Performance of a Relay System for Two Extreme Ends of a Vessel at 2.4 GHz

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***Abstract*—Due to the complex metallic environment onboard a vessel, it is difficult to establish a communication link in the ISM frequency band of 2.4 GHz between the two extreme ends of the vessel, i.e., the bridge room and the engine control room (ECR). Therefore, in this letter, a relay system is proposed to overcome the difficulty. The cargo hull with its analogous waveguide structure is found to be a good location for relay. The cargo hull's structure demonstrates wave guiding effect that is able to enhance radio wave propagation. Wideband channel sounding has been conducted over two independent links of a relay system: from the bridge room to the cargo hull, and from the cargo hull to the ECR. Based on the measured impulse responses, channel performances such as average received power, root mean square (rms) delay spread, and ray decay factor are studied and compared for the two links. A maximum usable bandwidth of 0.5 MHz can be achieved without using any equalizer at 2.4 GHz. Although this bandwidth is small, it is sufficient for the transmission of low-data-rate images.**

***Index Terms*—24 GHz, multipath, relay, ship propagation, waveguide effect.**

I. Introduction

As IS known, metallic structures create a complex and multipath-rich propagation environment. The ship vessel that consists of mainly metallic structures is one of the radio frequency (RF) harsh environments of research interest. Same-level propagation onboard a ship has been investigated by both narrowband and wideband channel characterization in [1]–[5]. In [1]–[3], narrowband channel measurement results are presented. In [1], received power level of signals transmitted in the frequency band of 800–2500 MHz between two adjacent compartments within a naval ship was examined. It was concluded that the source of bulkhead penetration was the rubber door gaskets and other nonconductive structures, such as hatch seals and insulation around pipes. In [2], opened/closed-door effect and polarization effect on the received power level for different transmitter-to-receiver locations with a maximum distance of 5 m was modeled in the frequency range of 800 MHz–3 GHz. It was found that the closing of a watertight door can result in an attenuation of 5–30 dB. Even if the cross-polarized component was taken into consideration, no significant gain improvement was observed. The study of path loss in a restaurant hall and along the corridor of cabins onboard a cruise ship was performed at 2.4 GHz in the frequency domain [3]. They are characterized by free-space path-loss law, while the path loss along the corridor can be modeled by using two slopes linear fitting, which is generally used for propagation along analogous waveguide structures such as mines and tunnels.

In [4] and [5], wideband channel measurements were conducted in the frequency domain using a vector network analyzer. In [4], channel impulse responses for transmission within compartments and along passageways at 2 and 5 GHz were studied. It was concluded based on the received power-level results that the usage of wireless LAN onboard a warship was possible. However, the usable bandwidth was limited since there were a significant number of multipath components. Path-loss exponent and root mean square (rms) delay spread were studied for channels inside rooms and along the starboard hallway in [5]. It was reported that neither of the studied parameters is dependent on frequency within the range of 800 MHz–2.6 GHz. For the design of any practical wireless systems, interlevel channel characteristics are as important as same-level channel characteristics. In [6], the propagation mechanisms at 255.6 MHz associated with the channel along a lift shaft connecting the ship from the top level to the bottom level were examined. The guiding effect of the lift shaft was identified, and a large delay spread was obtained due to the rich multipath components resulting from the complex metallic ship structure. From our previous experiments, it was found that wideband communication between the two key locations of the ship, i.e., the bridge room and the ECR, was possible at 79.125 MHz due to the guiding effect of the lift shaft connecting the two locations and also due to the low propagation attenuation in the VHF band [7]. In [8], the received power and coherence bandwidth of the commercial off-the-shelf Wi-Fi system was tested. Throughput and latency were studied based on the measured results. It was concluded that the wireless relay system may be useful and effective in a shipboard environment.

From the literature, it is found that the frequency of 2.4 GHz in the ISM band is popular for shipboard propagation. However, detailed wideband channel characteristics for interlevel propagation in the 2.4-GHz ISM band have not been addressed. It is known that signals suffer high attenuation when penetrating through levels of metals. Therefore, interlevel communication onboard a vessel is difficult. Furthermore, multipath components created by the metallic structures of the vessel limit the channel capacity if neither diversity nor equalization is applied. To achieve a reliable communication link with high channel capacity onboard a complex environment such as a vessel, a relay system can be used since the relay system is able to extend coverage, improve capacity, and thus reduce the power consumption. It has been applied for outdoor, indoor, and outdoor-to-indoor communication [9]–[11].

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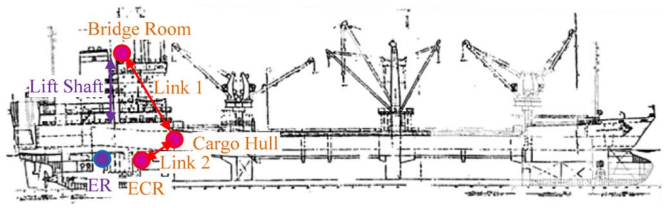


Fig. 1. Schematic drawing of antenna locations.

This letter discusses methods to enable wideband communication between two key locations of the ship, i.e., the bridge room and the engine control room (ECR) in ISM band at 2412 MHz. The lift shaft channel is tested and proved to be ineffective at this frequency. Therefore, a relay system is proposed inside the cargo hull to enable the communication. Based on wideband channel measurements, channel characteristics such as power delay profile (PDP), delay spread, and ray decay factor for the relay links, i.e., transmitter (Tx)–relay station (RS) and RS–receiver (Rx) of the relay, are studied and compared.

II. Channel Measurement

A. Measurement Sites

A measurement campaign was carried out over three days onboard a docked merchant ship in Singapore in February 2010. During the campaign, the crew onboard the ship continued to carry out their routine activities such as the servicing and maintenance of the ship and its engines. Propagation between two key locations—namely, the bridge room and the ECR—is examined. The bridge room is at the topmost level (level 7), while the ECR is near the lowest level (level B1) of the ship. The vertical separation between the two locations is equal to the height of the vessel (approximately 20 m). There is no line-of-sight (LOS) between the two locations. Instead, there are five levels (levels 7–3) of wooden cabins, a metallic deck at level 2, and a cargo hull at level 1 with dimensions $130 \times 22 \times 5$ m^3 (Length $\times$ Width $\times$ Height) separating the two locations. Note that the engine room where all the engines are housed is very close to the ECR. The relative positions of the four locations are labeled in Fig. 1.

It is also observed that the there is a lift shaft connecting the vessel from level 7 to 1. In order to achieve communication between the two key locations in the ISM band, the feasibility of utilizing the guiding effect of the lift shaft is examined. Both the transmitter and the receiver are placed 1 m away from the lift door at two ends of the lift shaft, i.e., the transmitting antenna at level 7 and the receiving antenna varied from level 6 to 1. However, when the receiving antenna is shifted down to the ECR at level B1, no reception is available. Therefore, a relay system located in the cargo hull is proposed. Link 1 refers to the propagation channel from the bridge room (Tx) to the cargo hull (RS), and link 2 refers to the channel between the cargo hull (RS) and the ECR (Rx).

B. System Setup

The spread spectrum sliding correlator sounding method is implemented in this measurement. A vector signal generator produces a binary phase-shift keying (BPSK) modulated broadband signal at a carrier frequency of 2412 MHz. The carrier frequency is spread using a 1023-b pseudorandom noise (PN) sequence. A high-power amplifier is used to amplify the signal before it is transmitted through an omnidirectional molopole at a data rate of 10 Msymbol/s. The same antenna is used to receive the signal. The received signal passes through a low noise amplifier before being down-converted to an intermediate frequency (IF) of 42 MHz, where it is sampled at 200 MSamples/s and stored for offline data processing. For each test, 50 consecutive frames were recorded.

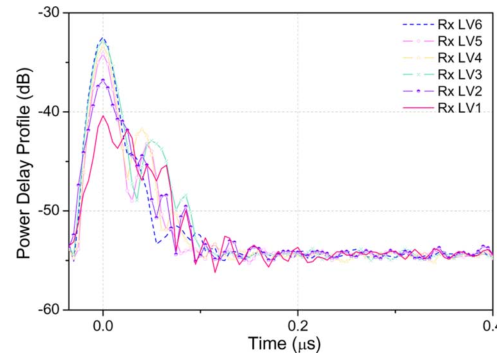


Fig. 2. Power delay profiles along the lift shaft at 2414 MHz.

III. Results & Discussion

If the channel is assumed to be time-invariant, the channel impulse response can be expressed as

$$h_b(n,\tau) = \sum_{i=0}^{N-1} a_i \exp(j\theta_i)\delta(\tau - \tau_i) \tag{1}$$

where i is the consecutive impulse index and N is the number of multipath components. a_i, θ_i, and τ_i are the strength, phase, and delay of the ith multipath component.

A. Testing of the Lift Shaft Channel

As presented in [6] and [12], the lift shaft is an effective channel for propagation at 255.6 MHz both within a ship and in an urban environment. Therefore, the effectiveness of the lift shaft as a waveguide at 2412 MHz is tested. This is done by conducting measurements along the lift shaft by moving the receiver from level 6 to 1 while fixing the transmitter at level 7. Both antennas are kept outside the lift door at a distance of approximately 0.9 m. The mean PDPs obtained at all six receiver levels are shown in Fig. 2.

Compared to the mean PDPs along the lift shaft obtained at 255.6 MHz in [6], the first cluster (0–0.2 μs) is common to both frequencies. However, the PDPs for 2412 MHz shown in Fig. 2 do not have the second cluster (> 0.2 μs). The first cluster consists of both the direct signal penetrating through the floor and ceiling and the guided signal along the lift shaft. The second cluster consists of signals reflected from highly reflective metallic structures and obstacles within the ship. From Fig. 2, it can be concluded that propagation at 2412 MHz is mainly via the lift shaft, where the waves are guided along it, and via direct penetration through the ceilings and floors. The guiding effect is further verified through a set of controlled measurements by opening/closing the lift door at the antenna level and varying the lift car level when the antenna positions are fixed. It was observed that an opened lift door will increase the received power, thus verifying the entry and exit of rays propagating via the lift shaft. It is also found that the amplitude of the received signals is higher when the lift car is out of the propagation path (i.e., not between the levels of the transmitting and receiving antennas). These findings are similar to those presented in [12], where propagation modes along a lift shaft are studied for urban warfare in UHF band. The second cluster is not observed at the higher frequency of 2412 MHz because the reflection, diffraction, and/or scattering loss is high at this higher frequency.

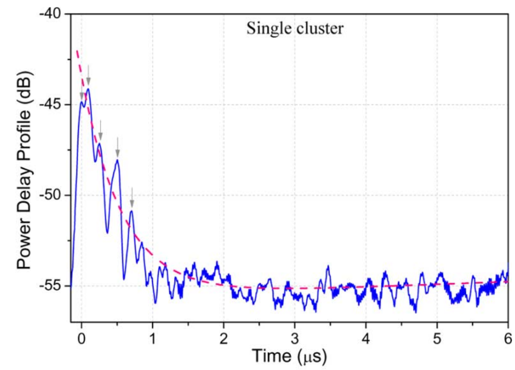
In Fig. 2, it can be seen that the amplitude of the first peak does not vary much for levels 6–3. The maximum difference in the amplitude of the first peak is 1.7 dB. When the receiving antenna is moved farther down to levels 2 and 1, the additional loss is approximately 4 and 3.6 dB, respectively. This higher loss is mainly due to the difference in floor and ceiling material. Between levels 7–3, the floors and ceilings are made of wood. From the deck level (level 2) and below, the floors and ceilings are made of thick metal slabs. When the receiving antenna is shifted farther down into the ECR located at level B1, no signal is received. This is because of the high attenuation brought by the thick metallic floor and ceiling between levels 1 and B1 and the thick metallic door of the ECR. Besides that, the lift shaft stops at level 1, and the guiding effect does not extend to level B1. Therefore, the signal at 2412 MHz is unable to reach level B1. Since communication is required between the two key positions at levels 7 (bridge room) and B1 (engine control room) in the ISM band, a relay system is therefore required.

B. Proposed Relay System

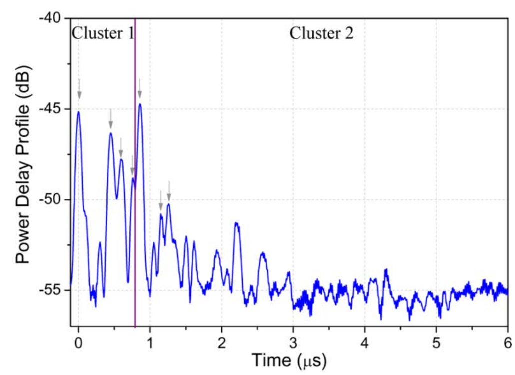
There are two advantages for implementing a relay system onboard the ship where the location of the relay is inside the cargo hull. First, the guiding effect of the cargo hull structure ensures that both the link from bridge room at level 7 to the cargo hull at level 1 [7] and the link from the cargo hull at level 1 to the engine control room at level B1 are achievable at any position within the cargo hull. Therefore, the relay station can function well anywhere within the cargo hull. Second, the retransmission of a relay system can overcome the high attenuation induced by the metallic structures between levels 1 (cargo hull) and B1 (ECR).

Fig. 3(a) and (b) shows the mean PDPs (taking an average of 50 consecutive frames) obtained for the link 1 between the bridge room and the cargo hull and the link 2 between the cargo hull and the ECR, respectively. It is noted that the arrival time of the first peak has been normalized to zero for ease of analysis. It can be observed that the difference in amplitudes of the first peaks in Fig. 3(a) and (b) is only 0.3 dB although the direct length of link 1 is approximately seven times that of link 2. This is because link 2 suffers higher attenuation due to the metallic environment associated with it. Comparing Fig. 3(a) and (b), it can also be seen that link 2 has significantly more multipath components indicated by the arrows. These multipaths have similar power levels in the first peak indicating a strong waveguide effect from the cargo hull. The cargo hull can be modeled as an oversized waveguide structure similar to those inside mines and tunnels [16]. Due to the large size of the studied cargo hull, thousands of waveguide modes are excited and exist.

Furthermore, the intermode and intramode decay and impulse peaks (e.g., the first peak in cluster 2 of link 2) resulting from reflections by metallic structures situated inside the cargo hull make the modes of propagation more complex. The guiding effect along the cargo hull is verified based on ray-tracing simulation in [17]. It was reported that the gradual decrease in signal strength shown in Fig. 3(b), cluster 1, is a result of the waveguide effect of the cargo hull. In Fig. 3(b), cluster 2, the impulse peaks are due to reflection from substructures within the cargo hull. Temporal variation caused by human activities on the deck or inside the cargo hull will not cause significant performance degradation to the two proposed links since propagation over the links is mainly via multipath propagation. It is found that the temporal variation caused by human activities is not significant. This can be verified quantitatively by the small standard deviation of the mean received power of the 50 consecutive instantaneous PDP frames. The mean power standard deviation of the two links is found to be 0.6 and 1.0 dB for links 1 and 2, respectively.



(a)



(b)

Fig. 3. Power delay profile for (a) link 1 and (b) link 2.

TABLE I
CHANNEL PERFORMANCE FOR TWO LINKS

Channel	Mean delay (ns)	RMS delay spread (ns)	Coherence bandwidth (MHz)
Link 1	193.7	215.7	0.9
Link 2	598.5	392.0	0.5

C. RMS Delay Spread

The mean delay and RMS delay spread values for a 5-dB signal-to-noise ratio (SNR) threshold are calculated for the two links and listed in Table I. As expected, both mean delay and rms delay spread are higher for link 2 due to the significant multipath signals caused by the significant guiding effect along the cargo hull. In the literature, the rms delay spread for similar environment such as the factory environment is reported to be between 30 and 300 ns [13]. The delay spread value obtained for link 2 is beyond this reported range. This is due to the complex

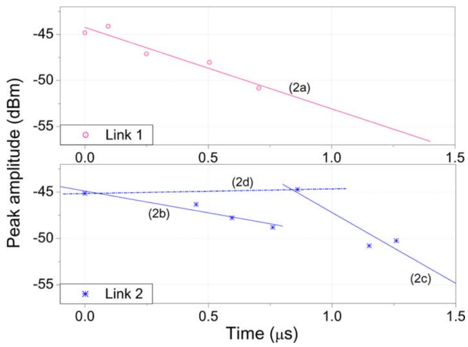


Fig. 4. Decay factor for both channels.

metallic environment onboard the ship and the severe waveguide effect induced by the cargo hull.

Taking the coherence bandwidth as the bandwidth over which the frequency correlation function is above 0.5, the maximum usable data rates (BPSK is assumed) for the two links are 0.9 and 0.5 Mb/s, respectively. Therefore, the maximum usable symbol rate for the link between two ends of the ship is 500 Kb/s if no equalizer is used. The achieved data rate is enough for voice communication and data communication: for example, voice encoded with GSM 6.10 codec that requires about 15 Kb/s, moderate frame rate, low-resolution color video that typically requires about 256 Kb/s [8].

D. Ray Decay Factor

$$p = -8.8t - 44 \tag{2a}$$

$$p = -4.7t - 45 \tag{2b}$$

$$p = -15t - 32 \tag{2c}$$

$$p = 0.49t - 45. \tag{2d}$$

Fig. 3(a) and (b) show the mean PDP of link 1 and 2, respectively. Fig. 3(a) shows a single-cluster PDP that can be fitted with an exponential function, whereas Fig. 3(b) shows a two-clustered PDP. The intracluster decay time constant [14] or the ray decay factor for single cluster in the Saleh–Valenzuela (SV) model and the intercluster decay time constant for multiple clusters are studied through linear fitting for the two links. The significant peaks and their fitted lines with respect to the arrival time are shown in Fig. 4. The corresponding linear models of intracluster decaying are given in (2a) for link 1 and (2b) and (2c) for link 2. The intracluster decaying model for link 2 is given in (2d). The maximum excess time of the significant peaks from link 1 is comparable to that of the significant peaks from cluster 1 of link 2. Comparing (2a) and (2b), the decay rate of cluster 1 in link 2 (4.7 dB/μs) is about half of that of link 1 (8.8 dB/μs). The lower decay factor is a result of the analogous waveguide effect induced by the metallic cargo hull. The significantly higher decay rate (15) of cluster 2 in link 2 is due to the impulsive peak resulted from reflections by metallic structures within the cargo hull. Because of the same reason, a negative intercluster decay rate of -0.49 dB/μs for link 2 is obtained when the transmitting antenna is placed in the complex metallic cargo hull. In the literature, the values of the decay factor for an indoor office building are between 2–14.1 dB/ns for LOS tests and between 1.06–84.1 dB/ns for non-LOS (NLOS) tests [15]; this shows that decay factor is heavily dependent on environment. The decay factor obtained is much lower due to the highly metallic and complex environment.

IV. Conclusion

In this letter, a relay system is proposed in order to achieve broadband communication between two extreme ends of a vessel at 2412 MHz in the ISM band. Channel characteristics such as average received power, rms delay spread, and ray decay factor are studied and compared for the two links used in the proposed relay system. It is found that the average power and delay spread is higher for link 2, while its associated decay factor is lower. Therefore, by performing relay within the cargo hull, the performance of the relay system is mainly limited by link 2 due to the significant multipath components caused by the metallic structures and the guiding effect of the cargo hull. If no equalizer is used, the maximum usable data rate is 500 Kb/s. This is sufficient for real-time voice or low-resolution video communication applications. The performance of the relay system can be improved by using equalization technique and diversity schemes.

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