly formulated. Authors proposed top-down/bottom-up algorithms to minimize the number of APs powered by renewable energy sources with satisfying the QoS requirement of users. In [16], a mathematical framework is developed to study the impact of network dynamics on the perceived video quality. After that, the close-form expressions of the video quality are given in terms of start-up delay, playback, and packet loss.

III. SYSTEM MODEL

We consider a green-energy-powered maritime wireless communication network, where a hosting vessel periodically captures surveillance video clips relevant for crucial spots in a vessel. Those videos should be uploaded to a content server and posted on the dedicated maritime information network sites, so that a relevant maritime authority administrator could view and download it. The system model is shown in Fig. 1, where the single- and two-vessel scenarios are shown in Fig. 1(a) and (b), respectively. Several orthogonal-frequency-division-multiplexing-based WiMAX infostations are deployed along the coastline, which is commonly used in wireless networks [17]–[19]. Packets can be transmitted over different subchannels without interference to each other. The video packets can be transmitted either through infostations or relayed by a DTN throw box. The infostations and the DTN throw boxes can harvest energy from natural environment by using solar panels or wind turbines. The packet frame follows the IEEE standard 802.16/WiMAX MAC frame structure.

A. Video Service

Video clips are divided into packets, and each packet has characteristics in terms of release time, playback deadline, and weight. The weight denotes its priority and contribution to the importance of the video packets. Video packets, which are delivered before their playback deadline, are assumed to be successfully decoded at destination, and the profit of weight is gained. Denote r_{jk} and d_{jk} as the flexible release time and deadline for video packet j on vessel k, respectively. Let w_{jk}, p_{jk}, and s_{jk} represent the weight of video packet j on vessel k, the processing time, and the starting time, respectively. In addition, $u \in \{1, \ldots, t\}$, i.e., the starting time of another video packet, is defined to avoid multiple video packets being simultaneously scheduled on one vessel. Obviously, r_{jk}, d_{jk}, p_{jk}, and s_{jk} can hold the inequality $r_{jk} \leq s_{jk}$, and thus, we have $s_{jk} + p_{jk} \leq d_{jk}$. To simplify the calculation, the above time indices are approximated to integers.

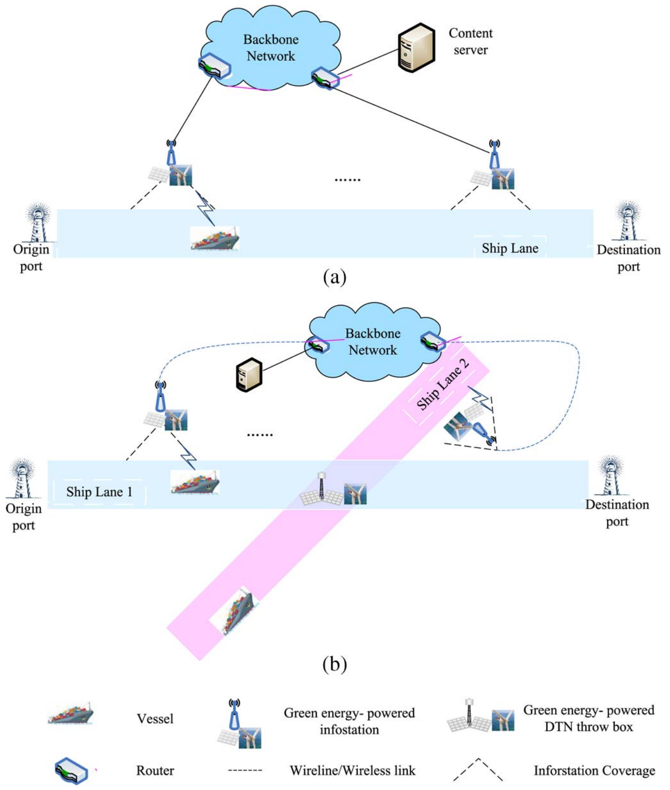

Fig. 1. System model.

B. Sustainable Energy Model

We suppose that the infostations and DTN nodes are powered by sustainable energy. For each infostation and DTN node, a battery is installed to store harvested energy for traffic transmission and energy backup. Harvested energy would be charged in the energy buffer, meanwhile, discharged by proceeding video packets. With the general energy charging and discharging processes, we try to model the energy buffer as a $G/G/1$ queue. The energy charging, the arrival, and the service time interval are independent and identically distributed with the mean and variance of the intercharging interval, which are noted as μ_a and υ_a; and the mean and variance of the energy interdischarge interval are expressed as μ_l and υ_l, respectively. In this paper, we consider the data packets scheduling under the situation that the harvested energy may not be enough to support the transmission traffic.

IV. PROBLEM FORMULATION

We jointly consider network throughput and the energy depletion probability as the metric of the formulated problem. In this paper, vessels may transmit packets with different weights, and packets can be transmitted by vessels to infostations or be sent and stored at the DTN throw box for other vessels to help in the transmission. We design energy content-aware video packets delivery schemes toward the maximum weights of accomplished data. To this end, we formally formulate the EVTMP, assuring energy sustainability of the network.

A. Energy and Content-Aware Time-Step-Based Formulation

Our goal is to maximize the total weights of whole delivered packets, with minimizing the probability of infostation and DTN throw box depleting their energy when they serve or store traffic demands. The following formulation is partially based on these criteria.

Variable $x_{jks_{jk}}$ decides whether packet j is transmitted through vessel k at the time interval $[s_{jk}, s_{jk}+p_{jk}]$ as follows:

$$x_{jks_{jk}}=\begin{cases} 1, & \text{if packet } j \text{ is performed on vessel } k \text{ at time} \\ & \text{interval } [s_{jk}, s_{jk}+p_{jk}] \\ 0, & \text{otherwise.} \end{cases}$$

Energy and content-aware time-step-based formulation is shown as

$$\max \quad \sum_{j=1}^{n} \sum_{s_{jk}=r_{jk}}^{d_{jk}-p_{jk}} w_{jk} \cdot x_{jks_{jk}} \tag{1}$$

$$\text{s.t.} \quad \sum_{j=1}^{n} \sum_{s_{jk}=u-p_{jk}+1}^{u} x_{jks_{jk}} \le 1, \qquad k \in \{1,2\}, \forall u \tag{2}$$

$$\sum_{s_{jk}=r_{jk}}^{d_{jk}-p_{jk}} x_{jks_{jk}} \le 1, \qquad k \in \{1,2\}, \forall j \tag{3}$$

$$x_{jks_{jk}} \in \{0,1\} \tag{4}$$

$$\mathcal{P}(0;x_0) < \varepsilon, \qquad k \in \{1,2\}, \forall j. \tag{5}$$

This formulation is a 0–1 integer nonlinear programming problem, which is known as $\mathcal{NP}$-hard. It involves four indices, namely, packet, vessel, time step, and energy constraint, i.e., depletion probability. The time steps coincide with the aforementioned packets. The first constraint avoids multiple packets simultaneously scheduled on one vessel; the second constraint means that one packet can be scheduled only once; the third constraint shows that $x_{jks_{jk}}$ can be chosen as 0 or 1; the fourth constraint depicts the energy sustainability guarantee. $\mathcal{P}(0;x_0)$ is the energy depletion probability of the infostations and DTN throw box with the initial energy x_0, which denotes how likely the infostations and DTN will deplete energy and become temporarily unavailable. In Section V, the expression of $\mathcal{P}(0;x_0)$ will be exploited by the queueing theory. Finally, $\varepsilon \ll 1$ is the threshold to ensure that the energy depletion probability should fulfill the requirement.

B. Complexity of EVTMP

We show that the EVTMP is $\mathcal{NP}$-complete even if it is an offline problem. First, we do not consider energy constraint to simplify the problem. The EVTMP is transformed into a decision problem by exploiting a threshold value. The EVTMP-DECISION is defined as whether there exists $\{w_{jk}, x_{jks_{jk}}\}$ with

$$\begin{cases} \max \sum_{j=1}^{n} \sum_{s_{jk}=r_{jk}}^{d_{jk}-p_{jk}} w_{jk} \cdot x_{jks_{jk}} \ge \overline{x} & \text{(6a)} \\ \sum_{j=1}^{n} \sum_{s_{jk}=u-p_{jk}+1}^{u} x_{jks_{jk}} \le 1, \quad k \in \{1,2\}, \forall u & \text{(6b)} \\ \sum_{s_{jk}=r_{jk}}^{d_{jk}-p_{jk}} x_{jks_{jk}} \le 1, \quad k \in \{1,2\}, \forall j & \text{(6c)} \\ x_{jks_{jk}} \in \{0,1\}. & \text{(6d)} \end{cases}$$

The EVTMP-DECISION can be verified in polynomial time, with coefficients satisfying $\max \sum_{j=1}^{n} \sum_{s_{jk}=r_{jk}}^{d_{jk}-p_{jk}} w_{jk} \cdot x_{jks_{jk}} \ge \bar{x}$, and for different $x_{jks_{jk}}$ with a total value not more than 1. Hence, the EVTMP is $\mathcal{NP}$.

Then, the EVTMP can be easily transformed into the Knapsack problem. Therefore, the EVTMP-DECISION can be reduced from a known $\mathcal{NP}$-complete problem in polynomial time, resulting in the EVTMP $\mathcal{NP}$-hardness. Since the EVMTP without considering energy constraint belongs to $\mathcal{NP}$ and is $\mathcal{NP}$-hard, we can conclude that the EVMTP considering energy restraint is $\mathcal{NP}$-complete [20].

V. ENERGY AND CONTENT-AWARE VIDEO TRANSMISSION FRAMEWORK

The optimization framework aims at completing delivery of video packets before their playback deadlines to maximize the total weights of delivered data packets, subject to the energy constraint. The framework jointly considers energy limitation, transient energy level, energy charging capability, and the depletion probability of infostations and the DTN throw box to fulfill the traffic demands. The video transmission scheduling policy with regard to binary variable $x_{jks_{jk}}$ should concern the video packet characteristics (i.e., release time, playback deadlines, and weights), available opportunities to connect infostations, and the battery energy limitation of infostations and DTN throw box. Since the formulated problem is $\mathcal{NP}$-complete, there is no efficient polynomial time solution. Therefore, we try to design efficient heuristic algorithms to address the formulated problem.

Here, tracking the dynamics of the charging capability and video uploading requirements, we present energy and content aware scheduling scheme to maximize the weights of delivered packets with the energy sustainability constraint. As such, we propose two algorithms to address the single- and two-vessel cooperative transmissions, i.e., an energy buffer-based decentralized online algorithm for single vessel and an energy buffer-based combinatorial decentralized-backward centralized algorithm for two vessels.

A. Leaky Bucket Energy Buffer-Based Decentralized Online Algorithm for Single Vessel

Here, a decentralized algorithm is designed to solve the EVTMP. Time slots can be allocated by infostations to upload data, but no reservation can be made in advance. Video packets are randomly generated, and a request message would be sent to the infostation within the communication range when a video packet is created. The infostation determines how to allocate time slots to transmit the packet according to its information, the initial energy level, and the energy charging capability of infostation. After that, the infostation acknowledges or rejects the uploading request in the form of token distribution.

Queueing Model of Energy Buffer for Infostations: We can obtain the charging and discharging process model of green energy shown in [21]. Let $A(t)$ and $L(t)$ denote the cumulative number of charging and discharging energy unit at time t, respectively. The initial energy level of infostation is $Q(0) = x_0$. Harvested energy from natural resource is stored in the energy buffer; meanwhile, it is discharged for video packets transmission. The residual energy in queue at time t is

$$Q(t) = A(t) - L(t). \tag{7}$$

Then, we investigate the energy depletion duration D of infostations, i.e., the duration from the start until the moment when AP depletes energy, which can be used to derive the probability that the infostations will use up energy when task is uploaded. We model the energy buffer as a $G/G/1$ queue, where energy charging and discharging are modeled as random processes. Since the processes of charging and discharging are dynamic, the infostation or the DTN throw box may deplete its energy when $Q(t) = 0$.

Resorting to the diffusion approximation [22], [23], we approximate the discrete buffer size $R(t)$ as a continuous process $X(t)$, and thus, the Wiener–Levy process (or Brownian motion) model is used [24] as

$$dX(t) = X(t+dt) - X(t) = \beta dt + Z\sqrt{\alpha}dt \tag{8}$$

where $Z \sim N(0,1)$ is a white Gaussian process with zero mean and unit variance. α and β denote drift and diffusion coefficients, which can be expressed as

$$\begin{cases} \beta = E\left(\lim\limits_{\Delta t \to 0} \frac{X(t)}{\Delta t}\right) = 1/\mu_a - 1/\mu_l \\ \alpha = \mathrm{Var}\left(\lim\limits_{\Delta t \to 0} \frac{X(t)}{\Delta t}\right) = v_a/\mu_a^3 + v_l/\mu_l^3 \end{cases}. \tag{9}$$

With the initial energy level x_0, the conditional probability density function (pdf) of the energy buffer size $X(t)$ at time t is

$$p(x,t;x_0) = \Pr\left(x \le X(t) \le x + dx | X(0) = x_0\right). \tag{10}$$

By using the Kolmogorov diffusion equation [24], we can obtain

$$\frac{\partial p(x,t;x_0)}{\partial t} = \frac{\alpha}{2}\frac{\partial^2 p(x,t;x_0)}{\partial x^2} - \beta\frac{\partial p(x,t;x_0)}{\partial x}. \tag{11}$$

As the queue length cannot be negative, we can derive the queue length as

$$p(x,0;x_0) = \delta(x - x_0), \qquad t = 0 \tag{12}$$

$$p(0,t;x_0) = 0, \qquad t > 0 \tag{13}$$

where $\delta(x)$ is the Dirac delta function. By applying the method of images [25], [26], the pdf of the energy buffer size could be expressed as

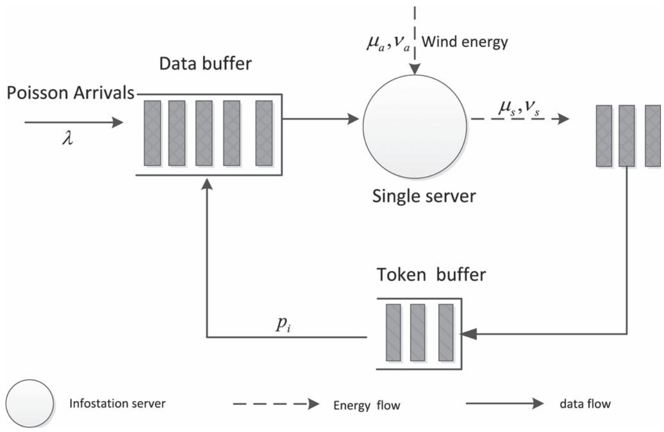

Fig. 2. Leaky bucket energy buffer diagram.

$$\begin{aligned} p(x,t;x_0) = \frac{\partial}{\partial x}\Bigg\{ & \Phi\left(\frac{x - x_0 - \beta t}{\sqrt{\alpha t}}\right) \\ & - \exp\left(\frac{2\beta x}{\alpha}\right)\Phi\left(-\frac{x + x_0 + \beta t}{\sqrt{\alpha t}}\right)\Bigg\} \end{aligned} \tag{14}$$

where $\Phi(x)$ is the standard normal integral, which can be formulated as

$$\Phi(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} \exp\left(-\frac{1}{2}y^2\right)dy. \tag{15}$$

Given $D(x_0) = \min\{t \ge 0 | X(0) = x_0, X(t) = 0\}$ as the energy buffer depletion duration and the initial energy level x_0, we can obtain the maximum energy duration for the service traffic. Then, we can apply the diffusion equation to capture the pdf of D. The detailed derivation of the pdf of D, i.e., $p_D(x,t;x_0)$ and $\mathcal{P}(0;x_0)$, is given in Appendix I.

Leaky Bucket Energy Buffer-Based Decentralized Online Algorithm for Single Vessel: Algorithm 1 shows a leaky bucket energy buffer-based decentralized online algorithm for a single vessel. Tokens are generated for each interval period within a token buffer. Each video packet is transmitted with a token until the buffer is empty. Fig. 2 shows a diagram of leaky bucket energy buffer. We assume that the process of video packet generating and requesting can be modeled as a Poisson distribution with λt, where λ is the average number of video packet arrivals in infostations per unit time. If a video packet arrives at time t, the next video packet should arrive at time $t + \tau$, where τ is a random variable having an exponential distribution with parameter λ [27].

In Algorithm 1, with the concept of video packet instance [28], we have multiple choices of packet scheduling between release time and deadline. In this decentralized algorithm, the time slot reservation is allowed. However, the reservation cannot be guaranteed until the packet starts to be transmitted. Although the packet is in process, it is also effected by rescheduling or abolishment with the arrival of new packets. At first, we calculate the longest survival time T for the infostation, which is the depletion duration from its initial energy level x_0 to the moment that the infostation used up its energy, i.e.,

$$F_D(T;x_0)=\int_0^T p_D(x,t;x_0)dt<\varepsilon \tag{16}$$

$$\int_0^T \left\{-\frac{(x_0+\beta t)^2}{2\alpha t}+\frac{1}{2}\left[\frac{(x_0+\beta t)^2}{2\alpha t}\right]^2\right\} \cdot \frac{x_0}{\sqrt{2\pi\alpha t^3}}dt \tag{17}$$

$$=\int_0^T \frac{x_0(x_0+\beta t)^4}{8\alpha^4 t^{7/2}\sqrt{2\pi\alpha}}-\frac{x_0(x_0+\beta t)^2}{2\alpha t^{5/2}\sqrt{2\pi\alpha}}dt \tag{18}$$

$$=\left.\frac{\beta^4 t^{3/2}x_0}{30\alpha^{5/2}}+\frac{2t^{1/2}\beta^3x_0^2}{5\alpha^{5/2}}-\frac{2t^{1/2}\beta^2x_0}{5\alpha^{3/2}}\right|_0^T\le\varepsilon. \tag{19}$$

Since $p_D(x,t;x_0)$ is nonholonomic, the integral expression in (16) cannot be directly obtained. Based on the first order of Taylor series expansion, we can approximate the expression of T in (19), where T indicates the energy deplete duration. Based on the solution of univariate cubic equation [29], we can further obtain the solution of T. If we have the univariate cubic equation

$$ax^3+bx^2+cx+d=0, \qquad a\neq 0 \tag{20}$$

with the solution of real number

$$x=-\frac{b}{3a}+\sqrt[3]{A+\sqrt{A^2+B^3}}+\sqrt[3]{A-\sqrt{A^2+B^3}} \tag{21}$$

where $A=bc/6a^2-b^3/27a^3-d/2a$, and $B=c/3a-b^2/9a^2$.

When the vessel sails in the coverage of the infostation, the vessel would send a request for data transmission. Once the infostation receives the request, it would list all the packet instances that have not been transmitted. By considering occupied time intervals and depletion probability for each packet instance, this algorithm has the superiority for the following cases.

Case (a): When an infostation receives a new request J_j, we schedule the packet in descending order of (w_i/p_i) until occupied $\geq t'$.

Case (b): In case that packet transmission is in progress, the packet J_j will be scheduled along with the packets already scheduled, if the summation of the current moment t and the processing time p_j is no more than T.

Case (c): If the summation of current time t and the processing time p_j is more than T, the packets that have been already scheduled will be preempted by packet J_j. The metric of preemption is $w_j>\sum w_r\cdot(1+(l_j/p_r))$, i.e., the packet with greater weight preempts existing scheduled packets. Otherwise, it will be appended to the list of I.

The number of tokens available in the token buffer is i, and the token distribution rate is p_i. In other words, the processing time of each packet determines token distribution rate. When a packet is processed, a token will be allocated for the next packet in the data buffer according to Algorithm 1. We truncate the intervals of token distribution, so that the packets that have received tokens will be aligned in the data buffer. This algorithm guarantees no congestion in the single infostation.

Algorithm 1: *Energy buffer based decentralized online algorithm for single vessel*

```
$I \leftarrow \emptyset$;
$occupied \leftarrow 0$;
for a new packet $J_i$ arrives at time $t$ do
    if $occupied + p_j < T$ then
        if $t > occupied$ then
            schedule $J_i$ at $t$;
            $occupied \leftarrow t + p_i$;
        else
            there exist some scheduled packets $J_r$ overlapped with $J_i$ during $l_r$
            if $w_i > \sum_r \left(1+\frac{l_r}{p_r}\right) w_r$ then
                replace packets $J_r$ with $J_i$ at $t$;
                $I \leftarrow I \cup \{J_r\}$;
                $occupied \leftarrow t + p_i$;
                repeat
                    reschedule $J_j \in I$ with highest $\frac{w_j}{p_j}$ at $occupied$;
                    $I \leftarrow I \backslash \{J_j\}$;
                    $occupied \leftarrow occupied + p_j$;
                until no packets can be rescheduled;
            else
                schedule $J_i$ at $occupied$;
                $occupied \leftarrow occupied + p_i$;
            end if
        end if
    end if
end for
```

B. Energy Buffer-Based Combinatorial Decentralized-Backward Centralized Algorithm for Two Vessels

Cooperative relaying transmission can further improve the total weight of delivered packets by creating more opportunities for wireless access. As route path of each ship is relatively stable, the global information in terms of the infostations deployment, the period of vessels passing the infostations, and the schedule of vessels are known *a priori*. Video packets are randomly generated, and the vessels send request messages to the server. After that, the time slots are allocated based on the information of the packets. The packets, which should be store-carry-and-forward by another vessel via the infostations en route, are selected by the infostation server. To inform which packets should be stored in DTN throw box and wait for another vessel to fetch, the server sends the acknowledgement or rejection messages to the vessel. Therefore, in this case, two vessels are scheduled by a centralized server, which also schedules the green-energy-powered infostations and the DTN nodes.

1) Emergency Information Delivery Scenario: For the two-vessel scenario, one of the most important issues is how to allocate the uploading traffic between the two vessels to maximize the total weight of delivered video packets, while the energy constraint of infostations and the DTN throw box can be met. For emergent packets, vessel 1 may stop current data transmission and help to transmit the video packets with urgent information immediately. After that, vessel 2 may help to relay the packet with urgent information and send these packets to the destination before the deadline, while the energy constraint of the DTN throw box should be fulfilled. We separate the scenario into the following cases according to the existing energy level of DTN node and infostations.

1) If there is sufficient energy in the DTN throw box, vessel 1 will help to transmit all the available video packets.
2) If the energy is not sufficient to serve all packets, the server will forward the packets to the DTN node.
3) When vessel 2 comes across the DTN node, it decides whether to help relay the packets or not according to its stock.
4) When any infostation finishes uploading the packets that it receives from vessel 1, then vessel 1 will be informed via interinfostation communication.

In the two-vessel scenario, vessel 1 is responsible for emergency information delivery (like warship), whereas vessel 2 acts as the relay node. Before vessel 2 comes across the DTN throw box, it does not carry any data. The store-carry-and-forward mechanism of DTN node should consider the initial energy level and discharging and charging capacity. T is used to determine whether a packet can be stored in DTN node or not, which is the processing time of all potential packets, i.e.,

$$F_D(T;x_0)=\int_0^{T} p_D(t;x_0)dt<\varepsilon. \tag{22}$$

2) Maximum Carry Delay C: The centralized algorithm determines which vessel should carry the packets under the energy constraint of the DTN node. We assume that the DTN node depletes its energy after receiving the packets from vessel 1. The discharging process of the energy buffer is not considered here, i.e., $\mu_l=v_l=0$, whereas the initial energy and charging parameters of the energy buffer are $x_o=0$, μ_a, and v_a. In this scenario, $\beta_C=1/\mu_a$, and $\alpha_C=v_a/\mu_a^3$. The minimal energy requirement of the DTN node is denoted by b. The maximal delay before passing the packet over to vessel is expressed as

$$C=\min\{t>0|X(0)=0,X(t)=b\}. \tag{23}$$

The detailed derivation of the pdf of C, i.e., $p_C(x,t;x_0)$, is given in Appendix II. Let T_2 denote the duration from the time the DTN node receives vessel 1's packets to the time that vessel 2 comes across the DTN node. Then, the DTN node calculates the probability that its energy reaches b before T_2, i.e.,

$$F_C(T_2;0)=\Pr(C\le T_2)=\int_0^{T_2} p_C(x,t;0)dt \tag{24}$$

$$\int_0^{T_2}\left\{-\frac{(b-\beta t)^2}{2\alpha t}+\frac{1}{2}\left[\frac{(b-\beta t)^2}{2\alpha t}\right]^2\right\}\cdot\frac{b}{\sqrt{2\pi\alpha t^3}}dt \tag{25}$$

$$=\int_0^{T_2}\frac{b(b-\beta t)^4}{8\alpha^4 t^{7/2}\sqrt{2\pi\alpha}}-\frac{b(b-\beta t)^2}{2\alpha t^{5/2}\sqrt{2\pi\alpha}}dt \tag{26}$$

$$=\left.\frac{\beta^4 t^{3/2}b}{30\alpha^{5/2}}-\frac{2t^{1/2}\beta^3 b^2}{5\alpha^{5/2}}-\frac{2t^{1/2}\beta^2 b}{5\alpha^{3/2}}\right|_0^{T_2}\le\varepsilon. \tag{27}$$

We can obtain T_2 by applying the truncating expansion equation of the Taylor series in (24) and the solution of univariate cubic equation in (27).

3) Energy Buffer-Based Combinatorial Decentralized-Backward Centralized Algorithm: We propose a combinatorial decentralized-backward centralized algorithm, taking into consideration energy constraint. Before vessel 1 and vessel 2 arrive at the coverage of the DTN throw box, the algorithm is distributed. Furthermore, when both vessels locate within the transmission range of the DTN throw box, the DTN node will schedule the transmissions of the two vessels to exchange information. The distributed algorithm is similar to Algorithm 1. We omit the redundant description and focus on the traffic affiliated with the DTN throw box.

$J=\{j_i\}$, $i\in[1,n]$, is the set of video packets that cannot be scheduled by vessel 1; J_1 is the set of video packets transmitted to the DTN node originated from vessel 1, which is selected by Algorithm 2. As the ships' routes and the ships' speeds are all relatively stable, they could be known *a priori*. Let x_0 denote the DTN initial energy when vessel 1 transmits data to it; x_0' is the residual energy in the DTN node. x_0' can guarantee that the DTN node has sufficient energy to make a transmission to vessel 2 if the length of stay in the DTN node for vessel 2 is very short. x_0'' indicates the energy level when vessel 2 contacts the DTN node; T_1 represents the total length of video packets, which is going to be transmitted to the DTN node; T_2 denotes the duration from the time that vessel 1 transmits the packets to DTN node until the time that vessel 2 receives the packets from the DTN node; T_3 is the time period for vessel 2 to receive the video packets, which are transmitted from the DTN node. In order to achieve the optimal residual threshold for the maximal energy utility based on the energy model, the following weight-driven DTN energy buffer management analytical framework is used.

Step 1: Given the DTN initial energy x_0 and the residual energy x_0', we can obtain T_1 as

$$F_D(T_1;x_0)=\int_0^{T_1} p_D(x,t;x_0-x_0')dt<\varepsilon. \tag{28}$$

Step 2: If a packet's uploading time is larger than T_1, i.e., $T_J>T_1$, we use (w_i/p_i) to sort the priority of packets that should be stored in the DTN node. Otherwise, if a packet's uploading time is smaller than T_1, i.e., $T_J<T_1$, it indicates that the energy is sufficient, which means that all the packets can be stored in the DTN node.

Step 3: When the DTN node is transmitting the data to vessel 2 within T_2, the energy charging process works as

$$F_C(T_2;0) = \Pr(C \le T_2) = \int_0^{T_2} p_C(x,t;0)dt. \tag{29}$$

By using transformation $b \leftarrow x_0'' - x_0'$, we can know whether the energy is sufficient to finish the transmission. If vessel 2 carries the packets, then we can calculate whether the packets can be successfully transmitted according to the energy constraint

$$F_D(T_3;x_0) = \int_0^{T_3} p_D(x,t;x_0'')dt < \varepsilon. \tag{30}$$

If $T_3 > T_1$, the packets stored in the DTN node should be passed over to vessel 2, which is the optimal solution to avoid energy waste. We can get $x_0'' \ge x_0 - x_0'$.

Based on $b \leftarrow x_0'' - x_0'$ and $x_0'' = x_0$, we can obtain the value of x_0' as

$$F_C(T_2;0) = \Pr(C \le T_2) = \int_0^{T_2} p_C(x,t;0)dt < \varepsilon. \tag{31}$$

Algorithm 2: *Energy buffer based combinatorial decentralized-backward centralized algorithm for two vessels*

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Two vessels decentralized algorithm is the same with Algorithm 1;
Backward Centralized algorithm
Input: $x_0 = x_0^{''} = constant$; $T_2$; $J$ is the set of total unscheduled packets in vessel 1, and $T_J$ is total processing time of all the packets relatively; $J_1$ is packets set to store in DTN node
Output: $x_0^{'}$, $J_1$
$J_1 \leftarrow \emptyset$;
$occupied \leftarrow t$;
Calculate $x_0^{'}$ according to Eq.27, Eq. 28 and Eq. 29; Calculate $T_1$ according to Eq. 35, Eq. 19 and Eq. 28;
for moment t vessel 1 store data into DTN node do
    while $J \neq \emptyset$ do
        Schedule $J_i \in J$ which has the highest $\frac{w_i}{p_i}$;
        if $occupied + p_i \le T_1$ &$occupied + p_i \le e_i$ then
            $occupied \leftarrow occupied + p_i$;
            $J \leftarrow J \backslash \{J_i\} \backslash \{J_{e_i} < occupied + p_i\}$;
            $J_1 \leftarrow J_1 \cup \{J_i\}$;
            $i \leftarrow i + 1$;
        else
            $J \leftarrow J \backslash \{J_i\} \backslash \{J_{e_i} < occupied + p_i\}$
        end if
    end while
end for
```

In Algorithm 2, vessel 2 helps vessel 1 to transmit unscheduled packets, which are stored in the DTN node by vessel 1 in advance. At moment t, vessel 1 decides which packets should be stored into the DTN node according to Algorithm 2. For each packet sent to the DTN node, a token is allocated. The number of tokens in the token buffer is i, and the token allocation rate can be derived by the processing time of video packet p_i.

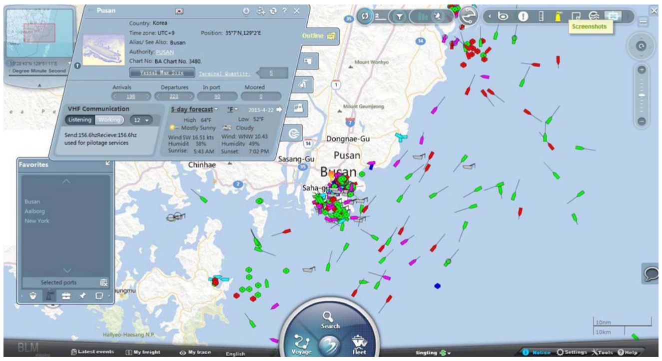

Fig. 3. Navigation routes for vessels in Busan Harbor of Korea.

4) Normal Information Delivery Scenario: Then, we consider the video packet delivery with normal information, where the videos from vessel 1 have normal weights, except the emergent information, and vessel 2 also has video packets for transmission. In this scenario, the maximal information from vessel 1 stored in the DTN node is J_1, since the video packets J_2 in vessel 2 do not impact on the energy level of the DTN node. However, the packets J_2 in vessel 2 and the new packets J_3 may conflict with the original packet from vessel 1 due to the overlapping processing time. After vessel 2 receives the video packets J_1 from the DTN throw box, the scheduling strategy will be the same with Algorithm 1. The total video packets can be expressed as $J \leftarrow J_1 \cup J_2 \cup J_3$. If the weights of packets J_2 are obviously higher than J_1, another vessel, i.e., vessel 3, will replace vessel 2 to carry those packets from the DTN node, which is beyond the scope of this work.

C. Time Complexity Analysis

Here, we analyze the performance of the proposed two algorithms in terms of time complexity.

For Algorithm 1, the time complexity is determined by the worst case of packets overlapping and preemption. Thus, we consider the worst case that all the packets N are overlapping with packet 1. In this situation, the time complexity is calculated as follows: $1 + 2 + \cdots + (N+1) = N(N+1)/2$. Therefore, Algorithm 1 runs in $\mathcal{O}(N^2)$ time, where N means the maximum number of overlapping packets.

For Algorithm 2, we allocate the scheduling of $J_i \in J$ that has the highest (w_i/p_i). It takes $\mathcal{O}(\log N)$ time to run the binary search method, where N is the number of packets stored in DTN node.

VI. PERFORMANCE EVALUATION

We use a video packets delivery scheduling system to evaluate the performance of our scheduling algorithms based on the real vessel traces in the Busan Harbor surrounded by waterbodies around Korea, as shown in Fig. 3. For each of vessel 1 and vessel 2, ten infostations are randomly distributed along their

TABLE II
SIMULATION PARAMETERS

Name	Value	Name	Value
Packet size	100 bytes	System bandwidth	10 MHz
Data rate	50 Mbps	Frame duration T_F	5 ms
Network region	100×100 km^2		

routes. Based on the BLM-Ship navigation software [30], we use the synthetic vessel trace method to estimate the trace, i.e., vessels sail in a straight line between the two adjacent position points, and the method of curve fitting to estimate the real-time location information of vessels. The locations of vessel 1 and vessel 2 are denoted by (φ_1, θ_1) and (φ_2, θ_2), respectively, where φ and θ are the latitude and longitude of vessels. The great circle distance S in navigation science can be obtained as

$$\cos S = \sin\varphi_1 \cdot \sin\varphi_2 + \cos\varphi_1 \cdot \cos\varphi_2 \cdot \cos D\lambda \quad (32)$$

$$D\lambda = \theta_2 - \theta_1. \quad (33)$$

We can use $S = \arccos(\cos S)$ to obtain the great circle distance [31] and project the possible complete route.

We set the mean and variance of the energy charging interval as $\mu_a = 2.75$ and $\upsilon_a = 1.09$. The mean and variance of the energy interdischarging interval are $\mu_l = 4.35$ and $\upsilon_l = 11.1$. The simulation configuration is shown in Table II. We compare our proposed algorithms with three classic scheduling algorithms, i.e., weight (packet with the heaviest weight is scheduled first), deadline (packet with the earliest deadline is scheduled first), and first input first output (FIFO) (packet with the earliest release time is scheduled first), in terms of normalized throughput, which is defined as the ratio of the throughput of delivered packets to the throughput of total packets. We modify the above three classic algorithms by considering the survival time T and the initial energy and energy consumption of infostations and DTN throw box.

Fig. 4 investigates the impact of packet deadline on normalized throughput for single-vessel scenario. We can observe that our proposed algorithm can significantly outperform the other algorithms. This is because our algorithms first serve the packets with the maximum ratio of weight to processing time, i.e., packets that are more important to the video quality and need less processing time than other packets. For the other three algorithms, weight algorithm outperforms deadline and FIFO algorithms. This is because the normalized throughput is closely related to the weight of packets and the weight algorithm schedules the packets with the heaviest weight first. For deadline and FIFO algorithms, they only consider deadline and release time instead of weight, which leads to lower performance than the weight algorithm.

Figs. 5 and 6 show the impact of energy parameters on the normalized throughput for the single- and two-vessel scenarios, respectively. We can observe that our algorithms outperform the other three algorithms. In Figs. 5(a) and 6(a), the normalized throughput decreases along with the increase in μ_a for both the single- and two-vessel scenarios. This is because energy may be insufficient for data transmission due to larger intercharging interval, and the throughput of delivered packets is decreased accordingly. In Figs. 5(b) and 6(b), the normalized throughput increases with the growth of the mean of interdischarging interval μ_l for both the single- and two-vessel scenarios. It can be found that the energy consumption decreases with larger interdischarging interval, which means that infostations are less likely to deplete its energy and thus can achieve higher normalized throughput.

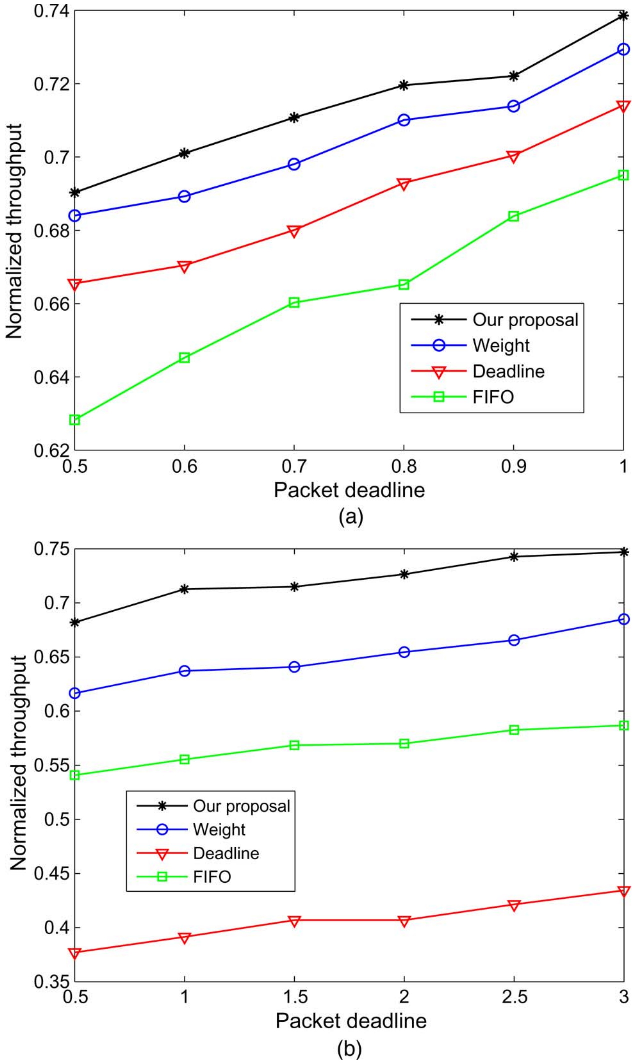

Fig. 4. Normalized throughput versus packet deadline. (a) Single-vessel scenario. (b) Two-vessel scenario.

In summary, our proposed algorithms for single vessel and two vessels significantly outperform the three existing algorithms, because our algorithms consider both weight and processing time of the packets. The weight algorithm has better performance than the FIFO and deadline algorithms, as weight has larger impact on the normalized throughput than deadline and release time.

VII. CONCLUSION

In this paper, we have investigated the network throughput and energy sustainability in the green-energy-powered maritime wireless network. We have modeled the green energy buffer as a $G/G/1$ queue. Based on the buffer model, we have formulated the EVTMP and proved that the formulated problem is $\mathcal{NP}$-complete. After that, two algorithms for both network scenarios of single vessel and two vessels have been

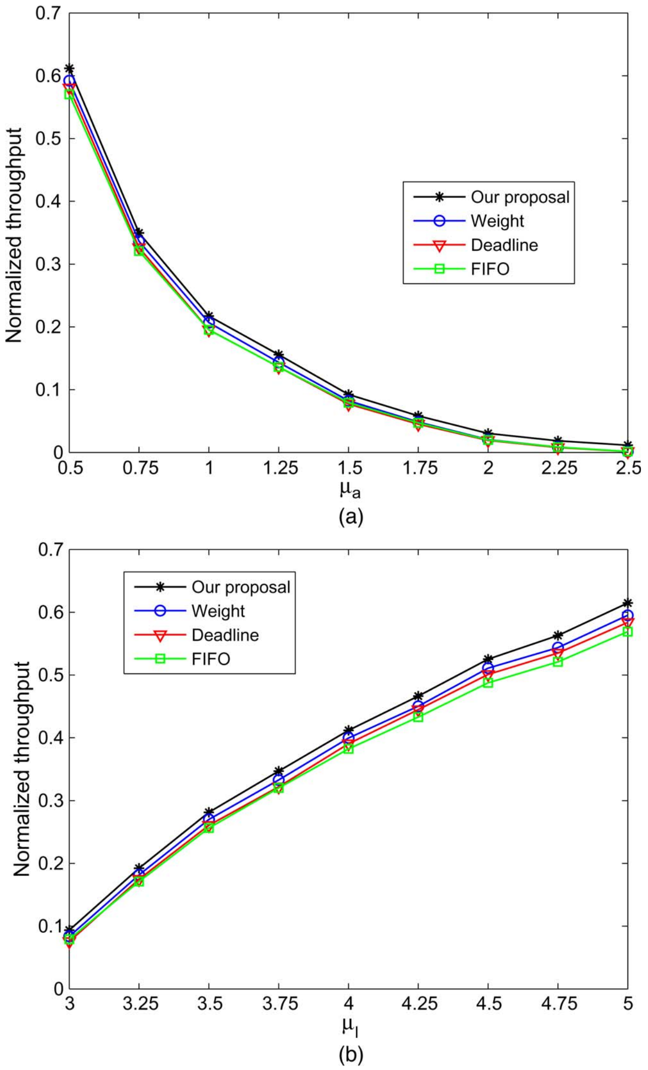

Fig. 5. Normalized throughput of different algorithms for single-vessel scenario. (a) Various mean of energy intercharging interval of infostation. (b) Various mean of energy interdischarging interval of infostation.

proposed to maximize the network throughput subject to the energy sustainability constraint. Our extensive simulation results show that our simple yet efficient algorithms can achieve high network throughput and energy sustainability. In our future work, we will study multivessel scheduling issues with various mobility patterns in green-energy-powered maritime wireless communications networks. Under the multivessel scenario, we need to jointly consider the scheduling scheme design and energy sustainability of each BS. Moreover, the routing paths design should be included to optimize both the energy sustainability and the network throughput.

APPENDIX I
DERIVATION OF THE PDF OF D

By using the Kolmogorov diffusion equation [24], the pdf of D could be obtained that

$$\frac{\partial p_D(x,t;x_0)}{\partial t} = \frac{\alpha}{2}\frac{\partial^2 p_D(x,t;x_0)}{\partial t^2} - \beta\frac{\partial p_D(x,t;x_0)}{\partial t}. \quad (34)$$

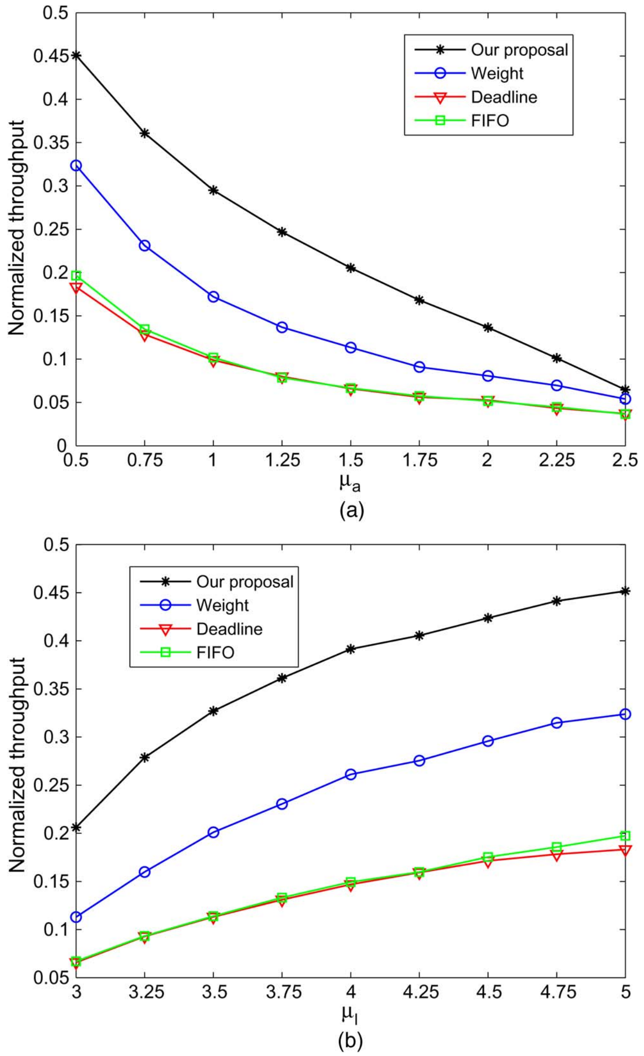

Fig. 6. Normalized throughput of different algorithms for two-vessel scenario. (a) Various mean of energy intercharging interval of infostation. (b) Various mean of energy interdischarging interval of infostation.

The conditional pdf of the energy buffer depletion duration is

$$p_D(x,t;x_0) = \frac{x_0}{\sqrt{2\pi\alpha_D t^3}}\exp\left\{-\frac{(x_0+\beta_D t)^2}{2\alpha_D t}\right\}. \quad (35)$$

With Laplace transform, the moment generation function of D can be expressed as

$$M_D(s) = \exp\left\{-\frac{x_0\left(\beta_D+\sqrt{\beta_D^2+2\alpha_D s}\right)}{\alpha_D}\right\}. \quad (36)$$

Then, we can obtain the mean and variance of the energy buffer depletion duration D, i.e.,

$$E(D) = -\frac{d}{ds}M_D(s)|_{s=0} = -\frac{x_0}{\beta_D}e^{-\frac{2\beta_D x_0}{\alpha_D}} \quad (37)$$

$$\begin{aligned}\mathrm{Var}(D) &= -\frac{d^2}{ds^2}M_D(s)|_{s=0} - E^2(D)\\ &= e^{\frac{-2\beta_D x_0}{\alpha_D}}\left[2x_0\beta_D^{-3} - x_0^2\beta_D^{-2}\left(1+e^{\frac{-2\beta_D x_0}{\alpha_D}}\right)\right].\end{aligned} \quad (38)$$

$\mathcal{P}(0;x_0)$ indicates the energy buffer depletion probability from x_0, which can be expressed as

$$\mathcal{P}(0;x_0) = \lim_{D\to 0}\int_0^D p_D(x,t;x_0)dt = \lim_{s\to 0} M_D(s) \tag{39}$$

$$\mathcal{P}(0;x_0) = \left\{\begin{array}{ll} 1, & \text{for } \beta_D < 0 \\ \exp\left\{-\frac{2x_0\beta_D}{\alpha_D}\right\}, & \text{for } \beta_D > 0 \end{array}\right\}. \tag{40}$$

We can observe from (40) that the energy buffer depletes with probability 1 when the energy charge rate is lower than or equal to the energy discharge rate $1/\mu_a \leq 1/\mu_l$. For the case that $1/\mu_a > 1/\mu_l$, the energy buffer depletion probability depends on the initial energy level x_0 and the mean and variance of energy charging and discharging rates, etc.

Denote the processing time of a packet j on vessel k as p_{jk}, which means that the uploading of the video packet lasts for p_{jk} time slots. $D(x_0)$ indicates the energy buffer depletion duration with the initial energy x_0. The infostation calculates the energy depletion probability before p_{jk} terminates, i.e.,

$$F_D(T;x_0) = \Pr(D \leq T) = \int_0^T p_D(x,t;x_0)dt. \tag{41}$$

APPENDIX II
DERIVATION OF THE PDF OF C

By applying diffusion approximation, we can obtain the pdf of C as

$$\frac{\partial p_C(x,t;0)}{\partial t} = \frac{\alpha}{2}\frac{\partial^2 p_C(x,t;0)}{\partial t^2} - \beta\frac{\partial p_C(x,t;0)}{\partial t}. \tag{42}$$

Then, we derive that the length of the queue cannot exceed b

$$p_C(x,0;0) = \delta(x), \qquad t = 0 \tag{43}$$

$$p_C(b,t;0) = 0, \qquad t > 0. \tag{44}$$

We obtain the pdf by applying the method of images [25], [26] as follows:

$$p_C(x,t;0) = \frac{b}{\sqrt{2\pi\alpha_C t^3}}\exp\left\{-\frac{(b-\beta_C t)^2}{2\alpha_C t}\right\}. \tag{45}$$

With the Laplace transform, the relative moment generating function can be expressed as

$$M_C(s) = \exp\left\{\frac{b}{\alpha_C}\left[\beta_C - \sqrt{\beta_C^2 + 2\alpha_C s}\right]\right\}. \tag{46}$$

The mean and variance of the maximum carry delay C are obtained as

$$E(C) = -\frac{d}{ds}M_C(s)|_{s=0} = \frac{b}{\beta_C} = b\mu_a \tag{47}$$

$$\mathrm{Var}(C) = -\frac{d^2}{ds^2}M_C(s)|_{s=0} - E^2(C) = bv_a. \tag{48}$$

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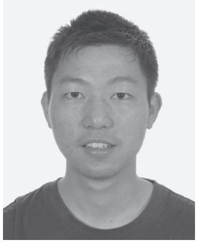

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