Over-the-Sea Radio Propagation and Integrated Wireless Networking for Ocean Fishery Vessels

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Abstract. To facilitate the mobile users on ocean fishery vessels to communicate efficiently and cost-effectively in any sea areas, this paper analyzes the applicability of existing wireless technologies to over-the-sea communications, especially their over-the-sea radio propagation effects. To make their respective advantages complementary to each other, this paper proposes an integrated wireless networking system which is composed of mobile ad hoc network, cellular mobile network, and satellite mobile network. The system architecture of the proposed heterogeneous wireless networking system is described, and the access selection mechanism is proposed with always-best-connected (ABC) concept for the benefit of mobile users. Lastly, this paper reports a developed prototype system to evaluate the feasibility and validity of our proposals.

Keywords: radio propagation, mobile ad hoc network, mobile communications, maritime communications.

1 Introduction

With the development of ocean fishery, mobile users on fishery vessels need effective ship-to-ship and ship-to-shore communications methods at any sea area. In such a environment, the major user requirements on communications are cost-effectiveness and full coverage of fishing areas. We firstly surveyed and evaluated whether the existing communications networks can be the candidate networking technology. Actually, there are pros and cons of the existing communications technologies. Currently the communications methods can be used on fishery vessels at sea include single sideband (SSB) shortwave radio, VHF (Very High Frequency) radio, FM radio, cellular phone, and satellite equipments. Among them, the SSB shortwave transmission can be used for long-range communications with reflected signals by the ionosphere. However, blind zones exist in SSB radio manner when the receiver is located away from the bounced distance, and it often suffers from serious interference problems because of overcrowding on the wavebands and atmospheric disturbances. The transmission distance of VHF radio is about 20 nautical miles and the VHF radio transceiver is mainly used only for voice communications. The FM radio is mainly used for short-distance ship-to-ship voice communications with effective transmission

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distance of 8 nautical miles. Another option is cellular phone, such as WCDMA mobile phone with a global positioning system (GPS), whose advantages are low equipment cost and cheap calling fee. Nevertheless, its drawback is the limited coverage of cellular base station signal, which usually can only cover the tens of nautical miles offshore. The last option is satellite mobile communication by the Inmarsat (International Maritime Satellite) system [1], which is suitable for ships far away from shores. However, the mobile users (e.g. fishermen) can not always afford it due to the expensiveness of satellite terminal equipment, high cost of maintenance and replacement, and high communication fee. The above discussion on the current available communication technologies shows that the maritime mobile users are still lack of the cost-effective communication methods to be used at sea.

To further evaluate the wireless technologies for the ship-shore and ship-to-ship communications at sea, the radio propagation effects of existing wireless systems are analyzed. In the analysis, the phenomena of curvature of the earth, propagation over water, diffraction are taken into account. The coverage capabilities of different wireless systems for over-the-sea communications are compared. To meet the user requirements of ocean fishery vessels on communications, this paper proposes to utilize the approach of integrated wireless networking. The proposed integrated maritime communication system is composed of three heterogeneous wireless networks, i.e., MANET (mobile ad hoc network) between ships, cellular mobile network, and satellite mobile network. The proposed system takes advantage of the pros of each individual wireless network. A MANET is a self-configuring multi-hop network that does not rely on available fixed infrastructure. In this paper, we advocate to set up MANET between ships for ship-to-ship communications at sea. The benefit of using MANET is that the ship-to-ship communications within a ship fleet can be achieved without involving satellite mobile network. For ship-to-shore communications, there are two options depending on the locations of fishery vessels. When the mobile users are within the radio coverage of cellular network such as ports and costal areas, the cellular mobile network can be employed. The satellite mobile network gets involved in the ship-to-shore communications only when the mobile users are not covered by cellular mobile network. In the last scenario, mobile terminals on board first access the MANET and then access satellite mobile network via a satellite gateway. Since the proposed system can support multiple transmission paths with the integration of the MANET, the cellular mobile network, and satellite mobile network, automatic access selection method is discussed for the mobile users to choose an always-best-connected communication path. To further evaluate the feasibility and validity of the proposed system and the relevant technical solutions, we are developing a prototype system, and we give a report of the current progress of our development.

The rest of the paper is organized as follows. Section 2 investigates over-the-sea radio propagation of different wireless systems. In Section 3, we present the system architecture of integrated wireless networking system, and describe always-best-connected access selection method in the proposed system. The Section 4 reports our developed prototype system. The Section 5 makes the final conclusions.

2 Over-the-Sea Radio Propagation

Radio propagation describes how radio waves behave when they are transmitted from one point on the earth to another. During the transmission, radio waves can be affected by the phenomena of reflection, refraction, diffraction, absorption, polarization and scattering.

For over-the-sea transmission to and from fishery vessels, the effect of earth curvature on the radio propagation needs to be taken into account.

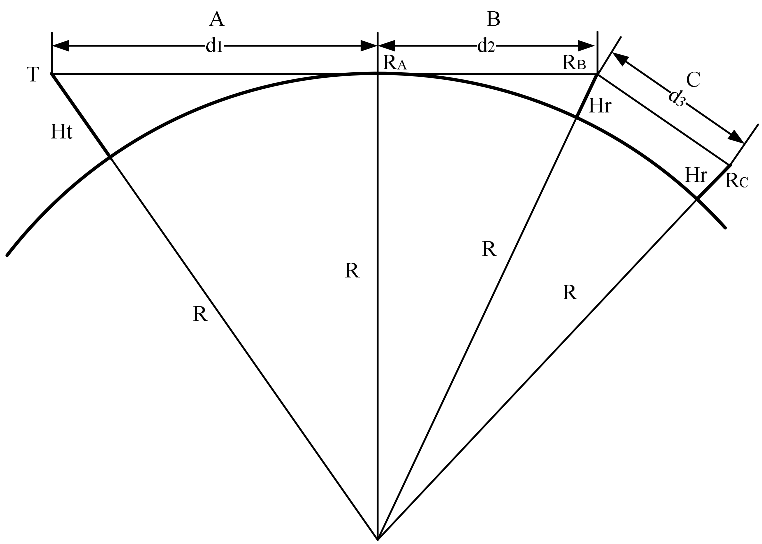

Fig. 1. Illustrative diagram of integrated maritime communication system

As shown in Fig. 1, the ship-to-shore radio propagation distance can be divided into three segments considering curvature of the earth: segment A, which is from T (the point of the base station) to $\boldsymbol{R_A}$ (the sightline of the base station) with length d_1 ; segment B, which is from $\boldsymbol{R_A}$ to $\boldsymbol{R_B}$ (the sightline of the terminal) with length d_2 ; and segment C, which is the shadow area beyond $\boldsymbol{R_B}$ [4].

Assume that the antenna heights of base station and terminal are H_t , and H_r , respectively. From trigonometry we have

$$d_1^2 + R^2 = (H_t + R)^2 \tag{1}$$

$$d_2^2 + R^2 = (H_r + R)^2 \tag{2}$$

and we get

$$d_1 = \sqrt{2RH_t + H_t^2}, \quad d_2 = \sqrt{2RH_r + H_r^2} \tag{3}$$

Since R »Ht,H_r, $d_1$and $d_2$can be approximated by

$$d_1 = \sqrt{2RH_t}, \quad d_2 = \sqrt{2RH_r} \tag{4}$$

where R is the earth radius and $R = 8500$ km.

Next, we analyze the path loss between transmitter and receiver. As we know, the free-space path loss is the loss in signal strength of an electromagnetic wave resulting from a line-of-sight path through free space, with no obstacles nearby to cause reflection or diffraction. It does not include factors such as the antenna gains at the transmitter and receiver, nor any loss associated with hardware imperfections. The equation for free-space path loss (PL) is given by $PL = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2$

where λ is the signal wavelength (in meters), f is the signal frequency (in Hz), d is the distance from the transmitter (in meters), c is the speed of light in a vacuum, 3×10^8 meters per second. A convenient way to express free-space path loss is in terms of dB as follows $L = 32.44 + 20 \lg f + 20 \lg d$ where d is the path length (in km), f is the frequency (in MHz).

When considering the effect of the earth surface, the expressions for the received signal become more complicated than that in case of free space propagation. The signals reflected off the earth surface need to be taken into account. For radio propagation over the land, the phase difference between the direct and the ground-reflected wave can be found from the two-ray approximation by considering only a line-of-sight and a ground reflection. The full path loss expression shows an interference pattern of the line-of-sight and the ground-reflected wave for relatively short ranges, and a rapid decay of the signal power beyond the turnover distance. For propagation distances substantially beyond the turnover point path loss tends to the fourth power distance law, i.e., 40dB/dec.

However, the propagation model would be different for land-to-mobile transmission over water. In this case, three-ray approximation can be employed for the radio propagation by considering only a line-of-sight and two water reflections. In addition to the direct wave, there are always two equal-strength reflected waves, one from the water and the other from the proximity of the mobile unit. The reflected wave, whose reflected point is on the water is counted because there are no surrounding objects near this point. The other reflected wave that has a reflection point proximal to the mobile unit also carries strong reflected energy to it. Therefore, the reflected power of the two reflected waves can reach the mobile unit without noticeable attenuation. The total received power at the mobile unit would be obtained by summing three components. It is deduced in [2] that the equation of radio propagation is the same as that expressing the power received from the free-space condition. Therefore, we may conclude that the path loss for land-to-mobile propagation over land, 40 dB/dec, is different for land-to-mobile propagation over water. In the case of propagation over water, the free-space path loss, 20 dB/dec, is applied.

Based on the above arguments, when the radio propagation path in the segment A, the path loss is expressed by

$$L_a = 32.44 + 20\lg f + 10\gamma_1 \lg d \tag{5}$$

where γ_1 is the path loss exponent, and γ_1 =2. In the segment B, diffraction arises because of the curved way in which waves propagate. By the Huygens-Fresnel principle, the propagation of a wave can be visualized by considering every point on a wavefront as a point source for a secondary radial wave. Considering the earth as a half-infinite blocking panel to the propagation, the E-field strength at the receiver is half of that received from free space. Hence, the resulted path loss by diffraction is 6 dB.

Meanwhile, the propagation model of three-ray approximation over water is not perfect in the segment B. For simplicity, assuming that the additional path loss falls off with path loss exponent γ_2 with respect to distance in the segment B, the path loss when the receiver is in the segment B can be expressed by

$$\begin{aligned} L_b &= 32.44 + 20 \lg f + 10\gamma_1 \lg d_1 + 10\gamma_2 \lg (d - d_1) \\ &= L_a + 10\gamma_2 \lg (d - d_1) \end{aligned} \tag{6}$$

where $\gamma_2 > 2$. The empirical value of γ_2 can be obtained by testing.

For diffraction in Segment C, the method given for diffraction over a spherical Earth specified by ITU can be used [3]. For simplicity, assuming that the additional path loss falls off with path loss exponent γ_3 with respect to distance in the segment C, the path loss when the receiver is in the segment C can be expressed by

$$\begin{aligned} L_c &= 32.44 + 20\lg f + 10\gamma_1 \lg d_1 + 10\gamma_2 \lg (d - d_1) + 10\gamma_3 \lg (d - d_1 - d_2) \\ &= L_b + 10\gamma_3 \lg (d - d_1 - d_2) \end{aligned} \tag{7}$$

where $\gamma_3 > \gamma_2 > 2$. The empirical value of γ_3 can be obtained by testing.

Next, we obtain the radio transmission distance for ship-to-shore and ship-to-ship communication cases by link budget analysis. A link budget is the accounting of all of the gains and losses from the transmitter, through the medium (free space, cable, etc.) to the receiver. Here, link budget analysis is employed to determine the coverage in the ship-to-shore and ship-to-ship radio transmissions.

For coastal cellular communications, UMTS WCDMA technology is assumed to be used for ship-to-shore radio coverage. UMTS WCDMA macro cell coverage is uplink limited because mobiles power level is limited to mobile terminal. The WCDMA link budget example is given in Table 1.

The ship-to-shore transmission distance by WCDMA cellular network d_{max} can be estimated by using (5),(6), and (7) with the Total available path loss $L_T = 152.2$ dB.

The estimation of d_{max} is given in Table 2. In Table 2, H_t is the antenna height of WCDMA BS, and H_t is set to 100m, 50m, 25m, 10m. H_r is the antenna height of mobile terminal on fishery vessel, and H_r is set to 10m. The frequency of WCDMA f is set to 2100M. L_a is calculated by (5), and $L_b = 10\gamma_2 \lg (d - d_1) = 10\gamma_2 \lg (d_2)$. In the calculation, γ_2 is set to 3. It is seen that $L_T = 152.2$ dB only supports the radio transmission of Segment A and Segment B for WCDMA system, i.e., $L_T = L_a + L_b$, and $d_3 = 0$.

Table 1. WCDMA Link Budget Example

TX	
Mobile max power = 0.125W (dBm)	21
Body loss-Antenna gain (dB)	2
EIRP (dBm)	19
RX	
BTS noise density (dBm/Hz)	-168
RX noise power (dBm)=-168+10*log(3840000)	-102.2
Interference margin (dB)	3
RX interference power (dBm)	-102.2
Noise and interference (dBm)	-99.2
Processing gain (dB), 12.2k voice=10*log(3840/12.2)	25.0
Required E_b/N_0 for speech (dB)	5
Antenna gain (dBi)	17
Cable and connector losses (dB)	3
Rx sensitivity (dBm)	-133.2
Total available path loss (dB)	152.2

Table 2. Estimated Ship-to-Shore Transmission Distance d of WCDMA Network

H_t (m)	d_1 (km)	L_a (dB)	L'_b (dB)	d_2 (km)	d_{max} (km)
100	41.23	131.18	21.02	5.01	46.24
50	29.16	128.17	24.03	6.31	34.46
25	20.62	125.16	27.04	7.96	28.58
10	13.04	121.19	31.01	10.81	23.85

Table 3. WLAN Link Budget Example

TX	
Transmitter output power (dBm)	27
Antenna gain (dB)	6
Cable loss (dB)	-3
EIRP (dBm)	19
RX	
Antenna gain (dBi)	6
Cable loss (dB)	-3
Rx sensitivity (dBm)	-90
Total available path loss (dB)	124

For ship-to-ship communications, IEEE 802.11s mesh network is assumed to be employed. The WLAN link budget example is given in Table 3. It is assumed that APs used are outdoor APs with maximum output power 500mW (27dBm). In this case, the antenna heights of APs H_t and H_t are set to 10m. The frequency of IEEE 802.11s f is set to 2.4GHz. By using(8), L_a is calculated to be 121.2 dB with

d_1 = 13.04 km. and $L'_b = L_T\text{-}L_a = 10\gamma_2 \lg d_2 = 2.8$ dB. In the calculation, γ_2 is set to 3. Then, we can get d_2 = 1:24 km, d_{max} = 13.24 km. In this case, L_T = 124 dB supports the radio transmission of Segment A and Segment B for WCDMA system as well.

3 Integrated Wireless Networking for Ocean Fishery Vessels

3.1 Networking Architecture

The investigation in Section 2 reveals the coverage capabilities of different wireless systems for over-the-sea communications. Considering the user requirements of cost-effectiveness and full coverage on over-the-sea communications, this paper proposes to utilize the approach of integrated wireless networking. The proposed integrated communication system is composed of MANET, cellular mobile network, and satellite mobile network. The illustrative diagram of the proposed system is shown in Fig. 2. In the proposed system, MANET between ships plays two roles: it is the transmission network for ship-to-ship communications, and it also acts as the transit network for ship-to-shore communications. MANET connects with satellite network via shipborne satellite gateway (S-GW), and connects with cellular network via shipborne cellular gateway (C-GW) depending on the offshore distance. It is supposed that the satellite network connects with the cellular network via a terrestrial gateway. The implementation of MANET between ships can be implemented by using the IEEE 802.11s wireless mesh network [5] or IEEE 802.16 WiMAX mesh mode [6].

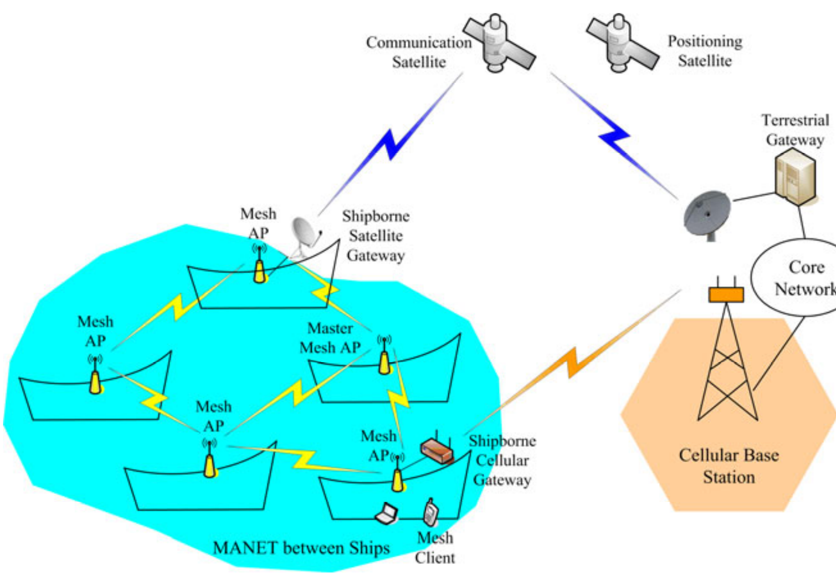

Fig. 2. Illustrative diagram of integrated maritime communication system

In an 802.11 mesh network, the network devices include mesh Mesh Access Points (Mesh APs) and Mesh Clients. The dual-mode phone with both cellular and WiFi interfaces and laptop computers with WiFi interface can be used as Mesh Clients to access the wireless mesh network. To establish a mesh network between ships, each ship firstly sets up a Mesh AP. One-hop wireless link is formed between neighboring ships, and then multi-hop wireless route via Mesh APs on the whole ship fleet can be established to support ship-to-ship communications. Shipborne cellular gateway (C-GW) enables those shipborne user devices without cellular interface (e.g., laptop PC) to access the cellular services. Shipborne satellite gateway (S-GW) enables those shipborne user devices without satellite interface (such as dual-mode phone, laptop PC) to access the satellite services when they are out of the cellular coverage. When using satellite mobile network alone without MANET at offshore areas, each ship needs to deploy satellite terminal. In the proposed system, MANET between ships operating with a satellite gateway deployed on one ship can finish the job. Thus, the proposed system helps to reduce the number of necessary satellite terminals and the deployment and maintenance costs caused by the satellite mobile network.

3.2 Always Best Connected Access Selection

The always best connected (ABC) concept allows a person connectivity to applications using the devices and access technologies that best suit his or her needs, thereby combining the features of access technologies to provide an enhanced user experience [8]. As shown in Fig. 2, the proposed system provides multiple wireless access options, i.e., the MANET between ships, cellular network, and satellite network, for the mobile users on board to select.

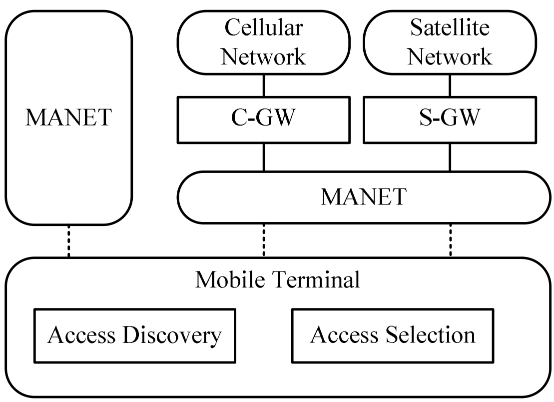

Fig. 3. Multiple access alternatives for mobile users

The mobile terminal first discover the multiple access network alternatives via the access discover module. To select the most desirable network from them, the mobile users can observe and analyze the attributes of networks and users such as price, bandwidth, coverage, and location of callee. After obtaining the relevant attributes, the next step for a mobile user is to capture the multiple conflicting attributes and make a proper decision on network selection. Some researchers directly design functions over the attributes and weights assigned on the attributes [9] [10]. As presented in [9], a cost function of a network is formulated in terms of the bandwidth, power consumption, and price. The network with the lowest value of cost function is selected. In [10], a consumer surplus function is defined as the difference of utility function and cost, and the consumer surplus function is used for the network selection. This problem of network selection can also be tackled with the Multiple Attribute Decision Making (MADM) technique [11] [12]. MADM is a process to make preference decisions over the available alternatives which are characterized by multiple (usually conflicting) attributes. In MADM, the attributes of alternatives are constructed as the decision matrix. The attributes in the decision matrix are aggregated with relative importance weights to yield a ranking order of alternatives for decision making. The selection of appropriate communication path in the proposed system can be based on service requirement (ship-to-ship or ship-to-shore), the network conditions, and the location of ships. The above-mentioned selection methods (e.g., MADM) can be used for the decision making. With the assumption of high cost of satellite networks, the following simplified decision-making can be employed. For ship-to-ship communications, the mobile users can use the MANET between ships only. For ship-to-shore communications, a ship-to-shore radio link can be established by only using the cellular network when the ships are within the coverage of cellular network. On the other hand, if the ships are out of the coverage of cellular network, a ship-to-shore communication path can be established by using MANET between ships, satellite gateway, and satellite system. Hence, the communication scenarios that the satellite system needs to be involved are reduced by using the proposed system.

4 Development of Prototype System

To further evaluate the feasibility of the proposed system and validity of the proposed technical solutions, we are developing a prototype system as shown in Fig. 4.

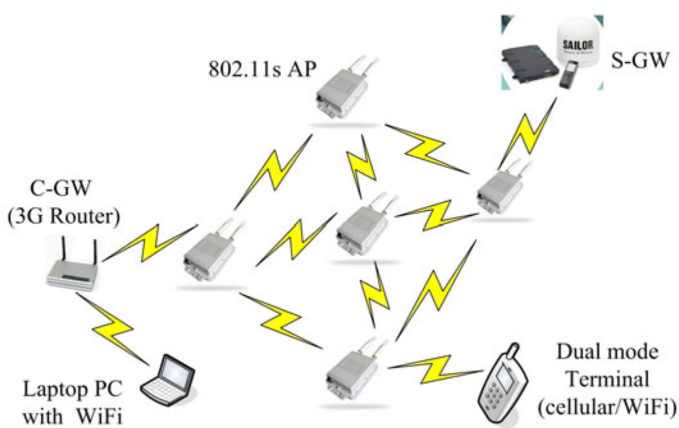

Fig. 4. Prototype system

The first step of establishing the prototype system is to construct the IEEE 802.11s wireless Mesh network. Multiple IEEE 802.11s outdoor APs are employed to form a multi-hop Mesh network. The mobile terminals used in the prototype system include the dual mode smart phone with both cellular and WiFi interfaces and the laptop PCs with WiFi interface. The mobile terminals act as the Mesh Clients to connect with the 802.11s Mesh network. Then, the cellular gateway (C-GW) and satellite gateway (S-GW) are developed for network integration. The C-GW can be implemented by using a commercial 3G router, which can route data between the 3G cellular network and WiFi network seamlessly. The S-GW can be developed based on a FBB satellite terminal, (e.g., FBB 150). Finally, the experimental prototype system is formed by integrating the 802.11s Mesh network, C-GW, S-GW, and mobile terminals. The access selection algorithm is implemented in the mobile terminal for mobile users to have always-best-connected access. The VoIP and video over IP applications are implemented via SIP protocol. The performance of the applications are to be tested in a few connection scenarios: connection with the 802.11s Mesh network, connection with remote mobile terminal via the C-GW, connection with remote terminal via the S-GW.

5 Conclusions

The mobile users on ocean fishery vessels need to be facilitated with effective communications technology in any sea areas. The over-the-sea radio propagation investigation in this paper reveals the radio coverage of existing wireless systems such as WCDMA and Wireless LAN. To support both ship-to-ship and ship-to-shore communications, this paper proposes an integrated wireless networking system composed of MANET (mobile ad hoc network), cellular mobile network, and satellite mobile network. The integrated wireless system takes advantage of the pros of each individual network. Hence, the ship-to-ship communications can be provided via the MANET between ships established, and the ship-to-shore communications can be accomplished via either shipborne cellular gateway or shipborne satellite gateway depending on the offshore distance. With the proposed system, the number of satellite terminals onboard within a ocean fishery fleet can be reduced, and always-best-connected communication path can be selected for the benefits of mobile users during their call setup according to their locations and radio coverage conditions. A prototype system has been under establishment at Hainan University to evaluate our proposals.

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