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Hierarchical Maritime Radio Networks for Internet of Maritime Things

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ABSTRACT Despite the potential benefits of a maritime Internet of Things, a number of issues hinder its realization, including the need for wide area coverage and cost-effectiveness. Toward these needs, a model is first presented for uplink maritime radio communications that hierarchically employ Wi-Fi and cellular links for data transmission from marine user equipments (MUEs) on a ship to a cellular base station with distributed antennas (DAs) along a coastline. Then, the performances are evaluated given in terms of average data rate and outage probability in the hierarchical maritime radio networks. When evaluating the performances, heterogeneous channel characteristics of the hierarchical networks are taken into account in which Rayleigh fading is considered for the MUE-ship links, whereas shadowed-Rician fading is considered for the ship-DA links. Moreover, the effects due to various transmission errors that can be occurred at different communication layers are reflected in determining the quality of service (QoS) requirements of a ship. With the help of authors' analysis, an antenna selection algorithm is proposed under which the minimum size of a service cloud can be found to support the QoS requirements of MUEs with a ship. The numerical evaluations demonstrate the validity of the proposed algorithm.

INDEX TERMS Cellular networks, distributed antenna (DA), data minimization, Internet of maritime thing (IoMT), hierarchical networks, maritime communications, quality of service (QoS), wireless communication.

I. INTRODUCTION

IN the terrestrial domain, the realization of the Internet of Things (IoT) has brought tremendous benefits to a variety of fields such as industrial control, home automation, and e-health care [1]. Its success has inspired great research efforts toward the realization of a maritime IoT, also called the Internet of Maritime Things (IoMT), to extend the benefits of the IoT to the maritime domain. IoMT system aims at providing internet services for maritime applications on and/or under water surface such as ocean sampling, environmental monitoring, oceanographic data collection, disaster prevention, assisted navigation [2]. However, the realization of an IoMT is hindered by a number of factors, for example, the need for a wide area coverage, cost-effectiveness issues, and so on. Among them, this paper focuses on the very restricted infrastructure of maritime radio networks. To realize an IoMT, the coverage requirements of maritime networks must be much larger than those of terrestrial networks, while various quality of service (QoS) requirements of marine user equipments (MUEs) are expected to be satisfied on a similar level as terrestrial user equipments.

For many decades, very high frequency- and high frequency-based communication systems have been integrated into maritime networks because they can cover a wide area [3]–[6]; however, they have small capacities and are unavailable for popular internet applications in maritime environments. As an alternative, satellite communications can provide such services [7]–[10], but it is not cost-effective for the ever-increasing level of human activity in the ocean.

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A. RELATED WORK

In order to support a variety of QoS requirements for MUEs in a cost-effective manner, terrestrial cellular communication technologies such as LTE, Wi-Fi, and WiMAX have been investigated for data transmission in maritime networks [11]–[19]. The authors in [11] developed a framework for applying cellular techniques in coastal networks. Moreover, to guarantee QoS requirement of MUEs, an antenna selection scheme was investigated, which can form a virtual service cloud for a target user. The work of [12] presents an architecture of coastal networks based on LTE technology which is similar to work of [11]. The network architecture was designed to support various maritime wireless service scenarios. Especially, the advanced technologies employed for cellular networks such as device-to-device (D2D) and multiple input multiple output (MIMO) are integrated into the proposed architecture to support more efficient data transmission. In [13], an LTE-Maritime system was first introduced, and the system performances in terms of reference signal received power, signal-to-interference-plus-noise ratio, and throughput were evaluated through field tests to identify the validity of the system. In [14], a coordinated satellite and terrestrial architecture was investigated to provide real-time and broadband internet services. Also, a voyage-based resource allocation strategy was presented to improve mobility robustness, coordinate inter-cell interference, and reduce system power consumption. The work of [15] designed a wireless multi-hop backhaul network for a heterogeneous maritime system for the purpose of not only expanding the coverage and but also improving the connectivity through an ad-hoc mesh network between the access routers in different boats. Then, the path selection algorithm was discussed for the improvement of throughput and coverage performances. The algorithm was based on the analysis of the quality of various types of links using signal-to-noise ratio (SNR) and expected transmission count metrics. In [16], high altitude platform (HAP)-based maritime communication was introduced to improve the quality of coverage on the sea. For the optimal operation of HAP, the topology design problem was formulated, which aims to minimize the total deployment cost subject to coverage, reliability, and topology constraints of maritime network. In [17], the maritime communication system including massive MIMO maritime base stations (BSs) was investigated. For hybrid digital and analog precoding, the large-scale channel state information (CSI) at the transmitter was only considered to reduce the implementation complexity and overhead of the system. Also, the problem of fairness-oriented precoding design was addressed for which a max-min optimization problem was formulated and solved in an iterative way. The authors in [18] evaluated the performances given in terms of the network throughput and energy sustainability in green-energy-powered maritime wireless communication networks. Using WiMAX technology, they investigated how to optimize the schedule of data traffic tasks for maximizing the network throughput. To this end, an optimization problem was formulated to maximize the weight of the total delivered data packets while guaranteeing that harvested energy can successfully support transmission tasks. In [19], a WiMAX-based maritime wireless mesh network was introduced, under which ships are network nodes that are connected to a BS on land across multiple hops. In the considered mesh network, a routing protocol that piggybacks routing information on WiMAX mesh medium access control (MAC) control messages was presented.

B. PROBLEM STATEMENT

Compared with terrestrial radio networks, there exist three crucial differences in the communication environments of maritime radio networks as described below. First is the different distribution and density of MUEs. In the marine networks, MUEs are usually clustered by ships and these ships are moved on routes. Whereas, in the terrestrial networks, users are distributed in the plane and they are directly associated to cellular BSs. Also, the density of MUEs is non-uniform in the marine networks, in which the density of ships is low while the density of MUEs is high with the ships. Second is the necessity of hierarchical networks. Compared with the terrestrial networks, there exists very restricted infrastructure of the maritime networks. As such, as a ship are further from offshore, the link qualities between MUEs on a ship and their associated cellular BSs are getting worsen, but the expectation of QoS requirement by the MUEs is still not reduced. To deal with this problem, data transmissions via hierarchical maritime networks are indispensable, in which each MUE on a ship transmits its data to a cluster head (CH) on the compass deck of the ship, and then the CH having a transceiver with high-gain antenna transmits the aggregated data to the BS, instead of MUEs. Such the hierarchical networks can allow MUEs to communicate over a long distance while guaranteeing various QoS requirements. Third is the consideration of heterogeneous channels. When adopting the hierarchical maritime networks, different channel characteristic must be considered. In the ocean, there are few obstacles such as mountains, buildings, and trees unlike on land. This means that the line-of-sight (LoS) path can be available between the CH and the cellular BS. On the other hand, since MUEs are non-uniformly distributed within a ship, non-LoS path is generally available between the MUE and the CH. Due to these differences, various communication issues such as network architecture and QoS-guaranteed mechanisms need to be re-considered.

However, to the best of authors' knowledge, there was no existing work that simultaneous considers the three crucial characteristics in maritime communication networks. Motivated by this fact, authors have aimed to conduct the numerical performance evaluation of maritime radio networks while reflecting the above three characteristics in the maritime networks.

C. CONTRIBUTION

Authors highlighted their contributions in this work as follows:

- In this study, an analytical framework was established to evaluate the performances of hierarchical maritime radio networks for data transmission from MUEs on a ship to a cellular BS on land. In the proposed framework, MUEs on a ship are clustered by the ship, and their distribution on the ship is modeled by Thomas cluster process. As a scenario of uplink data transmissions, each MUE on a ship first transmits its data to a CH on the ship compass deck through Wi-Fi links. Then, the CH having a transceiver with a high-gain antenna collects the data from the MUEs and re-transmits the aggregated data to distributed antennas (DAs) through cellular links, where the DAs are connected via high-speed wired communication links (i.e., optical fibers) to the cellular BS.
- Under the proposed network model, network performances given in terms of the average data rate and outage probability of a ship were numerically evaluated. When conducting the performance evaluations, heterogeneous channel characteristics of the hierarchical networks were reflected where Rayleigh fading is considered for the MUE-CH links, whereas shadowed-Rician fading is considered for the CH-DA links. In addition, various transmission errors that can be occurred at different communication layers were applied to determine the QoS requirements of a ship.
- With the help of performance evaluations, a simple antenna selection algorithm was proposed, which forms a virtual service cloud for MUEs on a ship to guarantee their QoS requirements under the considered networks. By means of the proposed algorithm, the minimum size of the service cloud can be driven to support the QoS requirements of MUEs and it can leads to energy efficient operations for the maritime radio networks.

D. NOTATIONS

Throughout this paper, upper case boldface, lower case boldface, $\mathbf{A}^H$, and $\|\mathbf{a}\|$ indicate a set $\mathbf{A}$, vector $\mathbf{a}$, the conjugate transpose and the L^2 norm, respectively. Also, the notations $\mathbb{E}[\cdot]$ denotes the expectation and $\mathbb{C}^{M\times 1}$ denotes the set of $M \times 1$ complex vectors.

II. SYSTEM MODEL

As illustrated in Fig. 1, uplink maritime radio networks are considered where DAs are located along a coastline and are connected via high-speed wired communication links to a cellular BS. MUEs are clustered by each ship equipped with a CH, which have a transceiver with an omni-directional antenna on the compass deck of the ship. Let $\mathbf{U}_i = \{1, 2, ..., |\mathbf{U}_i|\}$ be a set of MUEs on ship i and $\mathbf{C}_i = \{1, 2, ..., |\mathbf{C}_i|\} \subset \mathbf{C}_i^{all}$ is denoted as a set of DAs serving ship i, also called a service cloud for ship i, where $\mathbf{C}_i^{all}$ is the set of all DAs to which ship i can be associated.

In each ship, the MUEs attempt to transmit their data to a CH, and then the CH collects the data from the MUEs and re-transmits the aggregated data to the DAs. In these networks, the CHs can be regarded as mobile routers between

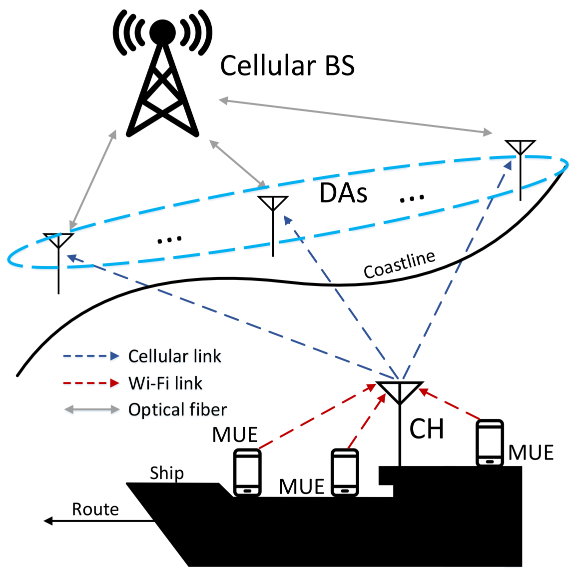


FIGURE 1. An illustration of hierarchical maritime radio networks.

the MUEs and DAs. Wi-Fi transmission is adopted for the MUE-CH because it is suitable for small-area communication networks. Thus, MUEs with a packet to transmit should follow a distributed coordination function (DCF) to access sharing channels such as 900 MHZ, 2.4 GHz, and 5 GHz spectrum bands. As the MAC protocol of the IEEE 802.11 standard, the DCF maximize the throughput while preventing packet collisions by employing a carrier-sense multiple access with collision avoidance (CSMA/CA) with binary exponential backoff [20]. On the other hand, for CH-DA links, cellular transmissions are adopted to support long-range coverage and high-rate transmission in the ocean. Different channel characteristics of the hierarchical networks are also considered. In the ocean, there are few obstacles such as mountains, buildings, and trees unlike on land. This means that the LoS path is available for the CH-DA links, whereas non-LoS paths are usually available for the MUE-CH links.

Clustered MUEs by ship are deployed by the Thomas cluster process, where each position is scattered using a symmetric normal distribution with variance σ^2 around the origin, and the CH on the ship is located at the origin. The positions of the MUEs are given as follows [21]:

$$f_X(\mathbf{x}) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{\|\mathbf{x}\|}{2\sigma^2}\right), \quad (1)$$

where $\mathbf{x}$ is the location of the MUEs with $\|\mathbf{x}\|^2 \leq l_{u,0}$ and $l_{u,0}$ is the length of ship.

The received signals at the set of DAs $\mathbf{C}_i$ for i-th ship can be expressed as follows:

$$\mathbf{y}_{\mathbf{C}_i,i} = \mathbf{h}_{\mathbf{C}_i,i} \cdot s_i + \mathbf{z}_{\mathbf{C}_i}, \quad (2)$$

where $\mathbf{h}_{\mathbf{C}_i,i} \in \mathbb{C}^{|\mathbf{C}_i|\times 1}$ denotes the channel coefficient between i-th ship and DAs $\mathbf{C}_i$, s_i denotes the information signal with power constraint, i.e., $|s_i|^2 \leq P$, P denotes maximum transmit power, and $\mathbf{z}_{\mathbf{C}_i} \in \mathbb{C}^{|\mathbf{C}_i|\times 1}$ denotes the complex additive white Gaussian noise with zero-mean and variance of N_0. As previously mentioned, a LoS path can exist in CH-DA links, such that the channel vector $\mathbf{h}_{\mathbf{C}_i,i}$ can be modeled with independent and identically distributed (i.i.d.) Rician fading with fluctuating (e.g. random) LOS component, i.e., shadowed-Rician fading, as given by $\mathbf{h}_{\mathbf{C}_i,i} = \overline{\mathbf{h}}_{\mathbf{C}_i,i} + \widetilde{\mathbf{h}}_{\mathbf{C}_i,i}$. The elements of the LoS component $\overline{\mathbf{h}}_{\mathbf{C}_i,i}$ are expressed as i.i.d. Nakagami-m random variables with average power Ω, where m denotes the severity of shadowing varying over the range $m \geq 0$. The elements of the scattered component $\widetilde{\mathbf{h}}_{\mathbf{C}_i,i}$ can be i.i.d. complex Gaussian random variables with zero-mean.

To serve the i-th ship, the set of DAs $\mathbf{C}_i$ is selected among all available DAs $\mathbf{C}_i^{all}$ according to the QoS requirement of MUEs on ships. When a ship travels according to its route, the set of DAs should be changed via handover procedure. Without loss of generality, this paper considers the specific time slot to evaluate the performance of the proposed network, such that the handover effect is not handled in this paper.

III. PERFORMANCE ANALYSIS

A. AVERAGE DATA RATE AND OUTAGE PROBABILITY FOR A SHIP

In this section, the average data rate and the outage probability are analyzed for CH-DA links in the considered maritime radio networks. Hereafter, the CH-DA links are also referred to as the ship-DA links interchangeably. The CSI of ship-DA links can be estimated by multiple CSI-reference signal (CSI-RS) process from a cellular BS, which is specified in LTE release 16 for the coordinated multiple-point operations such as the coordinated beamforming/scheduling, dynamic point selection, and joint transmission [22]. In case of orthogonal frequency division multiplexing systems adopted in LTE and 5G new radio, the channel estimation can be performed by discrete Fourier transform-based linear minimum mean square estimator [23] or singular value decomposition method [24]. In this work, it is assumed that full CSI is perfectly known at the receiver side, i.e., the cellular BS. If the perfect channel knowledge of ship-DA links is not available at the receiver side, a variety of receiver detection techniques that can improve the received SNR such as maximum ratio combining, equal-gain combining, and selection combining [25] may not be utilized. This is because under the imperfect channel knowledge, the receiver detection techniques do not guarantee the network performance enhancement, whereas the computational complexity at the receiver increases [26], [27].

For the ship-DA links, the maximum ratio combining scheme can be exploited to achieve a diversity gain. Thus, the receive beamforming vector can be constructed at the BS as follows:

$$\mathbf{w}_{\mathbf{C}_i,i} = \frac{\mathbf{h}_{\mathbf{C}_i,i}^H}{\left\|\mathbf{h}_{\mathbf{C}_i,i}\right\|}, \tag{3}$$

Based on (2) and (3), the average date rate of i-th ship is given as follows:

$$\begin{aligned}\overline{R_i} &= \mathbb{E}_{\mathbf{h}_{\mathbf{C}_i,i}}\left[\log_2\left(1+\gamma_i\right)\right] \\ &= \mathbb{E}_{\mathbf{h}_{\mathbf{C}_i,i}}\left[\log_2\left(1+\frac{P\left|\mathbf{h}_{\mathbf{C}_i,i}\cdot\mathbf{w}_{\mathbf{C}_i,i}\right|^2}{N_0}\right)\right] \\ &= \mathbb{E}_{\mathbf{h}_{\mathbf{C}_i,i}}\left[\log_2\left(1+\frac{P\left\|\mathbf{h}_{\mathbf{C}_i,i}\right\|^2}{N_0}\right)\right],\end{aligned} \tag{4}$$

where γ_i is the received SNR at the receiver side. For the shadowed-Rician fading, the moment generating function of $\left\|\mathbf{h}_{\mathbf{C}_i,i}\right\|^2$ is given as

$$M_{\left\|\mathbf{h}_{\mathbf{C}_i,i}\right\|^2}(s) = \frac{\left(\delta\left(s+1/(2b)\right)/(s+\delta)\right)^{m|\mathbf{C}_i|}}{2b\left(s+1/(2b)\right)^{\min\{|\mathbf{C}_i|,\mu\}}}, \tag{5}$$

where $\delta = \frac{m}{2bm+\Omega}$, $\mu = \max\{|\mathbf{C}_i|, \lfloor m|\mathbf{C}_i|\rfloor\}$, $\max\{\cdot,\cdot\}$ and $\min\{\cdot,\cdot\}$ denote the greater value between the two and the less value between the two, respectively. Based on (5), the following probability density function (PDF) of γ_i achieved [28] for $\gamma_i > 0$ is used:

$$\begin{aligned}f_{\gamma_i}(x) = &\sum_{j=0}^{\beta}\binom{\beta}{j}\cdot(2b)^{(m-1)|\mathbf{C}_i|+j-\beta}\cdot\delta^{m|\mathbf{C}_i|+\frac{j-\mu}{2}} \\ &\cdot\bar{\gamma}^{\frac{j-\mu}{2}}\cdot x^{\frac{\mu-j-2}{2}}\cdot e^{-\frac{\delta}{2\bar{\gamma}}x}\left[\frac{\mathcal{M}_{\frac{\mu+j}{2},\frac{\mu-j-1}{2}}\left(\frac{\delta}{\bar{\gamma}}x\right)}{\Gamma(\mu-j)}\right. \\ &\left.+\phi\cdot\frac{\mathcal{M}_{\frac{\mu+j+1}{2},\frac{\mu-j}{2}}\left(\frac{\delta}{\bar{\gamma}}x\right)}{\Gamma(\mu-j+1)}\right],\end{aligned} \tag{6}$$

where $\beta = (\mu - |\mathbf{C}_i|)^+$, $(x)^+$ denotes that if $x \geq 0$ then x, otherwise 0, $\lfloor x\rfloor$ denotes the largest integer value not greater than x, $\bar{\gamma} = \frac{P}{N_0}$ denotes the SNR, $\Gamma(\cdot)$ denotes the gamma function, $\mathcal{M}_{\upsilon,\nu}(\cdot)$ denotes the Whittaker function, and $\phi = \frac{m|\mathbf{C}_i|-\mu}{2b}\cdot\frac{\Omega\delta}{m}$. In addition, $2b$ is the average power of the multipath component, m is the severity of shadowing variation with $m = \sum_{j=1}^{|\mathbf{C}_i|} m_j$, and Ω is the average power of the LoS component with $\Omega = \sum_{j=1}^{|\mathbf{C}_i|}\Omega_j$.

With (6), the average data rate (4) for a given set of antennas $|\mathbf{C}_i|$ that constitutes the service cloud for ship i can be written as following lemma.

Lemma 1: The average achievable data rate of the i-th ship is obtained as follows:

$$\begin{aligned}\overline{R_i} = &\frac{1}{\ln 2}(2b)^{(m-1)|\mathbf{C}_i|}\cdot\delta^{m|\mathbf{C}_i|-\mu} \\ &\cdot\sum_{j=0}^{\beta}\left[\frac{\delta^j}{\Gamma(\mu)}\cdot\mathcal{G}_{4,3}^{2,3}\left(-\frac{\overline{\gamma}}{\delta}\middle|\begin{matrix}-\mu+j+1,1,1,0\\ j,1,0\end{matrix}\right)\right. \\ &\left.+\frac{\phi\cdot\delta^{j-1}}{\Gamma(\mu+1)}\cdot\mathcal{G}_{4,3}^{2,3}\left(-\frac{\overline{\gamma}}{\delta}\middle|\begin{matrix}-\mu+j,1,1,0\\ j,1,0\end{matrix}\right)\right],\end{aligned} \tag{7}$$

where $\mathcal{G}_{y,z}^{p,q}\left(\cdot\middle|\begin{matrix}\cdots\\ \cdots\end{matrix}\right)$ is the Meijer-G function.

Proof: See Section. VI-B. ∎

Given the QoS requirements of ship i denoted by R_i^{th}, the outage probability of the ship-DA links can be defined as follows:

$$P_{out}\left(R_i^{th}\right) \triangleq Pr\left(R_i \leq R_i^{th}\right) = F_{R_i}\left(R_i^{th}\right), \tag{8}$$

where $F_{R_i}(x)$ denotes the cumulative distribution function (CDF) of the random variable R_i and it can be obtained by following lemma.

Lemma 2: Since $R_i = \log_2(1+\gamma_i)$, the outage probability of ship i can be written as follows:

$$\begin{aligned} P_{out}(R_i^{th}) &= \Pr\left(R_i \leq R_i^{th}\right) = F_{\gamma_i}\left(e^{R_i^{th}\ln 2} - 1\right) \\ &= \sum_{j=0}^{\beta}\binom{\beta}{j}\cdot(2b)^{(m-1)|\mathbf{C}_i|+j-\beta} \\ &\cdot \delta^{m|\mathbf{C}_i|+\frac{j-\mu-1}{2}}\cdot\left(2^{R_i^{th}}-1\right)^{\frac{\mu-j-1}{2}}\cdot e^{-\frac{\delta}{2\bar{\gamma}}\left(2^{R_i^{th}}-1\right)} \\ &\cdot\left[\frac{\mathcal{M}_{\frac{\mu+j-1}{2},\frac{\mu-j}{2}}\left(\frac{\delta}{\bar{\gamma}}\left(2^{R_i^{th}}-1\right)\right)}{\Gamma(\mu-j+1)}\right. \\ &\left.+\frac{\phi\left(2^{R_i^{th}}-1\right)^{\frac{1}{2}}}{(\delta\bar{\gamma})^{\frac{1}{2}}}\frac{\mathcal{M}_{\frac{\mu+j}{2},\frac{\mu-j+1}{2}}\left(\frac{\delta}{\bar{\gamma}}\left(2^{R_i^{th}}-1\right)\right)}{\Gamma(\mu-j+2)}\right]. \end{aligned} \tag{9}$$

Using (9), the outage probability can be obtained with respect to the rate threshold R_i^{th}.

B. QOS REQUIREMENT FOR A SHIP

Let R_i^u denote the data rate requirement for MUE $u \in \mathbf{U}_i$ on ship i. As such, the data rate requirement for all MUEs on ship i can be defined as follows:

$$R_i^{th} = \frac{1}{P_{succ}}\sum_{u=1}^{|\mathbf{U}_i|} R_i^u, \tag{10}$$

where P_{succ} is the average probability of successfully transmitting a packet from a MUE and a CH, and it can be presented as follows:

$$P_{succ} = P_{succ}^{PHY}\cdot P_{succ}^{MAC}, \tag{11}$$

where P_{succ}^{PHY} and P_{succ}^{MAC} are the average probabilities of successful packet transmission at the physical (PHY) and MAC layers, respectively.

More specifically, at the PHY layer, data transmission is successful when the received signal power is larger than the threshold value ρ as follows:

$$\begin{aligned} P_{succ}^{PHY} &= \int_0^\infty Pr\left[h_u l_u^{-\alpha}P \geq \rho\right] f_D(l_u)\, dl_u \\ &= \int_0^\infty \exp\left(-\frac{\rho}{P}l_u^\alpha\right) f_D(l_u)\, dl_u, \end{aligned} \tag{12}$$

where h_u is the small-scale fading factor of inter-cluster channel u, which is modeled by Rayleigh fading with unit mean and $l_u^{-\alpha}$ is the large-scale fading factor of inter-cluster channel u, where l_u is the distance between MUE u and the CH and α is the path-loss exponent. Moreover, $f_D(l_u)$ is the PDF of l_u, which can be obtained using (1), as given by

$$f_D(l_u) = \frac{\frac{l_u}{\sigma^2}\exp\left(-\frac{{l_u}^2}{2\sigma^2}\right)}{1-\exp\left(-\frac{l_{u,0}^2}{2\sigma^2}\right)}, \quad l_u \leq l_{u,0}. \tag{13}$$

By replacing $f_D(l_u)$ in (12) with (13), P_{succ}^{PHY} can be rewritten as follows:

$$P_{succ}^{PHY} = \int_0^\infty \exp\left(-\frac{\rho}{P}l_u^\alpha\right)\frac{\frac{l_u}{\sigma^2}\exp\left(-\frac{{l_u}^2}{2\sigma^2}\right)}{1-\exp\left(-\frac{l_{u,0}^2}{2\sigma^2}\right)} dl_u, \tag{14}$$

which can be computed by various numerical computation tools.

At the MAC layer, given that Wi-Fi technology is adopted for data transmission between the MUEs and the CH, transmission is successful when only one MUE transmits its data to the CH in the given time slot. According to [29], P_{succ}^{MAC} can be given by the probability that exactly one MUE transmits to the CH on the sharing channel under the condition that at least one CM transmits, as given by:

$$P_{succ}^{MAC} = \frac{|\mathbf{U}_i|\,\tau(1-\tau)^{1-|\mathbf{U}_i|}}{1-(1-\tau)^{|\mathbf{U}_i|}}. \tag{15}$$

In (15), τ is the probability that a MUE transmits in a randomly chosen slot time, as given by

$$\tau = \frac{2(1-2P_{col})}{(1-2P_{col})(W+1)+P_{col}W\left(1-(2P_{col})^{|\mathbf{U}_i|}\right)}, \tag{16}$$

where W is minimum contention window size of Wi-Fi, and P_{col} is the probability that at least two MUEs out of $|\mathbf{U}_i|$ MUEs transmit in the given time slot at the same time as follows:

$$P_{col} = 1-(1-\tau)^{|\mathbf{U}_i|-1}. \tag{17}$$

Since (16) and (17) indicate that τ is the function of P_{col}, they construct a nonlinear system of equations with two unknowns. Thus, the value of P_{succ}^{MAC} is obtained by solving the nonlinear system, which can be easily performed by standard numerical methods. Using the derived P_{succ}^{PHY} and P_{succ}^{MAC}, the data rate requirement for all MUEs on ship i can be finally determined, i.e., R_i^{th}.

C. ANTENNA SELECTION SCHEME BASED ON QOS REQUIREMENT

With the help of authors' analysis, a simple optimization problem that aims to minimize the size of a service cloud for ship i is formulated while satisfying the QoS requirement of each MUE in the ship:

$$\begin{aligned} &\min |\mathbf{C}_i| \\ &s.t.\ \bar{R}_i \geq R_i^{th}, \end{aligned} \tag{18}$$

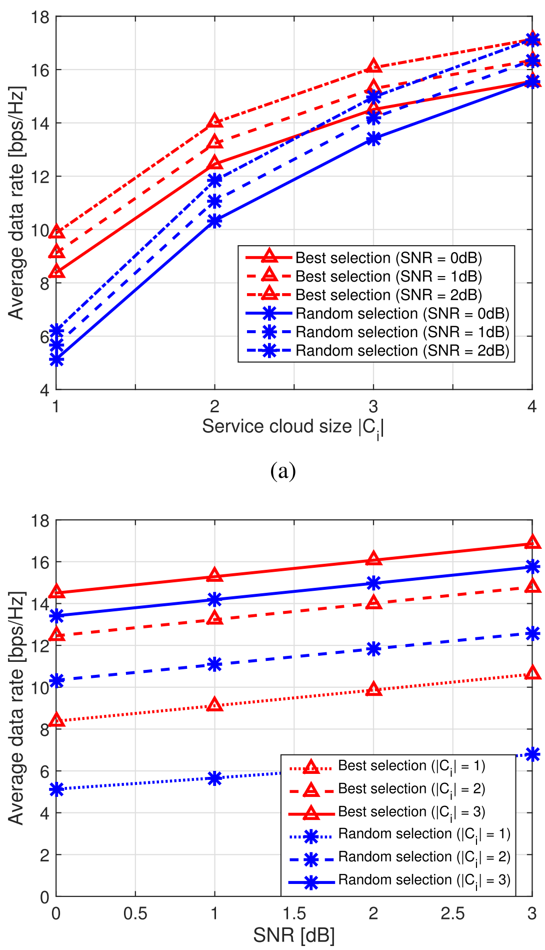
where $\bar{R}_i$ and R_i^{th} are from (7) and (10), respectively. The constraint in (18) can be replaced with $P_{out}\left(R_i^{th}\right) < P_{out,i}^{th}$ if the outage probability is regarded as a performance metric where $P_{out}\left(R_i^{th}\right)$ is obtained from (9) and $P_{out,i}^{th}$ is the maximum allowable outage probability for ship i.

The optimal solution of the problem (18) can be easily achieved from the following proposed algorithm:

IV. NUMERICAL EVALUATIONS

In this paper, DAs which are deployed at the coastline for uplink maritime radio networks are considered, and the following channel parameters [28] are adopted: $b = 0.063$, $(m_1, \cdots, m_{10}) = (0.740, 2.81, 4.89, 6.96, 9.03, 11.1, 13.2, 15.3, 17.3, 19.4)$, and $(\Omega_1, \cdots, \Omega_{10}) = (0.001, 0.144, 0.287, 0.431, 0.574, 0.717, 0.860, 1.00, 1.147, 1.29)$ for $\left|\mathbf{C}_i^{all}\right| = 10$. Specifically, the parameter sets are adopted as follows:$(m_1, \cdots, m_3; \Omega_1, \cdots, \Omega_3)$ for the case of $\left|\mathbf{C}_i^{all}\right| = 3$, the set $(m_1, \cdots, m_4; \Omega_1, \cdots, \Omega_4)$ for the case of $\left|\mathbf{C}_i^{all}\right| = 4$, the set $(m_1, \cdots, m_5; \Omega_1, \cdots, \Omega_5)$ for the case of $\left|\mathbf{C}_i^{all}\right| = 5$, and so on.

Fig. 2 shows the average data rates for a ship with different service cloud sizes $|\mathbf{C}_i|$ for Fig. 2 (a) and SNR values of ship-DA links for Fig. 2 (b), respectively, under the given $\left|\mathbf{C}_i^{all}\right| = 4$. For a performance comparison, two different antenna selection schemes are considered in determining the service cloud set $|\mathbf{C}_i|$: best selection and random selection schemes. Under the best selection scheme, the DAs are selected among $\mathbf{C}_i^{all}$ by the procedure described in lines 4–7 of Algorithm 1. On the other hand, the random selection scheme randomly chooses one possible set among all cases that can be made with $|\mathbf{C}_i|$ and $\mathbf{C}_i^{all}$. Fig. 2 illustrates that the best selection scheme performs equally or better than the random selection scheme, but the performance gaps between the two schemes decrease as the size of service cloud $|\mathbf{C}_i|$ increases. This is because as $|\mathbf{C}_i|$ approaches to $\left|\mathbf{C}_i^{all}\right|$, the number of possible cases that can be selected for a service cloud is reduced. This implies that the gain achieved through antenna selection diversity is reduced.



(a) (b)

FIGURE 2. Plot of average data rates for a ship under $\mathbf{C}_i^{all} = 4$ with different (a) service cloud sizes and (b) SNR values of ship-DA links.

Algorithm 1 DA selection algorithm

Input : CH-DA links: $(b, \Omega, m,)$, MUE-CH links: $(\alpha, \rho, l_{u,0}, W, |\mathbf{U}_i|)$

Output: $|\mathbf{C}_i|$

1 Initialize $|\mathbf{C}_i| = 0$;

2 **repeat**

3 Update $|\mathbf{C}_i| = |\mathbf{C}_i| + 1$;

4 Calculate the average data rates for all service clouds of size $|\mathbf{C}_i|$ in all available DAs $\mathbf{C}_i^{all}$ by using the following equation:

$$\overline{R_i} = \frac{1}{\ln 2}(2b)^{(m-1)|\mathbf{C}_i|} \cdot \delta^{m|\mathbf{C}_i|-\mu} \cdot \sum_{j=0}^{\beta}\left[\frac{\delta^j}{\Gamma(\mu)} \cdot \mathcal{G}_{4,3}^{2,3}\left(-\frac{\overline{\gamma}}{\delta}\middle| \begin{matrix} -\mu+j+1, 1, 1, 0 \\ j, 1, 0 \end{matrix}\right) + \frac{\phi \cdot \delta^{j-1}}{\Gamma(\mu+1)} \cdot \mathcal{G}_{4,3}^{2,3}\left(-\frac{\overline{\gamma}}{\delta}\middle| \begin{matrix} -\mu+j, 1, 1, 0 \\ j, 1, 0 \end{matrix}\right)\right],$$

which has been derived in (7);

5 Find the service cloud that maximizes the average data rate;

6 Calculate R_i^{th} according to the MUE-CH links channel environment by using the following equation:

$$R_i^{th} = \frac{1}{P_{succ}} \sum_{u=1}^{|\mathbf{U}_i|} R_i^u,$$

which has been derived in (10);

7 **until** $\bar{R}_i \geq R_i^{th}$;

8 **return** $|\mathbf{C}_i|$

Fig. 3 presents the outage probabilities for a ship with different service cloud sizes $|\mathbf{C}_i|$ under the given $\left|\mathbf{C}_i^{all}\right| = 4$. With the considered scenario, the outage probabilities are depicted according to the change in SNR values and data rate requirements in Fig. 3 (a) and (b), respectively. Same as the results of Fig. 2, the best selection scheme has equal

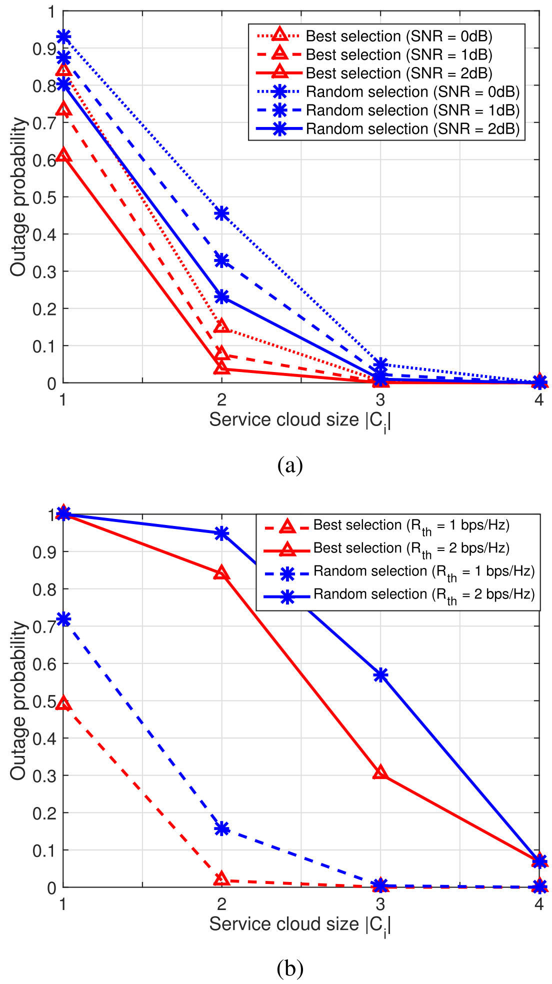


FIGURE 3. Plot of outage probabilities for a ship under $C_i^{all} = 4$ with different (a) SNR values given $R_i^{th} = 1.5$ bps/Hz and (b) R_i^{th} values iven SNR = 3 dB.

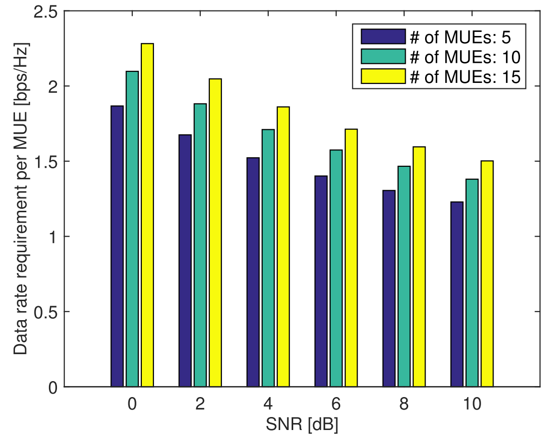


FIGURE 4. Plot of data rate requirements with different SNR values of MUE-CH link.

or better performance than the random selection scheme in terms of outage probability. More specifically, in Fig. 3 (a), it is identified that the outage probabilities of both selection schemes decrease as the service cloud size $|\mathbf{C}_i|$ increases. This is because the more antennas are used, the higher total data rate is achieved. Nevertheless, the convergence speed of the best selection scheme toward 0 of outage probability is much faster than that of the random selection scheme. Moreover, as shown in Fig. 3 (b), the outage probability under the given $R_i^{th} = 1$ bps/Hz is better than the outage when $R_i^{th} = 2$ bps/Hz. It is natural that the maritime network can easily guarantee the outage when the required QoS value is low.

Fig. 4 shows the data rate requirement per MUE with a ship under the change in the SNR of MUE-CH link. The number of MUEs of a ship is set to 5, 10, and 15 with homogeneous QoS requirement (i.e., $R_i^u = 0.1$ bps/Hz for all $u \in \mathbf{U}_i$) and IEEE 802.11 ac standard Wi-Fi parameters are followed as: PHY header=128 bits, MAC header = 272 bits, ACK = 112 bits + PHY header, propagation delay = 0.1μs, slot time = 9 μs, short inter-frame space (IFS) = 16 μs, distributed IFS = 34 μs, maximum backoff stages = 3, and minimum contention window size = 16 [30]. As shown in Fig. 4, as the SNR of MUE-CH link increases, the data rate requirement per MUE decreases. With (10) and (12), it is identified that the SNR of MUE-CH link has an effect on the probability of successful data transmission at the PHY layer, and it consequently affects the data rate requirement per MUE. As shown in Fig. 4, for the high SNR regime of MUE-CH link, a relatively small amount of redundancy data is required to guarantee the original QoS requirement, i.e., $R_i^u = 0.1$ bps/Hz, compared with the low SNR regime. Moreover, as the number of MUEs with a ship increases, the data rate requirement per MUE increases. This is because the increase in the number of MUEs results in the high collision probability at the MAC layer. This means the increase in the amount of redundancy data is also required to guarantee the successful original QoS requirement.

Table 1 shows the number of used DAs, i.e., the service cloud size $|\mathbf{C}_i|$, among all accessible DAs $\left|\mathbf{C}_i^{all}\right|$ for serving ship i with a change in data rate requirements R_i^{th} under the proposed and random selection algorithms. When the proposed selection scheme is exploited, the number of used DAs can be reduced compared with the random selection

TABLE 1. Service cloud sizes for serving ship *i* with different data rate requirements under the proposed and random selection algorithms.

$\left\|\mathbf{C}_i^{all}\right\|$		3	4	5	6	7	8
$R_i^{th} = 2$ bps/Hz	Proposed	2	1	1	1	1	1
	Random	2	2	2	2	1	1
$R_i^{th} = 4$ bps/Hz	Proposed	2	2	2	2	2	1
	Random	2	2	2	2	2	2
$R_i^{th} = 6$ bps/Hz	Proposed	3	2	2	2	2	2
	Random	3	3	2	2	2	2
$R_i^{th} = 8$ bps/Hz	Proposed	3	3	2	2	2	2
	Random	3	3	3	3	3	2

scheme regardless of data rate requirement. This means that the proposed scheme can contribute to the energy-efficient operations of maritime radio networks by minimizing the number of DAs. Moreover, it is identified that when the number of available DAs $\left|\mathbf{C}_i^{all}\right|$ increases, the required number of DAs decreases because of the antenna selection diversity. That is, the required number of DAs can be reduced if there are sufficiently enough DAs along a coastline.

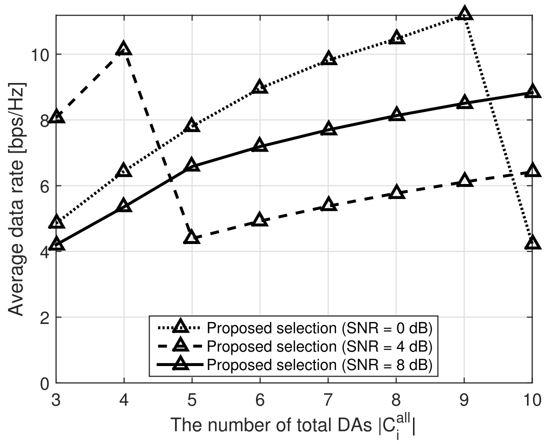


FIGURE 5. Plot of average data rates under the proposed algorithm.

Fig. 5 presents the average data rate for a ship with a change in the size of available DAs $\left|\mathbf{C}_i^{all}\right|$ with $R_i^{th} = 3$ bps/Hz under the proposed selection described in Algorithm 1. Within the considered sizes of $\left|\mathbf{C}_i^{all}\right|$, the average data rate for the ship achieved with the proposed algorithm is above the data rate requirement. In addition, in case of SNR $= 0$ dB, it is identified that as $\left|\mathbf{C}_i^{all}\right|$ increases, the average data rate increases, rapidly decreases at a specific value, i.e., $\left|\mathbf{C}_i^{all}\right| = 5$, and finally increases again. This results from the change in the size of the service cloud used to serve the ship. When $\left|\mathbf{C}_i^{all}\right| = 3, 4$, $|\mathbf{C}_i|$ is 2 to guarantee the data rate requirement R_i^{th}. However, when $\left|\mathbf{C}_i^{all}\right| \geq 5$, $|\mathbf{C}_i| = 1$ is sufficient to guarantee the requirement. This is because, as the number of accessible DAs for a ship increases, the antenna diversity gain also increases, which enables the use of a relatively small number of antennas in a service cloud.

V. CONCLUSION

Despite a variety of studies on maritime radio networks, there were the very limited existing researches that taken into account realistic maritime communication environments such as the clustered MUEs by a ship, the hierarchical network architecture, and the heterogeneous channels of hierarchical networks. Without simultaneous consideration of these characteristics, the performance evaluation of maritime radio networks cannot provide an explicit guideline with network operators to design and deploy maritime radio networks in practice.

Inspired by it, this paper aimed to conduct the performance evaluation of maritime radio networks while reflecting various realistic maritime communication environments at the same time. Authors first presented the *hierarchical network architecture* for maritime communications from MUEs on a ship to DAs which are connected to a cellular BS via optical fibers. Then, under the presented network architecture, the network performances given in terms of the average data rate and outage probability of *clustered MUEs by a ship* were numerically evaluated. When evaluating the performances, *heterogeneous channel characteristics* of the hierarchical networks were applied. In addition, with the help of our analysis, the antenna selection algorithm was proposed, under which the minimum size of a service cloud for a ship was derived while supporting the QoS requirements of MUEs.

Through numerical evaluations, it was verified that the number of DAs required to support QoS requirement of MUEs on a ship under the proposed algorithm is less than or equals to the number of DAs under the random selection algorithm. This meant that the proposed algorithm can contribute to the realization of energy or cost-efficient networks. Consequently, the results of this paper can provide a guidance on the practical design of maritime radio networks as well as information on the number of DAs required to guarantee QoS of a ship with clustered MUEs.

VI. DISCUSSION

A. FUTURE RESEARCH DIRECTIONS

In this paper, the DA selection algorithm has been proposed for the specific time slot with perfectly known CSI under no channel estimation error condition at the receiver, i.e., the cellular BS. Future work should consider the impact of movement of ship which results in the channel uncertainty, a lots of feedback cost of measuring the CSI, a receive beamforming design problem, and handover among the DAs. Furthermore, for the cases of multiple ships in considered maritime networks, there are various issues on radio resource management: how to assign sub-channels to each ship while guaranteeing the QoS requirement, how to allocate DAs to ships which move on their routes, and how to control the transmit power of each ship to optimize the network performance.

B. PROOF OF LEMMA III.1

Based on the definition, the achievable data rate can be written as,

$$\begin{aligned}
\overline{R_i} &= \frac{1}{\ln 2}\int_0^\infty \ln\left(1+\bar{\gamma}x\right) f_{\|\mathbf{h}_{C_i,i}\|^2}(x)\,dx \\
&\overset{(a)}{=} \frac{1}{\ln 2}\int_0^\infty \ln\left(1+\bar{\gamma}x\right)\cdot(2b)^{(m-1)|\mathbf{C}_i|}\cdot\delta^{m|\mathbf{C}_i|} \\
&\quad \cdot\sum_{j=0}^{\beta}\left(\frac{x^{\mu-j-1}}{\Gamma(\mu-j)}\cdot{}_1\mathcal{F}_1\left(\mu;\mu-j;-\delta x\right)\right. \\
&\quad \left.+\frac{\phi\cdot x^{\mu-j}}{\Gamma(\mu-j+1)}\cdot{}_1\mathcal{F}_1\left(\mu+1;\mu-j+1;-\delta x\right)\right)dx \\
&\overset{(b)}{=} \frac{1}{\ln 2}(2b)^{(m-1)|\mathbf{C}_i|}\cdot\delta^{m|\mathbf{C}_i|-\mu}
\end{aligned}$$

$$
\begin{aligned}
&\cdot \sum_{j=0}^{\beta} \int_0^{\infty} \mathcal{G}_{2,2}^{1,2}\left(-\overline{\gamma}x \middle| \begin{matrix} 1,1 \\ 1,0 \end{matrix}\right) \\
&\cdot \left[\frac{x^{\mu-j-1}}{\Gamma(\mu)} \cdot \mathcal{G}_{1,2}^{1,1}\left(\delta x \middle| \begin{matrix} 1-\mu \\ 0, 1-\mu+j \end{matrix}\right)\right. \\
&\left. + \frac{\phi \cdot x^{\mu-j}}{\Gamma(\mu+1)} \cdot \mathcal{G}_{1,2}^{1,1}\left(\delta x \middle| \begin{matrix} -\mu \\ 0, -\mu+j \end{matrix}\right)\right] dx \\
\overset{(c)}{=}\ & \frac{1}{\ln 2}(2b)^{(m-1)|\mathbf{C}_i|} \cdot \delta^{m|\mathbf{C}_i|-\mu} \\
&\cdot \sum_{j=0}^{\beta} \left[\frac{\delta^j}{\Gamma(\mu)} \cdot \mathcal{G}_{4,3}^{2,3}\left(-\frac{\overline{\gamma}}{\delta} \middle| \begin{matrix} -\mu+j+1, 1, 1, 0 \\ j, 1, 0 \end{matrix}\right)\right. \\
&\left. + \frac{\phi \cdot \delta^{j-1}}{\Gamma(\mu+1)} \cdot \mathcal{G}_{4,3}^{2,3}\left(-\frac{\overline{\gamma}}{\delta} \middle| \begin{matrix} -\mu+j, 1, 1, 0 \\ j, 1, 0 \end{matrix}\right)\right],
\end{aligned}
$$

where ${}_1\mathcal{F}_1(\cdot;\cdot;\cdot)$ denotes the confluent hypergeometric function of the first kind, also known as Kummer's function of the first kind. The equality (a) is from the inverse Laplace transform of (5) with an approximation [28], Also, the equality (b) holds from some relations between the natural logarithm and the Meijer-G function and between the confluent hypergeometric function of the first kind and the Meijer-G function [31],

$$
{}_1\mathcal{F}_1(a; b; c) = \frac{\Gamma(b)}{\Gamma(a)} \mathcal{G}_{1,2}^{1,1}\left(-c \middle| \begin{matrix} 1-a \\ 0, 1-b \end{matrix}\right).
$$

For the equality (c), authors exploit the fact that

$$
\begin{aligned}
x^{\mu-j-1}\mathcal{G}_{1,2}^{1,1}&\left(\delta x \middle| \begin{matrix} 1-\mu \\ 0, 1-\mu+j \end{matrix}\right) \\
&= \delta^{-\mu+j+1} \cdot \mathcal{G}_{1,2}^{1,1}\left(\delta x \middle| \begin{matrix} -j \\ \mu-j-1, 0 \end{matrix}\right),
\end{aligned}
$$

and the integration of the product of two Meijer-G functions can be represented by a Meijer-G functions as follows:

$$
\begin{aligned}
\int_0^{\infty} \mathcal{G}_{1,2}^{1,1}&\left(\delta x \middle| \begin{matrix} -j \\ \mu-j-1, 0 \end{matrix}\right) \cdot \mathcal{G}_{2,2}^{1,2}\left(-\overline{\gamma}x \middle| \begin{matrix} 1,1 \\ 1,0 \end{matrix}\right) dx \\
&= \frac{1}{\delta}\mathcal{G}_{4,3}^{2,3}\left(-\frac{\overline{\gamma}}{\delta} \middle| \begin{matrix} -\mu+j+1, 1, 1, 0 \\ j, 1, 0 \end{matrix}\right).
\end{aligned}
$$

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