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Maritime Networking: Bringing Internet to the Sea

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ABSTRACT Maritime networks establish wireless multi-hop networks to provide wireless broadband service at sea, connecting various kinds of ships, maritime buoys, and beacons. The maritime networks possess two distinguishing characteristics highly affected by maneuver at sea–dynamic link quality and bandwidth constrained, and dynamic network topology–that warrant specific attention. Unlike land vehicles, maneuver at sea is affected by sea surface movement and wave occlusions, which can cause unstable environment with a high rate of link breakages caused by low link stability, as well as low and highly variable bandwidth. In spite of the need to achieve performance close to high-speed terrestrial wireless broadband service on land, there is only a perfunctory effort to investigate maritime networks. There is an urgent need to refresh the interest to investigate, as well as to further enhance, maritime networks. This paper presents a review of the limited research works of this topic, which revolve around the networking issues in the link, network, and upper layers, in the literature. The objective is to establish a foundation in order to motivate a new research interest in maritime networks. Open issues are also presented to foster new research initiatives in this burgeoning and exciting area.

INDEX TERMS Maritime network, ship ad hoc network, wireless network.

I. INTRODUCTION

Maritime networks are wireless multi-hop networks comprised of nodes (e.g., ships, maritime buoys, and beacons) that establish connection among themselves and with a chain of shore stations with backhaul infrastructure along coastlines. The maritime networks provide broadband service to ferries, passenger and cruise ships, fishing ships, freighter ships, surveillance and patrol ships (e.g., for illegal fishing, smuggling, piracy, oil spill, and environmental monitoring), offshore operators (e.g., for oil exploration and drilling), and so on, in order to deploy and support maritime communication, navigation, and emergency response with satisfactory end-to-end quality of service (QoS) performance and user experience at low cost. Due to the rough movement of the sea surface, network infrastructure can be damaged, and so the multi-hop nature of the maritime networks minimizes the need to deploy network infrastructure on the sea [1].

A. MARITIME NETWORK ARCHITECTURE

Figure 1 shows a maritime network that is integrated with traditional communication system, particularly the satellite communication. The maritime network establishes connections among nodes, such as ships and maritime buoys, to form a wireless multi-hop network to reach shore stations. Ships can reach shore stations via: a) other ships, buoys, and beacons through multiple hops; or b) satellite if the shore stations are unreachable via other ships, buoys, and beacons in a network with low node density [1]. Large ships can form a multi-hop backbone network and provide network connections to smaller ships (or boats) in the neighborhood [2]. The multi-hop nature of maritime networks provides a sharing platform so that network resources, wireless broadband service, as well as satellite communication and services

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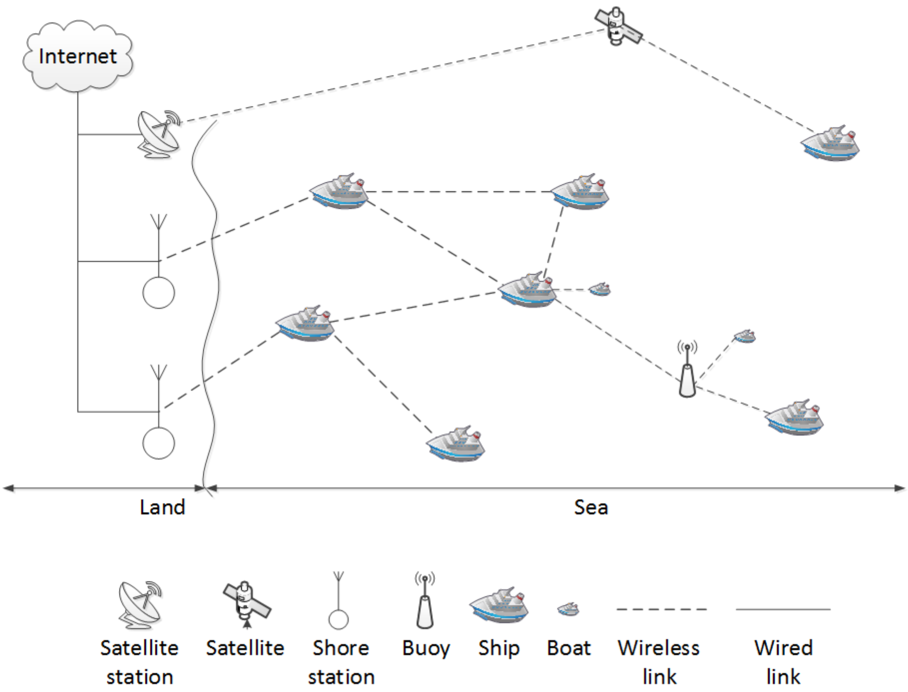

FIGURE 1. A maritime network, which is integrated with satellite communication, establishes a wireless multi-hop network under maritime environment.

(e.g., accurate location information provided by global positioning system (GPS)) can be shared among nodes. Hence, it is not essential for every single node to meet requirements for resources, services, and capabilities. The satellite and shore stations are connected to the Internet via backhaul links. In addition, a management architecture that prioritizes high-priority traffic flows in maritime networks is presented in Section V-A.

While maritime networks are comparable to MANETs and VANETs (see Section II-C), there are two main distinguishing characteristics, namely *dynamic link quality and bandwidth constrained* due to the effects of communication over sea surface, and *dynamic network topology* due to the characteristics of ship traffic (see Section II-E for more description). A maritime network should be distinguished from a distributed wireless sensor network (WSN), comprised of aquatic sensors, drones, or small boats (e.g., fishing boats), that collects sensing outcomes (e.g., ship location which is delay-tolerant information [3]) and forwards them to a nearby gateway or shore station using short-range transmission (e.g., IEEE 802.11 or Wi-Fi) at low antenna height, which are subsequently processed or combined, in surveillance based applications [3]–[5] (see Section II-D). In WSNs, a shore station provides a large transmission range in land-to-sea communication, and so the focus is sea-to-land communication, while in maritime networks, both land-to-sea and sea-to-land communications, a well as delay-intolerant information, are of concern.

B. OUR CONTRIBUTIONS

Although there is an urgent need to improve the network performance of maritime networks, there is only a perfunctory effort to investigate this topic, particularly in the past few years. This is despite 70% of the earth surface covered by water and the economic importance of the sea; for instance, 90% of the commercial goods are transported on maritime routes [6]. The main contribution of this article is to present a review of the limited works on maritime networks with a focus on the networking aspect, particularly the link, network, and upper layers. In addition to maritime network schemes and investigations, open issues are also covered. Since our focus is on the networking aspect, other topics that are not covered in this article include maritime applications (e.g., security-based applications [7]), middleware that seamlessly switch between maritime network (providing higher bandwidth and lower cost) and satellite system (providing connection despite low node density and channel quality) to provide a continuous wireless broadband service [5], [8]–[10], antenna designs to address the misalignment of directional antennas caused by rough sea condition [9], and radio signal propagation model for transmission through the sea surface. While a review of maritime networks has been presented in [11], [12], the foci were the various kinds of maritime networks (e.g., TRITON) in the literature, and routing protocols. In addition to providing a refreshed look at the need of more investigations on maritime networking, this paper explores various networking issues

TABLE 1. Comparison of various kinds of communications and networks.

Communication/ network	Wave	Band-width	Delay	Packet error rate	Cost	Stability	Environment/ traffic type	Availability
Satellite	Radio	Low	High	High	High	Low	Sea/ Ships	At most times and areas
LoS	Radio	Low	Low	Low	Low	High	Sea/ Ships	Depends on node density
Underwater	Acoustic	Low	High	High	Low	Low	Sea/ Sensors	Depends on node density
MANET/ VANET	Radio	High	Low	Low	Low	High	Land/ Road traffic	Depends on node density
Maritime	Radio	High	Low	Low	Low	High	Sea/ Ships	Depends on node density

and solutions in maritime networks, particularly those in the link, network, and upper layers. This article is timely due to the urgent need to refresh the interest to investigate, as well as to further enhance, wireless broadband service at sea with performance close to high-speed terrestrial wireless broadband service on land. This article aspires to establish a foundation and to spark new research interest in this area.

C. ORGANIZATION OF THIS ARTICLE

The rest of this article is organized as follows. Section II presents background. Sections III, IV, and V present the maritime networking issues in the link, network, and upper layers, respectively. Section VI presents simulation and implementation of maritime networking. Section VII presents open issues. Finally, Section VIII presents conclusions.

II. BACKGROUND AND MOTIVATING THE NEED FOR A SPECIAL FOCUS ON MARITIME NETWORKING

This section aims to provide a clear description of maritime networks in order to motivate the need to investigate this topic, which has received less focus over the recent years. We present an overview of the operating region of the wireless broadband service on land, and the common communication systems in the maritime environment. Next, we present similar and distinguishing characteristics compared to existing wireless networks and underwater networks. Lastly, some maritime network projects worldwide are presented. Table 1 presents a comparison of the different kinds of communications and networks presented in the rest of this section.

A. WHAT IS THE OPERATING REGION OF THE WIRELESS BROADBAND SERVICE ON LAND?

Due to the lack of multihop transmission, the wireless broadband service on land has a limited operating region, and it cannot be extended to cover the shipping route in the sea. As an example, Figure 2 shows the service-limited coverage offered by the main network operator (i.e., Telekom Malaysia) in Peninsular Malaysia along the Strait of Malacca. The figure shows that a particular network operator has a limited operating region that does not cover the sea. In addition to service-limited coverage, there are other factors that can reduce the coverage, such as the distance from a base station, the types of user devices, and the presence of obstacles (e.g., buildings and geographical features).

Due to the service-limited coverage and the lack of multihop transmission, the current wireless broadband service cannot be extended to the sea. Nevertheless, there have been investigations on extending the coverage from the land to the sea, such as [13]–[15].

B. WHAT ARE THE COMMON COMMUNICATION SYSTEMS IN THE MARITIME ENVIRONMENT?

Maritime communication specifications–including those that relate to network operators, wireless equipment, and radio channels–are generally regulated by the International Convention for the Safety of Life at Sea (SOLAS) and International Telecommunication Union (ITU) Radio Regulation. Currently, simple applications requiring less than 1 Mbps (e.g., emails and web surfing, navigation, emergency response, as well as search and rescue) [3], rather than multimedia communications requiring more data rate (e.g., video call requires 1 Mbps, and file transfer requires 2 Mbps [16]), are supported in maritime communication [6]. Commonly, maritime communication uses two main types of analogue communications.

Firstly, *satellite communication*, which is the dominant broadband communication system at sea, provides indirect ship-to-ship and ship-to-shore communications (see Figure 3a). On the shore, base stations integrated with *network operations centers (NOCs)* serve as shore-based relays for satellite communication, which uses geosynchronous equatorial orbit (GEO). While satellite communication provides connections at most of the times and areas, it has six main shortcomings:

(a) low bandwidth (e.g., INMARSAT GAN and INMARSAT BGAN provide data rates of up to 64 kbps and 432 kbps per satellite link, respectively);
(b) high propagation delay (typically a round trip time of approximately 600 ms [17]);
(c) high packet error rate (typically ranging from 10^{-3} to 10^{-1}) [18];
(d) high cost because of the large initial investment on satellite-related equipment (e.g., stabilizers for onboard antennas) [6], satellite launching cost, and data transfer cost (e.g., approximately US$13.75 per minute for a voice service [15] (or 30 times more expensive [19]) and approximately US$300 to US$2000 per month on satellite cost [14]), and so satellite communication is

FIGURE 2. Service-limited coverage of 3G and 4G for a main network provider (i.e., Telekom Malaysia) in Peninsular Malaysia. Blobs of 3G and 4G coverage are shown to overlay part of the map of Peninsular Malaysia. The map pin shows Port Klang, which is a container port located at the Strait of Malacca – one of the world's busiest shipping routes. The narrow stretch of sea is approximately 890 km between Peninsular Malaysia and Indonesian island of Sumatra.

either not installed [3] or used for exchanging a large volume of data, and data can be compressed before transmission [12];
(e) low stability with long duration and high frequency of link breakages;
(f) lack of coverage in certain areas, such as fjords, ports, and some polar regions, particularly relatively high latitude areas (e.g., Europe and US) where a small elevation angle can cause frequent link breakages.

Secondly, *terrestrial line of sight (LOS)* radio that provides direct ship-to-ship and ship-to-shore communications (see Figure 3b). Examples are high-frequency (HF) beyond line of sight (BLOS), HF extended LOS (ELOS), and ultra- or very-high-frequency (UHF/ VHF) LOS [9]. There are a range of VHF radio channels for a diverse range of purposes; for instance, a marine-band VHF channel at 156.975 MHz (or channel 79) caters for operational, navigation, and safety matters in maritime communications. The main shortcoming of LOS communication is its low bandwidth (e.g., a data rate of 9.6 kbps [15]), which is insufficient for providing broadband service. Nevertheless, compared to satellite communications, LOS communication has lower delay and lower cost. In [9], [14], the propagation characteristic of LOS is modeled using a two-ray model with path loss exponents.

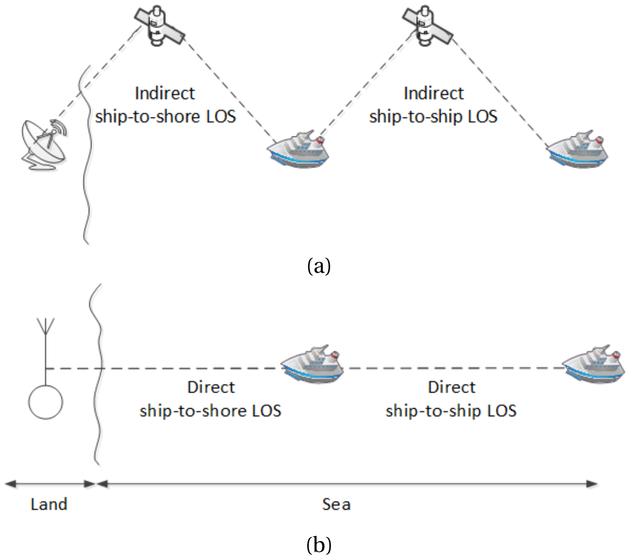

FIGURE 3. Common communication systems in the maritime environment.

One of the widely-used terrestrial LOS is automatic identification system (AIS) [20]. Each large ship is generally equipped with an AIS transponder, which is an automatic ship tracking system that transfers packets over VHF channels, for location awareness, collision avoidance, and ease of navigation. AIS transponder can also be equipped on maritime buoys and beacons. Using AIS, a ship can send navigation and location data (e.g., tonnage, longitude, latitude, heading, speed of ground, and destination), as well as sensor data (e.g., sea depth, temperature, and wind speed), to AIS base stations regularly (e.g., every 3 seconds to 3 minutes depending on the speed of ground of a ship [2]), and request such information of another ship from neighboring AIS-equipped ships or AIS base stations [21]. The data and requests are forwarded along a route from a ship, as a source node, to an AIS base station, whereby an intermediate node selects the nearest neighbor node towards the AIS base station as the next-hop node. AIS base stations on the shore collect navigation and location data, as well as sensor data, periodically broadcasted by AIS transponders onboard ships at sea, maritime buoys, and beacons. This data is subsequently sent to an AIS operation center that serves as the worldwide database for ship locations, providing information about the overall ship distribution and movement. Since AIS is used to exchange short messages, it has low bandwidth and does not support application data transfer. Actual AIS data can be displayed on real live AIS data website, electronic chart, or compatible radar. Such data has been used in a number of investigations, including the movement of ships (e.g., Rainbow and Secret ships in Singapore) [15], and the ship traffic in the English channel [22], the North Sea [22], the Mediterranean Sea [23], the Strait of Singapore [13], [24]–[26], as well as Singapore harbor and surroundings [15].

C. HOW ARE MARITIME NETWORKS SIMILAR TO EXISTING WIRELESS NETWORKS?

Maritime networks share some similar characteristics with other wireless networks, particularly mobile ad hoc networks (MANETs) and vehicular ad hoc networks (VANETs). The similarities are:

(a) maritime networks consist of mobile nodes (similar to MANETs and VANETs);
(b) maritime networks have high processing capability (similar to MANETs and VANETs);
(c) maritime networks do not have energy constraint although energy efficiency is desirable (similar to VANETs);
(d) maritime networks have high data storage capability (similar to VANETs);
(e) maritime networks use GPS or GALILEO that provides accurate location information (similar to MANETs and VANETs);
(f) maritime networks have network topologies characterized by traffic lanes (e.g., traffic directions and traffic regulations, such as maximum speeds and designated areas for making turns) (similar to MANETs and VANETs).

As an example, in [13], [24], [25], a pair of parallel shipping lanes in opposite directions at the Strait of Singapore is shown in Figure 4. Each lane has a width of 12 km to 20 km. Shore stations are located 10 km from the coastline, and are separated by approximately 72 km among themselves. The ship movement, which is based on real live data extracted from AIS, is characterized by two parameters, namely the inter-arrival time of a new ship entering the network, and the constant speed of a ship guided by the maximum speed of the shipping lanes.

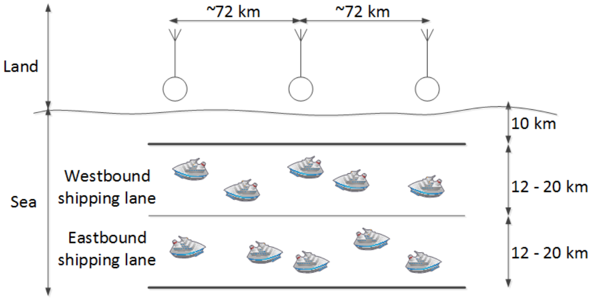

FIGURE 4. A pair of parallel shipping lanes in opposite directions at the strait of Singapore under investigation in [13], [24], and [25].

D. WHAT ARE THE DISTINGUISHING CHARACTERISTICS COMPARED TO UNDERWATER NETWORKS?

The maritime networks use radio propagation in the air, which is susceptible to signal reflection, scattering, refraction, pulse noise, and Doppler shift. The most widely used underwater communication is acoustic wave propagation [27] as radio propagation in water has a transmission range of a few meters only despite transmission at low frequencies (e.g., 30 Hz to 300 Hz) [28]. The acoustic wave propagation is susceptible to more types of noises related to the inherent optical properties (i.e., caused by the absorption, water scattering, and attenuation effects) and the apparent optical properties (i.e., caused by the radiance, irradiance, and reflectance quantities) [28]–[30]. Hence, maritime and underwater networks use different underlying hardware platforms that cannot be used interchangeably. As a result, underwater networks experience: a) lower bandwidth (e.g., on the order of kbps); b) higher delay (e.g., on the order of seconds); c) higher packet loss rate; d) lower stability; and e) shorter transmission range (e.g., up to 20 km) [28]. Hence, the focus of underwater networks revolves around the need to address the limitations of acoustic wave propagation, such as modulation schemes and coding techniques, to cover a larger transmission range and to achieve a lower bit error rate. Table 2 presents a comparison of the network performance achieved by radio propagation in the air and acoustic propagation in the water.

E. WHAT ARE THE DISTINGUISHING CHARACTERISTICS COMPARED TO EXISTING WIRELESS NETWORKS?

Maritime networks possess *two* main distinguishing characteristics compared to MANETs and VANETs.

Firstly, *dynamic link quality and bandwidth constrained*. The availability and quality of a link can be affected by two main variations: a) long-term variations, including different levels of path loss caused by weather condition and season (e.g., sea surface salinity and temperature) that affect water

TABLE 2. **Comparison of radio propagation in the air and acoustic propagation in the water.**

Performance measure	Radio propagation in the air (on the order of)	Acoustic propagation in the water (on the order of)
Data rate	kbps to Mbps	kbps
Delay	milliseconds	seconds
Transmission range	km (e.g., up to 100 km in IEEE 802.16d)	km (e.g., up to 20 km)

vapor concentration above the sea surface; and b) short-term variations, including sea-surface interference (e.g., two-ray, reflection, scattering, refraction, pulse noise, and Doppler shift), random ship location and ship-to-ship distance (e.g., the direction of a sea wave, which changes with time and location, affects the direction of a ship-to-ship connection, the antenna direction, and the direction of arrival of signal [19]), as well as the availability and unavailability of LOS due to wave occlusions. Wave occlusion occurs when the random and rough movement of the sea surface generates waves of sufficient height blocking a link between two nodes as shown in Figure 5. The effect of the variations can increase due to lower antenna height, smaller ship size (e.g., large ships can establish links for several minutes to hours [23]), unfavorable atmospheric condition, and wave occlusions. The variations can cause time-varying received signal quality, resulting in a high rate of link breakages caused by low link stability and short time interval of wireless connection. This causes low and highly variable bandwidth [31], resulting in lesser number of neighboring nodes and higher congestion level in the network.

Using the Pierson-Moskowitz's [32] sea state model, the sea state is characterized by sea wavelength, sea wave height, sea wave period, and wind speed. A higher sea state represents a rougher sea surface movement and a larger variation in the link quality. For instance, a sea state of 3.0 has a smooth and calm sea condition with lower impact on signal transmission and link quality, and a sea state of 6.0 has a higher sea wave with higher impact on signal transmission and link quality although communication is still functional [24], [33]. The Pierson-Moskowitz's sea state model has been applied in various investigations, including [13], [24], [25]. In [24], the Pierson-Moskowitz's sea state model is integrated into a two-ray path loss model to characterize radio propagation in a maritime environment. In [13], the Pierson-Moskowitz's sea state model is integrated into a single-dimensional Markov chain model covering factors that can cause a link breakage: a) the occurrence and non-occurrence of a wave occlusion; and b) the occurrence and non-occurrence of low signal-to-interference-plus-noise ratio (SINR).

Secondly, *dynamic network topology*. In general:

(a) ships have lower mobility (e.g., ships take longer time to make a turn, accelerate and decelerate [19]) whereby this can reduce link breakages caused by ships moving beyond their transmission ranges;

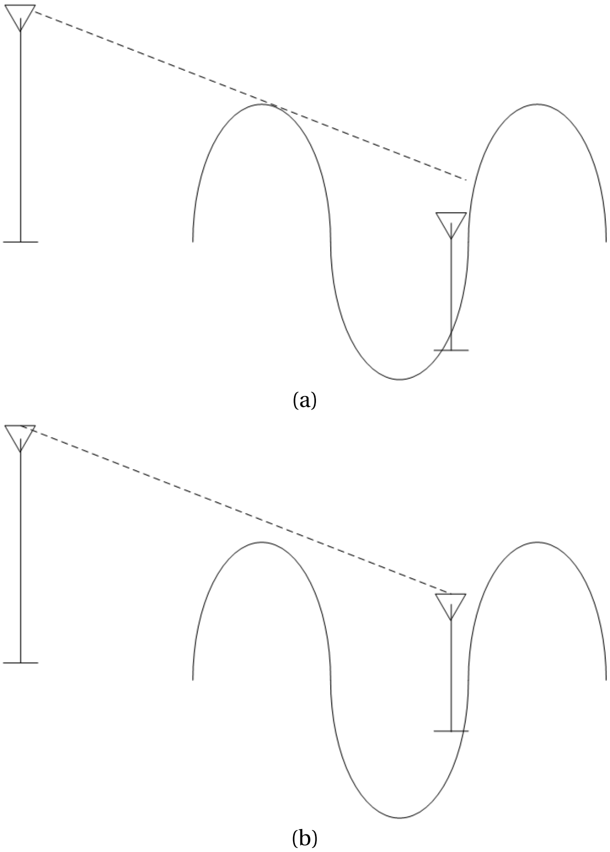
(a)
(b)

FIGURE 5. **Effects of wave occlusion. (a) The lack of the availability of LOS between a node pair. (b) The availability of LOS between a node pair.**

(b) ships are either moving in the same direction or small groups (e.g., two to five ships involved in a search and rescue mission);

(c) ships have traffic pattern characterized by ship movement trajectories, rather than pedestrians and cars;

(d) ships have traffic pattern that does not change with time of day [14];

(e) there is a long distance between two moving ships at sea (e.g., around 15 km to 25 km apart, with their relative distance changes randomly within 5 km from their respective base positions);

(f) ships have different node densities (or the number of nodes in an area) in different areas (e.g., higher node density among ships anchored at ports and surroundings, and lower node density among ships at sea) whereby a higher node density can increase the number

TABLE 3. Maritime networking and comparison to digital VHF projects.

Project/ network	Country	Single/ multiple hops	Data rate	Coverage (distance from coastline)	Wireless technology
TRITON [13], [14], [35]	Singapore	Multiple	6 Mbps	150 km	WiMAX
WISEPORT [15]	Singapore	Single	5 Mbps	15 km	WiMAX
MICRONet [34]	India	Single	1.7 Mbps	17.7 km	LR Wi-Fi
NORCOM (Digital VHF) [9]	Norway	Single	133 kbps	135 km	VHF
Digital VHF [9]	Japan	Multiple	1 kbps	70 km	VHF

of candidate routes during route discovery and maintenance, although this can increase routing overhead and network interference;

(g) ships are heterogeneous with different communication capabilities, such as satellite communication (e.g., 64 kbps and 432 kbps satellite links), and terrestrial LOS (e.g., HF, BLOS, ELOS, and UHF/VHF LOS).

The ship traffic can be characterized by the inter-arrival time and the speed of ships. Due to the curvature of the earth surface [13], [15], the circular distance between ships moving in a straight line is calculated using curve fitting. The network topology may depend on external factors (e.g., the availability of fishing ships [34] may depend on the weather condition and fishing season).

To achieve an efficient communication, the favorable characteristics [13] are: a) the antenna height is sufficiently high to ensure LOS (e.g., 15 meters above the sea surface provides a transmission range of up to 20 km [5]); b) the sea condition is relatively good to ensure no wave occlusion (e.g., sea state 3.0 in the Pierson-Moskowitz's sea state model [32]); and c) transmission power is sufficiently high (e.g., 25 watts can provide up to 35 km and 20 km ship-to-shore and ship-to-ship links, respectively) [22].

F. REVIEW OF GLOBAL MARITIME NETWORKING PROJECTS

Maritime networks have been investigated to provide cost-efficient wireless broadband service to ships. Establishing a maritime network has been shown to be feasible as there is a sufficient number of ships to provide network connectivity and route redundancy, and most ships can connect to shore stations via a single or multiple hops [9], [26]. Table 3 provides a summary of the maritime networking projects in the literature, and a comparison to the widely used terrestrial LOS communication system, particularly digital VHF, is made. This section also presents an example of a maritime networking project, which is part of the international sea traffic management (STM) initiative.

In Singapore, TRITON extends terrestrial wireless broadband network coverage to the sea through multi-hop mesh network, providing wireless broadband service to ships anchored by the Singapore harbor and areas near to the shore [14]. Shore stations are located at the harbor and along a shipping route near to the shore in the Strait of Singapore [15]. There are two main features. Firstly, IEEE 802.16d (worldwide interoperability for microwave access, WiMAX) mesh medium access control (MAC) protocol, particularly the distributed coordinated scheduling operation based on time division multiplexing, is adopted to schedule time slots (or transmission opportunities) among neighboring nodes in a distributed manner without the need of a shore station in order to reduce control overhead. WiMAX provides a data rate of at least 20 Mbps and a transmission range of between 50 and 100 km [6]. Secondly, delay tolerant network (see Section IV-A) is adopted to improve network performance under unreliable environment. Using WiMAX, guaranteed QoS can be provided, and the transmission range can be up to 35 km and 20 km for ship-to-shore and ship-to-ship communications, respectively [13]. In [9], using IEEE 802.16e at an antenna height of 16 m, the transmission range can be up to 45 km for ship-to-ship communication. A similar project that extends terrestrial wireless broadband network coverage to the sea using WiMAX is wireless-broadband-access for seaport (WISEPORT) in Singapore [15]. WISEPORT provides a data rate of around 5 Mbps and a transmission range of up to 15 km from the Singapore coastline.

Along the Parayakadavu beach in Kerala of India, MICRONet extends terrestrial wireless broadband network coverage to the sea through multi-hop mesh network, providing wireless broadband service to fishing boats located near to the shore [34]. The fishing boats, which move in small groups, form a wireless mesh network; and one of the fishing boats in the group establishes connection with shore stations located at the harbor. IEEE 802.11n, also known as long range Wi-Fi or LR Wi-Fi, along with a modified MAC based on time division multiple access (TDMA) that allows the shore stations to schedule time slots among nodes in a centralized manner, is adopted to provide connections over long distance. Using LR Wi-Fi, the transmission range can be up to 17.7 km between a shore station and a fishing boat. A prototype for MICRONet has been developed (see Section VI).

Digital VHF is investigated in Norway and Japan. In Norway, NORCOM uses digital VHF to provide a single-hop wireless broadband service with a large coverage (i.e., approximately 135 km from the Norwegian coastline) at a low data rate (i.e., up to 133 kbps) [6], [9]. In Japan, digital VHF provides a single-hop wireless broadband service with a smaller coverage (i.e., approximately 70 km from the Japanese coastline) at a low data rate (i.e., 1 kbps) [9].

In Malaysia, rather than extending terrestrial wireless broadband network coverage to the sea, maritime networks are being investigated to enable STM and the national eNavigation projects [36]. One of the main objectives is to improve the safety of navigation in the straits, particularly the Strait of Malacca. The international STM project, which runs between 2018 and 2020, mirrors the EU-funded STM validation project to: a) identify tailor-made STM requirements for Strait of Malacca; and b) validate a binary route exchange message protocol in ship-to-ship and ship-to-shore communications over VHF radio channels. The national eNavigation project, which was started in 2017, implements an AIS for remote monitoring of beacons and buoys so that it is in line with the International Maritime Organization (IMO) direction. Actual AIS data can be collected, analyzed, and displayed on real live AIS data website called e-Navigation (or e-NAV.my) [36].

III. LINK LAYER ISSUES FOR MARITIME NETWORKING

This section presents a review of research works addressing link layer issues in maritime networks for the enhancement of MAC protocols, and scheduling, as well as a discussion on emerging link layer technologies.

A. MODIFICATION OF WIMAX FOR EFFICIENT FLOODING OF ROUTING MESSAGES

In [24], a modification to WiMAX mesh MAC protocol has been proposed. WiMAX mesh MAC protocol, particularly the distributed coordinated scheduling operation, is a time-slotted protocol that has been selected as the preferred wireless communication protocol for maritime networks. Nevertheless, this protocol requires three-way handshakings (i.e., exchanges of request–grant–grant control messages between a sender node and a receiver node) for reserving time slots and transmitting packets, including the route request (RREQ) and route reply (RREP) messages. Consequently, routing schemes (e.g., *AODV*) that require the flooding of RREQ and the return of RREP during route discovery experience high initial response delay and routing overhead.

In the proposed scheme, RREQ and RREP messages are piggybacked and delivered on WiMAX mesh MAC control messages (i.e., MSH-DSCH messages), which are transmitted periodically in dedicated slots in the control subframes in a collision-free manner. This is possible because there are 154 bytes of unused capacity in each control subframe, while RREQ and RREP messages use less than 45 bytes. This means that RREQ and RREP are transmitted in the control subframe, rather than the data subframe, leaving more bandwidth in the data subframe for packet transmission. This also means that the flooding of RREQ and the return of RREP do not require the three-way handshakings, which are essential in the data subframe. The proposed scheme has been shown to increase packet delivery rate, as well as reduce initial response delay, end-to-end delay, and routing overheads.

B. SCHEDULING FOR TRANSMISSION OF MULTIMEDIA PACKETS

In [15], a scheduling scheme for delay tolerant network (DTN) routing scheme is proposed to increase the number of packets delivered before expiration in order to improve the quality of video transmission. The issue is formulated as a job-machine scheduling problem: the machines (or resources) are the shore stations, and the jobs are the video packets characterized by release time, deadline and weight, which represents the contribution of a packet to the video quality. Then, the job-machine scheduling problem is solved using 0-1 integer programming [37]. Based on rewards, a centralized controller allocates and schedules machines, which are the shore stations, to serve different video packets. The ships transmit each packet via ship-to-ship or ship-to-shore communications in a cooperative manner before the deadline of the packet expires to improve video quality. In this investigation, the underlying protocol is WiMAX mesh MAC protocol. Intermediate ships, which have DTN features (see Section IV-A), can receive and buffer packets, wait for opportunities to establish connections to next-hop nodes, and transmit the packets to the next-hop nodes whenever possible. The scenario is the Singapore harbor and its surroundings where shore stations are located along a shipping route near to the shore, and the ships move in pre-determined and fixed routes. The proposed scheme has been shown to increase normalized throughput compared to traditional scheduling schemes, including approaches based on deadline (i.e., a job with the earliest deadline is scheduled first), release time (i.e., a job with the earliest release time is scheduled first, specifically first-in first-out, FIFO), and weight (a job with the highest weight is scheduled first). The normalized throughput is the ratio of the reward of the accomplished jobs to the total weight of the jobs, and it has been shown to increase with increasing density of shore stations, and reduce with increasing job sizes.

C. EMERGING LINK LAYER TECHNOLOGIES

This subsection presents two emerging link layer enhancements that can be incorporated into the maritime networks, namely exploration and use of white spaces, as well as support for traditional communication systems and heterogeneous wireless broadband services.

1) EXPLORATION AND USE OF WHITE SPACES

Cognitive radio enables a node to explore and use white spaces (or underutilized channels allocated to primary users for other purposes), particularly in high-quality channels, in order to increase its bandwidth availability. There are four main tasks [16]. Firstly, *channel sensing* enables a node to scan channels and identify white spaces. There are various channel sensing approaches, such as energy detection (i.e., sensing for primary users' signal power), feature detection (i.e., sensing for primary users' signal characteristics including channel frequency and modulation rate), geolocation database (i.e., receiving white spaces and their location information from a database), and beacon-based approach (i.e., detecting beacons from primary users, which indicate the presence of their activities). Nevertheless, the best possible channel sensing approach under maritime environment is yet to be identified. Secondly, *channel selection* enables a node to select the most appropriate channel: a) with the right characteristics (e.g., the amount of bandwidth and the interference level) for different kinds of traffic requiring different QoS requirements under the maritime environment; and b) available at a particular location as the operating environment can be heterogeneous due to the transnational nature of maritime communications. In [38], nodes explore and use television white spaces at 700 MHz, which provides long-range transmission. Thirdly, *channel switch* enables a node to switch to another channel when the operating channel is no longer appropriate for transmission (e.g., low-quality channel, highly congested channel, the presence of primary users' activities in the channel, and the unavailability of the channel based on the transnational policy). The main challenge is to provide a seamless switch from a less favorable to a more favorable channel, which has the right characteristics to cater for the QoS requirements of the traffic, out of a set of available channels based on the transnational policy. This requires a MAC protocol that provides a robust control message exchange (or handshaking) so that the sender node and the receiver node can perform a channel switch successfully. Fourthly, *channel sharing* enables nodes to share network resources (e.g., channel capacity) and coexist with each other. The main challenge is that, not only does the unstable maritime environment have a high rate of link breakages caused by low link stability, the channel capacity is dynamic in nature even when the channel is available. This requires a scheduling mechanism that enables nodes to cooperate among themselves so that channel capacity is distributed and scheduled in a distributed manner to cater for the QoS requirements of nodes in a neighborhood, while taking into account the dynamicity of channel availability and the unstable marine environment. Further investigation could be pursued to investigate the four main tasks essential for exploring and using white spaces in the maritime environment.

2) SUPPORT FOR TRADITIONAL COMMUNICATION SYSTEMS AND HETEROGENEOUS WIRELESS BROADBAND SERVICES

Maritime network is an integrated communication system that operates with traditional (e.g., satellite communication and terrestrial LOS) and modern radio access technologies (e.g., IEEE 802.11n [4], [34] and IEEE 802.16d [14], [15]). Interoperating with traditional systems provides reliable communication and backward compatibility in the absence of modern systems, while interoperating with modern systems provides network performance enhancement. Each type of radio access technology is suitable to cater for different traffic classes and network scenarios, as well as for achieving different objectives (e.g., lower cost and energy consumption). As an example, VHF provides a data rate on the order of kbps to support simple applications, while IEEE 802.16 provides a data rate on the order of Mbps to support multimedia applications [35]. As another example, IEEE 802.11s forms a backbone network connecting ships, buoys, and beacons to shore stations, while satellite provides communication to nodes beyond the coverage of a shore station, as well as another ship, buoy, or beacon [8]. In addition, the MAC protocol must support extensions integrated to the radio access technologies, such as the use of both omnidirectional (suitable for discovering neighboring nodes [5]) and directional antennas (suitable for improving SINR). The header of a MAC frame can be revised to provide more information. For instance, path loss is the difference between the transmission power and the received power, and this can be identified by the receiver node if the transmitter node includes the transmission power in the MAC frame.

Further investigation could be pursued to investigate two main topics. Firstly, an accurate model of ship traffic, equipped with different radio access technologies, with real mobility generating highly dynamic traffic with different traffic classes. Secondly, a joint scheduling and medium access scheme that allocates resources efficiently and provides seamless handover among the available radio access technologies. The main challenge is that scheduling and medium access must take into account the heterogeneity of the radio access technologies in maritime networks, from satellite and terrestrial LOS (which are commonplace in the sea) to IEEE 802.11 and IEEE 802.16 (which are commonplace on land). Since the radio access technologies possess different capabilities in terms of data rate and transmission range, a seamless handover ensures that the network resource (i.e., channel capacity) can be shared among nodes in a neighborhood to improve the overall network performance, particularly in the event of a significant reduction in network resource, which can occur during a handover from IEEE 802.16 to satellite. This means that traditional scheduling schemes used on land, which prioritize high-priority traffic flows, may not be sufficient to cater for the needs of such traffic flows in the sea.

IV. NETWORK LAYER ISSUES FOR MARITIME NETWORKING

This section presents a review of the research works addressing network layer issues in maritime networks for the enhancement of routing schemes (i.e., delay tolerant network and traditional routing schemes), and their characteristics (i.e., robustness, the amount of routing overhead, and hop counts, as well as a discussion on emerging network layer technologies.

A. INVESTIGATION OF DELAY TOLERANT NETWORK ROUTING SCHEMES IN MARITIME NETWORKS

DTN provides intermittent connectivity that aims to maximize packet delivery under unreliable environment with a high rate of link breakages caused by low link stability, which

TABLE 4. Performance comparison of DTN routing schemes under maritime environment.

Routing Schemes	Packet delivery rate	End-to-end delay	Routing overhead
Epidemic routing [41]	High (≈ 100%)	High	High
MaxProp [43]	Medium (≈ 60%)	Medium	Medium
Spray and Wait [42]	Medium (> 50%)	Low	Low
RAPID [45]	Low (< 50%)	Medium	Medium

suits the maritime environment well. DTN routing adopts a *carry-and-forward* approach in the absence of an end-to-end connection between a source node and a destination node [39]. Since a route may not exist, the Internet paradigm does not hold. Intermediate nodes, which serve as data mules, receive and buffer packets (e.g., can store up to 200 packets [13]), wait for opportunities to establish connection to next-hop nodes, and transmit the packets to next-hop nodes whenever possible [15]. When the transmission fails, intermediate nodes, which also serve as custody holders that hold custody of received packets (rather than the source nodes), retransmit the packets.

1) DELAY TOLERANT NETWORK ROUTING SCHEMES

Under an unrealiable environment, DTN routing has been shown to improve network performance, although it generally experiences high end-to-end delay and low packet delivery rate [40]. Several DTN routing schemes have been investigated in the maritime context, including *epidemic routing*, *spray and wait*, *MaxProp*, *PROPHET*, and *RAPID*.

Epidemic routing [41] floods a network with copies of a packet until one reaches the destination node. When an intermediate node receives a copy of a packet, it copies and transmits the copies whenever it encounters and establishes a new connection with a next-hop node without the packet.

Spray and wait [42] floods a network with a *limited* number of the copies of a packet until one reaches the destination node. There are two main phases. During the spray phase, when a node receives a copy of a packet, it copies a limited number of the packet, and transmits them to a limited number of next-hop nodes. During the wait phase, when a node receives a copy of a packet, it stores the copy until it encounters a next-hop node or a destination node.

MaxProp [43] relies on historical data to estimate the delivery likelihood of each packet. Each node maintains a list of its past encounters with other nodes, and it exchanges this list whenever it encounters and establishes a new connection with a node. Historical data is important because: a) network topology and node movement possess certain characteristics (e.g., ships moving along traffic lanes) rather than being random; and b) a coming encounter is likely to occur when past encounters are frequent. A node estimates the delivery likelihood of a new node, which is the probability of the new node meeting the destination node, or participating as an intermediate node in the shortest route towards the destination node. Next, the node copies and transmits a copy of the packet to neighboring nodes based on the delivery likelihood in a prioritized manner. Hence, a new node with higher delivery likelihood is likely to receive a copy of the packet. A similar routing scheme is the *probabilistic routing protocol using history of encounters and transitivity (PROPHET)* [44].

Resource allocation protocol for intentional DTN (RAPID) [45] floods a network with a *limited* number of the copies of a packet. The number of copies is determined using per-packet optimization of a utility function based on a routing metric (e.g., bandwidth and delay). Hence, *RAPID* floods a network while taking into account the available network resources.

2) DELAY TOLERANT NETWORK ROUTING SCHEMES IN THE MARITIME CONTEXT

DTN routing schemes have been investigated in various maritime scenarios using real live data extracted from AIS, providing real ship location, speed and direction. Examples of ship traffic and scenarios include the Mediterranean sea [23] and the Strait of Singapore [25].

Table 4 shows the performance comparison of different DTN routing schemes investigated under maritime environment [23], [25]. The differences in the performance are attributed to the different characteristics and features of the different DTN routing schemes presented in the previous subsection. The table shows that: a) *epidemic routing* achieves a high packet delivery rate because it floods the copies of a packet without constraint, while flooding is limited by a number of copies of a packet in *spray and wait*, packet delivery likelihood in *MaxProp*, and network resources in *RAPID*; in addition, the packet delivery rate has been shown to reduce when transmission range reduces; b) *spray and wait* achieves a low end-to-end delay because it floods the lowest number of packets, followed by *MaxProp* and *RAPID*, and finally *epidemic routing* that floods the largest number of packets in the network; and c) *spray and wait* achieves a low routing overhead for the same preceding reason.

B. INVESTIGATION OF TRADITIONAL ROUTING SCHEMES IN MARITIME NETWORKS

Due to the similarities between maritime networks and other wireless networks, particularly MANETs and VANETs, traditional routing schemes proposed for mobile and static networks have been investigated in the maritime context.

1) TRADITIONAL ROUTING SCHEMES

Popular traditional routing schemes are optimized link state routing *(OLSR)*, destination sequenced distance

TABLE 5. Performance comparison of traditional routing schemes under maritime environment.

Routing Schemes	Packet delivery rate	Initial response delay	End-to-end delay	Routing overhead
AOMDV [14], [22], [47]	High	High	Low	Low
AODV [13], [14], [22], [24], [47]	Medium	Medium	Medium	Medium
DSR [47]	Medium	Medium	Medium	Medium
DSDV [22], [47]	Low	Low	Medium	High
OLSR [14]	Low	Low	High	High

vector *(DSDV)*, ad-hoc on-demand distance vector *(AODV)*, ad-hoc on-demand multipath distance vector *(AOMDV)*, and dynamic source routing *(DSR)*. Due to the unstable and unrealiable environment with a high rate of link breakages caused by low link stability, a ship has a large buffer to store packets including those with extended packet lifetime, until the packets are forwarded to a next-hop node in order to minimize packet loss [22].

OLSR, which is a proactive routing scheme, broadcasts two types of control messages, namely HELLO and topology control (TC). The HELLO message contains one-hop neighborhood information so that each node has two-hop neighborhood information upon receiving such messages from one-hop neighbor nodes. Each node selects multi-point relays (MPRs), which is a set of one-hop neighbor nodes that can reach all two-hop neighbor nodes, and broadcasts the MPRs information using TC messages to them. Subsequently, the node builds a topology table and a routing table.

DSDV, which is a proactive and table-driven routing scheme, maintains consistent and up-to-date routing information received from nodes in a routing table, and subsequently establishes routes from one node to another in a network. Both routing information and selected routes are updated periodically. Sequence numbers are used to prevent routing loops. The shortcoming is that routing overhead is high because periodic maintenance and update of unused and selected routes must be made despite the random and rough movement of the sea surface [46].

AODV, which is a reactive and on-demand routing scheme, establishes and maintains routes throughout their flow durations. A source node floods a network with RREQ, and intermediate nodes who receive this message rebroadcast it. Upon receiving the first RREQ, the destination node sends a unicast RREP along the route traversed by the received RREQ. Each node maintains a routing table that keeps track of routes from a source node to a destination node. The source node performs the same process during rerouting when a link breakage occurs, during which packets are buffered causing end-to-end delay to increase.

AOMDV, which is a reactive and on-demand routing scheme, establishes multiple loop-free and disjoint routes in a single route discovery process. Multiple routes can serve as backup routes under unreliable environment with a high rate of link breakages. Intermediate nodes can send RREP to the source node, and so this helps to reduce the effort of route discovery, whereas only a destination node can send an RREP message in *AODV*. This routing scheme improves network robustness, however the main shortcoming is that routing overhead, particularly RREP, increases due to the formation of multiple routes. In addition, if there is lack of backup routes, rerouting may take longer than that in *AODV*, and so *AOMDV* is not always better than *AODV*.

DSR, similar to *AODV*, is a reactive and on-demand routing scheme that establishes and maintains routes throughout their flow durations. DSR uses RREQ and RREP messages in a manner similar to AODV. The main difference with *AODV* is that intermediate nodes do not maintain routing tables, and so a source node includes routes in its packet headers during data transmission, resulting in large packet headers.

2) TRADITIONAL ROUTING SCHEMES IN THE MARITIME CONTEXT

Traditional routing schemes have been investigated in various maritime scenarios using real live data extracted from AIS. Examples of ship traffic and scenarios include a network with high node density (i.e., 60 nodes in a 200 km × 200 km area covering the English channel between Clacton-on-Sea in the UK and Middleburg in France) and a network with low node density (i.e., 30 nodes in a 300 km × 300 km area covering the North Sea) [22].

Table 5 shows the performance comparison of different traditional routing schemes investigated under maritime environment [13], [14], [22], [24], [47]. The differences in performance are attributed to the different characteristics and features of the different traditional routing schemes presented in the previous subsection. The table shows that: a) *AMODV* achieves a high packet delivery rate (or throughput) because it has backup routes; b) *DSDV* and *OLSR* achieve a low initial response delay because routes have already been set up prior to packet transmission in *OLSR*; in addition, *AODV* has a lower initial response delay than *AOMDV* because intermediate nodes rebroadcast lesser RREQ in *AODV*; c) *AOMDV* achieves a low end-to-end delay because both *AOMDV* and *AODV* have fast response to link breakage using link-layer information, and *AOMDV* has a lower end-to-end delay than *AODV* because it can switch to backup routes when a link breakage occurs; and d) *AOMDV* achieves a low routing overhead, and *AOMDV* has a lower routing overhead than *AODV* because it performs lesser reroutings since it has backup routes.

Overall, the networking performance reduces as ship density reduces as there are fewer ships available to form routes [22]. Due to the complexity of *AOMDV*, *AODV* is more preferred in maritime networks [24]. *OLSR* has the lowest packet delivery rate and throughput, and the highest end-to-end delay and routing overhead because: a) its proactive nature has caused the highest routing overheads because it broadcasts HELLO and TC messages periodically; b) node-joint routes can become hotspots with higher congestion level and also a single point of failure as many routes can be affected by a single link breakage [13]; and c) a higher broadcast frequency of HELLO and TC, which is necessary in rough sea condition (e.g., a sea state of 6.0 in the Pierson-Moskowitz's sea state model), reduces the time required to detect a link breakage, however this increases routing overhead and congestion level.

C. ENHANCEMENT OF ROBUSTNESS IN ROUTING SCHEMES

This subsection presents a review on research works enhancing the robustness of routing schemes using virtual nodes and tree structure, as well as network topologies of maritime environment.

1) ENHANCEMENT OF ROUTING SCHEMES USING VIRTUAL NODES

While a smooth and calm sea condition (e.g., a sea state of 3.0 in the Pierson-Moskowitz's sea state model) has a long duration of link availability with good link quality, it has a long duration of link unavailability as well. In [13], virtual nodes are formed to improve the robustness of a route. A virtual node is a group of nodes located within the transmission range of nodes in a previous hop virtual node. When a virtual node sends a packet to a next-hop virtual node, the same packet is sent to multiple nodes in the next-hop virtual node in a diversified manner. There is no increment in the transmission cost as long as the number of diversified transmissions is less than the maximum number of retransmissions needed to send a packet to a next-hop node in scenarios without virtual nodes. The proposed routing scheme is feasible based on the number of ships in the Strait of Singapore and the transmission ranges of a shore station and a ship being 15 km and 8 km, respectively. Each ship can select multiple next-hop nodes to establish multiple routes towards a shore station. The average hop count of the routes is found to be 1.8 hops. The proposed routing scheme has been shown to increase the probability of successful transmission, as well as reduce the packet drop rate and the number of transmissions.

2) ENHANCEMENT OF ROUTING SCHEMES USING TREE STRUCTURE

In [33], a routing scheme called MAC-based routing protocol (MRPT), which is a proactive scheme, is proposed to establish and maintain multiple routes in a tree structure, which serve as backup routes. So, nodes can join the readily available network with reduced initial response delay. Each node maintains its two-hop neighborhood information. A node chooses a neighbor node from whom it receives control messages as the next-hop node. Links with higher received signal strength (RSS), which indicates higher stability and availability (i.e., shorter distance), and routes with lower hop count are chosen at any time instant. The network is stable without frequent route changes as nodes have large transmission range and network topology changes slowly in the maritime environment. Several candidate links (or next-hop nodes) are maintained, and each candidate link has a RSS value greater than an upper threshold. There are four main features:

(a) *faster response to link breakage* because the underlying link layer can take less time (e.g., less than 5 seconds) to detect a link breakage, while traditional routing schemes, such as *OLSR*, that depend on missing Hello messages sent within a time interval (e.g., 30 seconds) can take more time (e.g., more than 1 minute) to detect a link breakage;
(b) *prevention of link breakage* because MRPT monitors link RSS, and so it can either repair a link locally, or switch to a backup route, prior to link breakage (e.g., RSS is lower than a lower threshold);
(c) *more efficient flooding of RREQ and RREP among ships and shore stations* because the underlying WiMAX mesh MAC protocol is modified to piggyback routing information (i.e., RREQ and RREP) on MAC control messages, namely MSH-NCFG which can carry more routing information compared to other MAC control messages (e.g., MSH-DSCH [24]) (see Section III-A for more description). There is no increment of routing overhead as routing information is piggybacked on existing MAC control messages;
(d) *loop-free routes are established* because sequence number is used.

MRPT has been shown to increase throughput [14], as well as reduce end-to-end delay and initial response delay. By piggybacking routing information on MSH-NCFG, the initial response delay is shorter, and the routing overhead is lower, than traditional routing scheme (i.e., *OLSR*).

3) ENHANCEMENT OF ROUTING SCHEMES BASED ON THE NETWORK TOPOLOGY OF MARITIME ENVIRONMENT

In [48], an observation of maritime network topology (i.e., mobility pattern) and network traffic is made, and subsequently a mobility-aware routing scheme is proposed. Based on real live data extracted from AIS, *four* main observations on network topology (a–d) and *one* main observation on network traffic (e) are made:

(a) there are approximately 22% of the ships being mobile at any point of time;
(b) given a transmission range of 10 km (e.g., using WiMAX transceivers), most stationary ships have a node degree of approximately 200, and most mobile ships have a node degree of approximately 50. A similar investigation in [19] shows that, given a

transmission range of 10 km, ships are connected most of the time;

(c) among the stationary ships within a time duration of one minute, 60% do not observe any changes, and 40% observe less than four changes, to their respective neighboring ships;

(d) among the mobile ships within a time duration of one minute, 40% do not observe any changes, 50% observe up to 7 changes, and 10% observe more than 7 changes, to their respective neighboring ships;

(e) most traffic is attributed to a single-hop or multi-hop ship-to-shore communication between a ship and a shore station, while a single-hop or multi-hop communication between two ships is rare.

Hence, in this investigation, a single-hop or multi-hop ship-to-shore communication between a ship and the nearest station on shore (based on the number of hops) is considered. The proposed mobility-aware routing scheme uses a weighted version of Dijkstra's algorithm to calculate the weight of a link based on the mobility characteristic of the nodes. In general, the weight value of a link between two stationary nodes has a value of 1, and the weight value of a link between two mobile nodes, or a mobile node and a stationary node, has a value given by the sum of the velocity of the two nodes. The mobility-aware routing scheme has been shown to provide two main improvements. *Firstly*, the number of mobile nodes serving as intermediate nodes is reduced from 11% to 2%, and so many routes are shifted from mobile nodes to stationary nodes. Hence, the number of nodes that do not observe any changes to routes within a time duration of five minutes has increased from 87.5% to 97.7%. This improves network scalability as the number of routing messages caused by reroutings reduces. *Secondly*, the number of route changes within an hour has reduced from 13.3 to 10.2, and the time period between consecutive changes on a route has increased by 31% from 27.9 to 36.7 minutes, with 10% of the routes lasting more than 120 minutes, hence increasing link stability.

D. REDUCTION OF ROUTING OVERHEAD

In [31], a selective broadcast scheme is proposed to reduce the flooding of routing messages (i.e., RREQ in *AODV*), which consumes high bandwidth, in bandwidth-constrained maritime networks. Each node knows its own location and the location of its destination node, and it broadcasts this information in RREQ among its neighboring nodes. Hence, each neighbor node knows its own location, as well as the locations of the sender node and the destination node. The neighbor node determines its broadcast region, which is an optimal region geometrically close to a line connecting the sender node and the destination node. Only neighbor nodes in the broadcast region forward the RREQ message. The proposed scheme has been shown to increase throughput and reduce routing overhead, which are expected to be more significant when node density increases.

E. INVESTIGATION OF SINGLE VERSUS MULTIPLE ROUTES

In [49], an investigation to determine whether single or multiple routes provide a better network performance is conducted using two joint MAC and routing schemes. The first scheme, which is based on three-way handshakings, establishes a *single* route. There are three main steps: a) a source node anycasts packets to upstream next-hop nodes that forward the packets; b) each upstream next-hop node sends an acknowledgement message to the source node; and c) the source node selects one of the upstream next-hop nodes, and sends a grant message to the node. A single route is established because only a single upstream next-hop node receives the grant message. The second scheme, which is based on two-way handshakings, establishes *multiple* routes. Out of the three main steps, this scheme performs the first two steps only. Multiple routes are established since multiple upstream next-hop nodes forward packets to their respective upstream next-hop nodes. The second scheme has been shown to reduce the number of retransmissions and end-to-end delay.

In [50], an investigation to determine whether a single or multiple routes provide better network performance *with respect to network congestion level* is conducted. Using a single route, the end-to-end delay is given by a selected route, which is expected to provide the minimum average end-to-end delay; while using multiple routes, the end-to-end delay is given by the minimum end-to-end delay among the multiple routes. While multiple routes seem to provide lower end-to-end delay, it can increase bandwidth requirement and its interference level can increase the congestion level. Replication gain, which depends on the advantages and disadvantages of using multiple routes, as well as the current network congestion level, is calculated. There are three main steps: a) estimate the delay distribution of each route by broadcasting probing packets periodically to measure round-trip delay; b) select an optimal route based on the estimated delay distribution; and c) determine whether to use a single route or multiple routes according to the replication gain. Investigation has shown that using a single route is more suitable at higher congestion levels, while using multiple routes is more suitable at lower congestion levels. The proposed scheme has been shown to increase bandwidth and packet delivery rate, as well as reduce end-to-end delay and packet loss rate.

F. EMERGING NETWORK LAYER TECHNOLOGIES

This subsection presents three emerging network layer enhancements that can be incorporated into the maritime networks, namely support for DTN, enhancement of multipathing in the maritime context, and prediction of network topology.

1) SUPPORT FOR DELAY TOLERANT NETWORKING

In DTN routing schemes, a node makes decisions on packet transmission whether [23]: a) to transmit all or part of its buffered packets (i.e., link connection time between two moving ships is long enough for packet transmission); or b) to wait for a forthcoming connection (i.e., estimated link connection time between two moving ships is longer for packet transmission). While the latter may seem to incur higher end-to-end delay, it can increase the reliability of packet delivery, contributing to a lower end-to-end delay in reality. Further investigation could be pursued to predict future contact opportunities and their durations between two nodes based on instantaneous and historical (e.g., deterministic and repetitive patterns) mobility information gathered using AIS, and the global view of a maritime network [23].

2) ENHANCEMENT OF MULTIPATHING IN THE MARITIME CONTEXT

Multipathing establishes multiple routes, which can be used either as backup routes as seen in AOMDV, or for simultaneous packet transmission. Multipathing has been investigated in the maritime context in [49], [50], and the focus is to address network congestion in [50]. Extension can be made so that multipathing provides *three* main advantages [51]. *Firstly*, it introduces route diversity and redundancy whereby multiple routes coexist at the same time to improve fault tolerance under unstable and unreliable environment with a high rate of link breakages caused by low link stability. *Secondly*, it provides resource pooling whereby multiple routes provide a pool of multiplexed resources that can minimize the congestion level of a single route. *Thirdly*, it provides traffic splitting for simultaneous packet transmission over multiple routes. By transmitting packets over multiple routes, multipathing addresses the dynamic link quality and bandwidth constrained maritime environment, whereby additional or alternative routes can be established to cater for applications with high bandwidth requirements and with bursty traffic, as well as to ameliorate the detrimental effects of bottleneck links. Hence, multipathing is foreseen to enhance robustness, which is pertinent to maritime networks. Further investigation could be pursued to deploy multipathing in maritime networks and address its shortcomings, including: a) to reduce the higher computational complexity and routing overhead in multipathing, b) to reduce the additional memory required to store more routes, and c) to achieve load balancing among multiple routes in order to minimize congestion level over a single route.

3) PREDICTION OF NETWORK TOPOLOGY

The current mobility pattern, which can be extracted from AIS, can be used to predict the upcoming changes to network topology [52]. For instance, some upcoming connections, such as a ship entering a network coverage area (or soon-to-be-available connection), and a ship leaving a network coverage area (or soon-to-be-broken connection), their durations, and their capacity, can be predicted. Proactive approaches can be applied to networking schemes, including resource allocation, admission control, and routing, based on the upcoming network topology and demand. This helps to support real-time multimedia transmission (e.g., video conferencing and voice over IP) that requires low end-to-end delay. For instance, resources can be allocated before a ship enters a network coverage, which can be predicted based on the current mobility pattern. Further investigation can be pursued to predict the upcoming changes to network topology, and the use of the prediction to benefit various networking schemes to support real-time multimedia transmission.

V. UPPER LAYER ISSUES FOR MARITIME NETWORKING

This section presents a review of the research works addressing upper layer issues in maritime networks for the enhancement of management architectures, as well as a discussion on emerging upper layer technologies.

A. MANAGEMENT ARCHITECTURE FOR CLASS-BASED PER-FLOW TRAFFIC PRIORITIZATION

In [39], a high-level service-oriented policy-based management architecture is proposed to provide class-based per-flow traffic prioritization so that high-priority traffic flows can minimize the effect of congestion and meet their QoS requirements. The architecture provides an abstract view that hides the complexity of the underlying network configuration to simplify network management, which is necessary due to the limited availability of skilled network operators at sea. Given a high-level policy, it is evaluated to generate low-level policy decisions matched with appropriate low-level management services. There are five main types of management services:

(a) *traffic monitoring* provides information on the incoming and outgoing traffic flows of a node;
(b) *traffic prioritization* matches a traffic flow with one of the traffic classes that provide differentiated service priorities and discard priorities based on various characteristics, such as delay and packet loss. Control information can be included in the packet headers so that differentiated priorities can be applied to the traffic flow along a route for achieving guaranteed QoS [5];
(c) *adaptive routing* changes a route that cannot meet the required QoS requirements to a better route;
(d) *resource reservation* probes multiple routes and reserves resources along routes with more resources (e.g., with lesser reservations by existing routes);
(e) *access control* prioritizes access of certain traffic flows (e.g., traffic flows from a commander's laptop).

The proposed architecture has been shown to reduce the end-to-end delay of high-priority traffic flows.

B. EMERGING UPPER LAYER TECHNOLOGIES

This subsection presents an emerging upper layer enhancement that can be incorporated into the maritime networks, namely self-organization. Due to the limited availability of skilled network operators at sea, maritime network requires self-organization. Self-organization includes: a) initialization; b) adaptation based on the current network capabilities and conditions, as well as the network goals, as time goes by; and c) re-configuration upon failures (or self-healing) to improve robustness. Self-organization can help in realizing self-configuration and self-optimization in the unstable environments that characterize maritime networks in which there is a high rate of link breakages, low link stability, and dynamic traffic flows. Further investigation could be pursued to achieve self-organization in various aspects of networking, including network architecture, congestion control, routing, scheduling, and MAC protocol.

VI. SIMULATION AND IMPLEMENTATION OF MARITIME NETWORKING

This section presents a simulation platform and two prototypes for maritime networks.

In [2], the TRITON simulation platform is implemented using a network simulator called Qualnet [53]. It consists of three main components. Firstly, the *sea terrain*, or the wave motion, changes the orientation and altitude (up-and-down motion) of an antenna on a ship, causing the antenna gain, which varies with angles, to fluctuate. Consequently, the transmission and received signal strength fluctuate, resulting in unstable signal reception. The sea terrain, which is a function of time and location, incorporates wave direction, as well as the Pierson-Moskowitz's [32] sea state model that includes wavelength, wave height, and wave period. The sea terrain calculates the degree of tilt of a ship, which is based on the magnitude of the wave and the ship size, and then calculates the antenna gain and antenna height, which are dependent on the wave altitude at the time of transmission. Secondly, the *two-ray path interference* is a reflected signal from the sea surface that interferes with, or even cancels, the main signal propagating in the air. The interference is based on the antenna height given by the sea terrain model. Thirdly, the *ship traffic* is based on real live data extracted from AIS, which is characterized by two parameters, namely the inter-arrival time of a new ship entering the network, and the constant speed of a ship guided by the maximum speed of the shipping lanes. The simulation platform is suitable for narrow shipping routes, such as the Strait of Malacca, the Strait of Singapore, and the English channel, that provide vital passage for passenger, cruise, and freighter ships.

In [9], the TRITON prototype consists of mesh nodes. Each mesh node is a processing unit equipped with an array of four directional antennas covering four sectors in different horizontal directions that constitute an omnidirectional antenna in order to support message broadcast. Each sector consists of three antennas in different vertical directions (e.g., 0°, a $+5°$ to $+10°$ tilt, and a $-5°$ to $-10°$ tilt depending on the operating channel frequency) in order to address low link stability whereby there is a high rate of link breakages under unstable environment. Each ship is installed with a mesh node operating at either 2.3 or 5.8 GHz. Measurements for packet delivery rate and response delay in single-hop and multi-hop transmissions are made. In the single-hop scenario, a mesh node is installed on a boat at 4.4 meters above the sea surface, and another mesh node is installed on a tower at 8 meters above the sea surface. Measurement results show TRITON provides a packet delivery rate of approximately 99% and a response delay of 3.1 ms at both 3.2 km and 6 km apart. In the two-hop scenario, mesh nodes are approximately 1.3 km and 1 km apart in the first and second hops, respectively. Measurement results show TRITON provides a packet delivery rate of at least 98%.

In [34], the MICRONet prototype consists of two main equipment from vendor Ubiquiti, namely a shore station (*Ubiquiti Rocket M5*) equipped with directional antenna (*Ubiquiti airMAX sector antenna AM-5G19-120*) installed on top of a 16-story building at approximately 56 meters above the sea surface, and a client (*Ubiquiti NanoStation M5*) equipped on a fishing boat at approximately 9 meters above the sea surface. There are two main software tools: a) *Ubiquiti airOS* configures and displays operating parameters and performance measures, such as transmission power, operating channel, and antenna gain, of both shore station and client; and b) *Ubiquiti airView*, which is a spectrum analyzer, analyzes noise in the operating environment and selects appropriate operating channels. Measurements for data rate and transmission range are made. Neighboring fishing boats, as user equipment without the client, communicate with one of the fishing boats equipped with the client. The client is equipped with: a) access point so that it can communicate with other fishing boats without LR Wi-Fi, and b) *Ubiquiti NanoStation M5* so that it can communicate with the shore station using LR Wi-Fi. Measurement results show MICRONet provides a data rate of approximately 1.7 Mbps and a transmission range of approximately 17.7 km.

VII. OPEN ISSUES

Due to the limited work in maritime networks in the literature, there is much to be explored. While there have been intensive investigations on certain topics in terrestrial networks, such as the use of multiple channels for transmission and the use of cognitive radio to utilize white spaces [54], there is lack of similar investigation under maritime environment. Traditional schemes can be enhanced to address distinguishing characteristics of maritime networks; for instance, using the connection-oriented transmission control protocol (TCP), sender nodes can increase its small window size caused by the unstable environment with a high rate of link breakages in order to increase throughput performance. In maritime environment, while there have been separate investigations on traditional and DTN routing schemes, there is lack of an investigation to compare their network performance under maritime environment. Focus can also be placed on investigating maritime networks for different purposes, such as search and rescue operations.

In addition to the emerging technologies in the link, network, and upper layers presented in Sections III-C, IV-F, and V-B, respectively, the rest of this section presents open issues that can be pursued in the networking aspect of maritime networks.

A. ENHANCEMENT OF NETWORK TOPOLOGY

The underlying network topology can be improved by:

(a) exploring the use of clustering techniques to improve network scalability and stability. Clustering segregates nodes in a network into smaller groups, each with a node elected as a leader to manage and handle control messages from its own cluster and neighboring clusters in order to reduce control messages in the network. Since ships have different node densities in different areas, cluster size can be adjusted to prevent leader nodes from congestion. Specifically, nodes form smaller clusters at areas with higher node density (e.g., among ships anchored at ports and surroundings), and larger clusters at areas with lower node density (e.g., among ships at sea);

(b) achieving a balanced trade-off between network stability and load balancing as mobility-aware routing schemes concentrate a large amount of traffic to a small number of nodes with low mobility causing bottlenecks;

(c) adjusting the choice of routing schemes (e.g., AOMDV and DTN) to achieve better network performance under different kinds of network topologies, including networks with high and low node densities [25], respectively, and so a hybrid routing scheme may be more suitable;

(d) adjusting the choice of transmission characteristics (e.g., transmission power and range) according to node density for topology control and management. This is because increasing the transmission power increases the number of disjoint routes and achieves a connected network as a result of increased node density [26] and the number of available links, while decreasing the transmission power reduces energy consumption and routing overhead. For instance, some temporary network disconnections may lead to a significant reduction in energy consumption [19], [26];

(e) addressing the effects of low node density (e.g., limited contact opportunities in a network with low node density);

(f) addressing the effects of environmental factors on hop counts (e.g., hop count increases when channel quality and node density reduce).

Meanwhile, investigation can also be made on the deployment of the shore stations, particularly on the number and the locations, as well as channel frequency for achieving an enhanced network performance. The choice of channel frequency affects the number of shore stations along a coastline; for instance, a particular area covered by 30 base stations at 3.5 GHz can be covered by only 2 base stations at 450 MHz [6].

B. INTEGRATION OF AERIAL NETWORKING INTO MARITIME NETWORKING

Aerial networks can provide a large coverage of wireless broadband service on the sea from the sky due to its elevated look angle [55]. Generally speaking, aerial networks are comprised of two main components. Firstly, the *aerial* segment consists of lightweight networking infrastructure (e.g., LTE-Advanced (LTE-A) base stations [56]) mounted on high-altitude platforms (e.g., high-altitude balloons [57], airships, and high-altitude long-endurance aircrafts [58]) and low-altitude platforms (e.g., unmanned aerial vehicles/ drones [1], and helikites [56]). The altitude platforms can be equipped with additional features, such as energy harvesting to improve energy efficiency [59] and software-defined radio with cognition (or intelligence) to explore and utilize white spaces [56]. The altitude platforms also have different characteristics; for instance, airships use lighter gas that can float up to 30 km above the ground level for years [56], and high-altitude balloons use helium gas that can float up to 20 km above the ground for months [57]. Secondly, the *terrestrial* segment consists of a stationary station installed on stationary or moving ships. The terrestrial segment can establish connection to existing infrastructure, such as satellite and terrestrial networks, for Internet access. The aerial and terrestrial segments are connected via high-speed links (e.g., fiber optic [56]), and both segments constitute a base station on the sea that provides wireless broadband service to nodes in the vicinity.

There has been lack of investigation on the integration of aerial networks into maritime networks in the literature. Investigation could be pursued in various aspects. *Firstly*, designing an air-to-water surface radio propagation model under maritime environment. This model is different from terrestrial radio propagation because radio propagation is mainly affected by free space path loss in the air until it reaches the sea surface in the air-to-water surface model. *Secondly*, achieving a balanced trade-off between altitude and energy consumption. While increasing the altitude of the aerial segment can increase coverage, the impact of free space path loss and energy consumption increases. *Thirdly*, based on the underlying network topology characterized by the ship traffic, investigating the use of clustering to reduce communication between nodes and the aerial segment in order to reduce energy consumption and network congestion. In the cluster structure, the leader of a cluster gathers and processes packets from nodes, and sends the packets to the aerial segment. Nodes may communicate with the leader in a single or multiple hops for coverage extension.

C. INTEGRATION OF UNDERWATER NETWORKING INTO MARITIME NETWORKING

Underwater networks use acoustic wave propagation, which is susceptible to noises, for underwater communication (see Section II-D for more details). In [1], an integration between underwater and maritime networks is proposed to support communication above and under the water. In general, there are two main components. Firstly, the *under the water* segment consists of underwater nodes that communicate with access points embedded in surface gateways (e.g., buoys). Secondly, the *above the water* segment consists of the surface gateways that form a maritime network to access wireless broadband service via shore stations, terrestrial LOS, and satellite.

There has been lack of investigation on the integration of underwater networks into maritime networks in the literature. Investigation could be pursued in various aspects. *Firstly*, deploying the surface gateways, which serve both under the water and above the water communications, while taking into account the transmission ranges of both kinds of communications and coverage, in order to achieve the optimal number of surface gateways. *Secondly*, achieving a balanced trade-off among network performances achieved by under the water and above the water segments, and the overall network performance.

D. WIDER ADOPTION OF MARITIME NETWORKING TECHNOLOGIES

In multi-hop transmission, nodes cooperate among themselves in packet forwarding, and so multi-hop connectivity must be supported by a sufficient number of nodes. According to [26], a maritime network is practical if 90% of the ships are connected to shore stations 90% of the time. Hence, a wide adoption of the maritime network is crucial to its success. The technology can become more common when the node density (e.g., ships adopting the technology, particularly along the shipping routes) increases, and more locations accept and support the technology. Due to the transnational nature of maritime communications, the operating environment can be heterogeneous. For instance, marine-band VHF channel at 156.150 MHz (or channel 3) is illegal for public use in the United States, although it is used for ship-to-shore communications in Europe. Nevertheless, there are some channels commonly used at the international level, such as: a) 156.800 MHz (or channel 16) caters for international distress, safety and calling [6], [60]; and b) 450 MHz to 470 MHz and 698 MHz to 862 MHz cater for international mobile telecommunications services as approved by ITU World Radiocommunication Conference 2007 [6]. Hence, further investigation could be pursued to address the heterogeneous operating environment in different areas (e.g., the use of different channel frequencies in different countries, and seamless handover) as a ship moves from one region to another.

E. EXTENSION OF THE SERVICE-LIMITED COVERAGE OF HIGH-SPEED TERRESTRIAL WIRELESS BROADBAND SERVICE ON LAND TO THE SEA

One prominent way in ensuring a good and reliable maritime network connectivity is to extend the service-limited coverage of high-speed terrestrial wireless broadband service on land, particularly along coastlines, to the sea through multihop network. There are *three* main factors that affect the coverage of a high-speed terrestrial wireless broadband service on land: a) base station specifications; b) types of networks deployed (e.g., GSM, GPRS, HSPA, or hybrid); and c) the number of users in an area. While the service-coverage may be large, the QoS depends on the types of networks deployed.

As shown in Figure 2, the current wireless broadband service on land has a limited (i.e., without multihop transmission) operating region along a coastline that cannot be extended to cover the shipping route in the sea. Hence, subscribing to a single network operator for a particular wireless broadband service may not be sufficient to get a reliable connectivity to the Internet, especially when users are on the move. This means that a user may be required to connect to alternative or redundant networks. Due to this reason, further research could be pursued to investigate the extension of the service-limited coverage of high-speed terrestrial wireless broadband service on land to the sea via multihop transmission with service availability and reliable connectivity in mind.

VIII. CONCLUSIONS

This article refreshes the topic of maritime networking through a review of the limited number of works on this topic and proceeds to discuss open issues ripe for further investigations. While the need to improve wireless broadband service at sea is essential to achieve performance close to high-speed terrestrial wireless broadband service on land, there is limited work on maritime networking in the literature. Nevertheless, the conventional communication systems at sea, particularly satellite communication and terrestrial line of sight, are plagued with shortcomings that are unable to support high-speed wireless broadband service. Maritime networks require separate attention due to its distinguishing characteristics whereby: a) the link quality and bandwidth are dependent on the sea condition, which can be calm or rough; and b) the network topology is dependent on the ship traffic. Recent works in maritime networking revolve around the maritime networking issues in the link, network, and upper layers. Future investigations could be pursued to: a) enhance network topology; b) integrate aerial networking into maritime networking; c) provide wider adoption maritime networking technologies; and d) extend the service-limited coverage of high-speed terrestrial wireless broadband service on land to the sea. This article has laid a solid foundation and refreshed new research interests in maritime networking for further investigation.

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Dr. Qadir is a member of ACM. He received the Highest National Teaching Award in Pakistan—the higher education commission's (HEC) Best University Teacher Award—from 2012 to 2013. He has been nominated for this award twice (2011, and 2012—2013). He is a regular Reviewer for a number of journals and has served in the Program Committee of a number of international conferences. He serves as an Associate Editor for the IEEE ACCESS, the *IEEE Communication Magazine*, and *Nature Big Data Analytics (Springer)*. He was the Lead Guest Editor for the special issue Artificial Intelligence Enabled Networking in the IEEE ACCESS and the feature topic Wireless Technologies for Development in the *IEEE Communications Magazine*.

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