Performance Study on Delay Tolerant Networks in Maritime Communication Environments

Hao-Min Lin*, Yu Ge†, Ai-Chun Pang*‡, Jaya Shankar Pathmasuntharam†
*Department of Computer Science and Information Engineering, National Taiwan University
‡Graduate Institute of Networking and Mulitimedia, National Taiwan University
{d97005, acpang}@csie.ntu.edu.tw
†Networking Protocols Department, Institute for Infocomm Research
{geyu, jshankar}@i2r.a-star.edu.sg

***Abstract*—Today, it is still hard to form an alternative network in a maritime environment besides using costly satellite links because of the lack of wireless infrastructure at sea. In the TRITON project, we are exploring the use of WiMAX-based mesh technology for over the horizon ship-to-ship communications with Delay Tolerant Network (DTN) features to provide less expensive wireless communication services at sea. In this paper, we study the performance on delay tolerant networks in the maritime communication environment. We compare the performance of different routing schemes including regular routing protocols such as Ad Hoc On Demand Distance Vector (AODV) Routing and Optimized Link State Routing (OLSR), and DTN routing protocols such as Epidemic Routing and Spray and Wait Routing. Simulation results, based on a maritime terrain model derived from actual measurements in the Strait of Singapore, show that DTN routing achieves better end-to-end packet delivery ratio than regular routing schemes in WiMAX-based maritime mesh networks.**

***Index Terms*—Delay Tolerant Network, Maritime Communication, WiMAX, Mesh Network**

I. Introduction

These days, ships are still heavily dependent on costly satellite links for communications because alternative and less expensive wireless communication services are not available at sea. Let us give an example, it costs about USD 0.03 per minute when making a phone call on land, but the similar phone call would be 30 times more when you call from a ship. To provide less expensive wireless communication services at sea, we target to form a WiMAX-based maritime mesh network for over the horizon ship-to-ship communications. Such a network structure is similar to a terrestrial Vehicular Ad hoc Network (VANET), which is composed of moving vehicles to extend the coverage of networks to land transport systems. Although the terrestrial VANETs and maritime mesh networks have similarities such as no power limitation at communication nodes, traffic lanes limiting network topologies, possibility of using GPS and GALILEO to achieve accurate positioning, etc., the unique characteristics of maritime communication networks lie in the mobility pattern of ships and the sea surface conditions that lead to time-varying received signal quality. Researchers have studied VANETs on highways, but only a few of them have studied its use in a maritime environment. To study the performance of WiMAX-based maritime mesh networks, we focus on the shipping lanes in the Strait of Singapore as Fig. 1.

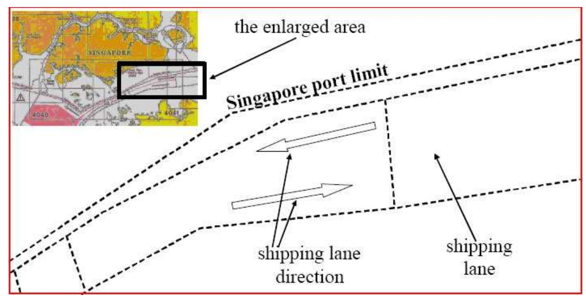

Fig. 1. An illustration of the directed shipping lane of Singapore [11].

In our previous work [11], we compared the performance of Optimized Link State Routing (OLSR) [13], Ad Hoc On Demand Distance Vector (AODV) Routing [14] and Ad Hoc On Demand Multipath Distance Vector (AOMDV) Routing [15] over a WiMAX mesh network in a maritime communication environment. The performance of these routing protocols is reasonable when the network has a high degree of connectivity.

The requirement for radio ranges for ship-to-ship and ship-to-base station in order to achieve ideal connectivity was previously studied [11] based on the analysis of real mobility data for large cargo and container ships. From our connectivity studies based on maritime mobility pattern and maritime radio propagation model, ideal radio ranges for a regular network with reasonable performance must be larger than 35 km and 20 km for ship-to-base station and ship-to-ship links, respectively. To achieve these distances, there are several conditions that have to be met. Antennas should be sufficiently high to ensure line-of-sight operation, RF transmit power has to be sufficiently high and the sea condition has to be relatively good to ensure no occlusion of links.

In this paper, we conduct the performance studies under "less" than ideal radio propagation situations such as lower profile boats, restricted RF transmission powers and harsher sea conditions, and hence the effective radio ranges have to be reduced. Under less than ideal connectivity conditions, regular routing protocols are expected to fail easily in finding paths, thus causing the packet delivery ratio to decrease. Under such circumstances, we choose to study the Delay Tolerant Network (DTN) configurations [20] in the maritime environment and explore if we can still have maritime communication networks with reasonable performance for ships.

Some researchers have proposed and studied various routing schemes for DTNs [20]. Epidemic Routing [6] is a flooding-based routing scheme to deliver packets to destination nodes; it may achieve up to 100% packet delivery ratio if there is no limitation on resources. As Epidemic Routing consumes vast amount of resources, Spray and Wait Routing [8] has been proposed for restricting end-to-end transmissions to be two hops and it has been shown to achieve more than 50% packet delivery ratio under the random way point mobility pattern. PRoPHET [7] is an one-hop relaying DTN routing scheme that routes packets by estimating the delivery probability of relay nodes from historical data. PRoPHET outperforms Epidemic Routing if the node buffer size is small. MaxProp [2] provides a delivery path by using a variation of Dijkstra algorithm to estimate delivery likelihood. MaxProp consumes less resource than Epidemic Routing and achieves more than 60% packet delivery ratio if node buffer size is sufficiently large. MORA [5] uses multi-objective robots to help relay nodes forward packets and it can co-exist with other DTN routing protocols when necessary. PEAR [9], [10] has been proposed to use the mobility entropy in community structured environments to select the next hop among candidate nodes. Most of the performance studies on DTN routing protocols have been conducted in buses, cars, sociological mobile environments or community structured environments.

However, the investigation on DTN routing in a maritime environment based on the WiMAX-based mesh technology has been rarely done in the literature. Our study is based on actual Automatic Identification System (AIS) data obtained from the Maritime Port Authority of Singapore. We have derived the ship mobility pattern and modeled various parameters such as antenna patterns, wave occlusions due to sea state, RF propagation impairments due to sea surface reflections, earth surface curvature, and ship rocking movements to ensure that the network is modeled accurately according to actual maritime environments.

In this paper, we compare the performance of the regular and DTN routing protocols over a WiMAX mesh network in a maritime communication environment. We choose Optimized Link State Routing (OLSR) and Ad Hoc On Demand Distance Vector Routing developed by Internet Engineering Task Force (IETF) to represent the regular routing protocols as they are well-known proactive and reactive routing protocols, respectively. For DTN routing schemes, Epidemic Routing and Spray and Wait Routing are chosen because they respectively represent multi-hop and two-hop DTN routing schemes. This paper is organized as follows. In Section II, we briefly introduce the system model and the DTN routing protocols that we have chosen for the intended maritime communication environment. In Section III, we discuss the simulation results. Finally, we conclude the paper in Section IV.

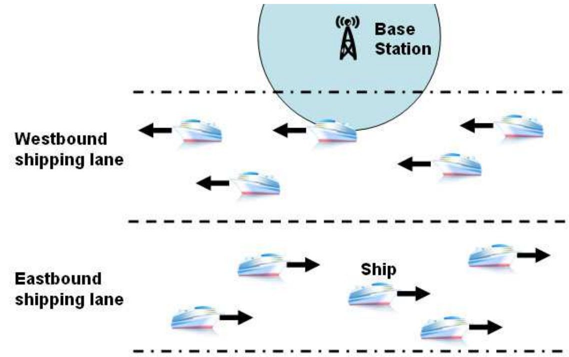

Fig. 2. A representative example for a maritime communication network in a narrow navigation channel.

II. System Model

A. Maritime Communication Environment

To accurately simulate a maritime communication environment, we have modeled the radio propagation impairments due to strong reflection from sea surface and random sea surface movements. The sea condition is modeled in the simulation according to Pierson-Moskowitz's sea states [24]. The propagation impairments and sea condition affect the transmission reliability over wireless links, which in turn affects the packet delivery ratio at the network layer.

Fig. 2 shows the network topology which we use to represent a busy narrow navigation channel in the Strait of Singapore with traffic separation by the International Maritime Organization. In Fig. 2, there are two parallel shipping lanes, each with a width of 12 km and a length of 71.5 km. The base station is located 1 km from the shore to allow flexibility in its deployment. In our previous work [11], the ship mobility has been characterized by two parameters: the inter-arrival time of a new ship to the network (t_i) and the constant speed of ship i (v_i). Here, t_i is the time difference between the arrivals of ship $i-1$ and ship i in a given shipping lane. t_i and v_i are random variables with the following probability density functions [1]:

$$p_{t_i}(x) = a \times b^x, and \tag{1}$$

$$p_{v_i}(x) = \frac{c}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/(2\sigma^2)} \tag{2}$$

where μ and σ are respectively the mean value and deviation of ship speed. a, b, and c are the factors to ensure best-fit between the functions and empirical data obtained from AIS and provided by the Maritime Port Authority of Singapore. For more detailed ship mobility model and the parameter setting, readers can refer to [12].

To represent a less than ideal maritime communication environment, we assume that the link distance between a land base station and a ship (BS-to-SS) is 10 km, and the link distance between two ships (SS-to-SS) is 6.3 km/4 km. From

[1]Each ship has i.i.d. t_i and v_i.

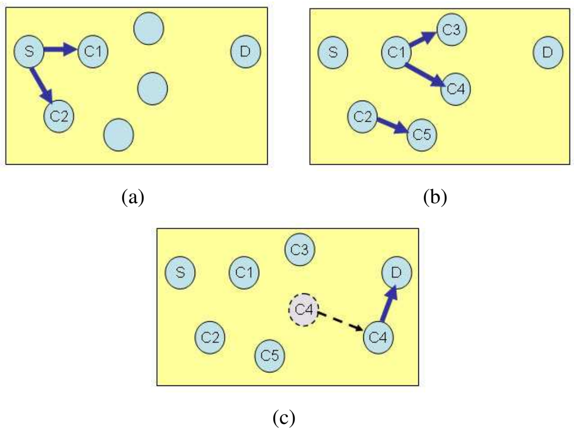

Fig. 3. (a) Source node copies message to its neighbors. (b) Copies-received node forward message to their neighbors. (c) Copies-received node moves and exchanges the message to its new neighbor (destination node).

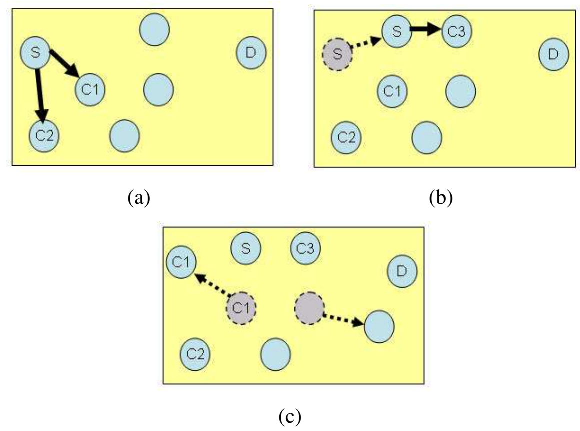

Fig. 4. (a) Source node copies message to its neighbors. (b) Copies-received node forwards message to their neighbors. (c) Copies-received node moves and exchanges the message to its new neighbor (destination node).

our experiments and demo in Phuket Island in International Conference on ITS Telecommunications (ITST) 2008, we have found that such settings are feasible in real systems. However, the configurations are not able to ensure reliable end-to-end paths in the network and lead to intermittent network connectivity [11].

B. DTN Routing in Maritime Communication Environment

As we mentioned above, the maritime communication environment is a particular type of Intermittently Connected Mobile Networks (ICMN) and the benefits to enable DTN in ICMN have been shown in [1], [3], [4], and [5]. In this paper, we focus on two DTN routing protocols: Epidemic Routing [6] and Spray and Wait Routing [8] to study the network performance in a maritime communication environment.

1) Epidemic Routing: In Epidemic Routing, each node maintains a message buffer for itself and its neighbors. When a message is generated by a source node, the source node assigns a unique ID to this message, transmits the message to its neighbors, and stores the message in its buffer; this process is shown in Fig. 3(a). The receiver node repeats this process until the message reaches the destination, as shown in Figs. 3(b) and 3(c). When a node encounters a new neighbor, the two nodes exchange the messages which are not in each other's buffer. Once a message is delivered to the destination, the message will be deleted from the message buffers at all nodes.

Epidemic Routing makes minimal assumptions on the ICMN and does not require global information and complicated algorithms for multi-hop packet forwarding. As such, Epidemic Routing is expected to perform well in the harsh maritime communication environment.

In the simulation, we optimize Epidemic Routing in the following two perspectives. First, we implement a $First - In - First - Out$ (FIFO) buffer at a node to drop outdated messages in the message buffer to prevent over-utilization of resources. Second, as a ship may contact with its neighbors in an intermittent way, we implement a $forwarded\ neighbor\ list$ at a node to avoid exchanging messages with its old neighbors.

2) Spray and Wait Routing: Spray and Wait Routing was proposed in [8], where each node in the network has two phases in the operation: Spray phase and Wait phase. An example of Spray and Wait Routing is shown in Fig. 4. In this example, we assume every source node has $message\ copies\ limit\ L$. In Fig. 4(a), when a message is generated by a source node, the source node turns into Spray phase and copies this message to its neighbors. The source node then stays in Spray phase and continues to send the message to its new neighbors until the $message\ copies\ limit\ L$ is reached. In Fig. 4(b), the source node encounters a new neighbor and copies its message to this neighbor. The source node turns into Wait phase when the $message\ copies\ limit\ L$ is reached. Once receiving a message, the copy-received node turns into Wait phase. Finally, node C3 encounters and forwards the message to the destination node, as shown in Fig. 4(c). Spray and Wait Routing reduces the consumption of network resources by limiting the maximum message copies that are forwarded to the relay nodes. The delivery rate of Spray and Wait Routing is decided by the contactable probability of the nodes and the number of message copies sprayed into the ICMN. As compared to Epidemic Routing, Spray and Wait Routing only allows one-hop relaying.

The comparison of the routing protocols including AODV [14], OLSR [13], Epidemic Routing [6], and Spray and Wait Routing [8] is presented in Table I. Epidemic Routing and Spray and Wait Routing forward packets only need to know their neighbors leave or join their connection area. Thus, we can implement a neighbor list for these two routing protocols from Neighbor Discovery Protocol (NDP) [16].

III. Simulation Results

In the simulation, we have built a maritime communication environment in QualNet 3.9.5 according to the characteristics of the Strait of Singapore. To accurately simulate a maritime

TABLE I
ROUTING PROTOCOL COMPARISON

Routing Protocol	AODV	OLSR	Epidemic	Spray and Wait
Routing Type	On-Demand	Proactive	Flooding-Based	Flooding-Based
Relay Type	Multi-Hop	Multi-Hop	Multi-Hop	One-Hop
Buffer	Small	none	Large	Large
Delay Tolerant	N	N	Y	Y
Routing Message	On-Demand	Periodically exchange routing messages	from Neighbor Discovery Protocol (NDP) [16]	from NDP [16]
Message Copies	One	One	Unlimited	L

TABLE II
SIMULATION SETTING

PHY-Model	IEEE 802.16d Mesh
Data Rate	5.5Mbps
Code Scheme	QPSK 1/2
Channel Bandwidth	16MHz
802.16d MAC Frame Duration	10ms
Buffer in MAC	2000 packets
Buffer in DTN routing	1000 packets
Number of spray copies L in Spray and Wait routing protocol	20
Traffic Type	CBR
Simulation Time	10000 seconds
Number of nodes	60

TABLE III
PIERSON-MOSKOWITZ SEA STATE TABLE [24]

Wind Speed (knots)	14
Significant Wave Height, W (meter)	1.0667
Average Wave Period, T (second)	3.5
Average Wave Length L (meter)	14.0201

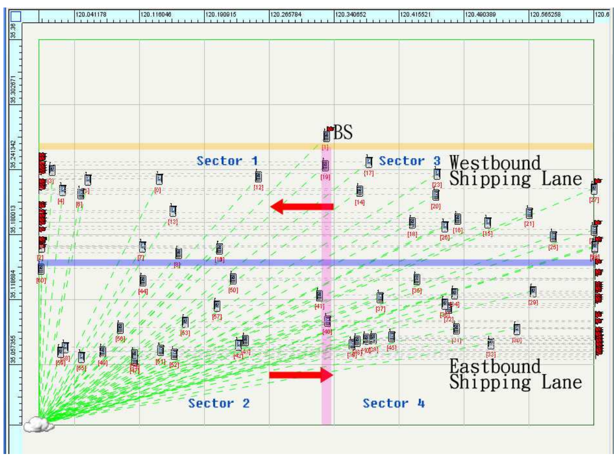

Fig. 5. The network topology in a maritime environment.

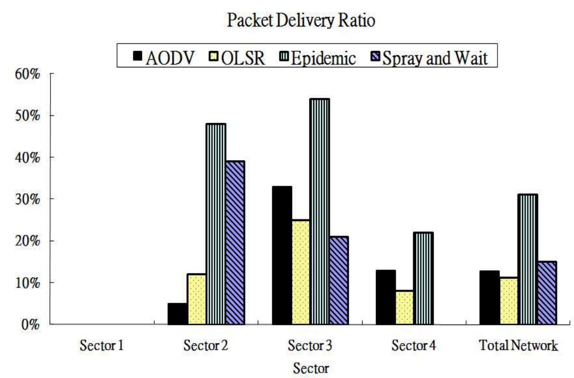

Fig. 6. Comparison of delivery ratios (BS-to-SS radio range is 10 km and SS-to-SS radio range is 6.3km).

communication environment, we introduce a maritime terrain model which is derived from actual measurements in the Strait of Singapore. We also implement the WiMAX Medium Access Control (MAC) protocol in mesh operational mode in the simulator. In our simulation, we assume the buffer size is 1000 packets because each ship can carry large storage. Table II shows the setting of simulation parameters, and Table III gives the sea condition.

We choose AODV [14], OLSR [13], Epidemic [6], and Spray and Wait [8] routing protocols to study the routing performance in a maritime communication environment. To compare the performance of different routing protocols, the observed network as depicted in Fig. 5 is divided into four non-overlapping regions, i.e., Sectors 1, 2, 3, and 4. From Fig. 5, we can see that the ships in Sector 2 and Sector 3 are moving closer to the BS while the ships in Sector 1 and Sector 4 are moving away from the BS and tend to be out of our target maritime communication network. In each simulation, two ships are randomly selected from each region as traffic sources to generate constant bit rate (CBR) traffic to the BS with the rate of one packet per three minutes.

Fig. 6 shows the packet delivery ratios for the routing protocols under investigation, and the transmission distance of an SS-to-SS link is 6.3 km. We observe that the packet delivery ratio of the four routing schemes for the Sector-1 ships is almost 0%. The reason is that most of the Sector-1 ships are moving out of the network coverage and the connectivity is poor in this area due to sparse ship deployment. This result implies that if we want to provide "acceptable" communication services in a maritime environment, the BS should be carefully placed so that the network connectivity for most of the ships will be maintained.

Similar to the phenomenon we observe for the Sector-1 ships, the packets of the Sector-4 ships are hardly delivered to the BS by using Spray and Wait Routing with one-hop relaying. However, for the routing protocols other than Spray and Wait Routing, the performance of the ships in the Sector 4

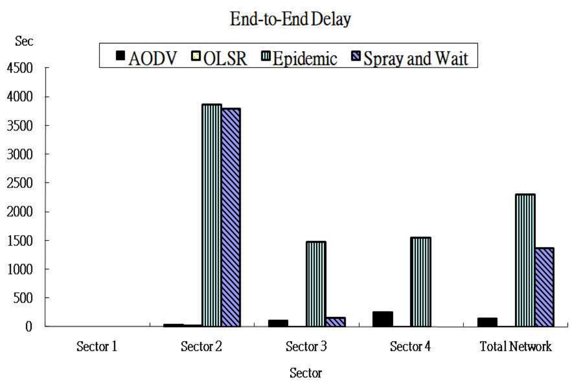

Fig. 7. Comparison of end-to-end delay (BS-to-SS radio range is 10 km and SS-to-SS radio range is 6.3km).

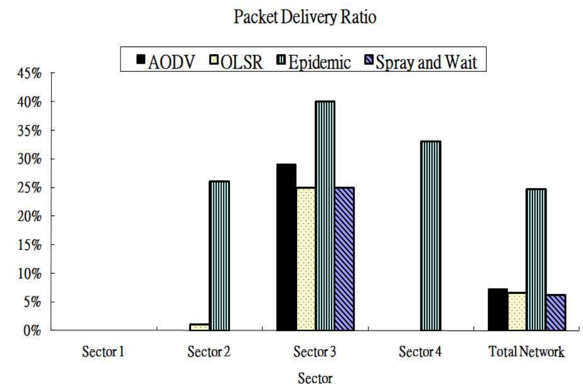

Fig. 8. Comparison of delivery ratios (BS-to-SS radio range is 10 km and SS-to-SS radio range is 4km).

is much better than that of the Sector-1 ships because of higher node density in Sector 4 [2]. In Sector 4, Epidemic Routing achieves the packet delivery ratio of 22%, which outperforms the AODV (13%) and OLSR (8%) routing protocols.

In Sector 2, the packet delivery ratios of Epidemic Routing and Spray and Wait Routing are 48% and 39%, respectively, which significantly outperform AODV (5%) and OLSR (12%). From the trace of the routing paths of AODV and OLSR in this area, we can see that an end-to-end path between a ship and the BS only exists when the ship crosses the boundary between Sector 2 and Sector 4.

The highest delivery ratio can be achieved for the Sector-3 ships. In this area, AODV and OLSR achieve 33% and 25% packet delivery ratios, respectively. Since the ships are moving towards the radio coverage of the BS, the potential path hop counts reduce. As a result, the probability in finding an end-to-end path increases significantly. The Epidemic Routing protocol achieves 54% packet delivery ratio and has the best performance among all routing schemes under investigation. In this sector, finding a multi-hop path is easier than finding an end-to-end path with at most two hops. That is why Spray and Wait Routing performs worse than AODV and OLSR in this sector.

Generally speaking, DTN routing protocols can achieve better packet delivery ratio (up to two times) than regular routing protocols at the expense of longer average end-to-end delay (can be as much as one order of magnitude higher) (see Figs. 6 and 7). Such delay is however expected as DTN protocols, by nature, are designed to withstand them.

Then we decrease the radio range of an SS-to-SS link to 4 km, and the curves of the packet delivery ratio for the routing schemes is shown in Fig. 8. In this scenario, there will be more difficulty in finding an end-to-end path, and the delivery ratio of regular routing protocols is less than 10%. The DTN routing schemes, especially Epidemic routing, still perform better than the regular routing protocols in Sectors 2, 3, and 4. We also

[2]When processing the ship mobility trace data, we removed the ships which anchor in the intended network area because they actually do not demand network services.

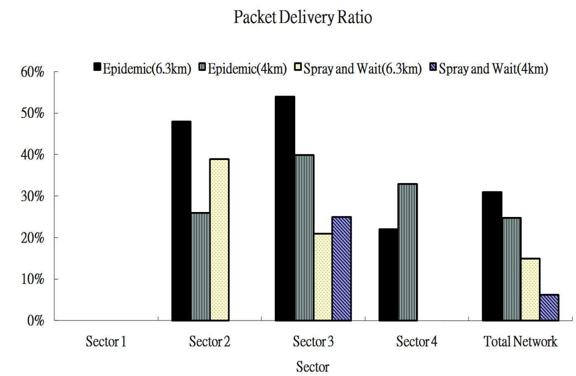

Fig. 9. Comparison of delivery ratios (BS-to-SS radio range is 10 km and SS-to-SS radio range is 6.3km/4km).

observe that Spray and Wait Routing is only helpful for the Sector-3 ships to deliver packets to the destination. From this result, we can conclude that one-hop relaying DTN routing protocols are only workable in Sector 3 under a single-BS configuration with small radio coverage.

Fig. 9 shows the effect of the SS-to-SS radio range on the packet delivery ratio. The delivery ratio basically decreases as the SS-to-SS radio range decreases. However, an opposite phenomenon is observed for Sector 3 with using Spray and Wait Routing and Sector 4 with using Epidemic Routing. The increase of the SS-to-SS radio range will result in the increase of the number of buffered packets. In this case, a large amount of packet loss would come from a careless design on the buffer. Thus how to implement a good buffer scheme is important to optimize the packet delivery ratio for DTN routing.

Let us conclude the above simulation results. As it is hard to find an end-to-end path in a maritime environment communication environment, DTN routing protocols are required to extend the radio coverage and provide cheaper wireless links than satellite links. In Figs. 6 and 8, Epidemic Routing has been proven to be superior to the other routing protocols in terms of the packet delivery ratio. Furthermore, the unacceptable performance of Sector-1 ships could be improved by adjusting the location of the BS and increasing the BS number, which will be one of future directions of this research.

IV. Conclusions

In this paper, we studied the performance of Delay Tolerant Network (DTN) routing for WiMAX-based mesh networks in a less than ideal maritime communication environment. We compared the performance of different routing schemes including regular routing protocols such as Ad Hoc On Demand Distance Vector (AODV) Routing and Optimized Link State Routing (OLSR), and DTN routing protocols such as Epidemic Routing and Spray and Wait Routing. The performance was evaluated in terms of the packet delivery ratio through QualNet simulation experiments, and the simulation was modeled based on actual trace data obtained from the Maritime Port Authority of Singapore. Simulation results indicated that DTN routing achieves higher packet delivery ratio than regular routing schemes in WiMAX-based maritime mesh networks.

Acknowledgment

This work was supported in part by the Excellent Research Projects of National Taiwan University under Contract 98R0062-05, and by the French Ministry of Foreign Affairs under the ICT-Asia Program.

References

[1] J. Ott, *DELAY TOLERANCE AND THE FUTURE INTERNET* , IEEE WPMC, September 2008.

[2] J. Burgess, B. Gallagher, D. Jensen, B. N. Levine, *MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks* , in Proc. IEEE INFOCOM, April 2006.

[3] J. Ott, D. Kutscher, *Bundling the Web: HTTP over DTN* , in Proc. ACM WNEPT Workshop, August 2006.

[4] C. Rigano, K. Scott, J. Bush, R. Edell, S. Parikh, R. Wade and B. Adamson, *Mitigating Naval Network Instabilities with Disruption Tolerant Networking* , IEEE MILCOM, November 2008.

[5] B. Burns, O. Brock, and B. N. Levine, *MORA Routing and Capacity Building in Disruption-Tolerant Networks* , Elsevier Ad hoc Networks Journal, 2008.

[6] A. Vahdat, D. Becker, *Epidemic Routing for Partially-Connected Ad Hoc Networks* , Duke Tech Report CS-2000-06, 2000.

[7] A. Lindgren, A. Doria, and O. Schelén, *Probabilistic routing in intermittently connected networks* , in Proc. ACM MobiHoc, 2003.

[8] T. Spyropoulos, K. Psounis, C. S. Raghavendra, *Spray and Wait: An Efficient Routing Scheme for Intermittently Connected Mobile Networks* , IEEE SIGCOMM Workshop, August 2005.

[9] H. Ochiai, H. Esaki, *Mobility Entropy and Message Routing in Community-Structured Delay Tolerant Networks* , ACM AINTEC, November 2008.

[10] H. Ochiai and H. Esaki, *Topology Change Tolerant Routing for Delay Tolerant Networks* , IPSJ DICOMO(in Japanese), July, 2008.

[11] P.-Y. Kong, H. Wang, Y. Ge, C.-W. Ang, W. Su, J. S. Pathmasuntharam, M. Zhou, and H. V. Dien, *A Performance Comparison of Routing Protocols for Maritime Wireless Mesh Networks* , IEEE WCNC, March 2008.

[12] J. S. Pathmasuntharam, J. Jurianto, P.-Y. Kong, Y. Ge, M. Zhou, R. Miura, *High Speed Maritime Ship-to-Ship/Shore Mesh Networks* , in Proc. IEEE ITST, 2007.

[13] T. Clausen, and P. Jacquet, *Optimized Link State Routing Protocol (OLSR)* , IETF RFC 3626, October 2003.

[14] C. E. Perkins, E. M. Royer, and S. R. Das, *Ad Hoc On Demand Distance Vector (AODV) Routing* , IETF RFC 3561, July 2003.

[15] M. K. Marina, and S. R. Das, *On Demand Multipath Distance Vector Routing in Ad Hoc Networks* , in Proc. IEEE ICNP, 2001.

[16] T. Narten, E. Nordmark, W. Simpson, and H. Soliman, *Neighbor Discovery for IP version 6 (IPv6)* , IETF RFC 4861, September 2007.

[17] IEEE Standard for Local and metropolitan area networks, Part 16: *Air Interface for Fixed Broadband Wireless Access Systems* , IEEE Std 802.16-2004, October 2004.

[18] IEEE Standard for Local and metropolitan area networks, Part 16: *Air Interface for Fixed and Mobile Broadband Wireless Access Systems, Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands and Corrigendum 1* , IEEE Std 802.16eTM 2005, February 2005.

[19] Y. Zhang, K. S. Tan, P. Y. Kong, J. Zheng, and M. Fujise, *IEEE 802.16 WiMAX Mesh Networking* , Wireless Mesh Networking: Architectures, Protocols and Standards, December 2006.

[20] DTN Working group, *http://www.dtnrg.org/wiki*

[21] A. Jindal and K. Psounis, *Fundamental mobility properties for realistic performance analysis of intermittently connected mobile networks* , IEEE Percom, 2007.

[22] M. Demmer and K. Fall, *DTLSR: Delay tolerant routing for developing regions* , ACM NSDR, 2007.

[23] Y. Ge, P.-Y. Kong, C.-K. Tham, and J. S. Pathmasuntharam, *Connectivity and Route Analysis for a Maritime Communication Network* , IEEE ICICS, 2007.

[24] W. J. Pierson Jr. and L. A. Moskowitz. *Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S. A. Kitaigorodskii* , Journal of Geophysical Research, 69:5181-5190, 1964.