

Maritime Mesh Network Simulation

Sihao Sun

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Yaling Yang, Chair

Allen B. MacKenzie

Walid Saad

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(ABSTRACT)

Maritime network plays an important role in civilian and academic applications. However, traditional maritime communication technologies cannot provide broadband services that can satisfy users' need. In this thesis, we proposed a buoy-based maritime mesh network and analyzed the maritime communication characteristics. Then we proposed a link-state-aware routing protocol to address link blockage problem when routing packets and built a simulator to evaluate the network performance. There are several parts of my work.

Firstly, we simulated ocean water field. Jerry Tessendorf proposed a method to create ocean surface based on Phillips spectrum which is a wind-driven, semi-empirical oceanography model. We implemented this algorithm in MATLAB and adjusted a key parameter in this algorithm.

Secondly, we proposed a link-state-aware routing protocol. Link stability is related to sea state and instant nodes elevation. In link-state-aware routing protocol, the transmitter will send predicted elevation information to receiver, and receiver will decide if the link is stable in next several seconds based on sea states and node elevation information.

Finally, we simulated this mesh network in network simulator 3 (NS3). This simulator will enable users to assess the network performance in various sea states. We also need to build a new mobility model, a new propagation model and implement a collision-free access method (spatial TDMA) model in simulation.

Maritime Mesh Network Simulation

Sihao Sun

(GENERAL AUDIENCE ABSTRACT)

Due to burst growth of network coverage, seamless broadband connectivity has been realized in both our daily life and industrial operations. However, wireless communication coverage fades away when moving just several miles away from the coast. Current marine communication technologies cannot provide stable and broadband service, so we proposed a buoy-based maritime mesh network. In this thesis, we built a network simulator which integrates with several new models after analyzed the dynamic ocean wave motion and maritime communication link characteristics.

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Chapter 1. Introduction

1.1 Current Maritime Technologies

Comparing to broad and stable wireless network coverage in land, maritime wireless communication is sparse, narrowband and unstable. However, customers on ocean cruise ships, workers on vessels or oil-rigs bases are in critical need for broadband connectivity for industry purpose or personal life.

Currently, there are four types of maritime communication technologies. The first one is satellite communications. Satellite communications can provide services to customers in static and mobile vessel. However, long delay, limited bandwidth and expensive price are drawbacks of satellite communication. A satellite service might charge about \$1500 per month for only a 128kbps link, which is totally unaffordable for many individuals and small business companies. The second option is MF, HF, or VHF radios for ship-to-shore communications. These technologies are narrow band and can only support voice communications due to the lack of bandwidth. The third type is

undersea fiber, which can be used to wire remote ocean site to the shore but the cost of deploying the fiber, however, is extremely high. The last way is point-to-point land-based microwave. This technology provides lower-cost and higher-capacity communications than satellite. However, line-of-sight (LoS) microwave service can only reach about 30km off the shore, which limiting the service range significantly. Above all, we can see that, unfortunately, none of these methods will provide satisfactory wireless service for customers.

1.2 Maritime Wireless Mesh Network

We propose a maritime wireless mesh network which is formed by compact, low cost and maintenance-free buoyed wireless base station. The illustration of this mesh network has been shown in Figure 1.1.

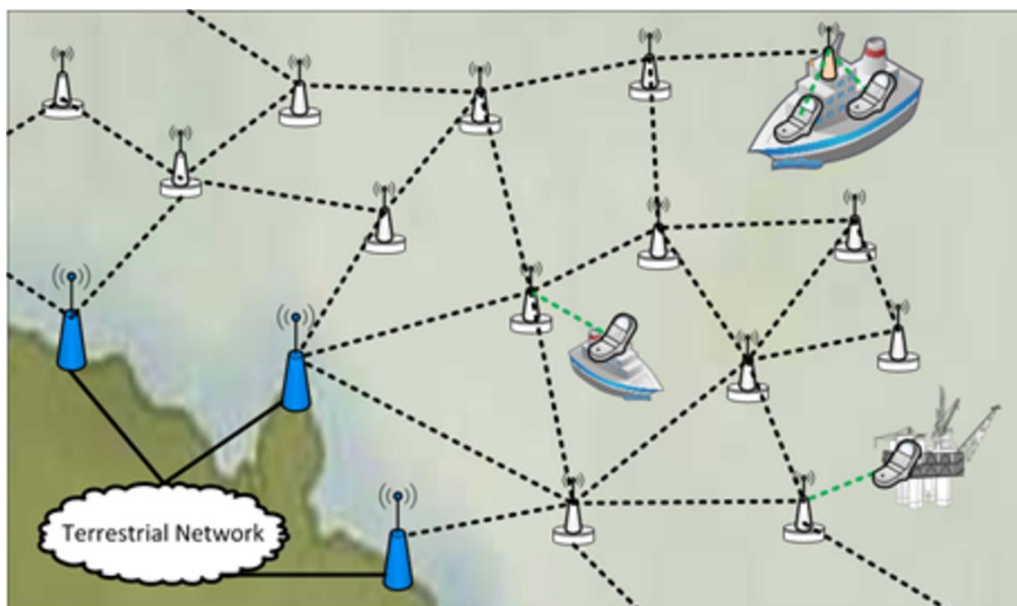


Figure 1. 1 Illustration of marine wireless mesh network

This proposed mesh network can mitigate the gap between current maritime technologies and users' requirement through the combination of energy harvesting, networking and communication technology.

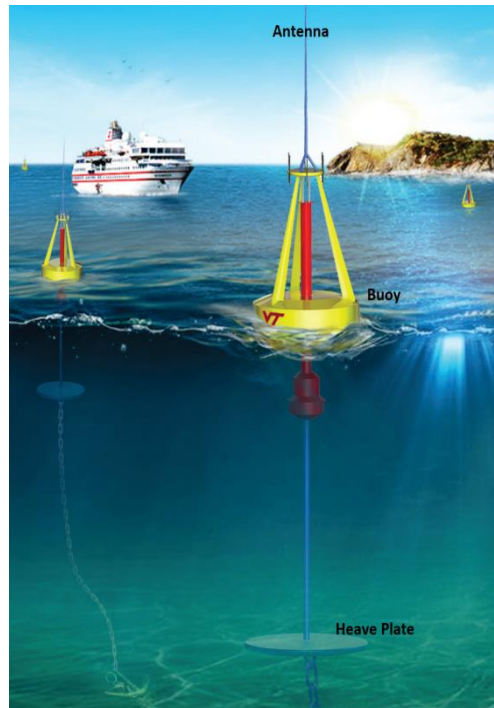


Figure 1. 2 Illustration of buoyed base station

Energy-harvesting buoy, which is shown in Figure 1.2, will continuously generate energy for base station to provide omnidirectional wireless coverage over several kilometers. This floating wireless base station with its anchor and some mechanical components which can simply drop into the water, providing a deployment cost that is even lower than terrestrial cellular system. Also with the help of multi-hop relaying, the mesh network formed by these powered base station can provide wireless broadband coverage for more than 100km off shore. TV white space band has been chosen as the backhaul link for this network because of high data rate, broader coverage and lower cost.

1.3 Related Work

In [1], the author proposes a wireless mesh network which is based on communication between neighboring ships and WiMAX. The author proposes TRITON system and analyzes the network performance in shipping lane with high ship density. However, if neighboring ship density

becomes sparse, the communication link will switch back to satellite link.

In [2], the author develops an open-source simulator based on NS3 and simulates TCP/IP maritime wireless network. An oscillation mobility model and a two-ray propagation model are built. At last, the author compares the simulation results with experimental results which are found in literature. However, the simulation and experimental results are based on ship-ship communication, and the oscillation mobility model and two-ray propagation model are too simple for real maritime mesh network.

1.4 Challenges

There are two unique challenges in maritime mesh network comparing to terrestrial mesh network. The first one is dynamic wave motion. The buoys on the ocean will move ups and downs along with ocean waves. The ocean waves will affect not only the LoS transmission, but also the propagation multipath effect. Therefore, we need to find an appropriate ocean wave model. The second challenge is that the communication link between two neighbor routers might be affected by ocean waves. When deploying mesh network on land, the mesh node will be mounted on top of high buildings or mountains, which will always keep stable LoS transmission. However, it is hard to find a high place on the ocean. Furthermore, it is hard to maintain the stability of a buoy-based station while building a very tall antenna pole. Therefore, the communication link between neighbor nodes might be blocked by ocean waves which are generated by strong wind. That might cause low-quality service or even blockage of wireless signals. As shown in Figure 1.3, if the LoS link is blocked by ocean wave, then this link becomes unstable. Here we also need to consider the effect of earth curvature.

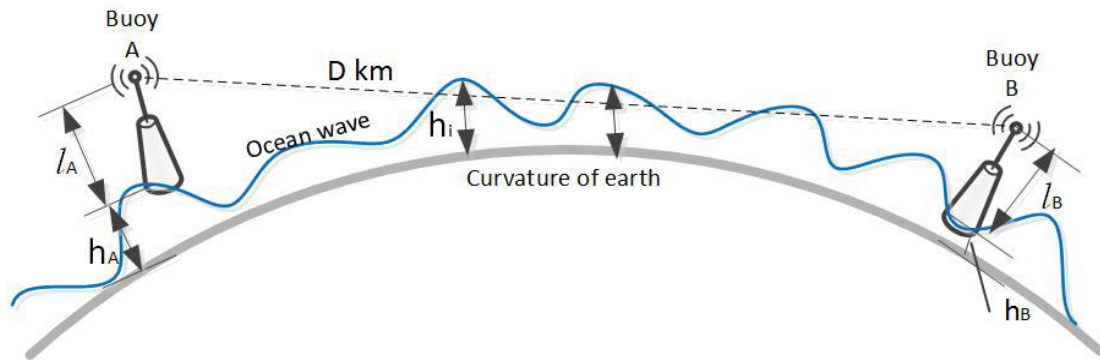


Figure 1. 3 Illustration of unstable link

Therefore, we need to carefully design the mesh network routing protocol according to maritime communication characteristics.

1.5 Contribution

The contributions of this thesis are summarized as follows:

1. We adjusted a key parameter in Phillips spectrum algorithm. Phillips spectrum is widely used in film industry and oceanography. When building ocean wave models in computer graphic, researchers focus on visual effect of ocean waves, rather than realistic wave height. In our scenario, we need wave height information to examine link stability, so we used an indirect method to adjust this parameter in Phillips spectrum.
2. We examined communication link stability in different sea states and summarized some statistical result based on Phillips spectrum model. We can conclude that communication links become increasingly unstable as the sea gets rough, so we proposed a routing protocol which will select active link in mesh network for routing packets.
3. We used Network Simulator 3 (NS3) to simulate this maritime mesh network and compare the simulation result between OLSR routing protocol and link-state-aware routing protocol. We can see the link-state-aware routing protocol has a better performance. To do that, we also built a

maritime mobility model and a maritime propagation model and implemented spatial TDMA in MAC layer of WiFi module.

1.6 Thesis Organization

The remaining part is organized as follows.

In Chapter 2, we introduced a method to simulate ocean water based on Phillips spectrum and Fourier transform and adjust a key parameter in Phillips spectrum.

In Chapter 3, we used ocean wave model built in Chapter 2 to examine the transmission link stability in maritime mesh network. We can conclude that sea states will significant affect link stability. Therefore, we proposed a link-state-aware routing protocol to address link blockage problem. The link-state-aware routing protocol can effectively route packet through predicting wave motion and link stability.

In Chapter 4, we built a NS3 simulator to simulate maritime mesh network and compare the simulation result between OLSR protocol and link-state-aware routing protocol. This simulator will enable users to evaluate the network performance in various sea states.

In Chapter 5, we drew the conclusion and pointed out some future work.

Chapter 2. Ocean Wave Simulation

To simulate the mesh network on ocean, we need to understand the ocean wave motion and build an ocean wave model. In this chapter, firstly, we will introduce some basic oceanography concepts. Secondly, we will introduce an ocean-wave model which is based on Phillips spectrum and implement this algorithm in MATLAB. At last, we will adjust a key parameter in Phillips spectrum.

2.1 Oceanography Concepts

In wind-driven ocean wave model, the waves are only produced by wind. Note that the spectra presented in different ocean wave models are only attempts to describe the ocean wave spectra in a very special condition, namely that a wind with constant velocity has blown for a very long time. This is the definition of fully developed sea [3].

Ocean wave model is used for describing sea states and wind wave energy.

Random-phase/amplitude model in oceanography is a complete description of wave vertical motion as the sum of statistically independent, harmonic waves. This random-phase/amplitude model can lead to the concept of one-dimensional variance density spectrum, which demonstrates how the variance of wave elevation is distributed over all frequencies that create ocean field.

Next we can extend random-phase/amplitude model to two-dimensional. This 2D variance density spectrum indicates how the variance is distributed over all directions and frequencies of wave components. This model can be seen as statistically independent, harmonic waves propagating in different directions across the ocean field. And 1D spectrum can be obtained from the 2D spectrum by integration over all directions.

In oceanography, angular wave number k is the spatial frequency of waves. It is usually defined as cycles per unit or radians per unit distance.

$$k = \frac{2\pi}{\lambda} = \frac{2\pi\nu}{v_p}$$

where λ is the wave length, ν is the frequency, v_p is the wave phase velocity.

The relationship between wave length and wave frequency is defined by dispersion relation. In deep water, the dispersion relation is

$$\omega^2(k) = gk$$

where g is gravity constant. There are also several other special conditions in which this dispersion relation is a little different. In our case, we assume the ocean is deep water.

2.2 Related Work

In [4], Darles et al presents a survey of ocean wave simulation methods. The advantage of Fourier domain approach is that it can avoid rounded shape waves and smooth ocean surface. This

approach assumes that ocean waves are superposition of sinusoidal waves with different frequency, amplitude and direction, which obtained from theoretical or measured data. Also we need to implement deep water simulation algorithm.

Fourier domain approach was firstly proposed by Mastin et al [5] with Pierson-Moskowitz spectrum (PM spectrum) [6] which is a fully developed sea spectrum. However, after analyzing realistic data during Joint North Sea Wave Observation Project (JONSWAP), Hasselmann et al. [7] found that the wave spectrum is never fully developed. JONSWAP spectrum is an optimized version of PM spectrum because it introduces some artificial factors. The problem of JONSWAP spectrum is that it is hard to decide some artificial factors in simulation unless we use empirical values.

Jerry Tessendorf proposed a Phillips spectrum [8] ocean wave model. This method uses pseudo-random generator and a theoretic wave spectrum. We will adopt this algorithm to build ocean wave field, because it is a comprehension algorithm which is widely used in film industry and oceanography.

2.3 Phillips Spectrum Ocean Wave Model

In [9], Jerry Tessendorf elaborated this Phillips spectrum method to simulate ocean water. Specifically, first, we assume that one point in ocean patch can be represented by superposition of sinusoids wave with complex and time independent amplitude, which is

$$h(\vec{x}, t) = \sum_k h(\vec{k}, t) \exp(i\vec{k} \cdot \vec{x})$$

where \vec{k} is a two-dimensional wave number.

Statistical analysis of ocean wave indicates that Fourier amplitudes of ocean field $h(\vec{k}, t)$ are

nearly statistically stationary, independent, Gaussian fluctuations with a spatial spectrum denoted by

$$P_h(\vec{k}) = \langle |h^*(\vec{k}, t)|^2 \rangle$$

$\langle \rangle$ denotes ensemble average.

Semi-empirical Phillips spectrum is

$$P_h(\vec{k}) = A \frac{\exp(-1/(kL)^2)}{k^4} |\vec{k} \cdot \omega|^2$$

where $L = V^2/g$ is the largest possible waves when wind speed is V , and A is a scaling factor.

We will talk about this scaling factor later in this chapter. Spatial spectrum of Phillips spectrum is shown in Figure 2.1.

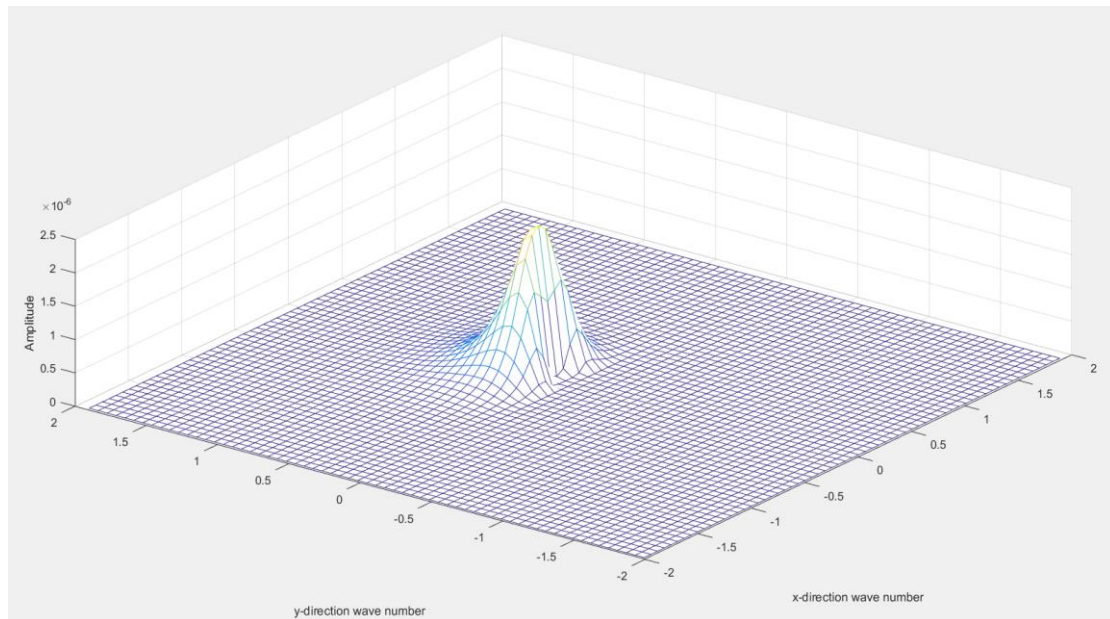


Figure 2. 1 Fourier amplitude of Phillips spectrum

Then, one realization of ocean field can be created by

$$h_0(\vec{k}) = \frac{1}{\sqrt{2}} (\varepsilon_r + i\varepsilon_i) \sqrt{P_h(\vec{k})}$$

where ε_r and ε_i are Gaussian random numbers with mean 0 and deviation 1. Here, of course, we can use other random-number distribution, like log-normal distribution. Different random-number distributions will produce totally different wave fields.

Here we also need to use dispersion relation in deep water

$$\omega^2(k) = gk$$

Next, the Fourier amplitude of the wave field realization at time t is

$$h(\vec{k}, t) = h_0(\vec{k}) \exp\{i\omega(k)t\} + h_0^*(\vec{k}) \exp\{-i\omega(k)t\}$$

At last, $h(\vec{x}, t)$ can be computed by two-dimensional inverse Fourier transform of $h(\vec{k}, t)$.

Using this method, a patch of ocean surface will be generated. The patch size varies from 10 meters to 2 kilometers. In our simulation, the patch size is 2 kilometers. The anticipated distance between neighbor nodes in our mesh network is about 10 kilometers, so one patch is not enough. We can use the exactly same patch to pave a broader ocean surface. Because we use Fourier transform to build $h(\vec{x}, t)$, so we can make sure the boundaries are continuous. Even such a tiled extension of ocean water field is periodical, the periodicity is unnoticeable if the patch size is large.

2.4 Parameter Adjustment

Phillips spectrum has a problem in our application. When constructing Phillips spectrum

$$P_h(\mathbf{k}) = A \frac{\exp(-1/(kL)^2)}{k^4} |\mathbf{k} \cdot \boldsymbol{\omega}|^2$$

A is a scaling factor, neither this value nor the calculation method is given, because people care more about the visual effect of ocean waves, not the realistic wave height in computer graphic. However, we need to know the realistic wave height, because sea states are related to link stability. Therefore, our preliminary task is to adjust this parameter. Instead of adjusting A directly, we use an indirect method, using the concept of significant wave height to reach our goal.

Wave height is defined as the height difference between the wave crest and wave trough. This characteristic sometimes is not obvious. Instead, another wave height, called significant wave height, is used. It was traditionally defined as the mean wave height of the highest one-third of waves:

$$\text{significant wave height} = H_{1/3} = \frac{1}{N/3} \sum_{j=1}^{N/3} H_j$$

Nowadays it is usually defined as:

1. four times the standard deviation of the surface elevation;
2. four times the square root of zeroth-order moment of wave spectrum.

Here if $S(\omega)$ is variance density function of ocean spectra, the moment m_0 , which is called the zeroth-order moment, is defined as

$$m_0 = \int_0^{\infty} S(\omega) d\omega$$

Therefore, we know that

$$H_{1/3} = 4\sqrt{m_0}$$

From the second definition, we know significant wave height is also related to wave energy. In our simulation, Phillips spectrum is a wind-driven model, which means we can assume wind is the only source of ocean energy. Therefore, if wind speed is same in realistic and in simulation, significant wave height should also be same.

$$\frac{\text{Significant Wave Height in Reality}}{\text{Significant Wave Height in Simulation}} = \frac{\text{Wave Height in Reality}}{\text{Wave Height in Simulation}}$$

Now we already have wave height in simulation, if we can find the ratio between significant wave height in reality and in simulation, we can find wave height in reality. And we need to use two definitions of significant wave height mentioned above.

First, we find significant wave height in reality from definition 2:

$$H_{1/3} = 4 \sqrt{\int_0^{\infty} S(\omega) d\omega}$$

where $S(\omega)$ is the variance density spectrum of Phillips spectrum. And

$$S(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left(-0.74 \frac{\omega_0^4}{\omega^4}\right)$$

Here, α is called Phillips constant, which is 00081 [10]; $\omega_0 = \frac{g}{U_{19.5}}$, g is gravity constant, and

$U_{19.5}$ denotes the wind speed 19.5 meters above sea surface, we can convert to wind speed at ocean surface using an empirical function:

$$U_{19.5} \approx 1.026 U$$

Figure 2.2 shows the one-dimensional variance density spectra $S(\omega)$ of Phillips spectrum in different wind speeds.

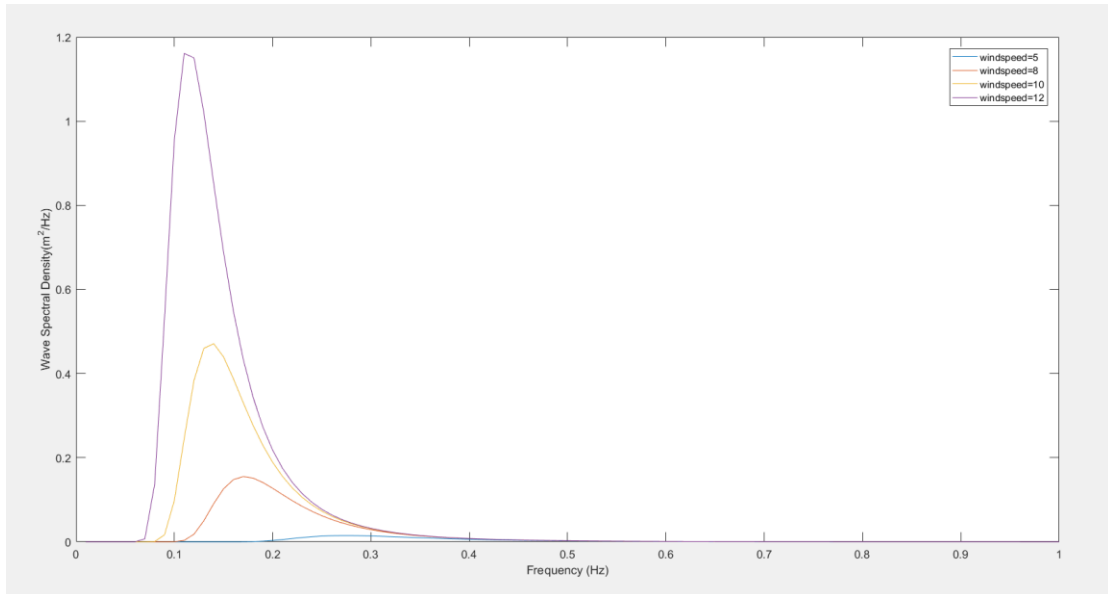


Figure 2. 2 One-dimensional Phillips spectra

From Figure 2.2 we can see that ocean wave energy concentrate on low frequency. With wind speed increasing, the energy will increase dramatically and most energy will move close to DC.

At last, we can find the relationship between significant wave height and wind speed in reality:

$$H_{1/3} \approx 0.22 \frac{U^2}{g}$$

Next we need to find significant wave height in simulation. This time we need to use definition 1.

In MATLAB, our data is discrete, so significant wave height can be expressed as:

$$H_{1/3} = 4 \sqrt{\frac{1}{N^2} \sum_{p,q} x^2(p,q)}$$

where $x(p,q)$ is the elevation of one point in ocean surface, N^2 is the total number of points in ocean wave field. The ocean surface is moving ups and downs, which means $\sum_{p,q} x^2(p,q)$ is not a constant. We can calculate significant wave height from spatial spectrum through Parseval's theorem:

$$\sum_{p,q} |x[p,q]|^2 = \frac{1}{N^2} \sum_{j,k} |X[j,k]|^2$$

Using Parseval's theorem, we can find significant wave height on spatial spectrum instead of on time domain.

So

$$H_{1/3} = 4 \sqrt{\frac{1}{N^4} \sum_{j,k} |X[j,k]|^2} = 4 \sqrt{\frac{2P_h(\mathbf{k})}{N^4}}$$

Therefore, we know the ratio between significant wave height in reality and in simulation, and we can find the wave height in reality.

Figure 2.3 shows the a screenshot of ocean wave animation

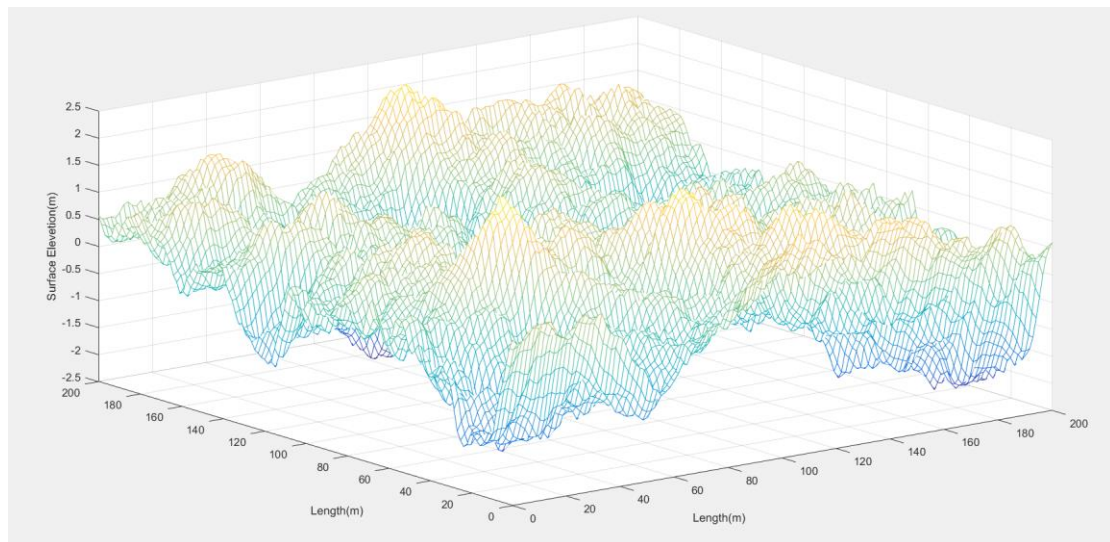


Figure 2. 3 A screenshot of ocean wave animation

Chapter 3. Maritime Mesh Network Routing Protocol

After we built an ocean wave model and adjust the key parameter, we can understand the dynamic wave motion. The ocean wave is the main factor to separate maritime and terrestrial mesh network. Based on statistical result from ocean wave model, we conclude that LoS communication link might be affected by sea states. This might cause low-quality communication links or even blockage of the wireless signals. In a wireless mesh network, such unstable communication links will cause packet delay. Without careful designed solutions, the entire mesh network might become totally unusable. Hence, our routing protocol design should be able to handle dynamic sea states. Based on OLSR protocol [11], we propose a link-state-aware routing protocol which can predict wave motion and choose the potential active routing path.

3.1 Problem Statement

Different sea states will affect multiple factors in maritime mesh network. Currently, we only consider LoS transmission. We simplify this problem as, if there is at least one ocean wave blocks LoS transmission link, we assume this link is corrupted; otherwise, we assume this link is stable. We define link stability as the ratio between how long the transmitter and receiver can see each other and total measurement time.

The effect of earth curvature is non-negligible when the distance between two nodes is about 10 kilometers. Figure 1.3 shows the transmission link between two nodes is blocked by ocean wave in maritime mesh network.

Based on ocean wave model we built in Chapter 2, we can find that there are two factors that affect link stability in maritime mesh network: sea states and instant surface-elevation of transmitter/receiver.

3.1.1 Relation between Sea States and Link stability

Sea state is a scale which measures the height of the waves. Each state has expected range of wind speeds.

With 10km 1-hop neighbor nodes distance separation and 5m antenna height setting, we simulated 1024 communication links in 100 time slots and calculated the link stability, which is shown in Table 3.1

Table 3.1 Relationship between link stability and sea state

Wind Speed (m/s)	Significant Wave Height (m)	Sea State	Link Stability
≤ 10	≤ 2.13	Fresh breeze	100.00%
11	2.58	Strong breeze	97.93%
12	3.07	Strong breeze	87.38%
13	3.60	Strong breeze	69.54%
14	4.18	Moderate gale	51.31%
15	4.80	Moderate gale	36.07%

Table 3.1 shows that the link stability is very sensitive to wind speed. If the wind speed is less than or equal to 10m/s, the ocean wave will not block any communication links. Therefore the maritime mesh network is very similar with terrestrial mesh network. However, if wind speed is greater or equal to 15m/s, the mesh network cannot work anymore due to in this multi-hop mesh network, every hop has a high blockage rate. In this case, nodes should stop their packet transmission to save energy and resume transmission in good sea states. Furthermore, if the wind speed keeps increasing, we should take some effective actions to protect our buoy-based station from irreversible damage.

3.1.2 Relation between Instant Nodes Elevation and Link stability

Figure 3.1 and 3.2 show the relationship between instant elevation of transmitter and receiver and link stability when antenna height is 5 meters and distance between neighbor nodes is 10 kilometers in different sea states.

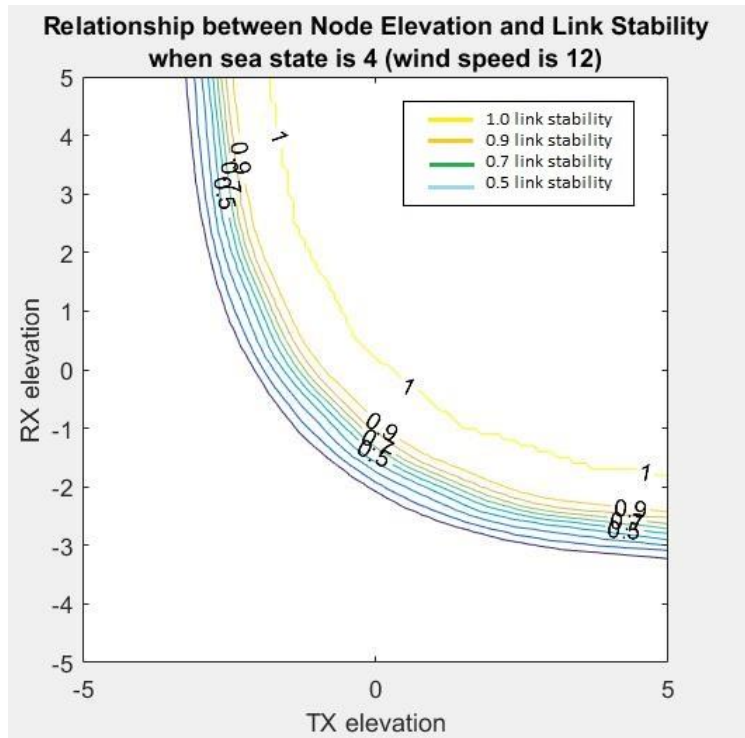


Figure 3. 1 Relationship between node surface-elevation and link stability when wind speed is 12m/s

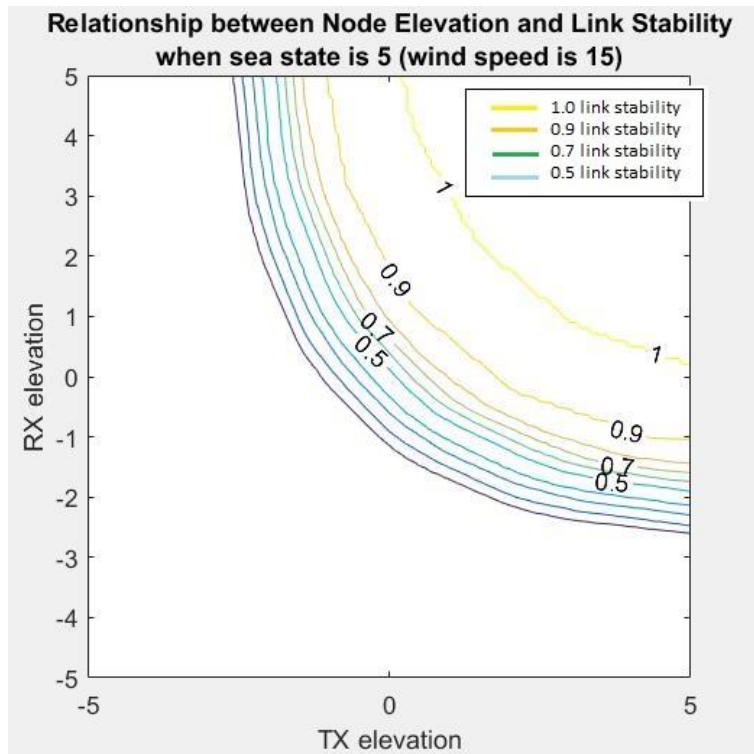


Figure 3. 2 Relationship between node surface elevation and link stability when wind speed is 15m/s

In both figures, different lines stand for different link stability when wind speed is 12m/s and 15m/s respectively. As shown above, the link stability is determined by instant elevation of transmitter and receiver. For example, if this pair of information is above the golden line (1.0 link stability), we can make sure that the communication link is stable, because in this circumstance, the wind cannot generate a giant wave in the middle of transmitter and receiver to block transmission link. However, if elevation of transmitter and/or receiver becomes lower, the link stability will decrease.

3.2 Link-State-Aware Routing Protocol

To solve the link blockage problem, we need to adopt a link-state-aware routing protocol. Each router should be able to predict the link stability based on sea states information and historical node elevation data. There are two main IP protocol routing algorithms, one is link-state (LS) routing algorithm; the other is distance-vector (DV) routing algorithm. We choose LS routing protocol because it reacts faster than DV routing protocol if the topology of the network changes frequently. And optimized link-state routing (OLSR) protocol is optimized for mobile ad hoc network. Therefore, we will implement the link-state-aware routing protocol based on OLSR protocol.

3.2.1 OLSR protocol

OLSR is optimized for MANET (mobile ad hoc network). Multipoint relay (MPR) is the key components which is an optimization of classical link-state protocol. Each node selects a set of its neighbor nodes as MPRs which are responsible for forwarding control traffic. In other word, the MPRs form the route from a source node to any destination nodes in the network. This technique

will reduce the message overhead.

There are four types of messages in OLSR protocol:

1. Hello message. Hello message is used for populating link information and neighborhood information periodically. Specifically, it is used for link sensing, neighbor detection and MPR selection.

2. Topology Control (TC) message. The purpose of TC message is disseminating links between itself and the nodes in its MPR-selector set. And TC message will only be emitted through MPRs.

Based on information in TC message, every node in network can construct its routing table.

3. Multiple Interface Declaration (MID) message. Every node with multiple OLSR interfaces must announce interface information describing its configuration to all other nodes in mesh network.

MID message will be broadcast to all nodes through MPR flooding mechanism. The main address is the OLSR interface address if there is only one OLSR interface.

4. Host and Network Association (NHA) message. NHA message is used for exchanging external routing information into an OLSR network.

Table 3.1 shows brief function introduction, default emission intervals and default holding time of these four message types.

Table 3. 1 OLSR message types introduction

Message Type	Function	Default emission interval	Default holding time
Hello	populating local link information and neighborhood information	2s	6s
TC	disseminating topology information through the network	5s	15s
MID	announcing multiple interface information	5s	15s
NHA	providing connectivity from the OLSR interface to non-OLSR interface	5s	15s

Each node in MANET should build a routing table which allows it to route data to destination nodes. The routing table is based on the information in local link information and topology information. More precisely, the routing table will be update when a routing message is received or neighbor appearance/loss. Update of routing table will not generate any message to be transmitted.

3.2.2 Philosophy of Link-state-aware Routing Protocol

Currently, MID and NHA messages are not in our consideration. Because in our simulation, there

is only one OLSR interface and zero non-OLSR interface, so there will be no MID and NHA messages exchange.

Sensors on buoy will measure wind speed and record node elevation data. Based on historical elevation information, routers will predict their elevation in the future. This is called predicted node elevation information. The predicted node elevation information should be included in hello message. After received a hello message from its neighborhood, the receiver will calculate the link stability according to the sea states and predicted elevation information of both transmitter and receiver.

As shown in Figure 3.1 and Figure 3.2, to achieve maximum throughput, we need to choose appropriate link stability as the threshold in different sea states. In link-state-aware routing protocol, if link stability between two nodes is above this threshold, we assume the communication link is available and it is a potential routing path; otherwise, we assume this link is unstable and we will not choose it when calculating routing table. Note that we need to choose this threshold carefully. If the threshold is too high, the node might lose topology information due to less available routing path; if the threshold is too low, link can be easily blocked by ocean wave in any hop.

Routing messages should be exchanged more frequently due to dynamic ocean wave. The information holding time should also be shortened. For example, if emission interval is one second and the communication between two nodes is assumed stable in the next second, then holding time should be set to one second; otherwise, holding time is set to zero.

Above all, instead of using default transmission interval and holding time of hello and TC message, we shorten the emission interval of messages and recalculate holding time based on node

elevation and sea states information. Therefore, routing table will be updated more frequently to accommodate dynamic wave motion.

Chapter 4. NS3 Simulation

Network Simulator 3 [12], which is a discrete-event computer network simulator, has been developed to an open-source, extensive network simulation platform and it provides a simulation engine for users to conduct simulation environment. We will implement this maritime mesh network in NS3 and we will prove that link-state-aware routing protocol has a much better performance in maritime mesh network. We use MATLAB to generate ocean wave data and use NS3 to read data file to find node elevation and sea state. Meanwhile, we need to build several new models according to maritime communication characteristics.

4.1 Mobility Model and Propagation Model

We assume that each buoy will be floating on ocean with its anchor and some mechanical components dropped into the water, moving ups and downs along with the ocean wave. In other words, mathematically, the x and y coordinate of each buoy are constant, but z coordinate, which

is the elevation of each buoy, will be determined by ocean wave motion.

In our maritime mobility model in NS3, the position of each node will not change once it has been set and until it is set again and we read node elevation information from ocean wave data file, which is generated by MATLAB. This mobility model will also output predicted wave elevation.

The propagation model is a default Friis propagation loss model. This is a temporary LoS propagation model, we just want to make sure that receiver and transmitter can communicate with each other if no ocean wave blockage. In the future, after the field experiment on the ocean using white space routers, we will plug the measurement results into the simulator to adjust this propagation model. Other functionality of this propagation model is that it can check if communication link is blocked by ocean wave. If so, we assume the link is corrupted. Here we also need to consider the effect of earth curvature.

4.2 Spatial TDMA Model

When the size of mesh network grows, collision will become unavoidable and network performance decrease significantly. To address this problem, we implemented spatial TDMA [13] in MAC layer. This defined protocol assigns transmission rights to nodes in the network in a local TDMA fashion and is collision-free.

Specifically, spatial TDMA is designed for multi-hop mesh network which the position of each node is fixed. The author develops a slot allocation method. Using compatibility matrix which is based on network topology, one can generate a set of cliques which can transmit simultaneously without causing any collision in network.

We can realize synchronization among all nodes if we attach a GPS chip on the router board. The synchronization accuracy of GPS time signals is $\pm 10\text{ns}$.

4.3 Link-state-aware Routing Protocol Model

To implement link-state-aware routing protocol, we need to revise OLSR module, which is a developed part in NS3. First of all, we need to change the packet format. In message header, we should send predicted ocean elevation information besides default valid time information. Then the receiver will determine the valid time based on the packet type. If it is a hello message, the valid time information should be calculated based on predicted nodes elevation and sea state. Otherwise, we use default valid time information.

Specifically, in our simulation, we only consider hello and TC message, because there is only one OLSR interface and no non-OLSR interface in each node. The emission interval of hello and TC message is 1 second. After exchanged hello message, if the receiver decides that the communication link between transmitter and receiver will be stable in the next second, the holding time will be 1 seconds.

As shown in Figure 3.1 and 3.2, we need to decide the threshold of link stability. We will choose different threshold to compare the throughput.

4.4 Simulation Setup

The setup of NS3 simulation is shown in Table 4.1.

Table 4. 1NS3 simulation setup

Transport Layer	UDP
Network Layer	IP
	Compare Link-state-aware routing protocol and OLSR protocol
Data-link Layer	Spatial TDMA
	802.11g protocol
Physical Layer	20MHz Bandwidth OFDM
	Center Frequency: 600MHz

600MHz is in TV white space spectrum (470-608MHz, 614-806Hz). There are several reasons for choosing this spectrum. Firstly, TV white space broadband connectivity can provide desirable data rate, which is important for the real-time application such as sending monitoring data or sending control command to sensors. Secondly, 600MHz signal can transmit in much longer distance because they operate in low frequency. Comparing to WiFi signal, they can reach 4 times distance with the same transmission power. Tens of kilometers transmit range has been shown in practical white space network deployment on land. Thirdly, with greater and broader coverage, the number of nodes in the mesh network is reduced [14]. Therefore, less energy-harvesting buoys are required to cover the target area, which reduces the manufacturing and deployment cost.

The parameters considered in simulation are presented in Table 4.2.

Table 4. 2 Simulation parameters

Transmission power	16dBm
Gain of transmitter	3dB
Gain of receiver	3dB
Height of antenna	5m
Wind speed	12m/s
Packet rate	100pkt/s
Packet size	1200bytes
Node distance	9950m
Total simulation time	60s

Figure 4.1 shows the topology of mesh network.

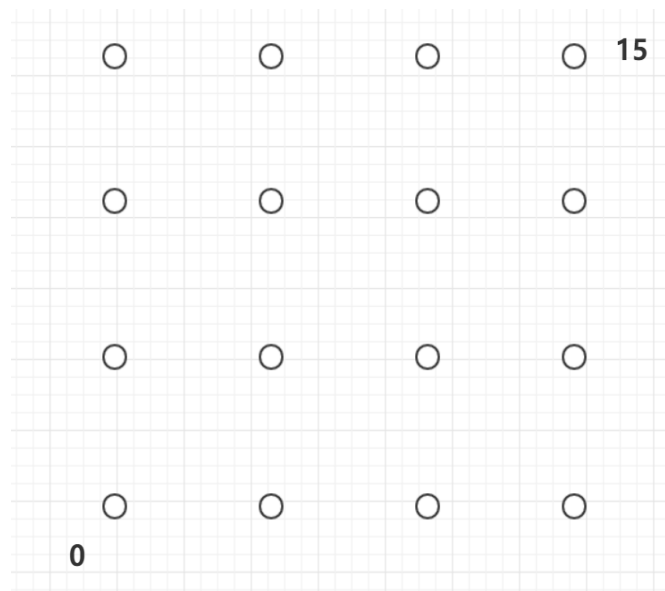


Figure 4. 1 Topology of simulation network

In Figure 4.1, node 0 is the source node and node 15 is the sink node.

We also integrate the mobility model and propagation model into this simulation.

4.5 Simulation Result

In our simulation, wind speed is 12m/s, and we know the blockage rate is about 12.62%. Here,

we need to give OLSR routing protocol and link-state-aware routing protocol 15 seconds to

exchange packets for coverage. Because link-state-aware routing protocol exchange routing packets more frequently, if we don't set starting time, link-state-routing protocol network will start sending packet earlier than OLSR protocol network.

Figure 4.2 shows the throughput graph if we use OLSR protocol.

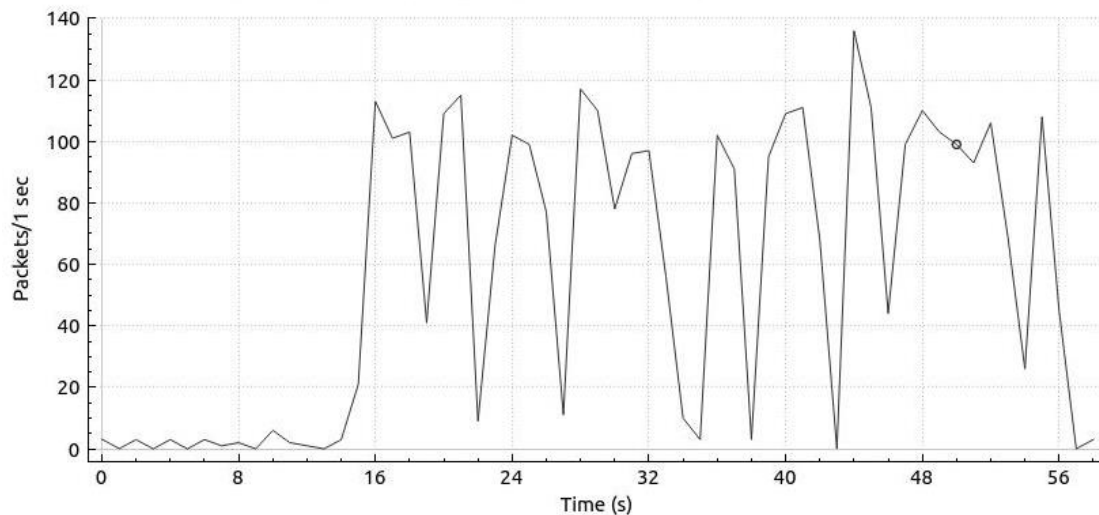


Figure 4. 2 Throughput graph when using OLSR protocol

We can see that OLSR protocol doesn't choose the best route in this multi-hop mesh network.

The throughput is very unstable, even sometimes the throughput decreases dramatically. There are two reasons. First, the communication link might be blocked by ocean wave when a router forwards a packet to destination; second, routing protocol packets might be dropped due to ocean wave blockage, so the source might lose the topology information of mesh network and stop sending packets.

For link-state-aware routing protocol, as shown in Figure 3.1 and Figure 3.2, we need to choose the link stability as the threshold. This threshold stands for a pair of values which contain wave elevation information at transmitter and receiver. Above this threshold, we assume this link is stable; otherwise, we assume the communication link will be blocked later, so this link will be abandoned.

Figure 4.3 and Figure 4.4 show the throughput graph when we use link-state-aware routing protocol but choose different threshold.

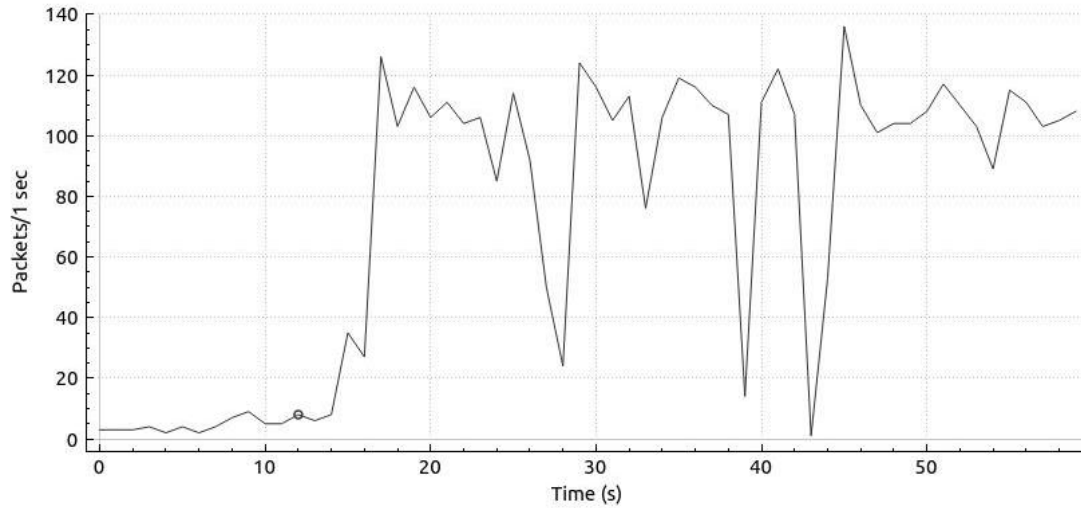


Figure 4. 3 Throughput graph when using link-state-aware routing protocol with threshold 1.0

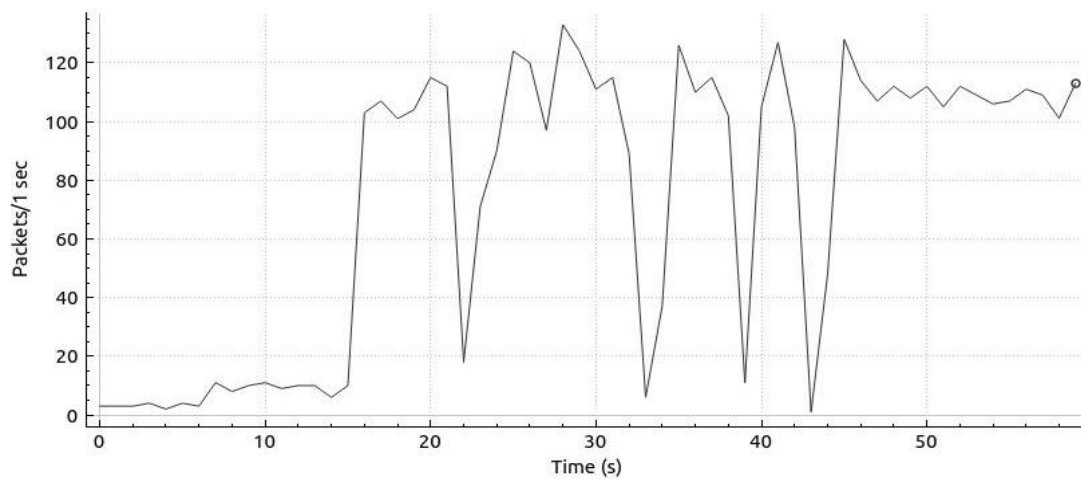


Figure 4. 4 Throughput graph when using link-state-aware routing protocol with threshold 0.9

Table 4.3 shows the throughput comparison among different threshold and OLSR protocol.

Table 4. 3 Throughput comparison

Protocol	Link-state-aware routing protocol				OLSR	
	Threshold	1.0	0.9	0.7		0.5
Throughput (packet)		4013	3907	3405	3282	3180

Link-state-aware routing protocol chooses the best route according to node elevation and sea state information. We can conclude that when wind speed is 12m/s, 1.0 is the best threshold.

Throughput is more stable and increase about 26% from 3180 packets to 4013 packets in this case.

In Figure 4.3 and Figure 4.4, even we implement link-state-aware routing protocol, sometimes throughput will decrease. The reason is that in this network topology, both node 0 (source node) and node 15 (destination node) only have two neighbor nodes to forward packets. Sometimes, both potential paths of either node are blocked by ocean waves. In this case, the throughput becomes unstable.

Comparing throughput of OLSR protocol and link-state-aware routing protocol with threshold 0.5, we can see that exchanging routing packet more frequently will not significantly improve the performance of the network, because the node still cannot choose the best routing path.

Chapter 5. Conclusion and Future Work

5.1 Conclusion

Current maritime technologies cannot provide broadband and acceptable price service for users.

In this thesis, we proposed a marine wireless mesh network that is formed by compact, low cost and buoyed wireless base stations. We analyzed ocean wave motion and maritime communication characteristics, and then we proposed a link-state-aware routing protocol and built an NS3 simulator with integrates with several new models to measure the performance of this network.

In chapter 2, we built an ocean wave model which is based on Phillips spectrum and Fourier transform. More importantly, we adjusted a key parameter in Phillips spectrum. Therefore, we can use this model to generate a realistic ocean wave height field. We used this ocean wave model to examine link stability in different sea states.

In chapter 3, we analyzed the maritime communication characteristic and proposed a

link-state-aware routing protocol which is an optimized version of OLSR protocol. Link stability is related to sea state and node elevation. In link-state-aware routing protocol, transmitter will send elevation information to receiver, and receiver will decide if the communication link is stable in the future. We can use sensors on buoy to measure surface-elevation and predict node elevation according to historical data.

In chapter 4, we used NS3 to simulate this mesh network. First, we designed a mobility model and a propagation model. Then we implemented spatial TDMA in MAC layer of WiFi module. At last, we compared the simulated result of OLSR routing protocol and link-state-aware routing protocol. We concluded that the link-state-aware routing protocol has better performance and more stable throughput.

5.2 Future Work

The Phillips spectrum is widely-used in oceanography and film industry. However, the capillary wave in this model is not realistic enough. Therefore, if a more accurate, precise model has been proposed, we can substitute Phillips spectrum model with new model.

Also, the propagation model is a temporary model and we only consider line-of-sight propagation at current stage. After the field experiment on the ocean using white space routers, the measurement result will be plugged into the simulator to adjust the key components such as propagation model, link capacity, etc.

At last, this work is just simulation part of sustainable ocean monitoring and surveillance system.

In the future, if more components, like unmanned aerial vehicles (UAVs) and autonomous underwater vehicles (AUVs), have been attached, we can build more models for our simulation

and evaluate the network performance.

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