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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 (WiMAX) technology. To this end, we formulate it as an optimization problem to maximize 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 optimization problem (EVTMP) is proved to be \textit{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 (DTN) throw-boxes. The green energy buffer is modeled \(G/G/1\) 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.

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 (HF/MF) and very high frequency (VHF) radios, long/medium 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, Fleet Broadband (FBB), the transmission can achieve a high data rate of up to 432kbps, 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 wide-band maritime communication network by innovative communication technologies from the land to the sea.

Green energy refers to eco-friendly and sustainable energy sources, e.g. wind, solar, modern biomass, etc. Among a variety of green energy sources, wind power grows rapidly at the rate of 30% annually, which achieved 198GW all over the world in 2010. Solar power is another popular green energy source, and cumulative global photovoltaic (PV) installations surpassed 40GW 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, especially 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 constructed easily and less maintenance is required, which can significantly reduce the cost. However, unlike 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-
In green-energy-powered maritime wireless networks, we have to consider not only the energy sustainability of each BS, but also the distinctive challenges of maritime wireless networks, e.g., wireless coverage, various mobility patterns and high-speed mobility, which is 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, 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 are respectively 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, and prove that the formulated problem is $\mathcal{NP}$-complete. Then, the energy buffer of infostations and DTN throw box are 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, 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 works. System model is provided in Section III and the problem formulation is presented in Section V. Section VI validates our approaches by simulations. Section VII concludes the paper. We summarizes 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], [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 (AIS). 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 recent years. The authors of [12] identified that green-energy-powered access points (APs) provide a cost-effective solution for wireless local area networks (WLANs). 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 ensures that the energy and 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 sub-carrier allocation (RNP-SA) 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 quality of service (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 relevant maritime authority administrator could view and download it. The system model is shown in Fig. 1, where the single vessel and two-vessels scenario are shown in Fig. 1 (A) and Fig. 1 (B), respectively. Several OFDM-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
TABLE I. Notations and definitions.

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<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>$r_{jk}(d_{jk})(p_{jk})(s_{jk})$</td>
<td>The release time(deadline)(processing time)(starting time) of video packet $j$ on vessel $k$</td>
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<tr>
<td>$w_{jk}$</td>
<td>Weight of packet $j$ on vessel $k$</td>
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<tr>
<td>$x_{jk}s_{jk}$</td>
<td>Binary variable denote whether packet $j$ on vessel $k$ is implemented at the time interval $[s_{jk}, s_{jk} + p_{jk}]$</td>
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<td>$A(t)(L(t))$</td>
<td>The cumulative number of arriving and leaving energy</td>
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<td>$X(t)$</td>
<td>A continuous process to approximate buffer size $R(t)$</td>
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<tr>
<td>$\alpha(\nu_{ij})$</td>
<td>Diffusion and drift diffusion coefficient</td>
</tr>
<tr>
<td>$\mu_{a}$ (or $\mu_{s}$)</td>
<td>The mean (variance) of energy inter-charging interval</td>
</tr>
<tr>
<td>$\mu_{l}$ (or $\nu_{ij}$)</td>
<td>The mean (variance) of energy inter-discharge interval</td>
</tr>
<tr>
<td>$x_0$</td>
<td>The initial queue length (energy level)</td>
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<td>$p(x; t; x_0)$</td>
<td>The conditional probability density function of the energy buffer size $X(t)$ at time $t$</td>
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<tr>
<td>$p_{D}(x; t; x_0)$</td>
<td>The probability density function of the buffer depletion duration $D$</td>
</tr>
<tr>
<td>$P(0; x_0)$</td>
<td>The energy buffer depletion probability from $x_0$</td>
</tr>
<tr>
<td>$M_D(s)$</td>
<td>The moment generation function of $D$</td>
</tr>
<tr>
<td>$E(D)$ (or $Var(D)$)</td>
<td>The mean(variance) of energy buffer depletion duration $D$</td>
</tr>
<tr>
<td>$P(0; x_0)$</td>
<td>The energy buffer depletion probability from $x_0$</td>
</tr>
<tr>
<td>$F_D(T; x_0)$</td>
<td>The energy depletion probability before $p_{jk}$ terminates</td>
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A single vessel scenario and a two vessels scenario are illustrated in Fig. 1. System Model. The energy charging, the arrival and service time interval are independent and identically distributed (i.i.d) with the mean and variance of the inter-charging interval, noted as $\mu_a$ and $\nu_{ij}$, and the mean and variance of the energy inter-discharge interval are expressed as $\mu_l$ and $\nu_{ij}$, 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.

**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 $k$. 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. Also $u \in \{1, \cdots, t\}$ the starting time of another video packet is defined to avoid multiple video packets being scheduled simultaneously on one vessel. Obviously, $r_{jk} \leq d_{jk}$, $p_{jk}$ 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.

**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 service time interval are independent and identically distributed (i.i.d) with the mean and variance of the inter-charging interval, noted as $\mu_a$ and $\nu_{ij}$, and the mean and variance of the energy inter-discharge interval are expressed as $\mu_l$ and $\nu_{ij}$, 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 work, 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 the transmission. We design energy content aware video packets delivery schemes towards the maximum weights of accomplished data. To this end, we formally formulate the energy and content aware vessel throughput maximization problem (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 that infostation and DTN throw box deplete their energy when they serve or store traffic demands. The following formulation is based partially on these criteria.

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

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

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

\[
\max \sum_{j=1}^{n} \sum_{s_{jk} = r_{jk}}^{d_{jk} - p_{jk}} w_{jk} \cdot x_{jksj_k} \\
\text{s.t.} \quad \sum_{j=1}^{n} \sum_{s_{jk} = u - p_{jk} + 1}^{u} x_{jksj_k} \leq 1 \quad k \in \{1, 2\}, \forall u \\
\sum_{s_{jk} = r_{jk}}^{d_{jk} - p_{jk} + 1} x_{jksj_k} \leq 1 \quad k \in \{1, 2\}, \forall j \\
x_{jksj_k} \in \{0, 1\} \\
\mathcal{P}(0; x_0) < \varepsilon
\]

The EVTMP-DECISION can be verified in polynomial time, with coefficients satisfy

\[
\max \sum_{j=1}^{n} \sum_{s_{jk} = r_{jk}}^{d_{jk} - p_{jk}} w_{jk} \cdot x_{jksj_k} \geq \bar{x}
\]

and for different $x_{jksj_k}$ with a total value not more than 1. Hence, EVTMP is $\mathcal{NP}$-

Then, the EVTMP can be easily transformed into the Knapsack Problem (KP). 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 EVTMP 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 regarding to binary variable $x_{jksj_k}$ should concern the video packet characteristics (i.e., release time, playback deadlines, 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.

In this section, 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 vessel and two vessels cooperative transmission, 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

In this subsection, a decentralized algorithm is designed to solve the EVTMP problem. 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 as 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

\[
Q(t) = A(t) - L(t).
\]

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 \( G/G/1 \) 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-Lévy process (or Brownian motion) model is used [24] as follows,

\[
dX(t) = X(t + dt) - X(t) = \beta dt + Z \sqrt{\alpha dt}
\]

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

\[
\begin{align*}
\beta &= E(\lim_{\Delta t \to 0} \frac{X(t)}{\Delta t}) = 1/\mu_a - 1/\mu_l \\
\alpha &= Var(\lim_{\Delta t \to 0} \frac{X(t)}{\Delta t}) = va/\mu_a^2 + vl/\mu_l^2.
\end{align*}
\]

With the initial energy level \( x_0 \), the conditional probability density function (p.d.f) of the energy buffer size \( X(t) \) at time \( t \) is

\[
p(x,t; x_0) = Pr(x \leq X(t) \leq x + dx | X(0) = x_0).
\]

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

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

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

\[
p(x,0; x_0) = \delta(x-x_0), \quad t = 0
\]

\[
p(0,t; x_0) = 0, \quad t > 0,
\]

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

\[
p(x,t; x_0) = \frac{\partial p(x,t; x_0)}{\partial x} = \Phi \left( \frac{x-x_0-\beta t}{\sqrt{\alpha t}} \right) - \exp \left( \frac{2\beta x}{\alpha} \right) \Phi \left( \frac{-x+x_0+\beta t}{\sqrt{\alpha t}} \right),
\]

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

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

Given \( D(x_0) = \min \{ t \geq 0 | X(0) = x_0, X(t) = 0 \} \) 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 probability density function of \( D \). The detail derivation of probability density function of \( D \), i.e., \( p_D(x;t;x_0) \) and \( \mathcal{P}(0;x_0) \) is given in Appendix 1.

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 the process of video packet generating and requesting can be modeled as a Poisson distribution with \( \lambda t \), where \( \lambda \) 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 \( \tau \) is a random variable having an exponential distribution with parameter \( \lambda \) [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. Even though the packet is in process, it is also affected 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
The solution of real number is:

\[ F_D(T; x_0) = \int_0^T p_D(x, t; x_0) \, dt < \varepsilon \]  

(16)

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

(17)

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

(18)

\[ = \frac{\beta^4 t^2 x_0}{30\alpha^{5/2}} + \frac{2t^{1/2} \beta^3 x_0^2}{5\alpha^{5/2}} - \frac{2t^{1/2} \beta^2 x_0^3}{5\alpha^{3/2}} \right\} \bigg|_0^T \leq \varepsilon. \]  

(19)

Since \( p_D(x, t; x_0) \) is non-holonomic, the integral expression in Eq. 16 cannot be obtained directly. Based on the first order of Taylor series expansion, we can approximate the expression of \( T \) in Eq. 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 a univariate cubic equation

\[ ax^3 + bx^2 + cx + d = 0, \quad a \neq 0, \]  

(20)

the solution of real number is:

\[ x = -\frac{b}{3a} + \sqrt[3]{\frac{3ac - b^2}{27a^2}} \pm \sqrt[3]{\frac{3ac - b^2}{27a^2} - \frac{b^3}{27a^3}}, \]  

(21)

here \( A = \frac{bc - b^3}{27a^2} - \frac{d}{2a} \) and \( B = \frac{c}{3a} - \frac{b^2}{9a^2} \).

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 \( J_i \), we schedule the packet in descending order of \( \frac{w_i}{p_i} \) until \( \text{occupied} \geq t' \).

- **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 already been scheduled will be preempted by packet \( J_j \). The metric of preemption is \( w_j > \sum w_r \cdot (1 + \frac{t}{\frac{1}{p_i}}) \), 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

1. \( I \leftarrow \emptyset \);
2. \( \text{occupied} \leftarrow 0 \);
3. **for** a new packet \( J_i \) arrives at time \( t \) **do**
   4. **if** \( \text{occupied} + p_j < T \) **then**
      5. **if** \( t > \text{occupied} \) **then**
         6. schedule \( J_i \) at \( t \);
         7. \( \text{occupied} \leftarrow t + p_i \);
      9. **else** there exist some scheduled packets \( J_r \) overlapped with \( J_i \) during \( l_r \)
         10. if \( w_i > \sum r \left( 1 + \frac{t}{p_r} \right) w_r \) **then**
             11. replace packets \( J_r \) with \( J_i \) at \( t \);
             12. \( I \leftarrow I \cup \{J_r\} \);
             13. \( \text{occupied} \leftarrow t + p_i \);
         14. **repeat**
             15. reschedule \( J_r \) with highest \( \frac{w_j}{p_j} \) at \( \text{occupied} \);
             16. \( I \leftarrow I \setminus \{J_r\} \);
             17. \( \text{occupied} \leftarrow \text{occupied} + p_j \);
         18. **until** no packets can be rescheduled;
         19. **else**
             20. schedule \( J_i \) at \( \text{occupied} \);
             21. \( \text{occupied} \leftarrow \text{occupied} + p_i \);
         22. **end if**
     23. **end if**
4. **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, as well as the schedule of vessels, is 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 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 inter-infostations communication.

In the two-vessel scenario, vessel 1 is responsible for emergency information delivery (like warship), while 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, 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.

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

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., \( \mu_1 = v_1 = 0 \), while the initial energy and charging parameters of the energy buffer are \( x_o = 0, \mu_o \) and \( v_o \). In this scenario, \( \beta_C = 1/\mu_o \) and \( \alpha_C = v_o/\mu_o^3 \). The minimal energy requirement of the DTN node is denoted as \( b \). The maximal delay before passing the packet over to vessel is expressed as

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

The detail derivation of probability density function of \( C \), i.e., \( p_C(x; t; x_0) \) is given in Appendix 2. Let \( T_2 \) denote the duration from 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 \( T_2 \).

\[
F_C(T_2; 0) = \Pr(C \leq T_2) = \int_0^{T_2} p_C(x; t; 0) dt \tag{24}
\]

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

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

3) Energy Buffer Based Combinatorial Decentralized-Backward Centralized Algorithm: We propose a combinatorial decentralized-backward centralized algorithm, taking into consideration of 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] \text{ is the set of video packets that cannot be scheduled by vessel 1; } J_1 \text{ 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 ships’ speeds are all relatively stable, they could be known a priori. Let } x_0 \text{ denote the DTN initial energy when vessel 1 transmits data to it; } x_0 \text{ is the residual energy in the DTN node. } x_0 \text{ can guarantee that the DTN node have 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_o'' \text{ indicates the energy level when vessel 2 contacts the DTN node; } T_1 \text{ represents the total length of video packets, which is going to be transmitted to the DTN node; } T_2 \text{ 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 \text{ 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 the following equation:

\[
F_D(T_1; x_0) = \int_0^{T_1} p_D(x; t; x_0 - x_0) dt < \varepsilon. \tag{28}
\]

Step 2: If a packet’s uploading time is larger than \( T_1 \), i.e., \( T_j > T_1 \), we use \( w_j / \rho \) to sort the priority of packets which 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 follows

\[
F_C(T_2; 0) = \Pr(C \leq T_2) = \int_0^{T_2} p_C(x; t; 0) dt. \tag{29}
\]

By using transformation \( b \leftarrow x_o'' - x_o' \), 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.

\[ F_D(T_3; x_0) = \int_0^{T_3} p_D(x, t; x_0')dt < \varepsilon. \] (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 \( x_0' \geq x_0 - x_0'' \).

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

\[ F_C(T_2; 0) = \Pr(C \leq T_2) = \int_0^{T_2} p_C(x, t; 0)dt < \varepsilon. \] (31)

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

1. Two vessels decentralized algorithm is the same with Algorithm 1;
2. **Backward Centralized algorithm**
   - Input: \( x_0 = x_0' = \text{constant}; T_2 \); \( J \) 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: \( x_0', J_1 \)
   - \( J_1 \leftarrow \emptyset \);
   - \( \text{occupied} \leftarrow t \);
   - 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 \( \text{occupied} + p_i \leq T_1 \) & occupied + \( p_i \leq e_i \) then
       - occupied \( \leftarrow \text{occupied} + p_i \);
       - \( J \leftarrow J \backslash \{J_i\} \backslash \{J_e_i < \text{occupied} + p_i\} \);
       - \( J_1 \leftarrow J_1 \cup \{J_i\} \);
       - \( i \leftarrow i + 1 \);
     - else
       - \( J \leftarrow J \backslash \{J_i\} \backslash \{J_e_i < \text{occupied} + p_i\} \)
     - end if
   - end while

**for moment \( t \) vessel 1 store data into DTN node end do**

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 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 \( p_i \).

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 \( J_3 \) in vessel 2 as well as 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 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

In this section, 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: \( 1 + 2 + \cdots + (N + 1) = \frac{N(N+1)}{2} \). Therefore, the Algorithm 1 runs in \( O(N^2) \) time, where \( N \) means the maximum number of overlapping packets.

For Algorithm 2, we allocate the scheduling of \( J_i \in J \) which has the highest \( \frac{w_i}{p_i} \). It takes \( O(\log N) \) 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 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 as \( (\varphi_1, \theta_1) \) and \( (\varphi_2, \theta_2) \), respectively, where \( \varphi \) and \( \theta \) are the latitude and longitude of vessels. The great circle distance \( S \) in navigation...
science can be obtained as follows:

\[
\cos S = \sin \varphi_1 \cdot \sin \varphi_2 + \cos \varphi_1 \cdot \cos \varphi_2 \cdot \cos D\lambda (32) \\
D\lambda = \theta_2 - \theta_1. 
\] (33)

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

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet size</td>
<td>100 bytes</td>
<td>System bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>50 Mbps</td>
<td>Frame duration ( T_F )</td>
<td>5 ms</td>
</tr>
<tr>
<td>Network region</td>
<td>100 \times 100 km²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We set the mean and variance of the energy charging interval as \( \mu_a = 2.75 \) and \( \nu_a = 1.09 \). The mean and variance of the energy inter-discharging interval are \( \mu_l = 4.35 \) and \( \nu_l = 11.1 \). 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 term of normalized throughput, which is defined as the ratio of the throughput of delivered packets over the throughput of total packets. We modify the above three classic algorithms by considering the survival time \( T \), and 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 which is more important to the video quality and needs 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.

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

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 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 energy and content aware vessel throughput maximization problem and proved the formulated problem is \( NP \)-complete. After that, two algorithms for both network scenarios of single vessel and two-vessel have been 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 multi-vessel scheduling issues with various mobility patterns in green-energy-powered maritime wireless communications networks. Under the multi-vessel scenario, we need to jointly consider the scheduling scheme design and energy sustainability of each BS. Moreover, the routing
normalized throughput can be expressed as

\[ P(0; x_0) \]

with Laplace transform, the moment generation function of

\[ D \]

probability density function of

\[ E \]

conditional probability density function of the energy

\[ D \]

buffer depletion duration is

\[ p_D(x, t; x_0) = \frac{x_0}{\sqrt{2\pi\alpha_D t^2}} \exp \left\{ \frac{(x_0 + \beta_D t)^2}{2\alpha_D} \right\} \].

(35)

With Laplace transform, the moment generation function of

\[ D \]

can be expressed as

\[ M_D(s) = \exp \left\{ -x_0 \left( \beta_D + \sqrt{\beta_D^2 + 2\alpha_D s} \right) / \alpha_D \right\} \].

(36)

Then, we can obtain the mean and variance of the energy

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

\[ Var(D) = \frac{d^2}{ds^2} M_D(s) \big|_{s=0} = E^2(D) \]

\[ = e^{-\frac{2\beta_D x_0}{\alpha_D}} \left[ 2x_0\beta_D^2 - x_0^2\beta_D^2 \left( 1 + e^{-\frac{2\beta_D x_0}{\alpha_D}} \right) \right]. \] (38)

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

\[ \mathcal{P}(0; x_0) = \begin{cases} 1, & \text{for } \beta_D < 0 \\ \exp \left\{ -\frac{2x_0\beta_D}{\alpha_D} \right\}, & \text{for } \beta_D > 0 \end{cases} \] (40)

We can observe from Eq. 40 that the energy buffer depletes

\[ \bar{E}(D) \]

probability density function of

\[ D \]

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 infostatulates the energy depletion probability before \( p_{jk} \) terminates,

\[
F_D(T; x_0) = Pr(D \leq T) = \int_0^T p_D(x; t; x_0) dt. \quad (41)
\]

**APPENDIX 2: DERIVATION OF PROBABILITY DENSITY FUNCTION OF \( C \)**

By applying diffusion approximation, we can obtain the probability density function of \( C \) as

\[
\frac{\partial p_C(x,t;0)}{\partial t} = \frac{\alpha}{2} \frac{\partial^2 p_C(x,t;0)}{\partial t^2} - \beta \frac{\partial p_C(x,t;0)}{\partial t} \quad (42)
\]

Then, we derive that the length of the queue cannot exceed \( b \).

\[
p_C(x,0;0) = \delta(x), \quad t = 0 \quad (43)
\]

\[
p_C(b,t;0) = 0, \quad t > 0. \quad (44)
\]

We obtain the p.d.f by applying the method of images [25], [26] as follows

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

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

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

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

\[
E(C) = \frac{d}{ds} M_C(s)|_{s=0} = \frac{b}{\beta_C} = b \mu_a \quad (47)
\]

\[
Var(C) = \frac{d^2}{ds^2} M_C(s)|_{s=0} - E^2(C) = b v_a. \quad (48)
\]

**REFERENCES**


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