An Analysis Model of DoA in Maritime Environment for Ship-to-ship/shore Wireless Communications

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***Abstract*—Wireless mesh ad hoc network is envisaged by us recently for maritime communications because of the lack of high-speed and low-cost communication systems in sea. A maritime simulator is developed for the purpose to simulate the sea environment and evaluate designs and protocols used in maritime mesh networks. In maritime simulator, modeling direction of arrival (DoA) of radio signal is critical since it determines antenna gain and received radio signal power at a receiver. In this paper, we propose an analysis model of DoA in maritime environment based on modeling sea wave movement as Trochoid wave and analyzing orientations of ships in various sea states. Simulations have been carried out and the results match very well with measured. The model can be used in simulation of wireless ship-to-ship/shore communications, and in finding maximum loss of antenna gain due to sea wave movement, which needs being considered in link budget when do network planning.**

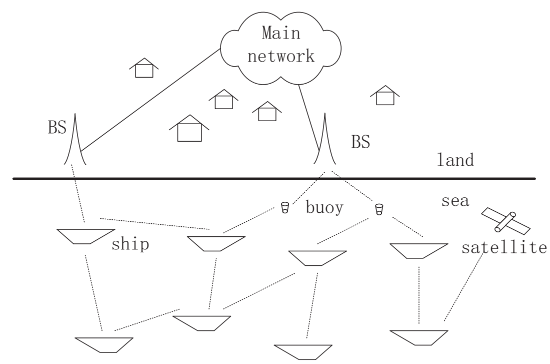

Fig. 1. Network Architecture for Maritime Wireless Mesh Communications.

I. Introduction

A maritime mesh ad hoc network is envisaged by us recently to provide high-speed and low-cost ship-to-ship/shore wireless communications [1]. The purpose is similar to an on-land vehicular network that for better vehicle's safety and higher transportation efficiency. In sea, such a wireless mesh ad hoc network can be used for better ship navigation, ship traffic management, sea condition surveillance, disaster rescue, location reporting and so on. In addition, with such a wireless network, ship crew and passengers can enjoy cheaper (compared to the relatively expensive satellite links) communication services like Internet, telephone, and FAX etc. The envisaged mesh ad hoc network is based on IEEE 802.16-2004 [2], as it allows long range access and multi-hop communications. We also developed and added some new features that are not supported in 802.16-2004, like supporting to mobility. Developments and investigations on ship mobility, mesh connectivity, radio channel properties, bandwidth allocations, and routing protocols are also carried out, and presented in reference [3] - [9], respectively.

In our project, a maritime simulator is developed for the purpose of simulations. The platform used is Qualnet as it supports integrated models of radio signal propagation and higher layer protocols. In simulations, it is required to simulate the antenna gains at the transmitter and receiver, by which the link loss can be calculated. As Omni-directional antenna is used in the maritime mesh ad hoc network in the project, it is necessary to calculate the direction of arrival (DoA) of radio signal, from which antenna gain can be calculated in simulations. For this purpose, we developed an analysis model of the radio signal DoA in maritime environment and present it in this paper.

The direction of arrive (DoA) of radio signal is closely related to the antenna orientation, effective height, and the distance between the transmitter and receiver. Since antennas are mounted on ships and sea surface moves all the time, these parameters are determined by the position and orientation of the ships. In this paper, Trochoid waves are used to model the sea wave movement, by which then the orientation of the ships, and DoA of radio signals can be obtained. The analysis model of DoA is integrated with Qualnet and simulations have been carried out to verify the model. It has been found that the simulation results match measurement very well, when simulation parameters are set the same as the experiment carried out in sea near Singapore west coast.

The organization of this paper is as follows. In section II the wireless mesh ad hoc network structure for maritime communications and the maritime simulator are introduced.

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Section III introduces model of sea waves, which is the basis to model the orientation of ships and then the orientation and effective height of antennas on ships. In section IV, model of DoA of radio signals is presented, and simulation results are presented in section V. Finally, the paper is concluded by section VI.

II. Network Architecture and Maritime Simulator

Figure 1 shows the high-level network architecture of the proposed wireless mesh network for maritime communications. The network is formed by neighboring ships, marine beacons and buoys, and is connected to terrestrial networks via land based stations (BSs) that are regularly placed along coastlines. In case of low ship density and hence there is no connections to land BSs, satellite links are used as backup communication means. The network envisaged is based on IEEE 802.16-2004 mesh mode, since this technology has advantages, such as: (1) it supports long-distance and multi-hop communications; (2) it has TDMA-based MAC and then QoS required services can be supported. Supporting to mobility is not included in the standard, and we developed it in our project.

A maritime simulator is developed and used to evaluate performance of protocols and designs in maritime environments. The simulator is developed with Qualnet that includes interfaces of modules from physical channels to network layer protocols. Figure 2 shows the structure of the simulator. It mainly consists of ship mobility module, radio channel module, and wave movement module. Ship mobility module simulates position of ships that changes along time. Radio channel module includes path loss model and fading property model in maritime environment. The module of sea wave movement simulates movement of sea surface, by which the orientation and effective height of ships and antennas can be obtained. As omnidirectional antenna is used in the project, from parameters of antenna orientation, radio signal DoA can be simulated, and then the gain of antenna can be calculated. By combining with the path loss model, the whole link gain/loss is therefore achievable. Finally, the received radio signal power can be simulated, as well as the bit-error-rate of the data. In above process, knowledge of movement of sea surface is critical, since it determines orientation of ships and antennas.

III. Sea Wave Movement Model

A general model of sea wave movement is Trochoid wave that is created by tracing the path of a point inside a circle as shown in Fig. 3. The parametric equations for a Trochoid wave are

$$\begin{aligned} z &= \sin x, \\ x &= a\phi - b\sin\phi, \\ z &= a - b\cos\phi, \end{aligned} \tag{1}$$

where a is the radius of the circle and b is the distance of the point to the center of the circle. In addition to above equations,

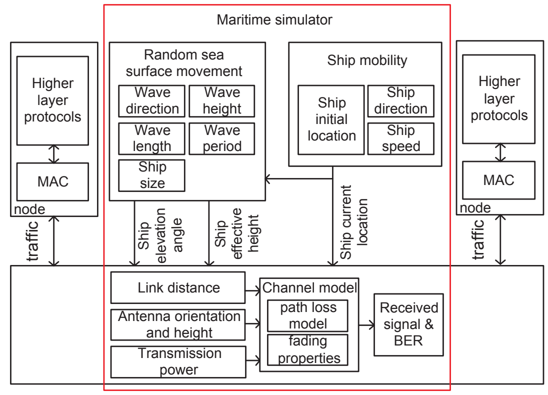

Fig. 2. Structure of maritime simulator developed.

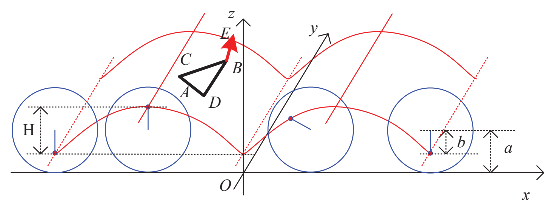

Fig. 3. Illustration of wave movement model

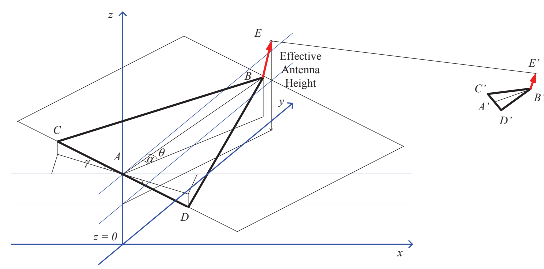

Fig. 4. Illustration of ship orientation model

we have $a = \lambda/2\pi$ and $b = a - H/2$, where λ and H are the average sea wavelength and the significant sea wave height of a given sea state, respectively. For a given location x and a time instant t, the angle ϕ is calculated by $\phi = 2\pi\left(x/\lambda - t/T\right)$, where T is the average sea wave period.

In above, a sea state is a description of sea wave and is characterized by parameters of sea wavelength(λ), sea wave period (T), and sea wave significant height (H) [10]. Usually, it is expected that a ship still has communication connections to neighbors in sea state 6.0.

IV. Model of DoA in Maritime Environment

As shown in Fig. 3, a ship is modeled as a triangle with three points (B, C and D) on surface of sea wave. Side CD is the bottom part of the ship, and point B is the ship head. Point A is the midpoint of CD, and it represents location of the ship. The length of CD represents the width of the ship, and AB is the length of the ship. The reason to model a ship as a triangle but rather than others like trapezoid, is a triangle's three points can always be assumed on the sea surface and then it's more convenient to calculate the orientation of the ship. In addition, it also because the width of a ship is much smaller than its length usually, and then a trapezoid can be treated as a triangle in this case.

Figure 4 shows more details of the model. The ship orientation is characterized by three angles, i.e., compass heading (θ), pitch (α), and roll (γ). As the heights of points B, C and D change with location and time, the ship orientation also changes when a ship anchors or makes way. Antenna (BE) is mounted on the ship head and is assumed vertical to the ship plane BCD, therefore, the antenna orientation is determined by orientation of ship. A neighbor ship is assumed and represented by B'C'D', with A' as midpoint of C'D' and B'E' as antenna mounted. The DoA of radio signal is defined as the angle of the line EE' to the plane of the receiving antenna, e.g., BCD if we assume the current ship user is receiving data. When DoA is obtained, the antenna gain can be determined in simulations with the maritime simulator.

With simulation environment of Qualnet, the known parameters include location of ship, i.e., (x_A, y_A), and simulation instant time t. As at the beginning of a simulation, the destination location of a ship making way is known, so the ship compass heading θ is known to us. In case of ship anchors in sea port, θ also can be assumed a known parameter since it could be randomly generated by the simulation codes. Other known parameters are λ, T and H of the sea state we are simulating, ship length L and width W, and antenna height h_a. In this study, we assume the antenna height is the height of the ship, on which the antenna is mounted.

Based on illustration of the model shown in Fig. 4, by some mathematical manipulations, the angle of roll (γ) is given by

$$\gamma = \tan^{-1}\frac{-4b\sin\left[2\pi\left(\frac{x_A}{\lambda}-\frac{t}{T}\right)\right]J_1\left(\frac{\pi W\cos\theta}{\lambda}\right)}{W}, \quad \gamma \in (-\pi/2, \pi/2) \tag{2}$$

and the effective height of point A is given by

$$z_A = a - b\cos\left[2\pi\left(\frac{x_A - \frac{W}{2}\cdot\cos\gamma\cdot\cos\theta}{\lambda} - \frac{t}{T}\right)\right] - \frac{W}{2}\cdot\sin\gamma. \tag{3}$$

The pitch (α) is then can be obtained by solving follows equation numerically,

$$z_A + L\cdot\sin\alpha = a - b\left\{\begin{array}{l}\cos\left[\frac{2\pi L\sin\theta}{\lambda}\cdot\cos\alpha\right]\cos\left[2\pi\left(\frac{x_A}{\lambda}-\frac{t}{T}\right)\right]\\ -\sin\left[\frac{2\pi L\sin\theta}{\lambda}\cdot\cos\alpha\right]\sin\left[2\pi\left(\frac{x_A}{\lambda}-\frac{t}{T}\right)\right]\end{array}\right\} \tag{4}$$

In case of $\alpha \approx 0$, the above equation becomes

$$\alpha = \frac{a - b\cos\left[2\pi\left(\frac{x_A + L\cdot\sin\theta}{\lambda}-\frac{t}{T}\right)\right] - z_A}{L}. \tag{5}$$

From above, the location of B, C and D are given by

$$\left\{\begin{array}{c} x_B = x_A + L\cdot\cos\alpha\cdot\sin\theta \\ y_B = y_A + L\cdot\cos\alpha\cdot\cos\theta \\ z_B = z_A + L\cdot\sin\alpha \end{array}\right. \tag{6}$$

,

$$\left\{\begin{array}{c} x_C = x_A - \frac{W}{2}\cdot\cos\gamma\cdot\cos\theta \\ y_C = y_A + \frac{W}{2}\cdot\cos\gamma\cdot\sin\theta \\ z_C = z_A + \frac{W}{2}\cdot\sin\gamma \end{array}\right. \tag{7}$$

and

$$\left\{\begin{array}{c} x_D = x_A + \frac{W}{2}\cdot\cos\gamma\cdot\cos\theta \\ y_D = y_A - \frac{W}{2}\cdot\cos\gamma\cdot\sin\theta \\ z_D = z_A - \frac{W}{2}\cdot\sin\gamma \end{array}\right. \tag{8}$$

The effective height of antenna is then given by

$$h_e = z_B - (a-b) + h_a\cdot\cos\alpha\cdot\cos\gamma \tag{9}$$

and the location of point E is

$$\left\{\begin{array}{c} x_E = x_B + h_e\sin\alpha\sin\gamma\sin\theta \\ y_E = y_B + h_e\sin\alpha\sin\gamma\cos\theta \\ z_E = z_B + h_e\cos\alpha\cos\gamma \end{array}\right. \tag{10}$$

Similarly, we can get the position of point E' at the neighbor ship ($x_{E'}$, $y_{E'}$, $z_{E'}$), and then the DoA of radio signal, i.e, the angle of line EE' to plane BCD is given by

$$|\varphi| = \sin^{-1}\frac{K}{\sqrt{(x_E - x_{E'})^2 + (y_E - y_{E'})^2 + (z_E - z_{E'})^2}} \tag{11}$$

where K is

$$K = \frac{|px_{E'} + qy_{E'} + rz_{E'} + s|}{\sqrt{p^2+q^2+r^2}} \tag{12}$$

and

$$\begin{array}{l} p = (y_C - y_B)(z_D - z_B) - (z_C - z_B)(y_D - y_B) \\ q = (z_C - z_B)(x_D - x_B) - (x_C - x_B)(z_D - z_B) \\ r = (x_C - x_B)(y_D - y_B) - (y_C - y_B)(x_D - x_B) \\ s = x_E\left[(z_C - z_B)(y_D - y_B) - (y_C - y_B)(z_D - z_B)\right] \\ \quad +y_E\left[(x_C - x_B)(z_D - z_B) - (z_C - z_B)(x_D - x_B)\right] \\ \quad +z_E\left[(y_C - y_B)(x_D - x_B) - (x_C - x_B)(y_D - y_B)\right] \end{array} \tag{13}$$

V. Simulation Results

The above model is integrated with other components of the maritime simulator in Qualnet and simulations have been carried out. Figure 5 shows the angle of ship compass heading, which is a snapshot of 2-minute measured data in sea close to Singapore west coast and used in the simulation as input of θ. The sea state of area that the measurement carried out is 3.0, of which sea wave period is between 2 to 6.5 seconds, sea wave significant height is 1.07 meter and average sea wavelength is 14.02 meter. The boat length, height and width is set as 15 meter, 6 meter and 4 meter, respectively.

Figure 6 and Fig. 7 shows the simulated angle of pitch and roll, respectively. The simulation parameters (sea state and ship size) are set the same as that of the measurement. The maximum simulated pitch and roll is close to 3 degree and 10 degree, respectively, and this matches the measured results very well. When the ship compass heading is close to 90 degree, both of simulated pitch and roll are close to zero, the same as indicated by Eq. 2 and Eq. 5, respectively.

TABLE I
SIMULATION PARAMETERS.

sea state	period(s)	average wavelength(m)	significant height
3.0	2-6.5	14.02	1.07 m
ship size	**length (m)**	**width (m)**	**height (m)**
large	40	12	15
medium	15	4	6
small	7	2	1.5
antenna	**beamwidth(^{o})**	**gain(dBi)**	**type**
	9	12	omnidirectional

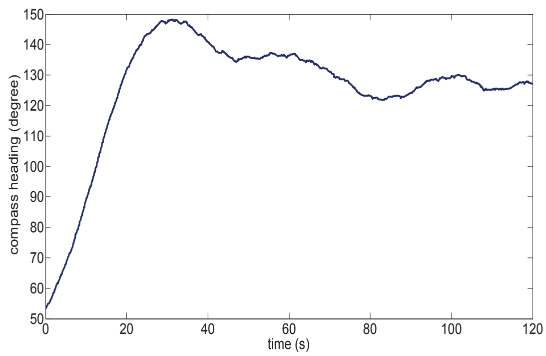

Fig. 5. Measured angle of compass heading in a 2-minute time duration.

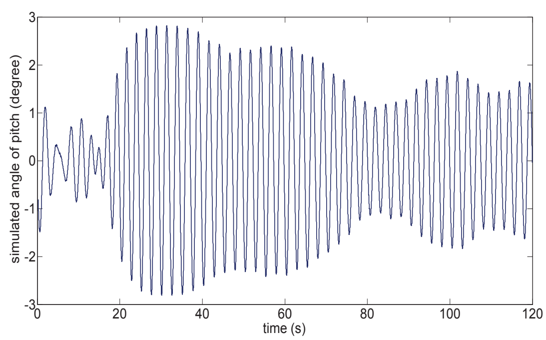

Fig. 6. Simulated angle of pitch.

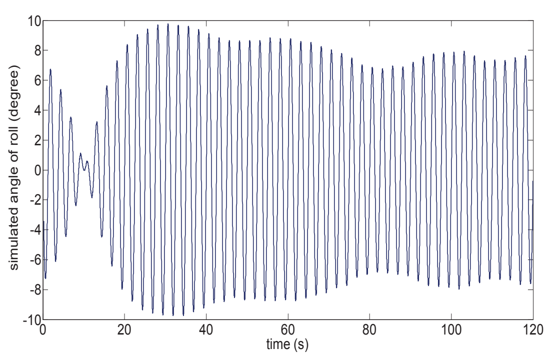

Fig. 7. Simulated angle of roll.

Figure 8 shows the simulated DoA with the same parameters as above. From the results, the DoA in the simulated period is in range of zero to 9 degree. As omnidirectional antenna is used to boost signal power in the project, this leads to

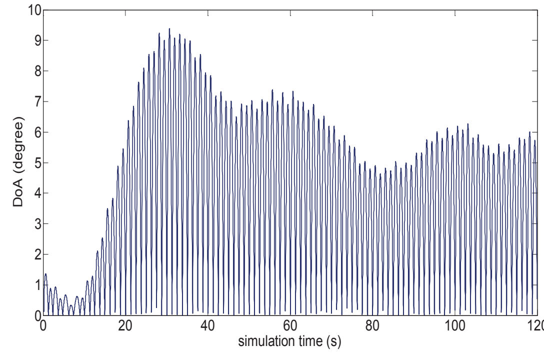

Fig. 8. Simulated DoA.

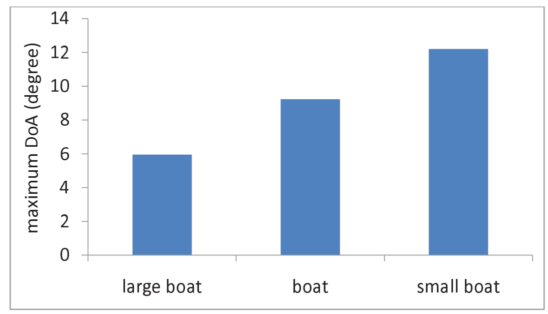

Fig. 9. Simulated maximum DoA.

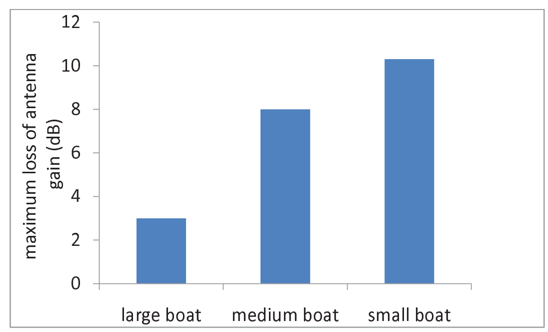

Fig. 10. Simulated maximum loss of antenna gain.

change of antenna gain at the receiver. At DoA close to zero, the received radio signal is at the direction of maximum available antenna gain, while when DoA is close to 9 degree, the available antenna gain losses due to deviation from the maximum direction. The loss of antenna gain depends on the antenna elevation gain pattern.

Clearly, maximum DoA changes when different size of ships are used. We simulated three cases in sea state 3.0 with different size of ships: small, medium and large boats. Table I lists dimensional parameters of the simulated ships, the sea state and the used omnidirectional antenna in simulation. The simulated maximum DoA and loss of antenna gain is shown in Fig. 9 and Fig. 10, respectively. With large boat, the maximum DoA is less than 6 degree, and the maximum loss of antenna gain is around 3 dB, which means with large size ships the received signal power will not be much affected by sea wave movement. When ship size decreases to medium, maximum DoA increases to about 9 degree, and the maximum loss antenna gain becomes about 8 dB. With small boat, they are 12 degree and 10 dB, respectively, and it means the received radio signal power will experience higher fluctuations due to sea wave movement. The maximum loss of antenna gain due to sea wave movement requires extra link budget in network planning.

VI. Conclusion

In this paper, an analysis model of radio signal DoA is proposed. The model is based on modeling sea wave movement as Trochoid wave and orientation analysis of ships in sea. Mathematical description of DoA is presented, and simulations has been carried out. Simulated pitch and roll of ships matches well with measurements in Singapore sea port. By using the model, maximum DoAs and corresponding antenna gain losses are simulated with different ship size. The model is useful in simulation of wireless links in maritime environment and network planning for maritime communications.

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