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Leveraging Maritime Wideband Communication Networks to Ensure Safety of Navigation Towards E-Navigation Strategy

By

Dalian Maritime University (DMU)

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Leveraging Maritime Wideband Communication Networks to Ensure Safety of Navigation Towards E-Navigation Strategy

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Abstract: This project aims at providing valuable insights on the video transmission scheduling for the maritime wideband networks. Notably, the alternative eco-friendly and renewable green energy in maritime environment will make the scheduling issue more challenging and fascinating. To the best of our knowledge, this is the first systematic work to do such investigation facing distinguished challenges with unique characteristics imposed in maritime wideband networks to ensure safety of navigation towards E-Navigation strategy. The problem is of great importance since related fundamental guidance is very limited. We give new idea of framework of maritime wideband communication networks, as well as the data transmission scheduling based on shipboard cooperative transmission. Simultaneously, an energy and content aware scheduling scheme is proposed to maximize the delivered video packets throughput in green-energy-powered maritime wideband networks, based on the analysis of green energy buffer model. Moreover, the data transmission scheduling based on a novel software defined heterogeneous network with fog computing capability for future maritime communications is proposed. Considering security issue, an efficient authentication protocol for secure communications in maritime wideband communication network is provided. Especially, the simulations in this project present real cases studies, which all depend on real ship route traces obtained from navigation software BLM-Shipping. Finally, we draw conclusions and highlight future research directions. This project provides valuable guidance and new ideas in the field of video transmission scheduling for future maritime wideband networks in the whole framework of E-Navigation.

In first section, we investigate the network through-put 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 net-work 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 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.

Maritime communication networks can extend wireless connections from land to the ocean, to guarantee safe navigation and provide ubiquitous broadband services. To better accommodate diverse maritime services under various circumstances, Space/Air/Sea networks should be effectively integrated so that the advantages of each segment can be leveraged efficiently. To simplify network configuration, as well as dynamically and efficiently manage network resources, this article proposes a software defined heterogeneous network with fog computing capability for future maritime communications, by utilizing the promising software defined networking (SDN) paradigm and fog computing technology. By exploiting the heterogeneity of the evolving relay stations based on satellite, airship and land infrastructure, this novel network architecture and network-wide resource allocation framework can effectively perform the traffic steering and navigation according to various ever-increasing services demands in a cost effective, flexible and agile manner, both for safety-related and non-safety related services. Two case studies are provided to illustrate how the proposed network operates.

Depending on the actual demand of maritime security, this paper analyzes the specific requirements of video encryption algorithm for maritime monitoring system. The un-manned ships are utilized to monitor and collect information on the sea, which is critical to maritime security. Once the video data were captured by pirates and criminals during the transmission, the security of the sea will be affected awfully. The shortcomings of traditional algorithms are as follows: the encryption degree is not high, computing cost is expensive, video data is intercepted and captured easily during the transmission process. In order to overcome the disadvantages, a novel encryption algorithm, i. e, the improved Hill encryption algorithm is proposed to deal with the security problems of the unmanned video monitoring system in this paper. Specifically, the Hill algorithm of classical cryptography is transplanted into image encryption, using an invertible matrix as the key to realize the encryption of image matrix. The improved Hill encryption algorithm combines with the process of video compression and regulates the parameters of the encryption process that according to the content of the video image, and overcomes the disadvantages that exist in the traditional encryption algorithm, decreases the computation time of the inverse matrix so that the comprehensive performance of the algorithm is optimal with different image information. Experiments results validate the favorable performance of the proposed improved encryption algorithm.

Keyword: *Marine, Software Defined Heterogeneous Network, Secure Communications, Smart Port/ Smart Pilot*

1. Academic Achievement I: Green Energy and Content-Aware Data Transmissions in Maritime Wireless Communication Networks

In this paper, we investigate the network through-put 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 net-work 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 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.

1.1 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].

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 (v_a)	The mean (variance) of energy inter-charging interval
μ_l (v_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

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 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 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.

1.2 Related Work

As a promising technology, there are many studies related to the maritime wideband network in both industry and academia [7]– [8] [9] [10] [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.

1.3 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]–[18] [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, $u \in \{1, \cdots, t\}$, 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 $r_{jk} \leqslant s_{jk}$, and thus, we have $s_{jk}+p_{jk} \leqslant d_{jk}$. To simplify the calculation, the above time indices are approximated to integers.

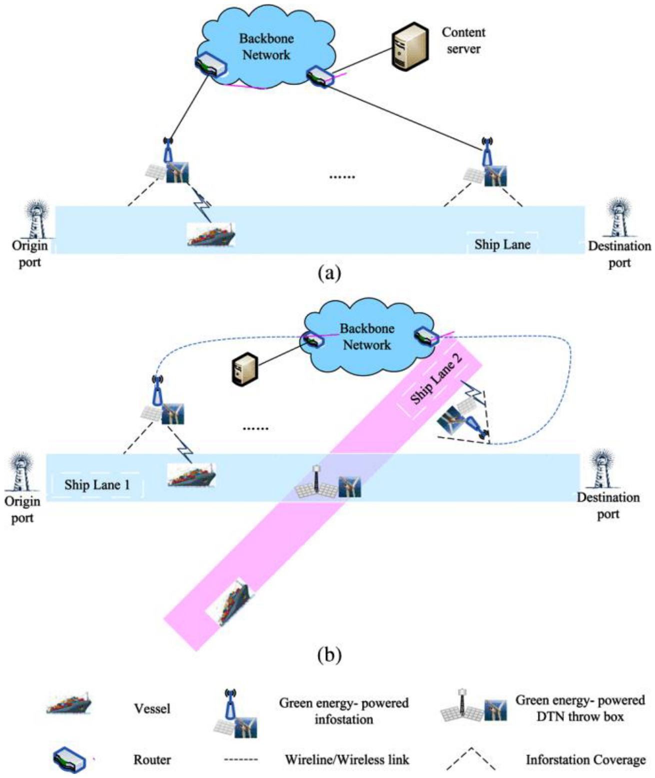

Fig.1 System model

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.

1.4 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

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

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

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

$$x_{jks_{jk}} \in \{0,1\} \qquad (4)$$

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

This formulation is a 0–1 integer nonlinear programming problem, which is known as 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. $P(0;x_0)$ is the energy depletion probability of the infostations and DTN throw box with the initial energy x0, which denotes how likely the infostations and DTN will deplete energy and become temporarily unavailable. In Section V, the expression of $P(0;x_0)$ 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 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

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

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

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

1.5 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 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.

1) 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

$$Q(t) = A(t) - L(t) \qquad (7)$$

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

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

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

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

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

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

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

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

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

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

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

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

$$p(x,t;x_0) = \frac{\partial}{\partial x}\left\{\Phi\left(\frac{x - x_0 - \beta t}{\sqrt{\alpha t}}\right) - \exp\left(\frac{2\beta x}{\alpha}\right)\Phi\left(-\frac{x + x_0 + \beta t}{\sqrt{\alpha t}}\right)\right\} \qquad (14)$$

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

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

Given $D(x_0)=\min\{t \geqslant 0 | X(0)=x_0, X(t)=0\}$ as the energy buffer depletion duration and the initial energy level x0, 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., $p_D(x, t;$ x0$)$ and $P(0; x_0)$, is given in Appendix I.

2) 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].

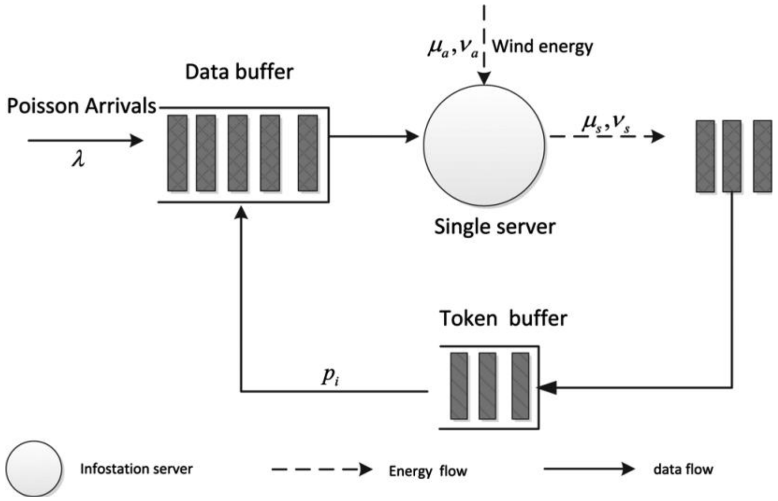

Fig. 2.Leaky bucket energy buffer diagram

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.,

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

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

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

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

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 *Jj*, 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 *Jj* 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 *Jj*. The metric of preemption is $wj>\sum wr\cdot(1+(l_j/pr))$, 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 pi. 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 <u>C</u>, i.e., $pC(x,t;x_0)$, is given in Appendix II. Let*T2* 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 *T2*, i.e.,

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

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

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

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

We can obtain *T2* 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; *J1* 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; *T1* represents the total length of video packets, which is going to be transmitted to the DTN node; *T2* 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; *T3* 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 x0 and the residual energy x′0, we can obtain T1 as

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

Step 2: If a packet's uploading time is larger than *T1*, i.e., *TJ>T1*, 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 *T1*, i.e., *TJ<T1*, 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 *T2*, the energy charging process works as

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

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

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

If *T3>T1*, 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

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

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

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 $occupied + p_i \leq T_1$ $\&occupied + p_i \leq e_i$ **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 *J1*, since the video packets J2 in vessel 2 do not impact on the energy level of the DTN node. However, the packets J2in vessel 2 and the new packets *J3* may conflict with the original packet from vessel 1 due to the overlapping processing time. After vessel 2 receives the video packets J1from the DTN throw box, the scheduling strategy will be the same with Algorithm 1. The total video packets can be expressed as $J \leftarrow J1 \cup J2 \cup J3$. If the weights of packets *J2* are obviously higher than *J1*, 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 $O(N^2)$time, where N means the maximum number of overlapping packets.

For Algorithm 2, we allocate the scheduling of $Ji \in J$ that has the highest (wi/pi). It takes O(log*N*) time to run the binary search method, where *N* is the number of packets stored in DTN node.

1.6 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 by ($\varphi 1,\theta 1$)and ($\varphi 2,\theta 2$), 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.

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		

We set the mean and variance of the energy charging interval as μ_l=2.75 and υ_l=1.09. The mean and variance of the energy interdischarging interval are μ_l=4.35 and υ_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.

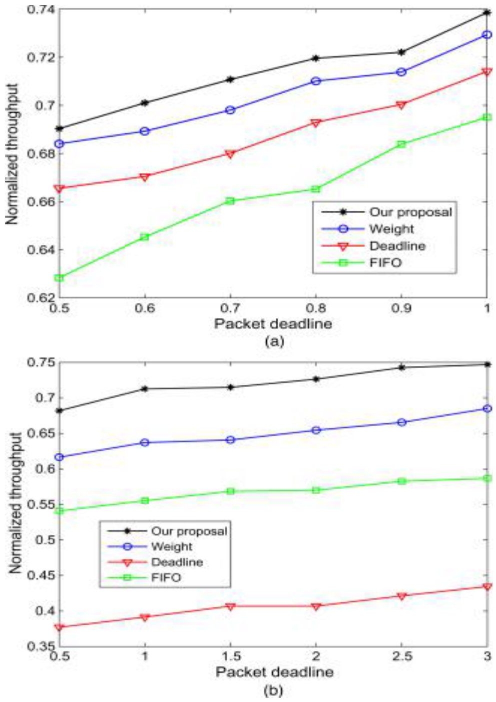

Fig.4. Normalized throughput versus packet deadline (a) Single-vessel scenario. (b) Two-vessel scenario.

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.
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.

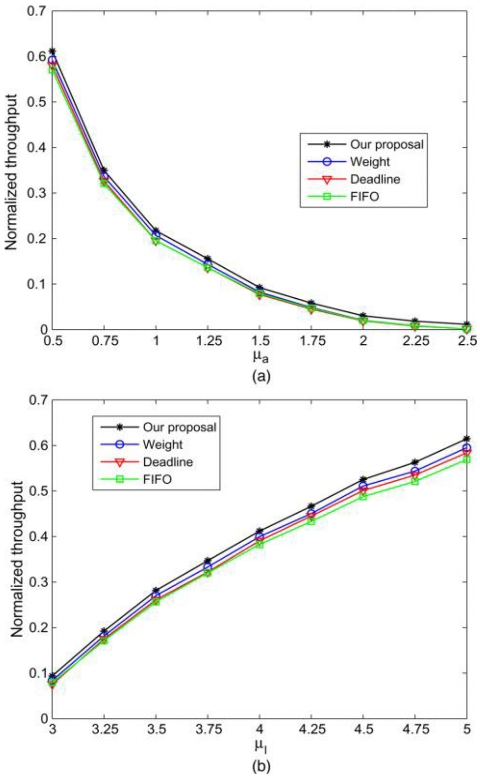

Fig.5. Normalized throughput of different algorithms for single-vessel scenario (a) Various mean of energy intercharging interval of infostation. (b) Various mean of energy interdischarging interval of infostation.

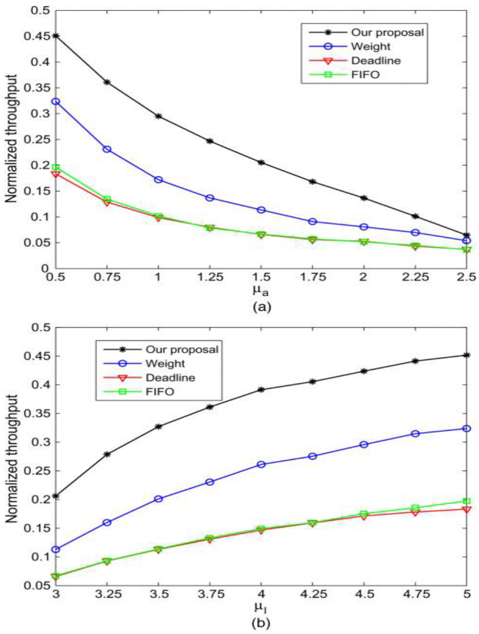

Fig.6.Normalized throughput of different algorithms for two-vessel scenario (a) Various mean of energy intercharging interval of infostation. (b) Various mean of energy interdischarging interval of infostation.

1.7 CONCLUTION

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 *NP*-complete. After that, two algorithms for both network scenarios of single vessel and two vessels 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 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 Derivation of the PDF of *D*

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

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

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.,

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

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

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

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

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

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 $1/\mu a \le 1/\mu_l$. 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 x0. The infostation calculates the energy depletion probability before p_{jk} terminates, i.e.,

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

APPENDIX Derivation of the PDF of *C*

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

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

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

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

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

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

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

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

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

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

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

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

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2. Academic Achievement II: Data Transmission Scheduling Based on A Software Defined Heterogeneous Network With Fog Computing Capability For Future Maritime Communications

2.1 Introduction

With the boosting growth of maritime transportation and navigation, the demand of maritime communications is increasing rapidly, while the existing maritime communications could only meet the basic needs of the communications between ship and ship (shore). However, the amount of data generated by E-Navigation services is increasing, and will continuously skyrocket for the future unmanned ships. The lack of reliability, security, and the availability of high-throughput and affordable maritime communications are the essential impediment. Thus, there has been growing interest in the domain of emerging maritime wideband communication networks, and some research programs have been proposed to provide effective connectivity in maritime intelligent transportation systems. It is envisioned that a "maritime highway" system will be built to deal with the maritime distress, urgency, safety, and general communications, and thereby facilitate a myriad of attractive applications related to monitoring, safety, infotainment and cargo online management. With rapidly evolving applications, maritime communication networks can not only revolutionize the navigation pattern to be safer and more efficient, but also extend broadband services from the land to the ocean with low cost, which perfectly meets the requirements of E-Navigation strategy and realizes the harmonization of marine navigation systems and supports shore services driven by user needs.

The maritime communications face many technical challenges, which are summarized as follows:
(1) **Compatibility issues among different navigation systems**. Along with the improvement of navigation technology, a multitude of individual systems operate independently, such as GPS, AIS, VTS, GMDSS and Beidou navigation systems. However, these systems have huge differences, which causes the serious compatibility issues. Specifically, coast radio stations, the fundamental components of GMDSS system, face compatible issues of in a variety of monitoring and communication means. These issues are complicated and challenging as that not only satisfy the growing communication needs and threat the normal operation of the shore station service, but also decide whether the E-Navigation strategy can continue to promote.
(2) **Inherent limitations on inter-operability and lack of an unified coordination**. The traditional maritime communication systems have inherent limitations such as low transmission rate, poor connectivity, low resource utilization, less scalability and flexibility. Although heterogenous communications techniques are employed to explore different advantages for maritime communication networks, due to the lack of inter-operability, an unified coordination and control platform, it is difficult to fully harness the benefits and support various services under various circumstances. The variety of services/use cases should be supported effectively, but the current maritime communications networks cannot achieve this goal.
(3) **The digital and integrated transformation requirement of coast radio stations**. IMO has been aware of the significance of the digital and integrated transformation of coast radio stations. A unified framework of digital coast stations, integrating the Very High Frequency (VHF), Medium Frequency (MF) and High Frequency (HF) radio stations, is proposed to implement the intensive management of communication resources. This framework could curtail the waste of resources due to multiple equipments operating in parallel, poor inter-connectivity between coast radio stations. Finally, it could facilitate an integrated coastal system of sea area based on hierarchical management.

Therefore, we advocate that the future maritime communication systems should be heterogeneous, collaborative and inter-operable to accommodate various kinds of applications and services both for vessels and coast radio stations in various sea situations. A flexible and adaptive network architecture is urgently needed to tackle new emerging challenges in maritime communications. It expects to meet the communication demands of future intelligent navigation, transportation, and even Internet services over the sea, and provide effective communications services from near shore to far sea, which covers all sea areas of interest. In addition, it must enable rapid delivery of navigation-related security and control information for shore-to-ship, ship-to-shore, and ship-to-ship communications, broadcast text, image, sound and other documents, send urgent electronic chart correction information, and provide digital interface, to achieve seamless connections with ship information systems.

To this end, in this article, we propose a novel software defined network architecture for future maritime communications (SDNM), by leveraging two emerging technologies, namely, Software Defined Networking (SDN) and Fog Computing (FC), which can better perform the resource scheduling and traffic steering to support maritime services. SDN platform is exploited for better flexibility, scalability, and programmability with global knowledge to improve the efficiency and network reconfigurability, while FC can make computing capability closer to the end users and provide real-time processing to facilitate location-based services. With the new network architecture, the aforementioned technical challenges for maritime communications can be well addressed and emerging services for both navigation and customers' services can be enabled.

2.2 A SPACE/AIR/SEA INTEGRATED NETWORK FOR MARITIME SERVICES

A vessel network is a wireless network over the sea for vessel communications, which can be considered as one of the most important supplements and extensions to terrestrial vehicular networks, such as vehicular ad hoc networks (VANETs). The data transmission modes over the sea include ship-shore communication, ship-ship communication, ship-based information collection such as ECDIS/VTS/COMPASS/RADOR, and hydro meteorology sensor. In this article, as shown in Fig. 1, we propose a Space/Air/Sea integrated maritime network architecture, which is a multi-layer heterogeneous network with satellite-based, airborne-based and land-based/shore-based access capabilities, respectively. This heterogeneous network can accommodate services such as network access, data transportation, and information gathering, and so on.

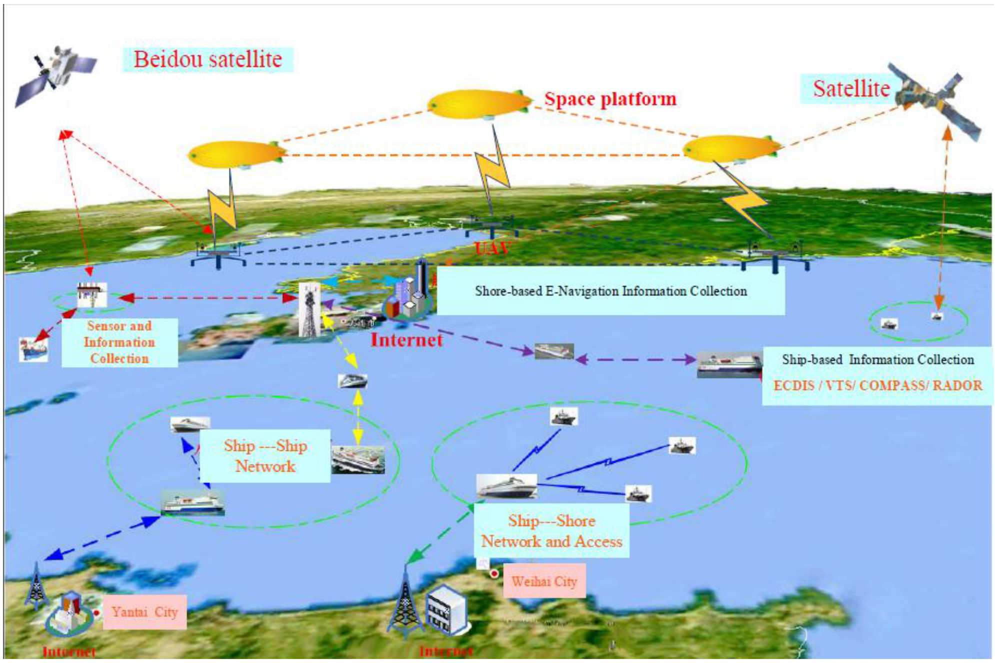

Fig.1. Space/Air/Sea Integrated Maritime Network Framework

Specifically, SDN is utilized to integrate the dispersed and independent infrastructure (a.k.a. satellite, space platform and coast stations across the coastline) into a unified platform. The Software Defined Heterogeneous networking technology allows isolated virtual networks to be completely customized, which could create multiple logically virtual networks to share the same physical infrastructure resource pool, through network function virtualization (NFV) [7]. Virtual network customization can be performed on the network topology, management policies, security mechanisms, resource management strategies, protocol stack, and so on. The SDN technology enables multiple logical virtual networks on a common infrastructure platform to be inter-operable more efficiently. Consequently, a large number of individual infrastructures can be better coordinated and controlled by a virtual signaling control network, through a common and unified interface. It is also possible to utilize the Universal Plug and Play (UPnP) protocol to provide the widely applicable and released effective protocol [8], which can provide practical, configuration-free implementation options for different vendors and communication methods. Moreover, this system can be connected to different satellite-based, airborne-based and land-based equipment, forming a unified and multi-functional access network. To create a virtual signaling control network, there are three steps to be carried out.

(1) Firstly, the virtual signaling control network topology should be customized, which includes the appropriate nodes and links, and the capacity of the corresponding services.
(2) Secondly, the virtual signaling control network is mapped to a physical network, which is also called network embedding/mapping.
(3) Finally, a service-oriented protocol stack can be customized to better suit the service/use case. In addition, sub-virtual signaling control networks can be created on the virtual signaling control network to support multiple services simultaneously.

In so doing, it can bring many benefits. For instance, when a vessel is in distress, it is crucial to convey distress information and other important safety and rescue related information. The proposed system can provide centralized control and intelligence to manage resources to disseminate those information and take appropriate actions.

The land-based access infrastructure is also called infostation system, which is deployed on shore-side, or on the islands near the shore. An infostation is responsible for shore-based E-navigation information collection. The infostation could also provide network access near the shore, but not the open sea. Since the infostations are deployed shore-side sporadically, the full network coverage cannot be guaranteed. The land-based infrastructure is suitable for large volume data transmissions with delay tolerance. Additionally, maritime safety information which is not urgent, such as weather forecast and hydro meteorological information, could be dispersed through this network.

The space-based infrastructure refers to the geostationary satellites, MEO satellites and low polar orbit satellites, as well as the BeiDou navigation satellite system. The satellite-based access network is suitable for urgent situation without excessive bandwidth requirements. For example, the distress alert message transmissions and receptions, as well as control signalling message dispersion. At the same time, uninterrupted network connections could be established, which is feasible for 24-hour Internet browsing, long range transmissions and navigation urgent information acquirements. Nonetheless, the tremendous monetary expense to launch satellites causes huge business expenditure, especially for real-time voice service and video downloading. Hence, the cost of large capacity data transmissions is suppressive via this kind of access.

The airborne-based access infrastructures are composed of various kinds of space platforms such as airships, unmanned aerial vehicles (UAVs), etc. Compared to the satellite-based access network, the airborne-based access network provides delay tolerant services due to the limited coverages of airships and UAVs. Specially, it could store local information at a space platform, which is very suitable for distress situations at sea. When a distress event occurs, a airborne-based platform could fetch the local navigation information, i.e., the position of the distressed vessel and the surrounding environment. Then, the nearby vessels can receive distress messages, and carry out the search and rescue operations accordingly.

2.3 SDN-BASED SPACE/AIR/SEA INTEGRATED NETWORK WITH FOG COMPUTING CAPABILITY

In this article, we study this Space/Air/Sea integrated network, combining the respective advantages of these three kinds of access networks. Targeting at different services, priority and communication modes, various network resources could be utilized.

A. Network Architecture

The salient characteristics of communications at sea require safer navigation (i.e., distress communication) and ubiquitous broadband services for voice, data, image or even video services. Therefore, in this article, we aim to simplify network configuration and manage network resources efficiently by integrating SDN paradigms into maritime networks. SDN has been regarded as a new revolutionary technology in networking recent years, which deems to replace the traditional distributed network control, within centralized, systematic and programmable manner to control the network. The core idea of SDN is the separation between network control plane and data plane [9].

Fog computing is a term created by Cisco that refers to extending cloud computing to the edge of an enterprise's network [10]. Also known as Edge Computing or fogging, fog computing facilitates the operation of compute, storage and networking services between end devices and cloud computing data centers.

(1) Save core network bandwidth: As the middle layer of the cloud and the terminal cloud, the fog is on the communication path between the user and the data center. Fog filters, aggregates user messages (such as sensor messages sent over and over), sends only the necessary messages to the cloud, and reduces stress on the core network.
(2) High reliability: In order to serve users in different regions, the same service will be deployed in all regions of the fog node. This also makes high reliability an inherent property of fog computing, and once an area of service is anomalous, user requests can quickly move to other nearby areas.
(3) Global Control: Because of the distribution in different regions, the service of fog computing can learn the background information of the region, such as whether the bandwidth is tight in the region. According to this knowledge, a video service can decide whether to reduce the video quality in the region in time to avoid the delay.
(4) Power Savings: Data center power consumption has become an important cost, with cooling systems accounting for a negligible share. Fog computing nodes because of geographical dispersion, will not generate a large amount of heat concentrated, does not require additional cooling system, thereby reducing power consumption.

The SDN-based heterogeneous networks can facilitate efficiently to exploit various network resources for diverse services at various scenarios. A SDN-based integrated network architecture with fog computing capability is shown in Fig. 2. It could provide flexibility, scalability, and programmability. Moreover, the fog computing technology could especially offer delay-sensitive and vessel position awareness services which could deal with the distress and safety related scenarios at sea. Different vessels can just exploit the unified operations, and only need to follow the command and control in the vessel determined ahead of time.

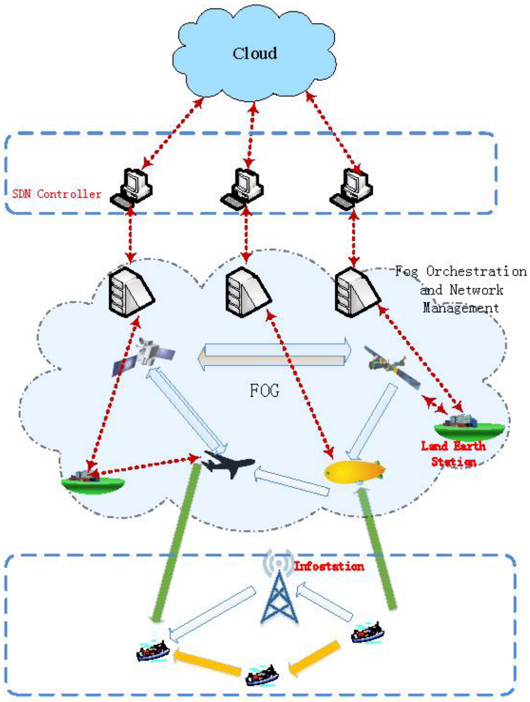

Fig.2. SDN-based Space/Air/ Sea Integrated Network Architecture Leveraging Fog Computing

The SDN control network consists of the following entities:

(1) SDN Controllers: SDN Controllers in a software defined network (SDN) are the “brains” of the network. A SDN controller is logically situated between network devices at one end and applications. The controller also uses protocols such as OpenFlow to configure network devices and select the optimal network path for application traffic. In maritime scenario, SDN controllers can be integrated into a selected subset of routing facilities, and they are all working together to manage the whole network. The control signaling messages are generated by the SDN controllers. Therefore, the SDN controllers manage the global network by utilizing reliable transmission medium. In the nutshell, the SDN controllers act as supervisors which are responsible for the fog orchestration and network management;
(2) SDN Terminals: They are the terminals which can execute the SDN commands for services. Vessels are the executing SDN terminals to forward data to Space/Air/Sea based infrastructures. Every vessel should be equipped with an onboard unit, called OBU as in VANETs, which can execute the SDN commands. Communications over vessels can be controlled with the OpenFlow, which provides the control signaling for SDNs [11];
(3) SDN Access Stations: The SDN access stations in this scenario refers to shore-side infostations, space platforms (e.g., airships and UAVs) and satellites, which are connected to the Land Earth Station, which could then connect to the maritime administration authorities or company depending on the exact services. The space platforms, satellites and infostations can be a part of Fog agents with running the OpenFlow. A fog coordinator, hereby the SDN controller, manages and controls all the fog agents [12].

By combing SDN with FC capability in maritime networks, the following benefits can be achieved:

(1) Flexible Management: The network organization and infrastructure deployment can be simpli-fied. The hardware and infrastructure facilities across the whole network could be configured and coordinated in a centralized manner with SDN.
(2) Quality of Services (QoS): Protocols and application maintenance becomes easier. The network protocols and software updating, programming and modification, can be conducted in a centralized way through open interfaces, compared with the traditional distributed fashion which requires on-site manual efforts. QoS provisioning can be carried out by centrally coordinating routing facilities and resource utilization through the SDN control plane.
(3) Resource Utilization: With the SDN, network resources can be shared through the virtual network, according to the priority of the services, the collected resources are allocated efficiently. The control signaling messages are generated and managed by the SDN controllers, which have the global view of the network and can efficiently manage network resources and better support diverse services.

B. Communication Technologies

The long distance from a vessel to a shore-side infostation, a space platform, or a satellite will demand innovative communication technologies in heterogeneous wireless networks. The vessel-to-vessel and vessel-to-inforstation communications can be realized with a maritime wireless ad-hoc/mesh network by exploiting both cognitive radio technology or LTE technology. In this scenario, vessels are terminals which connects other vessels or land stations through multiple hops.

The static, inflexible spectrum allocation policy of Federal Communications Commission (FCC) has already caused the exhaustion of available spectrum suitable for long distance transmissions, while a lot of licensed spectrum bands at sea (a.k.a., “white space/spectrum hole”) are extremely under-utilized [13]. In light of this observation, FCC relaxed the spectrum ruling and opened the opportunistic access to unlicensed users as long as the use of a licensed spectrum does not significantly impact the services of the incumbent licensed users. Cognitive radio technology can be utilized in maritime environments to release the spectrum from shackles of authorized licenses users, as shown in Fig. 3. This is a two-tier network architecture, composing of a maritime cognitive radio provider (MCRP), infostations, CR-routers, spectrum sensing nodes, vessel terminals, and secondary users (SUs) (users in vessels). The MCRP has some licensed spectrum, e.g., AIS bands or VDES bands licensed to maritime industries, to provide basic reliable communication services and common control signaling. It can provide these services to vessels and shore-side infostations using the harvested spectrum resources by utilizing cognitive radio technologies. The CR-routers could be deployed in the marine infrastructures, i.e., buoys, drilling platform or lighthouses. They form a mesh network offering multi-hop communication services for vessel terminals, exploiting the spectrum jointly sensed by CR-routers for MCRP. In the second tier, the vessel terminals can further provide spectrum resources for the SUs in vessels. This network architecture could operate efficiently to support heterogenous traffic requirements for various types of SUs.

Airborne wireless communications or the stratosphere airship wireless communications can be carried out among stratosphere airships and/or UAVs. The stratosphere airship is a kind of controllable aircraft, lighter than air and powered by solar energy, which relies on air buoyancy to remain in the air. It has its own propulsion system, and it is convenient to realize vertical take-off and landing, independent of airports or runways. It is perfectly feasible for maritime urgent situations. When there is a marine accident, we need to temporarily set up a makeshift wideband network, transmit on-site videos or images which can benefit the rescue missions. Airships or UAVs can hover over the arbitrary location around the distress spot on scene. The channels of airborne wireless communications are quite stable, which are not affected by bad weather troposphere and can support 24 hours continuous operations. The communications between vessels and airbornes can be achieved through LTE technology. The communications between airbornes refers to the backbone network transmissions in space.

Satellite communications could realize the communications between two earth stations (e.g., vessel, aircraft and shore-based authority on land). A typical satellite link involves the communications between an earth station and a satellite. The satellite serves as a responder and reflects signals back to the earth, where it is received and re-amplified by earth stations or terminals. The satellite communication channels allocated by ITU is now extended to 117MHz–275GHz. The L/C/Ku microwave bands are allocated for satellite communications. Multiplexing technologies such as TDM/FDM have been intensively used. The advantages of satellite communications are as follows: the coverage area is large and the communication distance is long; multiple access connection is easy; it is flexible without geographical restrictions; it is highly reliable; and the communication cost is independent of the distance. Unfortunately, the disadvantages are also very obvious: it needs advanced space technologies; it has longer signal delay; the satellite life is short; the communication bandwidth is limited; and the cost is high.

Perceiving that maritime wireless communication networks could combine the advantages of all three kinds of communication networks and avoid the disadvantages of any one-kind network operations, the SDN-based heterogeneous network provides a practical and cost-effective multi-tier network architecture to construct an integrated maritime wireless communication infrastructure.

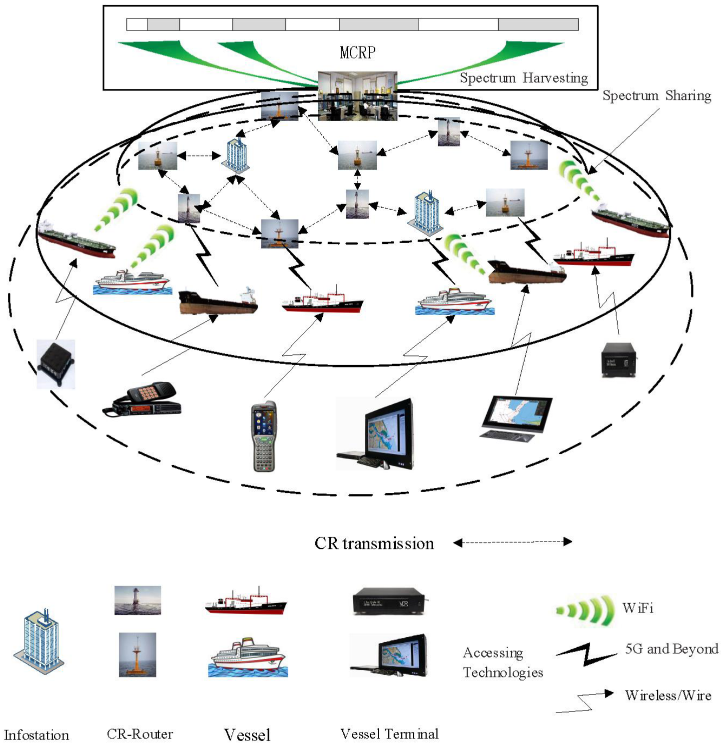

Fig.3. Maritime Cognitive Networks with Heterogeneous Connectivity

C. Software Defined Reconfigurability

The future Space/Air/Sea integrated maritime network that we advocate should be heterogeneous, collaborative and inter-operable to support different applications and services for vessels in various sea situations. The network has dynamic and multi-tier characteristics. On the one hand, the network is also dynamic due to continuous movements of vessels in space and time. On the other hand, the application and computation of the whole network need be updated frequently, which brings up the dynamic nature of communications and computations, due to the a multitude of service demands simultaneously for vessels and passengers towards distress, urgency, safety and routine priorities. Software defined Space/Air/Sea integrated networks can be configured dynamically at a large scale, adapting to the constantly changing situations. The computation and communication resources of wireless terminals are usually required to be shared with other existing tasks, which are usually variable, and should be reconfigured. The operational modes of shore-side infostations, space platforms and satellites could be changed in a software defined manner. In this way, the geographical service coverage can be dynamically adapted to various network requirements and services.

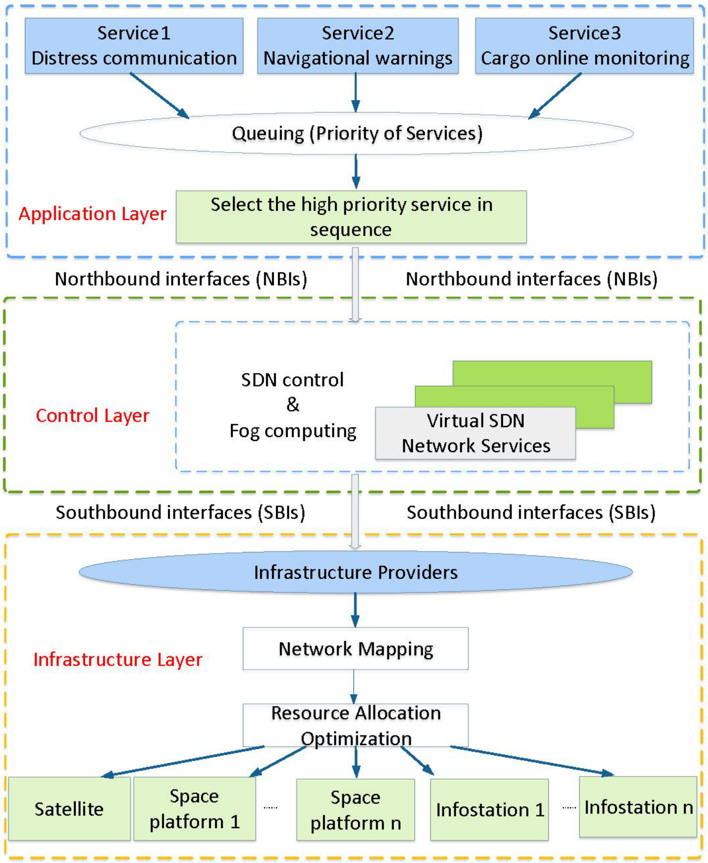

Fig.4. The Resource Allocation Framework for SDNM

From a technical perspective, the SDN controller performs two main procedures: virtual network requirement determination, and virtual network resource availability and allocation. The network enables SDN and NFV functionalities, partitions and assigns a amount of resources (e.g., bandwidth, computing resource and storage) to different virtual networks, where the resources can be used in an isolated, disjunctive, or shared manner [14]. SDN network architecture is divided into three layers: application layer, control layer and infrastructure layer. The Resource Allocation Framework for SDNM is illuminated in Fig. 4. Consequently, based on the exact service specifications, the centralized SDN network could meet the resource requirements for each virtual network (VN), including inter-VN and intra-VN operations.

When multiple types of information messages arrive at the same time, the information center processes the services with the highest priority first, i.e., for the distress situation. In this situation, the distress message is first passed to the control layer of the SDN-based network architecture in which the SDN controller with global knowledge of the network state, and then according to the needs of the distress service, the SDN network responds quickly and selects an appropriate virtual network that can support the requested service, if possible. Here, we add the fog computing combining with the SDN control, because in distress situation especially, significant computing is needed in order to assess the situation locally instead of forwarding raw data to remote control center to assess the situation. Then, the control center sends the corresponding signaling to the infrastructure layer. The signaling control network is then mapping the virtual network a physical network, which is also called network embedding/mapping. During this determination process, optimization problem can be formulated and optimal algorithm can be derived to determine needed resources to support the requested services. Depending on the situation, the despatched resources may be dynamically adjusted to adapt to the variations of network-wide status and diverse service requirements.

2.4 USE CASES

The SDN-based Space/Air/Sea integrated network can efficiently facilitate the integration of information. According to various tasks and circumstances, the network can come up with the appropriate intelligent strategy accordingly. Through this network, the information transmission becomes more efficient and reliable. In this section, to demonstrate the effective use of this novel and flexible network architecture, we present the use cases for the safety-related distress (e.g., alert messages and on-scene videos) and non-safety related services, respectively.

A. Safety-related Case

For the distress watch-keeping in maritime administration authorities, the equipment monitoring and service provisioning are done through software. When a vessel is in distress (e.g., on fire), this SDN-based Space/Air/Sea integrated network could promptly and efficiently trigger and manage the distress alert system. With the objective of maximizing the distress broadband information (especially, image and video services) to be transmitted, the SDN controller could promptly perform two main procedures: virtual network requirement determination and virtual network resource allocation. Since the distress information has the highest priority, the communication and computation resources could be allocated to support this safety-related service firstly. The communication and computation architecture of this safety-related scenario is demonstrated in Fig. 5.

The components of this network collaboratively provide the alert and rescue services. Since it handles delay-sensitive services, the following procedures are performed:

(1) In distress situation, tremendous computing is required to process the emergency situation locally with least possible delay instead of forwarding original data to remote control center to compute and control. Hence, the distressed vessel sends a distress alert message to fog computing agents nearby, which directs it to the rescue coordination center (RCC). Then, the logically centralized SDN controller, which receives the alert message from fog agents, manages and makes a flexible network configuration that satisfies the subsequent communications with broad band demands. With the global view of the network-wide requirement and status, the SDN controller addresses the issue of inter-VN and intra-VN operations. Consequently, virtual networks are embedded into the physical underlaying network through network mapping and resource allocation. Then, resource determination on how to utilize satellite, space platform or land-based infostations nearby, as well as exact locations of space platforms and the portion of each to relay the detailed distress alert messages (distress images and videos) is made depending on the resource availability, service requirement and traffic flow. The control signaling is transmitted via OpenFlow to the distressed vessel terminal.

(2) Since the fog stores all the local vessel information, it can automatically choose the vessels nearby, which has the indispensable search and rescue power beyond the RCC. The above steps utilize the combination of front-end processing, wide-area processing, and spatial processing;
(3) For further on-scene rescue-assisted video service for the rescue aircraft and vessels, it could be supported via space platforms and/or land-based infostations. They both can provide the broadband communication services, based on either the LTE technology or the CR technology to harvest enough idle spectrum. Especially, the space platforms and land-based infostations are all managed by the FC facilities. Various space platforms, nearby vessels, and infostations can also cooperate to extend the transmission range. The SDN controllers are responsible for the whole network orchestration and network management, together with the coordination of various fogs nearby.

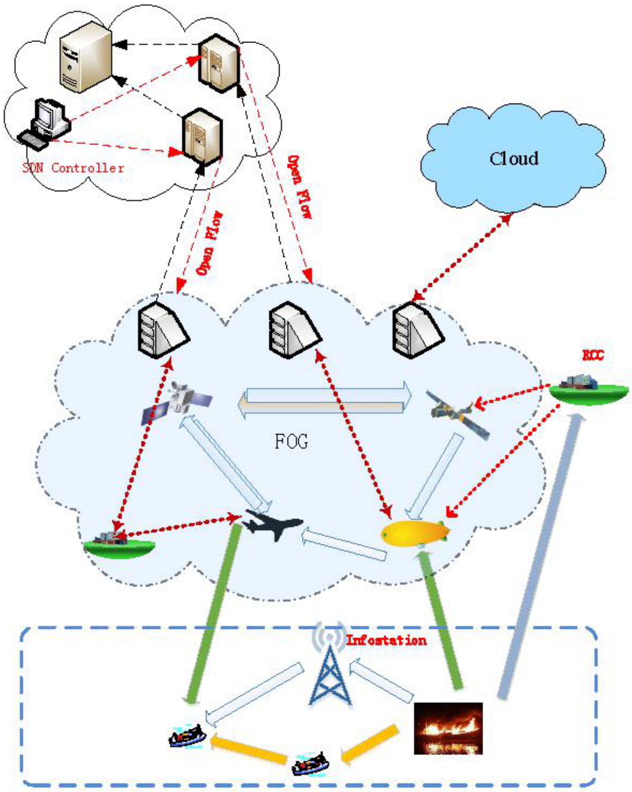

Fig.5. Safety-related scenario

B. Non-Safety Related Case

For the non-urgent service such as surveillance videos uploading, cargo online monitoring, infotainment, the requirement should focus on high capacity transmissions with low cost because of the delay-tolerant nature. In this scenario, The CR technology should be fully utilized to harvest enough spectrum to opportunistically upload the videos.

Similarly, when a vessel requests this kind of service, the procedures in Fig. 4 should also be performed. The SDN controllers can allocate appropriate infrastructures including satellite, space platform, land-based infostations, as well as the nearby vessels to cooperatively exploit the delay tolerant network (DTN) technology from the network-wide view. The DTN paradigm utilizes the store-carry-forward routing scheme. Therefore, it could obtain information about other vessels and navigation data (i.e., position, course, velocity, departure port, destination port, etc.), which could be easily realized by the centralized FC-assisted SDN control. Finally, the virtual networks are embedded into the physical network substrate via appropriate mapping and resource allocation strategies.

C. Comparison with conventional schemes

For conventional resource allocation, resources are directly allocated to terminals. In contrast, in our proposed network framework, collective of resources are allocated to different virtual networks to fully satisfy the service requests, according to the spatial and temporal variation in maritime traffic demands. Therefore, the benefits of this dedicated heterogeneous network, when handling safety-related and non safety-related situations, are listed as follows:

(1) Flexible Management: The network resource could be configured and coordinated in a SDN manner through open interfaces, due to the software configuration mode. For example, the locations of space platforms are automatically identified according to the distress position and other global information, compared with the traditional distributed fashion which requires on-site manual efforts.
(2) Rapid Response: Once a vessel is in distress over the sea, the network can respond in an efficient and timely manner. The control signaling messages generated by the SDN controllers, which have the global view of the network and can efficiently manage network resources and better support diverse services. The rescue power could be rapidly improved by announcing to RCC and the vessels nearby with SDN and FC capability.
(3) Broadband Communication Guarantee: Depending on the LTE or CR technology which har-vesting enough idle spectrum, the urgent broadband services could be enabled. Accordingly, the situation of the vessel in distress, the surrounding environment, such as the distribution of the vessels, the current situation of the wind, the situation of the goods, the personnel status, and so on, can be effectively monitored and the corresponding data can be collected and transmitted through various links for efficient and prompt rescue. Compared with the traditional way handling the distress situations, the future heterogeneous maritime network is collaborative and compatible with traditional systems, and can flexibly accommodate various kinds of applications and broadband services for vessels in various sea areas.

2.5 CONCLUSIONS AND FUTURE WORK

In this article, we have proposed a novel heterogeneous network, i.e., a SDN-based Space/Air/Sea integrated network architecture with FC capability. For the dedicated communications over the sea, we have designed the salient network architecture composing of various components with various functionalities. Use cases on both the safety-related and non-safety related services are discussed to demonstrate how the proposed network architecture operates and how we can benefit. However, it does require novel networking platforms, more complicated network protocols and complex controllers to guarantee the performance gain. For the future work, we will study the following issues:

(1) Design appropriate resource management and fog orchestration that takes SDN characteristics into account to support FC. For a given service and an optimization objective, how to manage the land-based infostation, space platforms, and satellites with the SDN should be carefully investigated in order to maximize the gain from this network architecture;
(2) Investigate the design of resource allocation schemes for SDN controllers to improve the load-balancing and the tradeoff between latency and cost, when dealing with different priorities of maritime services;

(3) Study the joint communication-motion control for vessel platooning [15], especially for the un-manned navigation vessels (UNVs).

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3. Academic Achievement III: The application of improved Hill encryption algorithm in the video monitoring system of the unmanned ship

3.1 Introduction

According to the actual demand of maritime security, this paper analyzes the specific requirements of video encryption algorithm for maritime monitoring system. The un- manned ships are used to monitor and collect information on the sea that is critical to maritime security. Once the video data is captured by pirates and criminals, the security of the sea will be affected awfully. In this paper, a better encryption algorithm is proposed to deal with the security problems of the unmanned video monitoring system. Specifically, the Hill algorithm of classical cryptography is transplanted into image encryption, using a invertible matrix as the key to realize the encryption of image matrix and overcoming the disadvantages that exist in the traditional encryption algorithm, at the same time, saving the computation time of the inverse matrix [1]. The algorithm combines with the process of video compression and regulates the parameters of the encryption process that according to the content of the video image, so that the comprehensive performance of the algorithm is optimal in different image information. The results of the experiment that the algorithm has good performance in the influence of adjacent pixels, and the information entropy of images is more smaller than other algorithm.

The threat of maritime piracy has mushroomed enormously in the past few years, especially in the detailed sea area below are piracy affected areas where the terror and threat of sea pirates have reached looming proportions: The strait of Malacca, the South China Sea, Gulf of Aden and so on. The news channels on a daily basis have several incidents to report about pirates attacking crew and looting the vessel or hijacking a ship, and even causing harm to the crew when their ransom demands are not met by the authorities. Unmanned ship video monitoring system has been envisaged to prevent maritime distress, as an important device to maintain maritime security, then the maritime administration to monitor the sea and collect a large amount of data by unmanned ship video monitoring system. Last, analyzing the data and taking timely and favorable measures in response to the corresponding situation. At the same time, it can collect information of special area and obtain important information through this system, and experts can use these information to study whether the area can be expanded and whether there are available resources. Video may be stole and changed by pirates and other terrorists in the process of transmission that will pose a serious threat to information security of the sea, it is inconvenient to sea navigation and transportation and other activities of the sea. As a result, the encryption of video data has become a priority, which is beneficial for the security of the sea and it also can reduce losses and casualties.

With the development of information technology and the continuous progress of the society, the demand of information is becoming more and more abundant, it is hoped that the communication can be made conveniently, quickly and flexibly by voice, data, image and video in many ways whenever and wherever. In the past, because of the limitation of network transmission technology and image compression ability, the interaction of image and video information is a kind of extravagant demand for people. In recent years, with the increase of network bandwidth and the development of video image compression technology that people can carry out transmission of image and video through a variety of ways, In particular, with the progress of wireless transmission technology that the communication technology is affecting people's production and life in an unprecedented scale and degree. The transmission of video and image information by wireless channels has become an urgent demand of application and the rapid development of network transmission technology, especially the wireless transmission technology that brings convenience to us, as but it also brings hidden danger: sensitive image information may be stolen easily and copied and spread illegally. Therefore, the security problem of image information has become a very important and crucial problem.

Although the research of video encryption [2] technology has been carried out for nearly 20 years, but the existing secret strategy is not perfect and there is a large space for improvement, the encryption strategy of images that transmitted under wireless conditions, which degree of security is low. There are many different encryption methods and their respective systems have been formed but no performance of encryption strategy is satisfactory for all users. There are huge differences between various encryption strategies and the debate is violent. So far, a unified international standard has mot formed.

Video information security is a interdisciplinary subject spanning mathematics, cryptography, information theory, probability theory, computational complexity theory and so on, it is related to video compression, network transmission and application standards closely, which makes video encryption technology [3] becomes a problem that has not been completely conquered. In this paper, according to specific requirements of the wireless video monitoring system and combining with the research results of video encryption technology, a new video encryption algorithm is proposed-Improved Hill [4] encryption algorithm. The algorithm combines with the process of video compression and regulates the parameters of the encryption process that according to the content of the video image, so that the comprehensive performance of the algorithm is optimal in different image information. The results of the experiment that the algorithm has good performance in the influence of adjacent pixels, and the information entropy of images is more smaller than other algorithms.

The content arrangement of the paper:
In the second part: Introduced the function of the unmanned ship , research of related technology, research of video image, as well as the research direction of the video image, a new algorithm is proposed that according to the application characteristics of the unmanned ship video monitoring system.

In the third part: the module function of the unmanned ship video monitoring system is introduced detailed. This paper introduces the specific location of the encryption module in the whole system and the relationship that with other functional modules. In the course of communication that introduce three kinds of communication methods.

In the fourth part: Introducing the idea of Hill encryption algorithm and the key matrix briefly, and the traditional algorithm is improved to adapt to the needs of encryption.

In the fifth part: Comparing the traditional algorithm with the improved algorithm from three aspects, then concludes that the improved algorithm has certain advantages.

In the sixth part: Summarizing the improved encryption algorithm and putting forward the research direction of improving the algorithm in the future.

3.2 Related work

In recent years, driverless cars and UAVs are becoming more and more popular among the public. Google Corporation is a pioneer in the field of research and development of driverless vehicles, at the end of May 2015 year, the company announced that its unmanned vehicle project was developing to automatic direction that exclusion of human intervention. The prototype test of the automatic driverless vehicle will be carried out, it is expected that test of driving on the road can be carried out in a few years. At present, Google is making about 100 automatic vehicle models. UAVs are trying to enter into people’s lives, too. According to foreign media reports, online shopping giant Amazon is seeking permission from the US government to launch UAV flight test in the US. In fact, in the field of unmanned technology, research and exploration of unmanned ships are also under way, and ships floating on the sea will probably enter the unmanned era in the future. British Rolls Royce is optimistic about this, as one of the world’s largest engine makers and shipbuilders that is determined to develop unmanned vehicles and offshore unmanned ships. There are slender difficulties in developing the unmanned craft at the technical level, and now there are many ships equipped with automatic equipment. The era of unmanned ships is considered in the future. "In the near future, the unmanned ship will keep pace with the unmanned drones, the submarines and the unmanned vehicles that are being tested by Google", aid Oscar Levand.

As far as water is concerned, the demand of unmanned ships is strong. For example, while working on cruise and search, driverless technology can increase the number of ships that because it doesn't need to be manned and the size is small, its reaction is more responsive. To monitor the condition of the sea and collect important information by unmanned ship, ship are attacked by pirate or the terrorist during the voyage, using video to capture the locations, numbers, features of the pirates, use of weapons equipment and other important information, the information are transmitted to shore with unmanned vessel monitoring system. It should set a fixed time to transfer the collected information to the shore, it is convenience for shore personnel access to valid information in good time. Video should be sent to shore forcibly and take action in time in an emergency. The video data must be secure enough, once the data were intercepted and tampered that not only to miss the best time to rescue and lose strong evidence.

In the multimedia computer technology application system, there are two research directions of video image processing. One is the compression encoding of the video image; the other is real-time processing of video image and protection of video information. In the video image compression algorithm, h.264 compression [5]algorithm as an international standard, because it has higher compression and it is able to provide a high quality image and supported by most of the operating platform, it also has good compatibility. H.264 has the following advantages: 1. Higher coding efficiency: H.264 saves nearly 0.5 of its bandwidth compared with its predecessor H.263 and MPEG-4.2. High quality images: H.264 can provide video images of high quality in low bit rate, and image transmission of high quality on lower bandwidth is the highlight of H.264 application. 3. Improving network adaptability: H.264 can work in low delay mode that under the real time communication applications (such as video conferencing), and can also work in video storage or video streaming server that without delay. 4. Using hybrid coding structure: H.264, like previous H.261, H.263 that use the hybrid coding structure, which is DCT transform coding and DPCM differential coding. At the same time, in order to improve the efficiency of compression coding, H.264 introduces a new coding methods under the structure of mixed coding, which adds new encoding methods, such as multimode motion estimation, intra prediction, multi frame prediction, it's content is based on variable length coding and 4x4 two-dimensional integer transform and improves the efficiency of coding. 5. H.264 has less coding options: A considerable number of options are often required to encode in H.263 that adds difficulty of coding, while H.264 achieves a concise "regression base" that reduces the complexity of the coding. 6. H.264 can be applied in different situations: H.264 can use different transmission and playback rates according to different environments, and provide a rich tool of error handling that can control or eliminate the packet loss and bit error. 7. error recovery function: H.264 provides a tool to solve the problem of network transmission packet loss, which is suitable for transmitting video data in a wireless network with transmission of high bit error rate. 8. Higher complexity: Performance boost of H.264 is achieved at the expense of increasing complexity, it is estimated that the computational complexity of H.264 encoding is three times more than H.263 and the decoding complexity is twice as much as H.263.

The protection of video image information is to prevent sensitive information from being stolen and altered easily, copied and disseminated illegally, including information encryption technology and information hiding. The encryption algorithm is based on the design of text data, the implementation is: To convert meaningful clear text into meaningless cipher text that is to prevent the information obtained during the process of data transmission by illegal interceptors. Video file has the characteristics of large data volume and require high real-time requirements, so it is difficult to gratify the requirements of video information on encryption efficiency that using traditional encryption algorithms in sometimes. Spatial image encryption is to encrypt the gray [6] scale of the image, because the gray scale (pixel value) of the image is the byte data that can be encrypted by means of data encryption. Therefore, data encryption algorithm can be transplanted into gray scale encryption algorithm, which includes data encryption standard, simple Hill matrix encryption, sequence encryption algorithm. A new image encryption algorithm is proposed in this paper that according to the traditional Hill algorithm, using an invertible matrix as a key to encrypt the image matrix, then transposing the encrypted image, the last step is double- layer encryption of matrix.

3.3 SYSTEM MODEL

In this paper, we propose to use the LAN technology to construct the unmanned video monitoring system, the video node is connected with the different monitors of the unmanned ship through the local area network, the control center can communicate with the maritime cloud service centre that achieve the effect of information sharing. Compared with other methods, it has an advantage that it can be applied to unmanned ships of different sizes, so that we can design the unmanned ship video monitoring system according to the unmanned ships size and structure, it just only to change the number of video monitoring nodes and location on the base of different requirements. The unmanned video monitoring system focuses on the security of ship navigation and cargo transportation. Monitoring the different locations over surface by configuring a certain number of cameras and other technological means, the information will be compressed and encrypted by SecurCore processor of DSP core and transmitted with three ways Fig. 1. When the distance is far, the com-munication will be achieved by satellite and cloud platform and other shore-based or air-based facilities. We can select the corresponding schemes according to the distance, which saves the cost, decreases the time of communication, avoids the waste of resources. The specific information transmission paradigms are shown in Fig. 2.

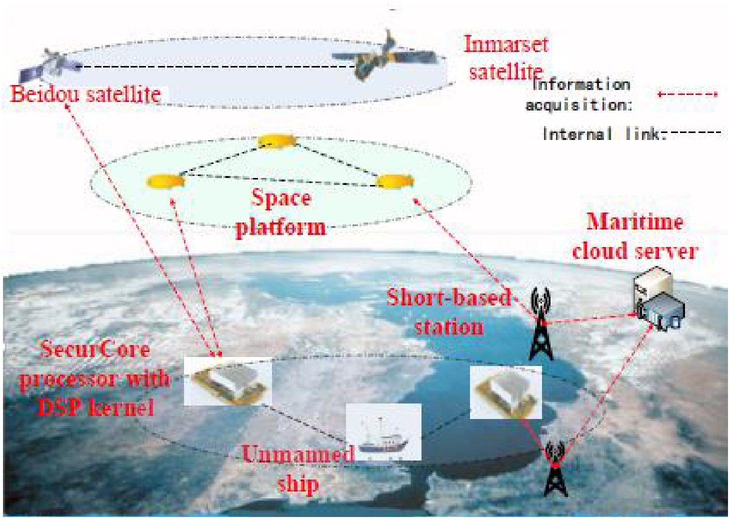

Fig.1. Information Transmission Diagram

A. Video acquisition module

The acquisition module of the video data is the input stage of information and its performance is very important to the whole system, the quality of the original video and image will determine the final image clarity of the ship borne monitoring platform, which includes camera and corresponding control parts. The monitoring contents include the travel records of the ships and the meteorology of the sea as well as the transportation of the goods and so on, it also can store and print the pictures according to the needs.

B. Video compression and encryption module

The compression and encryption module of the video is the core of the unmanned video monitor system and its performance affects the overall performance of the whole system directly. The compression of video data is limited by many conditions, such as the transmission bandwidth , image resolution a, frame rate, maximum delay of coding, performance of processor. Therefore, the video compression module needs to be coordinated with the transmission module, the encryption is integrated into the compression and their relationship is very close. The module of compression and encryption can be implemented by SecurCore processor of DSP core.

C. Video transmission module

While the video data is completed by the hardware compression and it also need to be sent to the service platform through the network. However, there will be some problems in the process of sending, such as the simultaneous transmission of multiple monitoring nodes or the blockage of the networks, it may occur that data is disappeared. In the process of data transmission the network that will judge the size of the packet, when the size of the packet is more than or less than the certain limit that the packet will be discarded, the specific scope is 64 1500 bytes. RTP is used to transmit video files and it is a real-time network transmission protocol that is often used for single point data transmission and it is very suitable for the transmission of audio and video data.

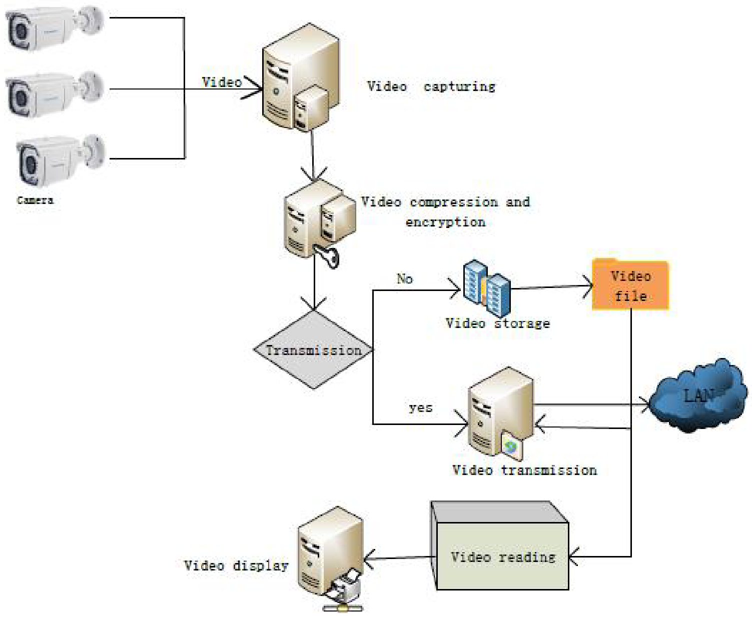

Fig.2. Flowchart of information processes

D. Video playback module

In the system, the video service center needs to play video and image, according to their different purposes the implementation are adopted by different ways. The purpose of the video broadcast of the unmanned ship is adjusting the camera easily, so that can make better that track the target. On the ship's service platform, the purpose of the display is to have a clear understanding of the experiment site and analysis things what happened after that, Therefore, image definition must be high taht should be enhanced before playing.

E. Video Storage Module

It is a part of the important functions of the system that the storage of video data during the experiment process, which to analyze the situation of the experimental field after the experiment is possible. The maritime cloud server center is analysis and disposing center of the experimental data that has intense computing power and large storage space, it is appropriate to backup and long-term archival of experimental data. The transmission of data can be reduced by using the mode of maritime cloud server center storage. However, the data obtained by unmanned ship are transmitted by the wire-less channel, and the noise and interference are unavoidable. After being processed a few steps, the data will increase the corresponding noise of process. The definition of video image is the most important index of the system, in order to archive the data of high quality and remove unnecessary noise and interference, the video data will be stored in the unmanned shipboard monitoring platform.

3.4 IMPROVED HILL ENCRYPTION ALGORITHM

The idea of Hill algorithm is to convert l clear text letters [7] into l cipher letters by a series of linear transformations, the decryption only requires one inverse transformation and the key is the transformation matrix itself. Hill password is one of the multiple-letter substitution codes and it’s also called the matrix transformation password, the multi-letter substitution cipher is a more convenient overview by using transitional matrix. The vector of cryptograph is: $C = KM\,(modN)$.

$$C = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_l \end{bmatrix} \tag{1}$$

$$M = \begin{bmatrix} m_1 \\ m_2 \\ \vdots \\ m_l \end{bmatrix} \tag{2}$$

$$E(x) = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{3}$$

$$K = (k_{ij})_{lxl} = \begin{pmatrix} k_{11} & k_{12}\cdots & k_{1l} \\ k_{21} & k_{22}\cdots & k_{2l} \\ \vdots & \vdots & \vdots \\ k_{l1} & k_{l2}\cdots & k_{ll} \end{pmatrix} \tag{4}$$

In the formula: C is cryptograph and M is clear text and the key K is an invertible matrix. The decryption formula: $M = k^{-1}c\left(modN\right)$. All the arithmetic operators are performed under the mode *N=26*.

Example 1:

Suppose the key $K = \begin{pmatrix} 6 & 7 \\ 3 & 8 \end{pmatrix}$, while the encryption come true by using the Hill password ,according to the above calculation can get a result that $K^{-1} = \begin{pmatrix} 8 & 19 \\ 23 & 6 \end{pmatrix}$,Suppose the good is clear text that to be encrypted, then the clear text is divided into two groups:(6,14)is "go" and (14,3)is "od". The process of encryption is

$$\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = K \begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = \begin{bmatrix} 6 & 7 \\ 3 & 8 \end{bmatrix} \bullet \begin{bmatrix} 6 \\ 14 \end{bmatrix} (\bmod 26) = \begin{bmatrix} 134 \\ 130 \end{bmatrix} (\bmod 26) = \begin{bmatrix} 4 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = K \begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = \begin{bmatrix} 6 & 7 \\ 3 & 8 \end{bmatrix} \bullet \begin{bmatrix} 6 \\ 14 \end{bmatrix} (\bmod 26) = \begin{bmatrix} 134 \\ 130 \end{bmatrix} (\bmod 26) = \begin{bmatrix} 4 \\ 0 \end{bmatrix}$$

The result of encryption is "EABO". The process of decryption is

$$\begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = K^{-1} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} 8 & 19 \\ 23 & 6 \end{bmatrix} \bullet \begin{bmatrix} 4 \\ 0 \end{bmatrix} (\bmod 26) = \begin{bmatrix} 32 \\ 92 \end{bmatrix} (\bmod 26) = \begin{bmatrix} 6 \\ 14 \end{bmatrix}$$

$$\begin{bmatrix} m_3 \\ m_4 \end{bmatrix} = K^{-1} \begin{bmatrix} c_3 \\ c_4 \end{bmatrix} = \begin{bmatrix} 8 & 19 \\ 23 & 6 \end{bmatrix} \bullet \begin{bmatrix} 1 \\ 14 \end{bmatrix} (\bmod 26) = \begin{bmatrix} 274 \\ 107 \end{bmatrix} (\bmod 26) = \begin{bmatrix} 14 \\ 3 \end{bmatrix}$$

Get the correct clear text in the last.

A. Self Invertible Matrix

In the encryption formula, If *K* has inverse matrix *K−1* and *(K−1K)M = M = K−1C(mod26)*, which is possible to realize the decryption. Essentially, using the invertible matrix *K* is important when you encrypt/decrypt. How do you see a matrix can be invertible? It depends on the determinant that is [10] non-zero(all of the above operations are performed under mode N = 26). So we know that the invertible matrix *K* has the inverse of the mode of N = 26, only if *GCD(detK, 26) = 1*. Here, we use the *GCD(x, y)* to denote the largest common divisor of the integer x and the integer y, using detK or |K| to represent the determinant of the matrix *K*. The Hill encryption algorithm is applied to the image matrix *P* to get the corresponding Hill image encryption algorithm, the encryption process is *C = Ek (P) = K • P* and decryption process is *P = Dk (C) = K−1 • C = K−1 • K • P = P* .

The basis of the algorithm:
If matrix A satisfies A = A−1, then A is called a self-invertible matrix. Assumptions

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \tag{5}$$

It is n × n self-invertible matrix, n is even and n is 2, then it is written as:

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \tag{6}$$

In the formula, A_{11},A_{12},A_{21},A_{22} . is (n/2)×(n/2) matrix. Results from the self inverse of A:

$$A \bullet A = A \bullet A^{-1} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = I \tag{7}$$

Result from formula (6):

$$A_{12} A_{21} = I - A_{11}^{2} = (I - A_{11})(I + A_{11}) \tag{8}$$

According to formula (7), if$|A_{12}|$is a factor of$|I-A^2_{11}|$ and$|A_{21}|$ is another factor. Suppose there is a constant *k*,

$$A_{12} = k(I - A_{11}) \tag{9}$$

Then:

$$A_{21} = (I + A_{11}) / k \tag{10}$$

From the formula (9) can get second matrix equations:

$$A_{11}A_{12} + A_{12}A_{22} = 0 \tag{11}$$

When the formula (8) is established, $|A_{11}|$and$|A_{12}|$will be exchanged, then:

$$A_{11}A_{12} = A_{11} \bullet k(I - A_{11}) = k(I - A_{11}) \bullet A_{11} = A_{12}A_{11} \tag{12}$$

The formula (11) to (10) that obtain:

$$\mathrm{A}_{12}\mathrm{A}_{11} + \mathrm{A}_{12}\mathrm{A}_{22} = \mathrm{A}_{12} \bullet (\mathrm{A}_{11} + \mathrm{A}_{22}) = 0 \tag{13}$$

While $A_{12} \neq 0$ get the result:

$$\mathrm{A}_{11} + \mathrm{A}_{22} = 0 \tag{14}$$

The algorithm steps are as follows:
First step: Chose *(n/2) × (n/2)* matrix A_{22}.
Second step: Getting the result through a series of calculations: $A_{11}= -A_{22}$
Third step: Taking $A_{12} = k (I - A11)$ that the k is a prime number.
Fourth step: Counting the $A21= (I – A11) = k$ or $A21 = (I + A11) k$.
Fifth step: Merging into a complete matrix.

B. Self-invertible matrix Hill encryption scheme

The steps of improved Hill encryption algorithm are as follows:

Step − 1 m × m self-reversible matrix is generated as the key matrix of this algorithm.
Step − 2 Dividing the original image into *m* × *m* block image.
Step − 3 The *i* pixels of each image block will be grouped together and made up *m*× *m* temporary image block, it is convenient for future encryption operation.
(1) The temporary image matrix is encrypted with the key matrix A.
(2) Transposing the encrypted image matrix and double-layer encrypting the matrix.
Step − 4 Put the obtained matrix into the *i*th position of the final encryption matrix.

The process of decryption is the reverse process of encryption, the block diagram of the specific encryption algorithm is shown in the Fig. 3.

The following algorithm is obtained that self-reversible matrix algorithm:

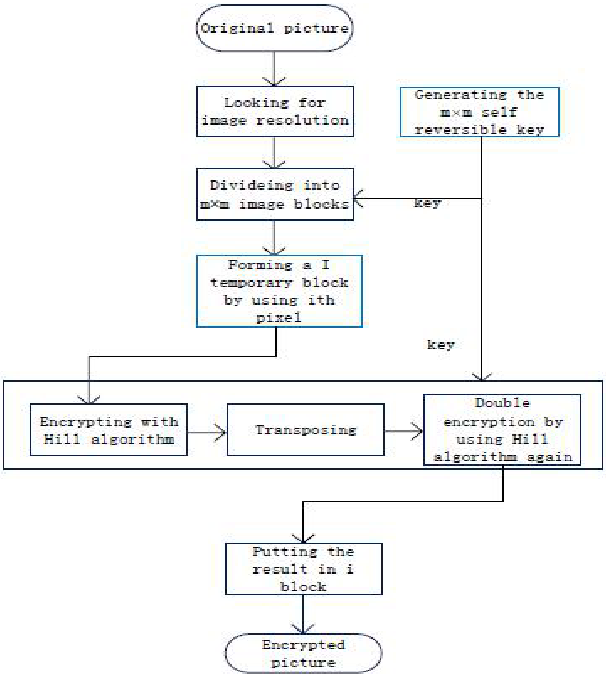

Fig.3. Flowchart of encryption

C. *Security Analysis of Hill Algorithm*

The key conditions of Hill encryption algorithm are character information and digital correspondence table and encryption matrix. Character information and digital correspondence table expression that the greater the order of the encryption matrix the cryptanalysis and calculation will be more difficult. The definition of the encryption matrix and the solution of the matrix are also very important to the [11] encryption and decoding of the algorithm. From the point of cryptanalysis code, using traditional passwords to encrypt video has a lot of drawbacks, the broken translator can sum up the analogous rules from the statistical string frequency and find out the exit of cryptanalysis. With the rapid development of science and technology, the deciphering time is less than before. But Hill encryption algorithm [12] uses matrix multiplication and inversion in linear algebra, it is better to resist frequency analysis and it is difficult realizing the decoding. Hill encryption algorithm has set up three handicaps for the translator, which is incomprehensible to decipher. Because you don't know anything about that dimension variables of the text conversion, order of the corresponding letters, access method of the encryption matrix. If you want to decipher the code you should guess the three things correctly at least. But it is difficult to guess correctly at the same time. There is no password that can not be broken completely, and the Hill algorithm is no exception. Generally speaking, it is difficult decoding that only knows the attack of cipher text, but it is easy to be broken by using attack of clear text.

Assuming the opponent already knows the value L and it also mastered l different tuples L at least. $M_i = \begin{bmatrix} m_1 \\ m_2 \\ \vdots \\ m_l \end{bmatrix}, C_i = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_l \end{bmatrix}$, $1 \leqslant i \leqslant l$. The conditions were fulfilled that $C_i = E(M_i;K) = e_K(M_i)$ $(1 \leqslant i \leqslant l.)$

Defining two matrices that are $M=(m_{ij})_{l \times l}$ and $C = (c_{ij})_{l \times l}$. Then has a matrix equation: $C = K \bullet M(mod26)$. In the formula, $l \times l$ matrix K is an unknown key. If the M is reversible that can be calculated that: $K = C \bullet M^{-1} (mod26)$. Thus the encryption algorithm is broken (if M is not reversible, we must try another l plaintext-cipher text pair). Criminals use various shortcomings of the encryption algorithm to carry out attacks, from the overall result, Hill algorithm is still a simple and efficient algorithm.

3.5 EXPERIMENTAL RESULTS AND ANALYSIS

In order to test the correlation between the two pixels adjacent to the vertical, adjacent, horizontal, the following tests are performed. Firstly, 1000-3000 pairs of pixels adjacent to the horizontal, vertical, diagonal direction are randomly selected from the graph, and the correlation formula is used to calculate the correlation [13].

$$r_{xy} = \frac{\operatorname{cov}(x, y)}{\sqrt{D(y)}\sqrt{D(x)}} \tag{15}$$

$$D(x) = \frac{1}{N}\sum_{i=1}^{N}(x_i - E(x))^2 \tag{16}$$

$$\operatorname{cov}(x, y) = \frac{1}{N}\sum_{i=i}^{N}(x_i - E(x))(y_i - E(x)) \tag{17}$$

In the formula, x and y are the gray values of two adjacent pixels in the image. *E(.), D(.)* and *Cov(.)* are the expectation, variance and covariance respectively, r is the correlation [14] coefficient of adjacent two pixels. The higher the value of its value is close to 1, the higher the correlation of adjacent pixels. If images were encrypted by Hill self-invertible matrix encryption algorithm and improved algorithm respectively, then compare the correlation between adjacent pixels in 3 directions.

The related data of Table 1 show that the adjacent pixels of the original image are large data, the correlation coefficient is close to 1 that can be seen the adjacent pixels are highly correlated, the pixels correlation of traditional Hill encryption algorithm is around 0.2, but Improved algorithm is more precise in reducing the correlation of adjacent pixels, making the size of data is close to 0. From the correlation of adjacent pixels that improved encryption algorithm is much better than traditional Hill encryption algorithm.

Fig. 4 and Fig. 5 represent the correlation distribution diagrams of two horizontal adjacent pixels in the original and traditional Hill encryption images, and the correlation distribution of Fig. 5 is more diffuse than Fig. 4, but the correlation distribution between the original image and the traditional Hill encryption image is not obvious enough. Fig. 6 shows the improved algorithm encryption image, the comparison [15] between Fig. 6 and Fig. 5 shows that the correlation distribution is separate completely. From the analysis of the distribution degree of correlation graph, it is shown that the improved encryption algorithm is better than traditional Hill encryption algorithm.

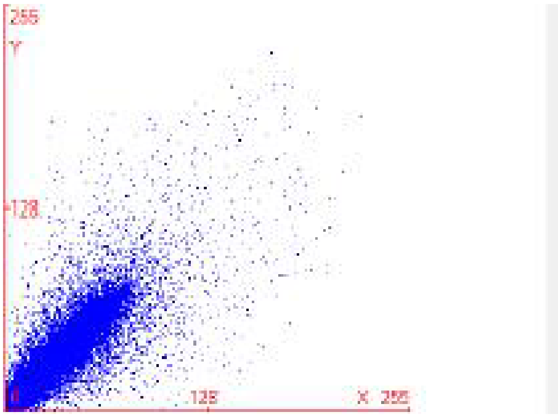

Fig.4. Correlation distribution diagram of original image

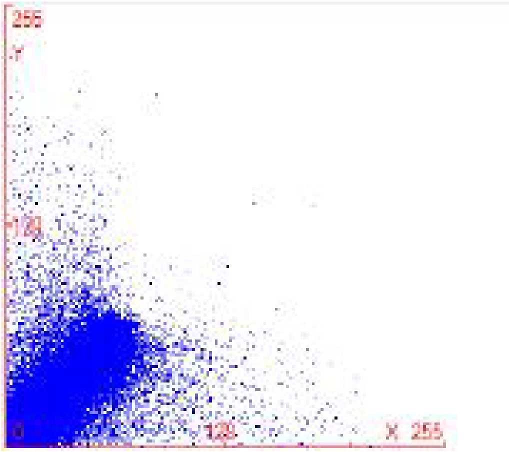

Fig.5. Correlation distribution of Hill encryption algorithm

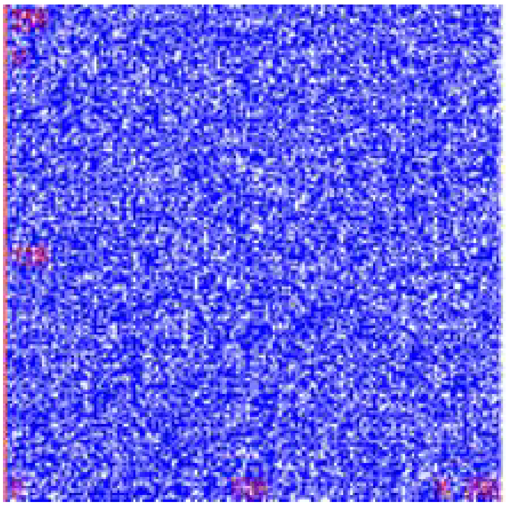

Fig.6. Correlation distribution of improved encryption algorithm

A. Histogram Analysis of Encrypted Image

The variance is used to evaluate the consistency of histogram distribution and indicate the degree of dispersion between the histogram and its average value, the consistency of the distribution is expressed by the size of variance value. The smaller variance, the more uniform distribution. The histogram of image is represented by $hist_i$, and the formula of variance is

$$S = \frac{1}{256}\sum_{i=0}^{255}(hist_i - aver)^2 \tag{18}$$

The aver is

$$aver = \frac{1}{256}\sum_{i=0}^{255} hist_i \tag{19}$$

If the pixel value can be distributed evenly in the range of (0-255) after encryption, the uniform distribution of gray histogram will be regarded as the ideal state. From the above three images, it is found that the histogram (Fig. 8) of the original image (Fig. 7) is uneven, the uniformity of distribution is not ideal, the distribution effect (Fig. 10) of the traditional Hill encryption image (Fig. 9) has not been improved obviously, which has poor performance, and the pixels correlation of the image is not weakened. Compared with the traditional Hill encryption histogram, the histogram (Fig. 12) of the improved algorithm encryption image (Fig. 11) is more concentrated and more gentle. The value of the variance is obviously smaller than variance of the traditional Hill encryption algorithm, which weakens the correlation greatly and it's result is ideal.

Fig.7 Original image

Fig.8 Histogram of original image

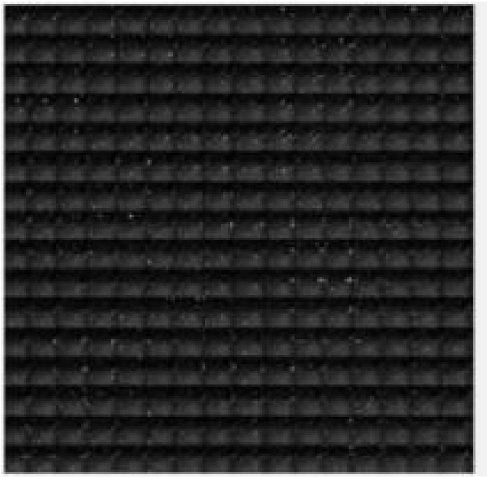

Fig.9 Hill encryption image

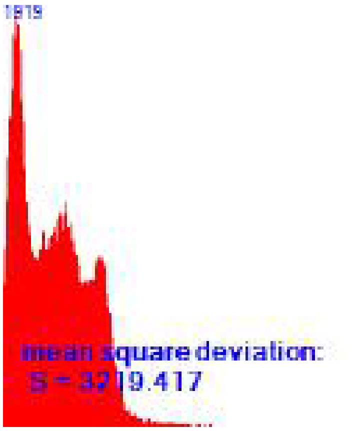

Fig.10 Histogram of Hill encryption image

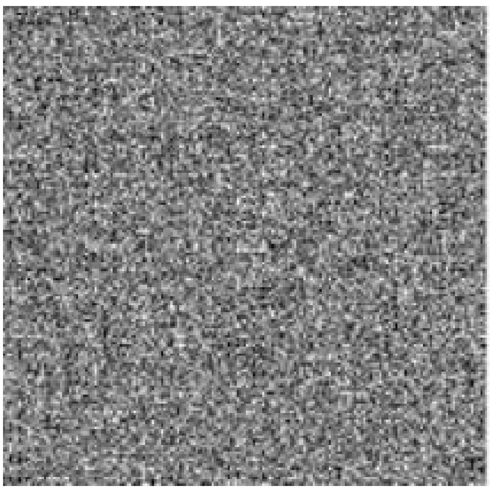

Fig.11. Improved Hill encryption image

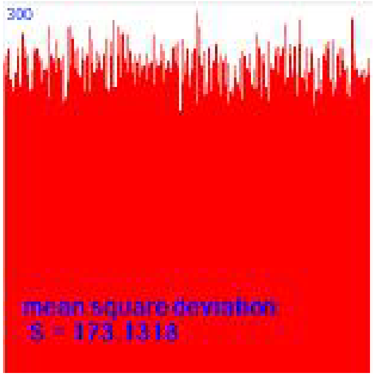

Fig.12. Histogram of improved Hill encryption image

B. Information Entropy and Diffusivity Test

Information Entropy is a concept that used to measure the amount of information in information theory, which contains information content of an image, the system is more orderly that information entropy is more low. The information entropy of the image is

$$H(m) = -\sum_{i=0}^{L-1} p(m_i)\log_2 p(m_i), \sum_{i=0}^{L-1} p(m_i) = 0 \tag{20}$$

L and mi in the formula indicate that gray value is mi and description is *L*, P_{mi} indicates the probability of the appearance of gray value. When the probability of gray value appears in the image is equally, it is largest that information entropy of the image, and its gray distribution is identical. When information entropy is equal to 8 which is proved the random distribution of images is more ideal.

Diffusion is an important nature in the encryption algorithm that is proposed by Shannon in a document, an excellent encryption system must have good diffusivity. The meaning is that when a bit is changed in the original image, the encryption image will be changed in an unpredictable way. The diffusivity of the image encryption algorithm indicates that the output pixels of the encrypted image [16] should be dependent on the input pixels of the original image in a very complicated way, which can resist the attacker's analysis of the algorithm. Attackers usually make small changes to the original image, and then use the algorithms used as attackers to encrypt the original and modified images, and compare the relationship between the original and the encrypted images by comparing two images. This kind of attack becomes a difference attack [17]. One pixel of the original image is modified by the attacker, looking at the changes in the result, it is possible for attacker to find a relationship between the original image and the encrypted image. If a small change in the original image can cause significant changes in the effects of diffusion and chaos, the efficiency of the differential attack is very low and the attack is invalid. In order to verify the influence of a pixel change in the entire encrypted image, two measurement methods are commonly used one is pixel change rate and the other is uniform average change intensity. Two encrypted images are represented by C_1 and C_2 respectively, only one pixel is different in their corresponding original images, the gray values of images C_1 and C_2 at coordinates (i, j) are represented by $C_1(i, j)$ and $C_2(i, j)$ respectively.

$$D(i,j) = \begin{cases} D(i,j) = 0, C_1(i,j) = C_2(i,j) \\ D(i,j) = 1, C_1(i,j) = C_2(i,j) \end{cases} \tag{21}$$

The pixel change rate (NPCR) is defined as:

$$NPCR = \frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1} D(i,j)}{M \times N} \times 100\% \tag{22}$$

In the formula, M is width and N is height of image $C_1$and C_2. The meaning of NPCR is to calculate the percentage of different pixels in two images.

The uniform average change intensity (UACI) is defined as:

$$UACI = \frac{\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\left|C_1(i,j) - C_1(i,j)\right|}{255 \times M \times N} \times 100\% \tag{23}$$

TABLE II

Correlation coefficient

information	*Artwork*	*Hill encryption*	*Article encryption*
entropy	6.234655	6.234655	7.997266
NPCR	0.00	0.000015258789	0.000244240625
UACI	0.00	0.0000150194355	0.0017941463694

From table II ,we can know the information entropy of the original image is equal to 6, the entropy of the traditional Hill encryption algorithm is about 6 that is [18] encrypted. It proves that the traditional Hill encryption algorithm does not make a significant change in the probability of the random distribution of the image, and there is no more agreement on the grey distribution. The information entropy is smaller than the image is more orderly and the probability of the random distribution of the image is smaller. After the improved encryption algorithm to encrypt image, the information entropy is increased from the original data to 8, the information entropy is greater, random distribution of the image is more ideal, the more consistent in the grey distribution and the encryption effect is more ideal.

From the pixel change rate, we can learn that the results of the improved algorithm are larger than the traditional Hill algorithm on the numerical value, and the results of the uniform average change intensity have a little difference.

3.6 CONCLUSION

In this paper, we introduced the video monitoring system of the unmanned ship and the module of the system briefly, aiming at the favourable security and efficient efficiency of traditional image encryption technology, an improved algorithm is proposed that based on Hill encryption algorithm. The algorithm is that a $m \times m$ self-invertible matrix is generated as the key matrix of this algorithm, then dividing the original image into $m \times m$ block image. The *i*th pixels of each image block will be grouped together and make up a temporary $m \times m$ image block, it is convenient for future encryption operation. The temporary image matrix is encrypted with the key matrix A, transposing the encryption image matrix and double-layer encrypting the matrix and putting the obtained matrix into the *i*th position of the final encryption matrix.

We use double-layer encryption strategy to decide the degree of scrambling and enhance the security of the encryption system. Results of experiments show that the algorithm has high efficiency of scrambling and the disorderly effect is uniform and the correlation of adjacent pixels is small, which changes the statistical information of the image and that is more ideal in the random distribution of the image and gray level. Through the analysis of its performance theory and experimental results, it has been shown that the improved algorithm is more successful than traditional Hill encryption algorithm and has great developmental potentialities. From the influence of pixel change rate and uniform average change intensity of encrypted image, the algorithm has not greatly improved the pixel change rate and value is too small that does not reach more than 0.9. Therefore, considering the improvement in these two aspects will be a direction for the future.

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4. Academic Achievement IV: Application of Collaborative Network Technology in Smart Port/Smart Pilot

With the core technology of our own patent "Software-based shipboard smart bridge system" (authorization number: ZL201210065854.9), "An integrated solution for smart port combing big data and IoT technology" (application number: 201710192195.8) and based on the "Beidou high-precision positioning 3D panoramic perception piloting method" (application number: 201710170036.8), we developed the "Smart Port Space-Time Information Cloud Platform". It includes two major subsystems, namely, "portal collaborative information exchange" and "multi-dimensional panoramic precision pilotage." Focusing on the current smart port application requirements, through the combination of high-tech means such as Internet of Things, big data, and cloud computing, Beidou high-precision positioning, LoRa Internet of Things, multi-mode cooperative communication, and space-time information perception and integration, a new generation of smart port space-time information cloud platform is built. It could realize the seamless connection and coordinated interaction between various resources on the supply chain of the port and various participants, so as to form a modern intelligent port with information, intelligence, and optimization.

The characteristic advantages of the Smart Port/Smart Pilot system are mainly reflected in:

1) **Novelty:** The technologies of LoRa Port Private Network, CPS Cooperative Perception, and Spatio-temporal Information Fusion are closely linked to form a system integration method for smart port applications. The construction of the spatio-temporal information cloud platform reflects a new concept of smart ports.
2) **Advanced:** The smart port space-time information cloud platform involves key technologies such as multi-agent sensing, multi-source information fusion, cooperative communication, cooperative control, and distributed computing. Through these core technologies, cross-integration, the core competitiveness of the product is realized.
3) **Uniqueness:** The space-time information cloud platform has great market potential in the industrialization of smart ports. Through the CPS space-time information sensing and fusion technology, it has tapped its landing application products in the field of collaborative information exchange in ports and precise multi-dimensional pilotage.

4.1 Smart Harbour/Port

In order to speeding up the process of port informationization and intelligence, and promote the upgrading and efficiency upgrading of ports. The nationwide is developing a demonstration project for smart ports. At present, it mainly focuses on the integration of information management systems and data centers, and has not yet achieved a complete system of collaborative information exchange between port operations vehicles, port vessels, dock containers, and operating personnel. The port intelligence has not yet formed a standardized application. The system, based on the multi-mode LoRa distributed port private network system, will provide an optimized solution.

The ultimate smart port may be the fully automated port where all devices are connected via the so-called Industrial Internet of Things. In port operations we see an integration of various infrastructures, both physical and IT. That includes different network technologies like radio, LAN, WAN and WLAN, RFID and positioning technologies. The Fig. 1 shows the smart port data service, includes: Green Center Solutions, Data Center Infrastructure, Data Center Services, and Big Data Analysis & Application. Fig. 2 and Fig. 3 describe the smart port scenario and architecture.

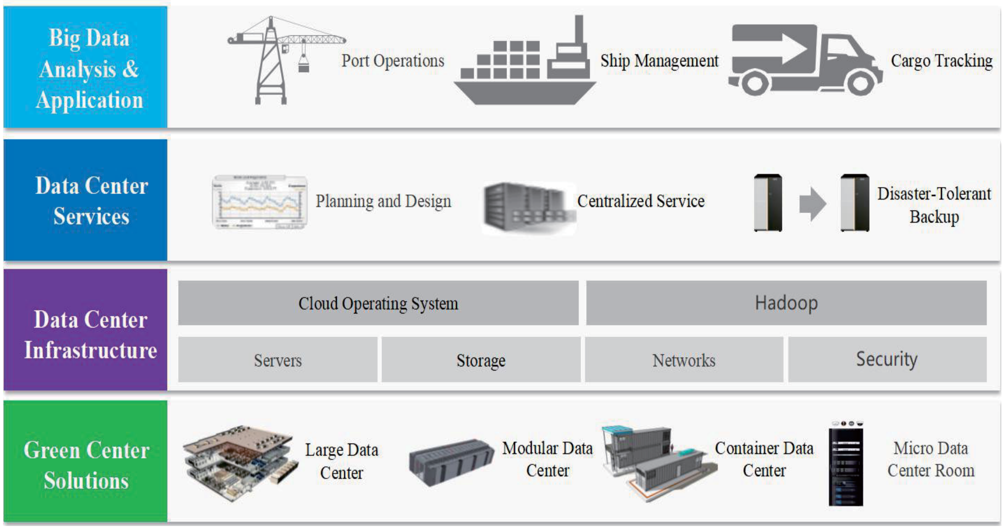


Fig. 1 Smart Port Data Service

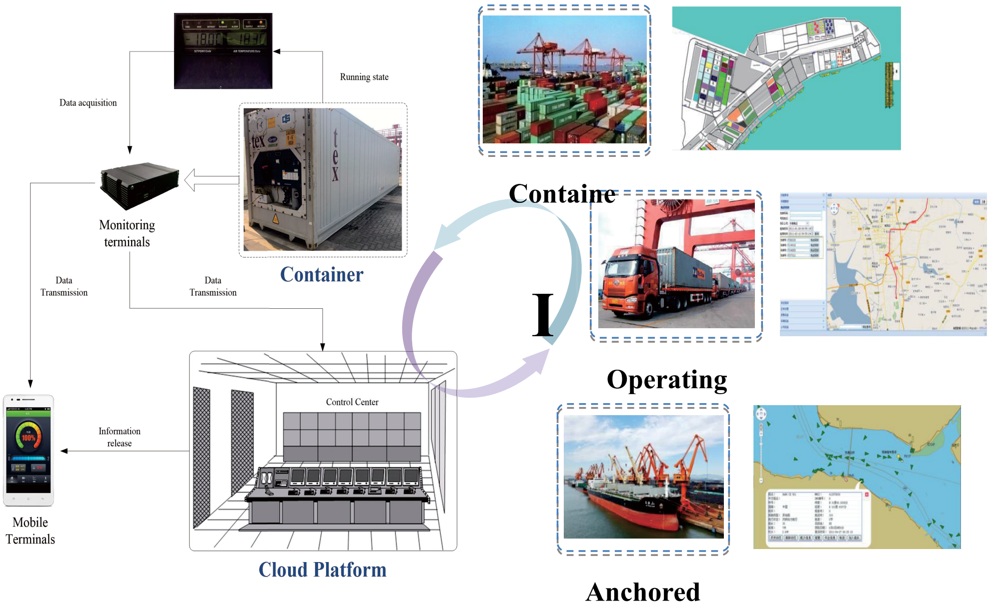


Fig. 2 Smart Port Scenario

IAMU International Association of Maritime Universities (DMU)

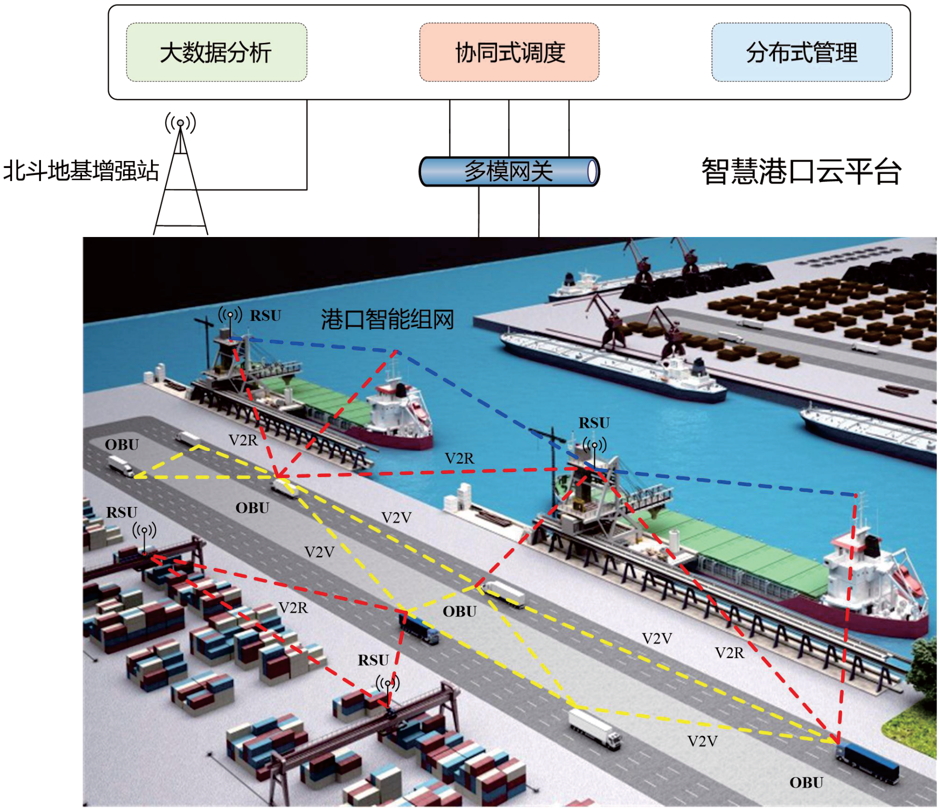


Fig. 3 Smart Port Architecture

Contents of port construction :

1）Beidou Foundation Enhancement Station (Real-time positioning with Centimeter level)

2）Multi-mode Intelligent Networking (LoRa + WiFi + Beidou)

3）Big Data Cloud Platform (Intelligent analysis and decision making)

4）Smart Port Integrated Services (Thorough perception and collaboration)

Here, BeiDou Navigation Satellite System is Chin’s global navigation satellite system which has been developed independently. BeiDou Navigation Satellite System is composed of three parts: the space section, the ground section and the user section.

Innovation:

1) Through multi-mode LoRa distributed networking, collaborative information exchanges are performed between vehicles, ships, containers, and operators to break the traditional centralized networking mechanism and combine with Beidou’s high-precision space-time information platform to form a three-dimensional port intelligence system ;

2) Through the real-time information interaction between vehicle-vehicle, vehicle-vehicle, and vehicle-cargo, autonomous coordination and intelligent guidance mechanisms are formed. The multi-agent collaborative information exchange system can truly eliminate information islands and ensure the reliable transmission of information.

3) The service area partition mechanism using multi-agent mobile probability distribution provides an optimized allocation strategy for port business services. Based on different service areas, strict priority message distribution mechanism ensures the provision of reliable services for high-priority services.

4.2 Smart Pilot

According to the statistics of the International Pilotage Association, 80% of the world's marine accidents are pilotage accidents; according to the accident statistics and special research results of the British Shipowner's Insurance and Pals Association, the Japan Coast Guard Agency, the Bremen Shipping Economic Research Institute, and the Australian Department of Transportation, 80 % of pilotage accidents were caused by human error. The current auxiliary pilot system uses AIS, radar and electronic chart systems, with an accuracy of about 10 meters. Important information is not intuitively displayed, and pilots are more accustomed to relying on visual observation. The multi-dimensional panoramic precision pilotage system of port ships adopts advanced technologies such as 3D GIS, panoramic video, high-precision real-time positioning, and ECS electronic charts, providing pilots with an intuitive and real-world experience of "what you see is what you get", and assisting pilots to be faster and more Accurate piloting work is safely completed. Fig.4 describes the smart pilot scenarios, including Offshore Scenario, Channel Scenario, and Harbour Scenario. Fig.5 describes the smart pilot modes. The demo of smart pilot is shown in Fig. 6.

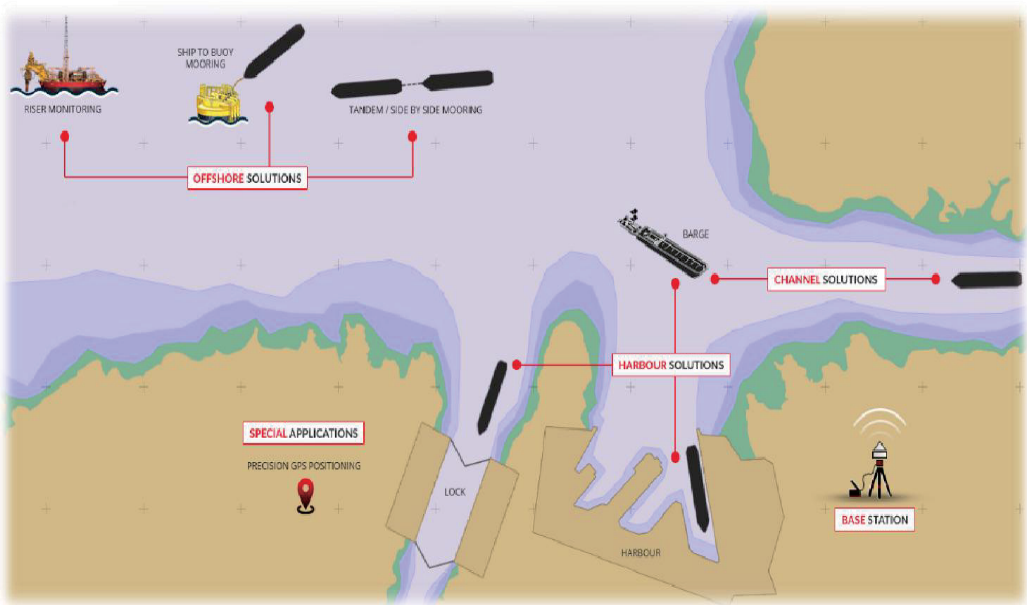
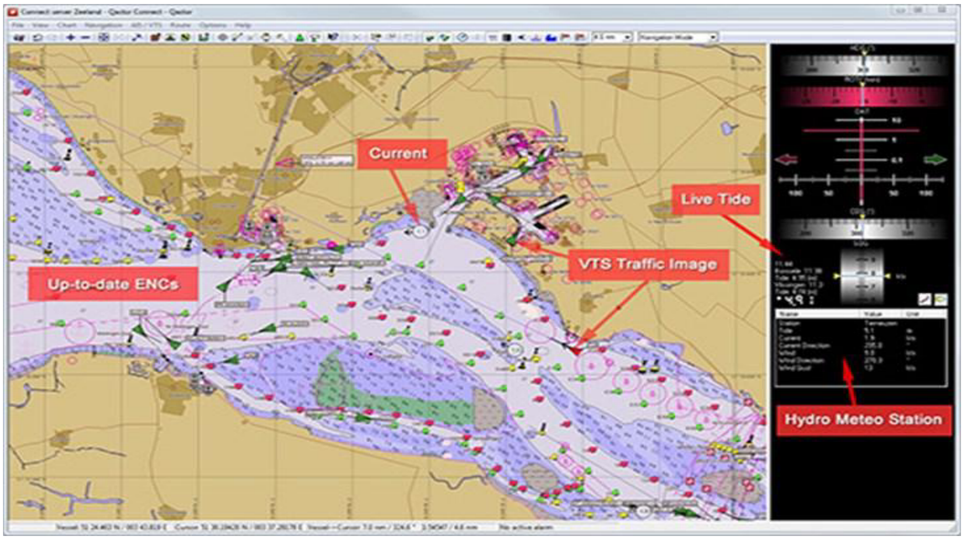
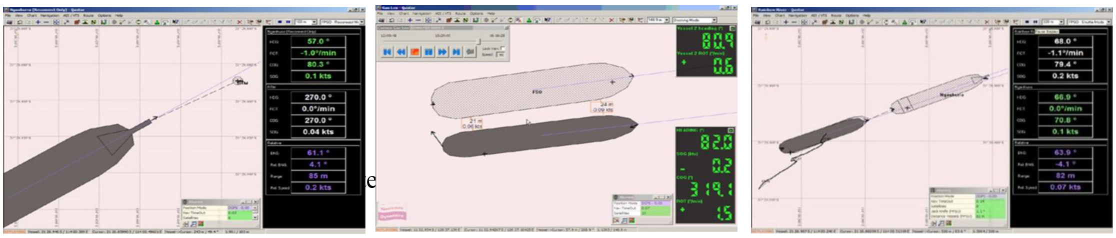


Fig. 4 Smart Pilot Scenario





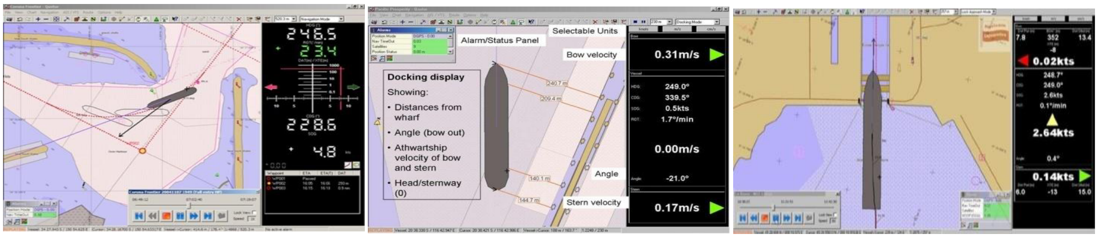
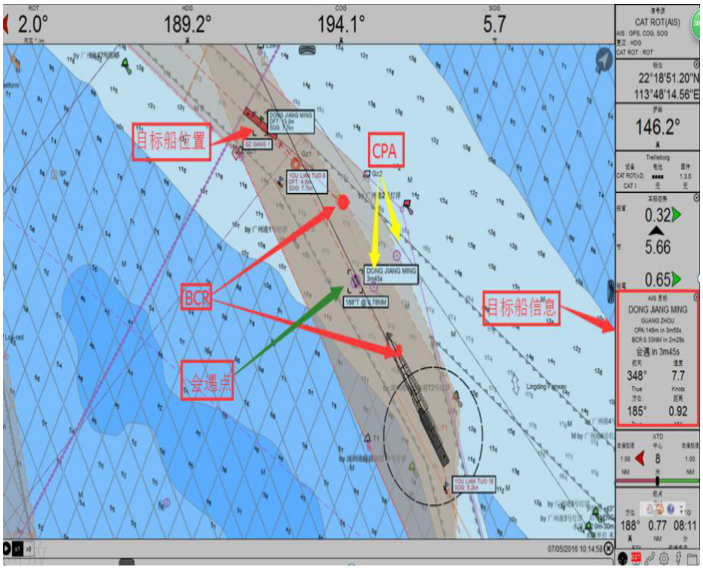
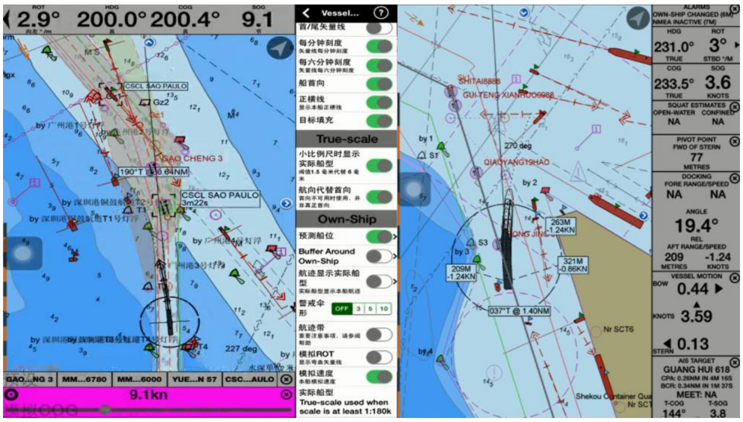


Fig. 5 Smart Pilot Modes





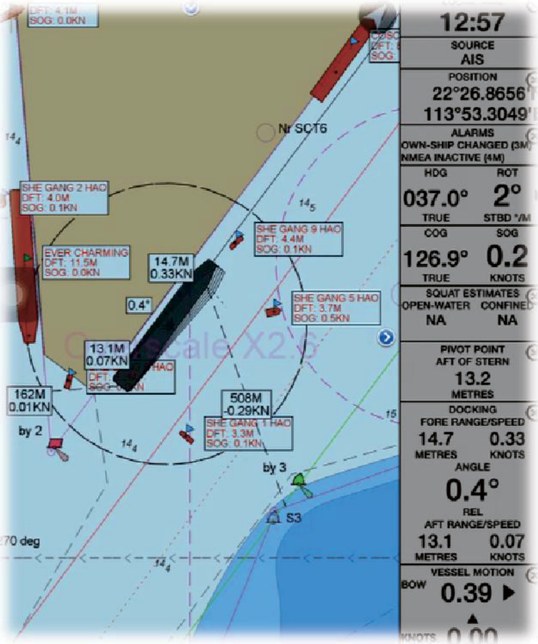


Fig. 6 Smart Pilot Demo

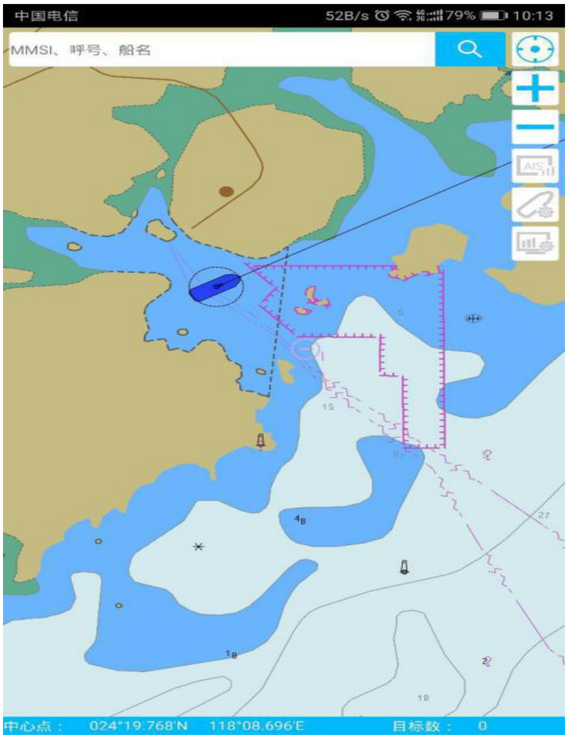
Our Solutions and Innovation:

1) Using drone as a carrier, using three-dimensional tilted photographic measurement technology to obtain three-dimensional GIS data in the port area, through professional processing, rapid completion of modeling, output of real three-dimensional GIS model, can be full-scale, full-featured to demonstrate the real environment of the port area, With the advantages of high precision, high efficiency, high realism and low cost.

2) The traditional sub-camera monitoring has the problems of analysis deviation or error, decision delay or error, and delay in emergency response; the system adopts panoramic video technology and supports roaming, which can realize panoramic, real-time and multi-angle monitoring of the whole site, and can realize cross-camera Target detection, tracking recognition, intelligent alarm for abnormal situation under panoramic monitoring.

3) Adopt a series of processing methods such as standardization of observation data, estimation of clock difference, formation of differential observations, and solution of integer ambiguity; Beidou high-precision real-time positioning technology eliminates most of the errors from satellites, propagation and reception, and the positioning accuracy is achieved. Sub-meter-level; realizes information fusion of 3D GIS, panoramic video and electronic charts, and supports one-click switching of 3D panoramic view and electronic chart view.

4) Innovation based on SAR shipborne radar to solve the problem of navigating in fog. Fig.7 shown our Smart Pilot Interfaces and Solutions.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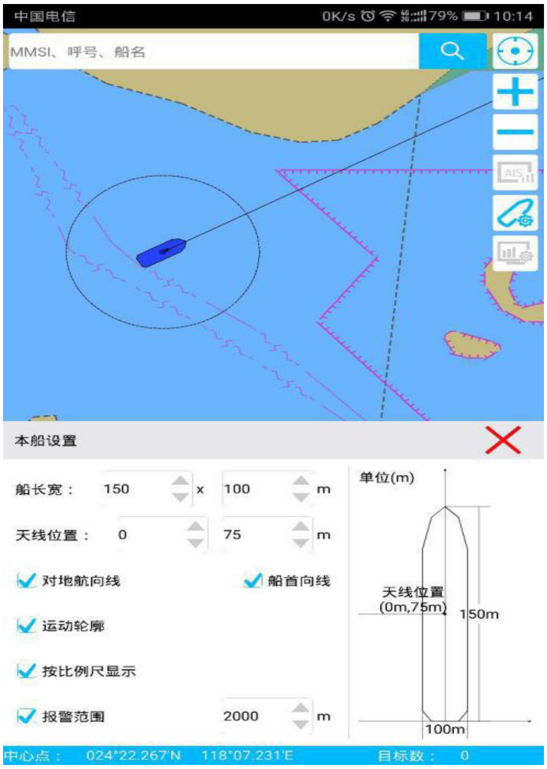
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Fig.7　Smart Pilot Interface

Fig.8 Smart Pilot Application

After repeated testing and evaluation, our scheme "Smart Port Multi-Mode Communication Protocol and Resource Scheduling Algorithm" is applied to LoRa Multi-Mode Gateway products. It shows that the algorithm can ensure the accuracy and real-time performance of the communication system under the complicated port environment. In summary, the “development and industrialization of cloud-portable space-time information cloud platform” in this project conforms to the current industrial development trend of smart ports and intelligent transportation. In the process of project development, the key technologies used are of advanced level and have strong technological innovation, which plays an important supporting role in the development and industrialization of the smart port space-time information cloud platform. Fig.8 shows the Smart Pilot Application.

In summary, with the development of large-scale, automated, and intelligent ships, smart ships are the mainstream of marine transportation development. The smart pilot relying on demilitarization will surely go from qualitative to quantitative, from manual to automatic, and from experience to scientific development. The automatic berthing control technology of ships has become a difficult problem to be solved, including the accurate sensing and integration of information, and the use of deep learning, neural networks, artificial intelligence AI technology, etc. . In particular, the integration of GIS big data information in the GIS of the port area promotes the deep integration of maritime space information, artificial intelligence, intelligent control and other technologies and transportation.

International Association of Maritime Universities

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