

Feasibility evaluation and performance enhancement of surface-wave-based communication in metallic structures

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Funding information

This work was supported by Institute of
Information & communications
Technology Planning & Evaluation (IITP)
grant funded by the Korea government
(MSIT) (No. 2023-00227466, Development
and system demonstration of metal
surface-wave magnetic field
communication technology in extreme
environments).

Abstract

This study verifies the feasibility of surface-wave communication as a solution to the severe attenuation and multipath fading encountered by free-space wireless systems in metallic environments. Surface-wave characteristics on dielectric-coated metal surfaces are analyzed in terms of field distribution and attenuation with respect to dielectric thickness and frequency. Experiments conducted in a structure emulating a watertight door show that placing a dielectric layer on the metal surface increases the received signal strength by about 5 dB and improves throughput by more than fourfold compared with the case without the dielectric layer. Additional experiments comparing surface-wave and free-space communication in the same ship-like structure demonstrate that surface-wave communication achieves approximately a 7 dB increase in received signal strength and more than a 15-fold improvement in throughput relative to free-space propagation. These results confirm that surface-wave techniques can significantly enhance wireless coverage and reliability inside dense metallic structures and provide practical insights for future industrial wireless communication system design.

KEYWORDS

channel model, communication performance, dielectric thickness, experimental results, surface wave

1 | INTRODUCTION

Wireless communication inside ships has become increasingly important to support crew communication and implement sensor networks. Conventional wireless systems rely on free-space waves that propagate three-dimensionally through reflection, scattering, and diffraction caused by surrounding media. However, ship-board environments composed of metallic bulkheads, decks, and watertight doors create complex propagation conditions that differ significantly from free-space

characteristics. Consequently, various path-loss models have been investigated, which are typically categorized into empirical, deterministic, and statistical approaches. Empirical models provide simplified predictions based on measurement data [1–3], whereas deterministic models use ray-tracing or electromagnetic simulations to accurately reproduce detailed propagation paths and attenuation characteristics [4, 5]. By contrast, statistical models treat the interior of a ship as a complex resonant cavity and probabilistically analyze the electric field distribution, enabling robust performance prediction in

multipath-dominant environments [6, 7]. Although these studies offer useful insights into the path-loss behavior, they do not fully resolve the instability of propagation paths or the severe signal attenuation observed in highly complex metallic structures.

To address these challenges, recent studies have focused on surface waves. Unlike conventional free-space waves that propagate in three dimensions, surface waves are guided along the interface between two media. These waves exhibit strong electromagnetic field confinement near the surface, resulting in a quasi-two-dimensional energy distribution. Because electromagnetic energy is confined to a two-dimensional surface, the path loss increases linearly with distance rather than quadratically, allowing a significantly higher received power at long distances compared with free-space waves under the same transmit power. The theoretical foundation of surface waves dates back to the late 19th century. Sommerfeld established a theory describing wave propagation along conductive surfaces and demonstrated the efficiency of such propagation at low frequencies [8, 9]. Subsequently, Marconi provided empirical validation through transatlantic communication experiments [10]. Zenneck later introduced what is now known as the Zenneck wave, a nonradiative surface wave that propagates along metal surfaces with gradual attenuation [11–13], and Goubau proposed the use of dielectric coatings to reduce transmission loss [14]. These foundational theories were applied in the Cold War era of US Navy communication and radar systems, and led to the development of high-frequency (HF) surface-wave technologies and towed submarine antenna systems, which enabled efficient long-range maritime communication.

Surface waves have attracted renewed interest in modern applications because they can propagate along curved metallic structures while offering relatively stable transmission paths, even in the absence of conventional waveguides. This makes surface-wave-based wireless communication a promising alternative for reducing cabling costs and enhancing the deployment flexibility inside metallic structures, such as the shipboard environments shown in Figure 1. Accordingly, experimental and simulation studies have been conducted to investigate the feasibility of surface-wave communication in metallic environments [15, 16]. Furthermore, the practical scope of these applications has been extended to the Industrial Internet of Things (IIoT) by validating wireless-coupled channel models on single conductors [17] and complex structures, such as right-angle bent metal pipes [18]. Moreover, research integrating reconfigurable intelligent surface (RIS) technology and reconfigurable porous platforms has demonstrated the potential to dynamically control or partition surface-wave propagation paths and



(A)



(B)

FIGURE 1 Example of a metal-structured ship: (A) exterior view of the ship (hanarae-ho) and (B) corridor inside a ship (corridor with watertight doors onboard the dredge Samuel de Champlain [online]. Available at https://commons.wikimedia.org/wiki/File:Champlain_tunnel.jpg, by H. Cozanet, licensed under CC BY-SA 3.0/2.0 FR).

minimize propagation losses [19–22]. Building on these advancements, recent studies introduced sophisticated analytical models using surface-wave ray tracing to precisely evaluate the propagation loss in such reconfigurable environments [23]. Furthermore, advanced wave steering techniques, such as surface-wave metaprisms, are being developed to enable frequency-dependent beam control, further expanding the potential of smart radio environments [24].

This study summarizes the theoretical foundations of surface waves and experimentally verifies their propagation characteristics. In addition, we investigate the feasibility of employing surface-wave-based communication in metallic environments, where conventional free-space wireless communication is difficult to implement. Section 2 reviews the basic theory of surface-wave propagation. Section 3 quantitatively analyzes the distance-dependent performance of surface waves on a

dielectric-coated metallic plate through simulations and experiments, focusing on the influence of dielectric thickness. Section 4 experimentally examines a scenario in which a watertight door in a ship is simplified as a slit in a shielding chamber and analyzes the conversion of electromagnetic waves emerging from the slit into a surface-wave mode on a dielectric-coated metal surface. Finally, Section 5 provides the concluding remarks.

2 | THEORETICAL SURFACE WAVE

Surface waves can be excited in various configurations, such as imperfect conductors supporting Zenneck waves, dielectric-coated metal surfaces [14], and surfaces with inherent roughness [25]. However, Zenneck waves exhibit restricted transmission ranges in the GHz band, while roughness-induced waves exhibit poor reproducibility and extremely short propagation distances. To overcome these limitations, this section focuses on intentional dielectric coatings, such as silicon or paint layers, to provide a controllable and repeatable platform for surface-wave propagation. Such dielectric loading is a proven technique in electromagnetics for optimizing performance, as evidenced by recent research on dielectric-coated antennas [26]. This approach of utilizing dielectric layers is essential for maritime wireless communications, which require both consistent performance and long-range connectivity.

As shown in Figure 2, when a dielectric layer is applied to the surface of an infinitely large metallic plane on the xy -plane, a surface wave is generated, and in this structure the surface wave propagates in the TM mode.

In the structure shown in Figure 2, the surface-wave component can be obtained by solving Maxwell's equations. Let the permittivity and wavenumber of free space

be denoted by ϵ_0 and k_0 , respectively, and those of the dielectric layer by ϵ_1 and k_1 . According to the wave equation, the H_y component satisfies (1), and the H_y fields in free space and the dielectric can be expressed as (2).

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + k^2\right)H_y = 0 \quad (1)$$

$$\begin{aligned} H_{y0} &= Ae^{-jp_0z-j\beta x}, & \text{for } z > d \\ H_{y1} &= Be^{-jpz-j\beta x} + Ce^{+jpz-j\beta x}, & \text{for } 0 < z < d. \end{aligned} \quad (2)$$

In (2), p_0 denotes the propagation constant in the z -direction in free space, and p represents the z -direction propagation constant within the dielectric. The parameter β denotes the propagation constant in the x -direction in both free space and the dielectric. When the dielectric layer is sufficiently thin, the boundary conditions at each interface can be applied to obtain the z -direction propagation constant in free space, which is expressed as

$$jp_0 \approx d \cdot k_0^2 \frac{(\epsilon_r - 1)}{\epsilon_r}. \quad (3)$$

Here, d denotes the thickness of the dielectric layer, and ϵ_r represents its relative permittivity. Because all the terms on the right-hand side of (3) are real, the propagation constant in the z -direction in free space becomes a negative imaginary quantity. This implies that the surface wave generates an evanescent field along the z -direction, causing the electromagnetic energy to remain confined near the surface during propagation. According to (3), the attenuation constant jp_0 in the z -direction within free space is proportional to the dielectric thickness and to the square of the operating frequency while being unaffected by the dielectric permittivity when ϵ_r is sufficiently large. Thus, the surface waves become more strongly confined near the surface as either the dielectric thickness or operating frequency increases.

Surface waves possessing these characteristics offer advantages in terms of transmission distance compared with free-space waves. Conventional free-space waves propagate three-dimensionally, and their received power decreases proportionally to $1/r^2$. By contrast, surface waves propagate two-dimensionally, and their received power decreases proportionally to $1/r$. Consequently, surface waves can propagate over longer distances than free-space waves under identical transmission conditions, which has been confirmed analytically [27]. As shown in Figure 3, when a dipole antenna is used as the transmitter, the electric field of a surface wave at a receiving point (r, z, ϕ) can be expressed as follows:

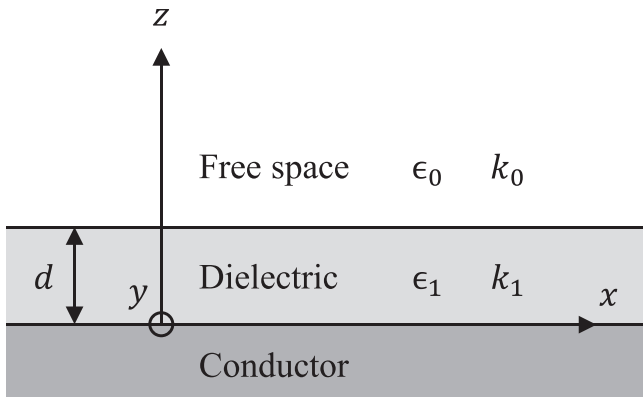


FIGURE 2 Two-dimensional structure enabling surface-wave propagation.

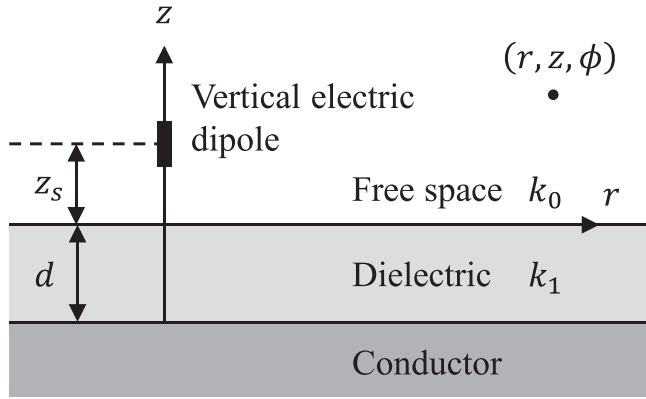


FIGURE 3 Two-dimensional structure with a vertical electric dipole antenna enabling surface-wave propagation.

$$E_z^{\text{sur}} = -\omega\mu_0 \sqrt{\frac{1}{2\pi r}} e^{j\frac{3\pi}{4}} \sum_i \frac{\gamma_1(\lambda_i^*) \tan(\gamma_1(\lambda_i^*)d) (\lambda_i^*)^{5/2}}{q'(\lambda_i^*) \gamma_0(\lambda_i^*)} \cdot e^{j\gamma_0(\lambda_i^*)(z+z_s) + j\lambda_i^* r}, \quad (4)$$

$$\gamma_j(\lambda_i) = \sqrt{k_j^2 - \lambda_i^2}, \quad (5)$$

$$q(\lambda) = k_1^2 \gamma_0 - jk_0^2 \gamma_1 \tan(\gamma_1 d), \quad (6)$$

$$q'(\lambda) = -\frac{k_1^2 \lambda}{\gamma_0} + \frac{jk_0^2 \lambda}{\gamma_1} \tan(\gamma_1 d) jk_0^2 \lambda d \sec^2(\gamma_1 d). \quad (7)$$

Here, μ_0 denotes the permeability of free space, and λ_j^* represents the propagation constant in the r -direction, which is obtained as a solution to $q(\lambda) = 0$. From (4), it can be observed that the magnitude of the electric field of the surface wave is proportional to $1/\sqrt{r}$. Thus, unlike conventional free-space waves, whose path loss is proportional to $1/r^2$, the path loss of the surface waves is proportional to $1/r$. However, when the surface wave propagates on a finite metallic plane rather than an infinite plane, the field expression changes accordingly, as discussed in Section 3.

3 | EXPERIMENTAL ANALYSIS OF SURFACE-WAVE PROPAGATION ON A METAL PLATE

In this section, we experimentally verify the theoretical surface-wave characteristics described earlier. The experimental setup was configured in its simplest form by placing a dielectric layer on a finite metal plate. The overall setup is shown in Figure 4.

As shown in Figure 4A, a dielectric layer was placed on top of the metallic plate, with the transmitting and

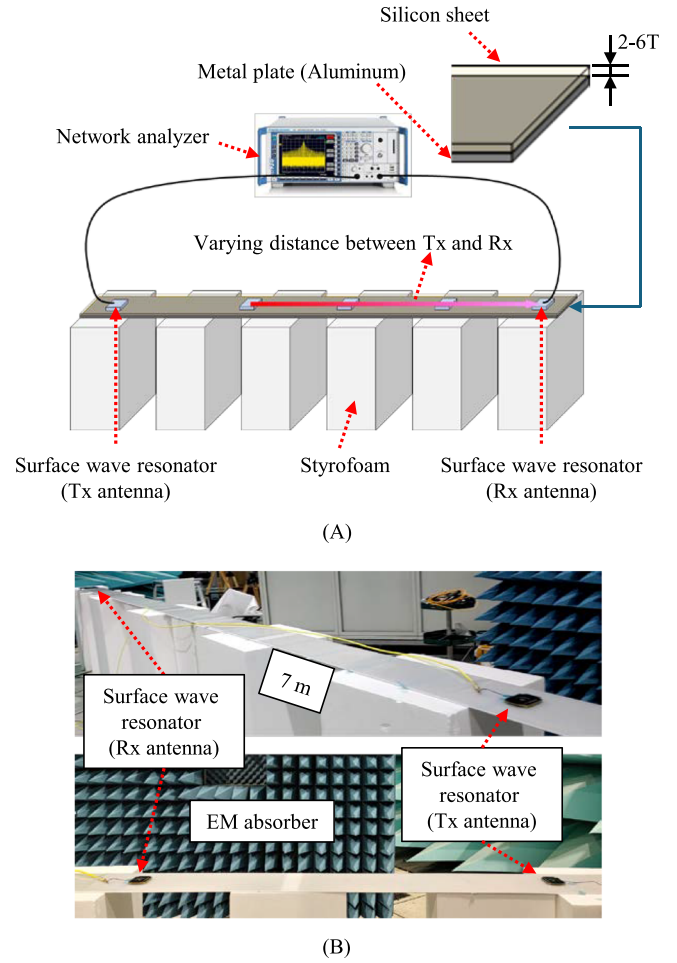


FIGURE 4 Simplified structure for surface-wave measurement experiments: (A) conceptual schematic and (B) actual configuration.

receiving antennas positioned at opposite ends. Both antennas employed inverted patch-type surface-wave resonators provided by Sunny Wave Tech, and an Anritsu MS46122A network analyzer was used to measure the S21 parameters. Because the transmit and receive units generate not only surface waves but also free-space waves, multipath propagation can occur because of reflections from the surrounding environment. To suppress these effects, a styrofoam support structure was installed, as shown in Figure 4A, and electromagnetic absorbers were placed around the measurement area, as shown in Figure 4B. Under this setup, the dielectric thickness is varied among 0, 2, 3, and 4 T, while the transmitter–receiver separation is adjusted from 0.15 to 6.5 m to measure S21. For all experimental conditions, the transmission power was fixed at 0 dBm, and measurements were performed over 16 001 frequency samples spanning from 1 to 7 GHz.

Figure 5A shows the raw S21 measurements obtained at 1–7 GHz while varying the separation distance when

the silicone thickness was 0 T. As shown in the figure, the overall S21 level decreases with distance; however, an accurate comparison is difficult owing to fading. Although the absorbers were placed around the setup, fading still occurred because the surface waves were partially reflected at the metal edges and contributed to the multipath components received by the antenna. Moreover, because surface waves experience a relatively low propagation loss along the surface, the resulting fading effect becomes more pronounced.

To mitigate these fading effects and enable comparison across different dielectric thicknesses and transmitter-receiver distances, we computed the channel power by averaging the raw data over a specific frequency range. Here, averaging refers to calculating the mean of the raw S21 samples over a selected bandwidth. Figure 5B presents the results obtained by averaging over the 2–3 GHz band

(that is, a 1-GHz bandwidth) for all dielectric thicknesses and all tested distances. As shown, the S21 magnitude increases as the dielectric thickness increases compared with the baseline case of 0 T (no dielectric). However, although Section 2 indicates that the surface-wave power should scale proportionally to $1/r$, the measurements in Figure 5B do not exhibit this behavior; notably, the 4-T case does not show a clear decrease with distance. This discrepancy arises because the experiments were conducted on a finite metallic plane rather than on an infinite plane, as assumed in the theoretical derivation in Section 2.

These results suggest that when a finite metallic surface is used, the theoretical $1/r$ -dependent surface-wave channel model must be modified. Figure 6 illustrates the distance-dependent channel power when the average bandwidth is set to 2 GHz.

As shown in Figure 6, the measured channel power for the case without a dielectric layer exhibited a slight increase compared with free-space propagation, which may indicate the presence of surface-wave propagation. However, this increase is primarily attributed not to surface-wave effects but to currents flowing along the edges of the metallic plate. This phenomenon was verified through simulations, as shown in Figure 7.

Figure 7 shows the simulation results for a finite metallic plate without a dielectric layer. As shown in Figure 7B, a strong E_z field is observed near the edges of the metallic plate, and this edge-induced field is the primary reason why the received field strength appears larger than that of free-space propagation. To examine this phenomenon in greater detail, additional simulations were performed

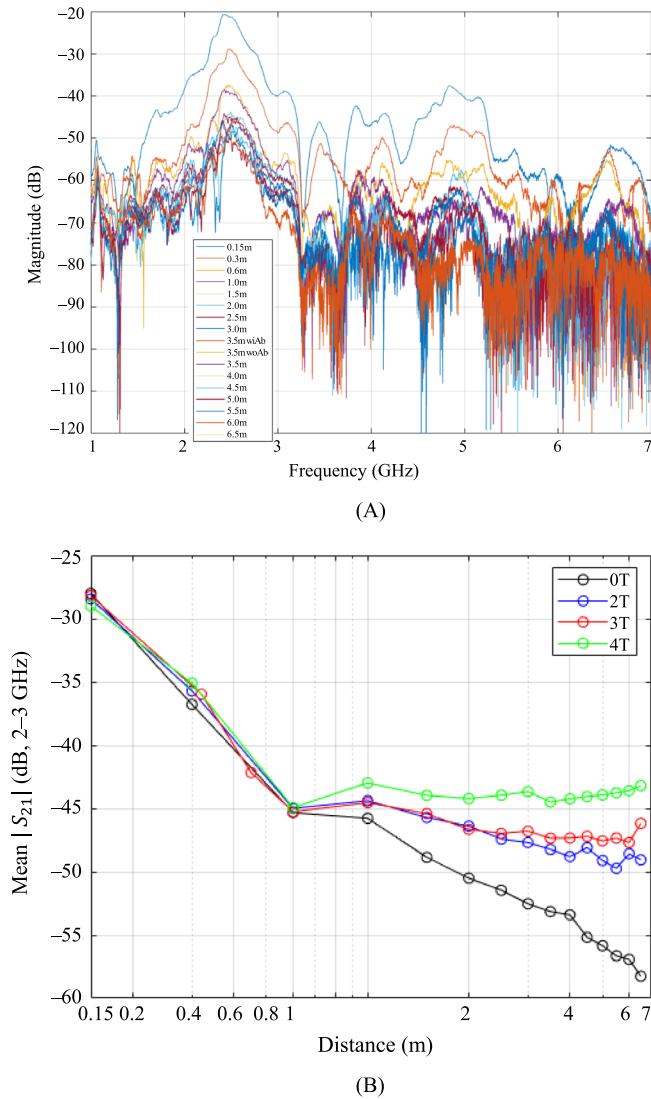


FIGURE 5 Measurement results: (A) S21 raw data for the 0 T case and (B) average S21 at various distances for all thicknesses.

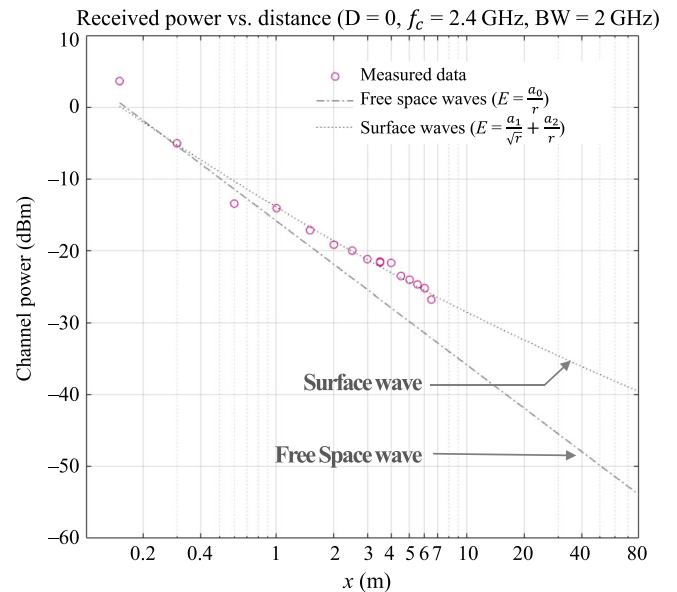


FIGURE 6 Channel power for the 0-T dielectric thickness.

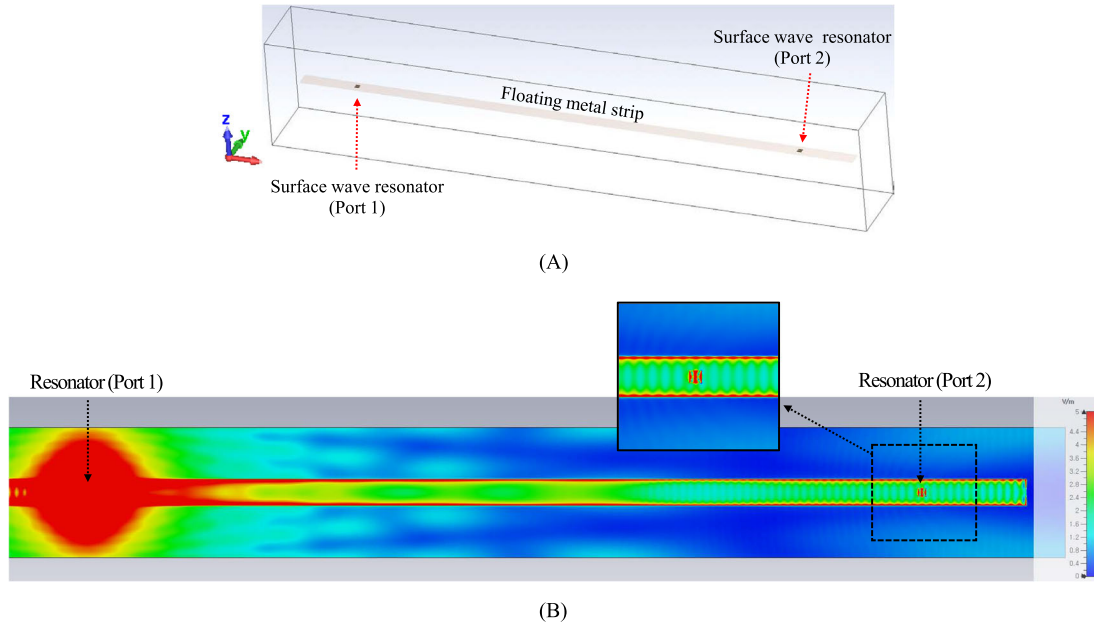


FIGURE 7 Simulation results for the finite-plane structure: (A) simulation model and (B) E_z (top view).

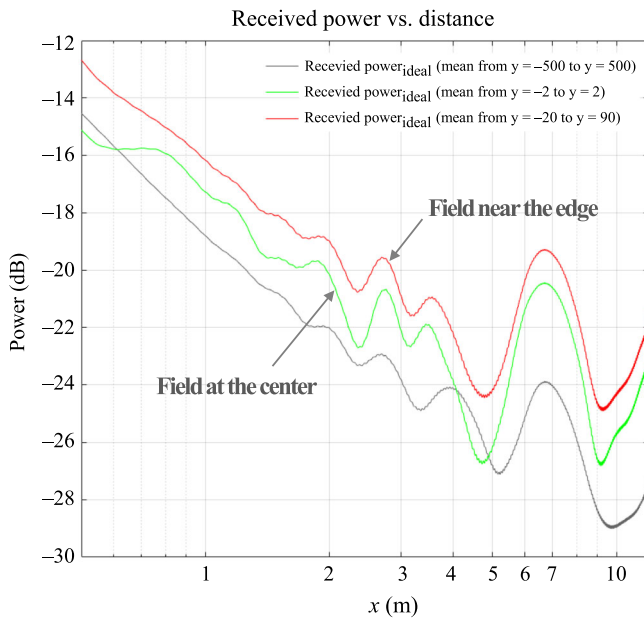


FIGURE 8 Channel power simulation results for a 0-T finite plane with varying receiver positions.

under the same conditions while varying the distance between the transmitter and receiver. The received field was compared for two cases: when the receiver was located near the edge and when it was positioned at the center of the metallic plate. The results, shown in Figure 8, demonstrate that the received field becomes significantly stronger as the receiver approaches the edge.

Next, when a surface wave is generated, corresponding to the case of a 2-T dielectric layer, the results are

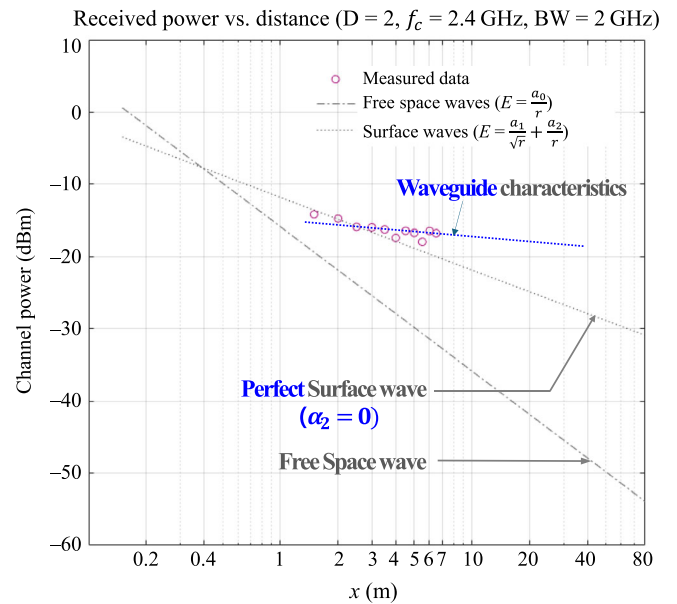


FIGURE 9 Channel power for the 2-T dielectric thickness.

replotted using a 2-GHz averaging bandwidth, as shown in Figure 9.

In Figure 9, the two dotted lines represent the $1/r^2$ decay of free-space propagation and the $1/r$ decay of ideal surface-wave propagation, whereas the solid blue line shows the fitted curve based on the measured data. Unlike the theoretical surface-wave model, the measured power decays more slowly with increasing distance. This behavior occurs because, unlike the idealized infinite-plane case, the dielectric layer on a finite metallic plate acts similarly to a waveguide, allowing even free-space

wave components to propagate with a relatively low loss. Consequently, when the metallic plate has a finite size, the electric field of the surface wave did not strictly follow the theoretical $1/\sqrt{r}$ dependence. Instead, it can be expressed as a combination of a term inversely proportional to distance and one directly proportional to distance, as shown in the following equation:

$$E = \frac{\alpha_1}{\sqrt{r}} + \frac{\alpha_2}{r}. \quad (8)$$

4 | VALIDATION OF SURFACE-WAVE-BASED WIRELESS COMMUNICATION

In this section, we present the experimental results related to the application of surface-wave communication. Specifically, we investigated the surface-wave magnitude for different silicone thicknesses in a ship-like environment, where conventional wireless communication is difficult, and evaluated the communication performance of surface-wave propagation in two representative structures.

Ships are almost entirely composed of metal, which makes wireless communication highly challenging. In particular, bulkheads along corridors consist of metallic walls and doors. When the door is closed, silicone is applied between the door and frame to ensure watertight sealing. Unlike metals, silicone allows electromagnetic waves to pass through, albeit with some attenuation. An experimental setup was constructed to emulate this characteristic, as shown in Figure 10.

As shown in Figure 10, the transmitter was placed inside a shielded room such that the radiated signal exited through a slit in the metallic wall. A dielectric layer was attached to the exterior surface of the wall to allow the wave emerging from the slit to couple into the surface-wave mode. The receiver is positioned on top of the dielectric layer at a distance of 0.98 m from the slit. Both the transmitter and receiver employed inverted patch-type surface-wave resonators provided by Sunny Wave Tech, and the S21 parameter was measured using a Keysight Technologies N9918A analyzer. Because the surface wave propagates along the metallic wall of the shielding room and the receiver is located on the same plane as the slit, the free-space components are significantly suppressed, enabling the dominant measurement of surface-wave propagation. Figure 11 shows the measured S21 when the thickness of the dielectric layer was 1 mm.

As shown in Figure 11A, the raw S21 data exhibited severe fading. Although part of this fading is caused by

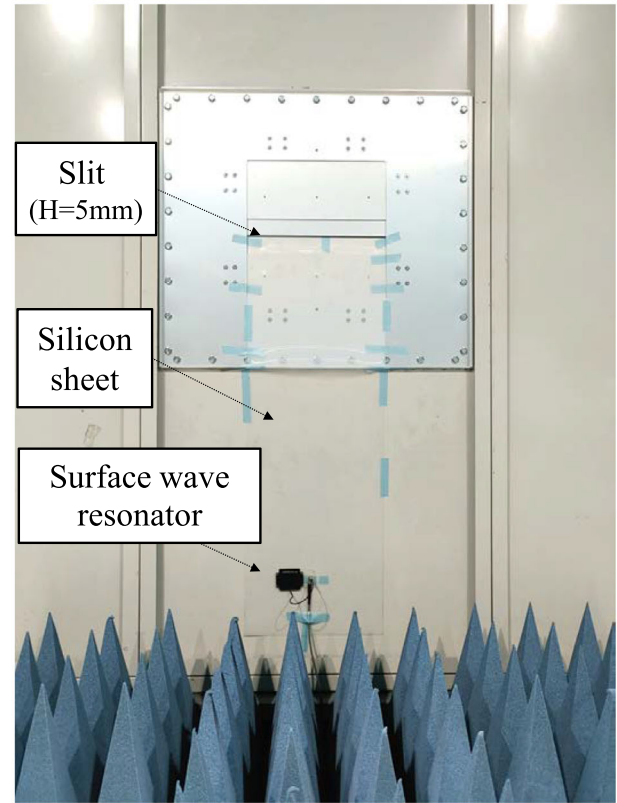
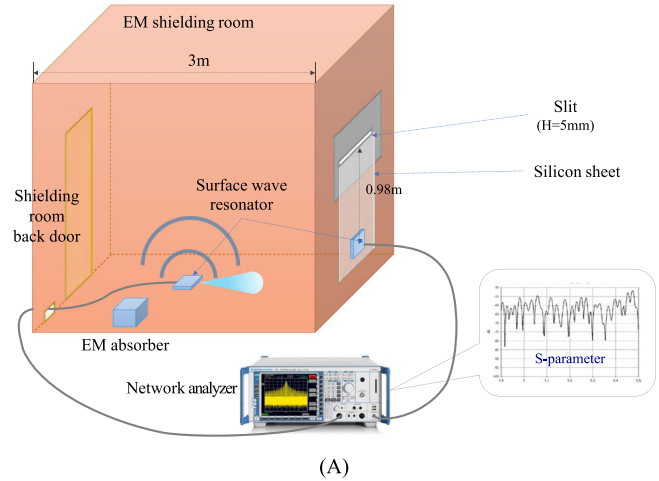


FIGURE 10 S21 measurement experiments for different dielectric thicknesses: (A) conceptual schematic and (B) actual configuration.

multipath components associated with the surface-wave propagation along the metal surface, the dominant factor is the extensive multipath generated inside the shielding room. The fading effect was suppressed by averaging the raw data, enabling a clearer observation of the frequency-dependent trend of S21. The averaged results are shown in Figure 11B.

In Figure 11B, the red curve corresponds to a window size of 41, and the blue curve corresponds to a

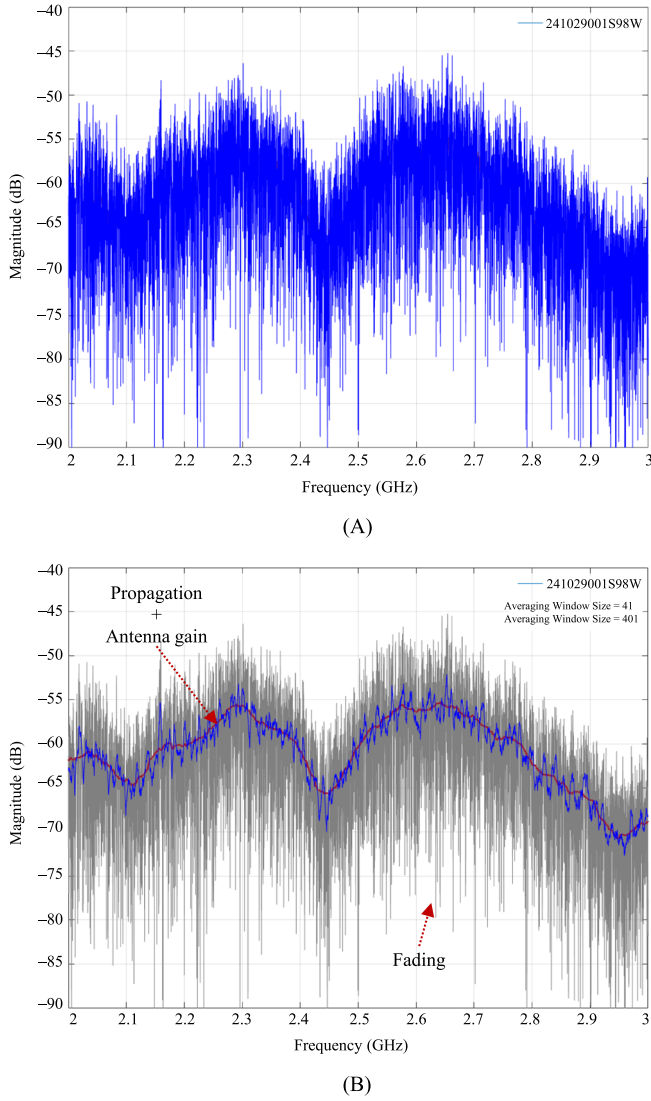


FIGURE 11 S21 measurement result: (A) raw data and (B) fading suppression results.

window size of 401, where the window size represents the number of frequency samples used for averaging. For example, a window size of 41 indicates that the S21 value at a given frequency was obtained by averaging the raw S21 samples within 20 frequency points around that frequency. A larger window size further reduces the fading effect and is therefore useful for identifying the underlying frequency dependence of S21. The results obtained for the dielectric thicknesses of 0, 2, 3, and 4 mm, each averaged with a window size of 401, are shown in Figure 12.

As shown in Figure 12, the magnitude of S21 in the Wi-Fi band increases with the dielectric thickness, indicating that the surface-wave strength increases with the dielectric thickness.

Next, we conducted experiments to evaluate the communication performance of surface-wave propagation under the same conditions in which the wave exits

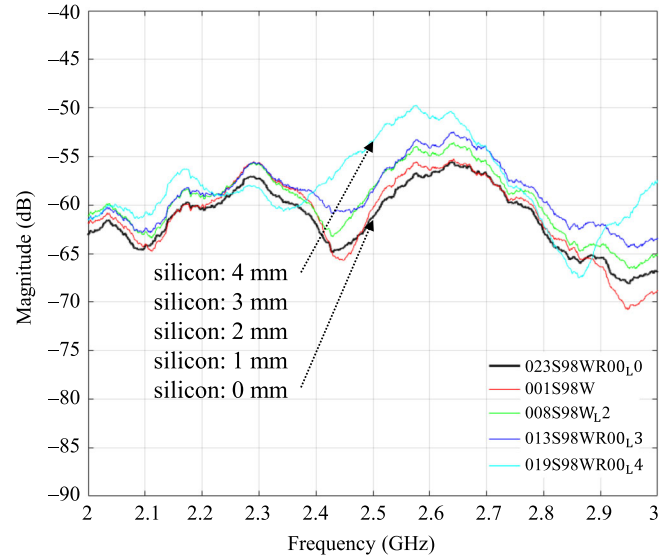


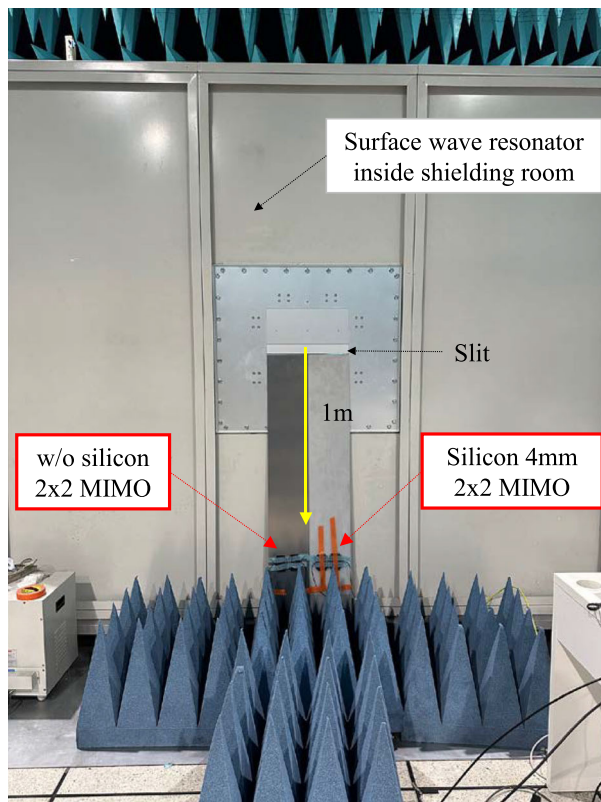
FIGURE 12 S21 measurement results for different dielectric thicknesses with fading suppression.

through the slit. As mentioned earlier, surface waves propagate along the surface; therefore, a metallic plate was placed adjacent to the slit to assess the performance of the surface-wave communication. In the first performance evaluation experiment, the metallic plate was positioned nearly perpendicular to the slit, and the communication performance with and without the dielectric layer was compared. The experimental configuration is shown in Figure 13.

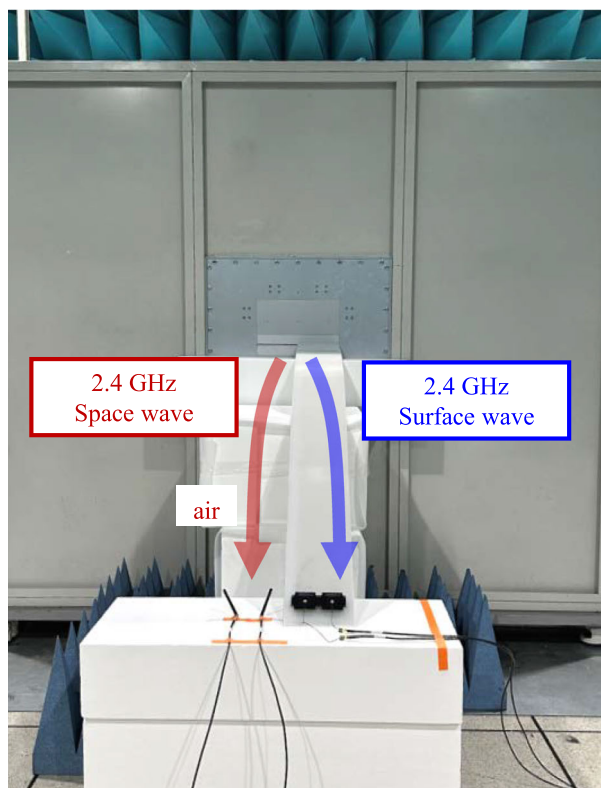
Figure 13A illustrates the experimental setup used to compare the surface-wave communication performance with and without the dielectric layer. A metallic plate was placed perpendicular to the slit, and one side of the plate was left without a dielectric, whereas the other side was covered with a dielectric layer to enable performance comparison under identical conditions. The transmitter was located inside the shielded room, and the receiver was placed on the metallic/dielectric surface at a distance of 1 m from the slit. The same surface-wave resonators used in the previous experiments served as the transmit and receive antennas. However, unlike earlier measurements, a 2×2 MIMO system was employed in this experiment.

A Wi-Fi access point (AP) developed using a Qualcomm chipset was used, and the communication performance was evaluated using the measurement software provided with the AP. As shown in Figure 14, the software measures the throughput over a fixed time interval and reports the average throughput as a performance metric.

Figure 13B presents the experimental setup used to compare the communication performance of free-space and surface-wave propagation. Unlike the dielectric



(A)



(B)

FIGURE 13 Experimental setup: (A) for comparing surface-wave communication performance with and without a dielectric layer and (B) for comparing the performance of free-space and surface-wave communication.

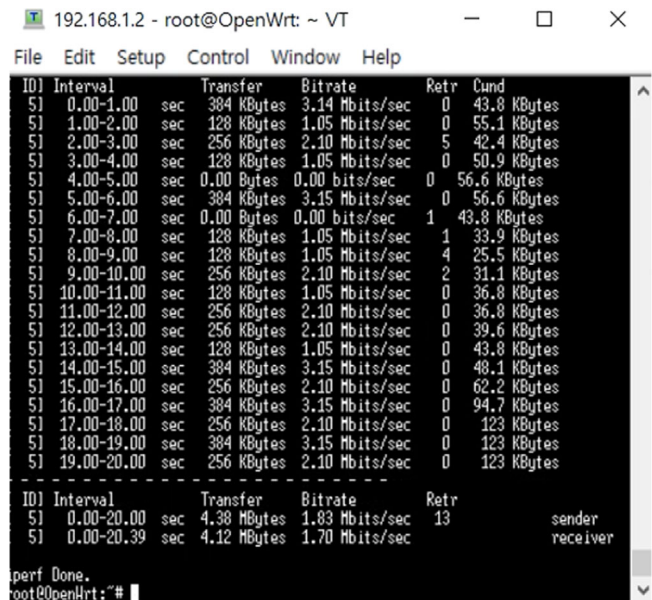


FIGURE 14 Example of communication performance (throughput) measurement.

comparison experiment shown in Figure 13A, the metallic plate shown in Figure 13B is curved. This design prevents the formation of a direct free-space propagation path from the slit to the receiver, thereby minimizing the influence of free-space components and allowing a clearer assessment of surface-wave performance. The dielectric thickness for the surface-wave propagation was set to 4 mm. The transmitter employed the same surface-wave resonator from Sunny Wave Tech used in the previous experiment.

For the receiver, a conventional whip antenna was used to measure free-space waves, whereas an identical surface-wave resonator was used to measure surface-wave propagation. Both receivers were placed 1.8 m away from the slit along the metallic surface. The same measurement software described earlier was used to evaluate the communication performance.

Although the exact transmit power could not be determined because of the adaptive power control (APC) enabled in the Wi-Fi system, all configurations, including the transmit antenna, AP, and system settings, were kept identical for cases with and without a dielectric layer.

Table 1 summarizes the communication performance obtained with and without a dielectric layer. The received signal strength was approximately 5 dBm higher in the presence of the dielectric. Although a direct comparison is difficult owing to the APC function of the Wi-Fi system, which prevents the verification that an identical transmit power was used, the case without the dielectric likely corresponds to the AP transmitting at its maximum allowable power. Therefore, it can be inferred that the presence of the dielectric resulted in a received signal strength of at

TABLE 1 Comparison of communication performance with and without a dielectric layer.

	Signal power	Avg. thro.
W/o dielectric	−84 dBm	7.79 Mbps
With dielectric	−79 dBm	28.6 Mbps

TABLE 2 Comparison of communication performance of free-space and surface-wave communication.

	Signal power	Avg. thro.
Space wave	−87 dBm	1.83 Mbps
Surface wave	−80 dBm	29.3 Mbps

least 5 dBm higher. Since higher received signal strength generally leads to improved throughput, the measurement results show that throughput increases from 7.79 Mbps (without dielectric) to 28.6 Mbps (with dielectric), representing approximately a fourfold improvement.

Table 2 compares the communication performance of free-space waves and surface waves. The received signal strength of the surface-wave case was approximately 7 dBm higher than that of free-space propagation. Correspondingly, the throughput increased from 1.83 Mbps for free-space propagation to 29.3 Mbps for surface-wave propagation, yielding an improvement of roughly 15-fold.

Although practical implementations may require additional consideration, the experiments described in this section demonstrate that surface-wave communication through silicone-filled gaps between ship bulkheads can provide reliable and high-quality communication. Furthermore, these results suggest that surface-wave-based techniques offer a promising solution for overcoming wireless communication challenges in metallic structures.

5 | CONCLUSIONS

This study experimentally demonstrates the feasibility of surface-wave-based communication as a means of overcoming the limitations of conventional free-space communication and enabling stable wireless connectivity within metallic structures. In experiments based on the theoretical model, we verify that the S21 performance improves with increasing dielectric thickness and that the surface-wave path attenuation on finite metallic structures decreases more gradually than the simple $1/r$ law predicted for ideal infinite planes. In the shielding structure experiments emulating a ship environment, we confirm that surface waves can propagate through

metallic slits and that both the received signal strength and throughput improve significantly when a dielectric layer is present. Notably, the results show that surface-wave communication can achieve throughput enhancements of more than 15-fold compared with free-space propagation.

These findings indicate that surface waves represent a promising technology for fundamentally improving wireless communication performance in metallic environments, with potential applicability to future 6G systems and industrial IoT deployments. Furthermore, the quantitative analysis of the dielectric design parameters and structural configurations presented in this paper provides essential groundwork for optimizing communication coverage and guiding future antenna design.

ACKNOWLEDGMENTS

This work was supported by the Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No. 2023-00227466, Development and system demonstration of metal surface wave magnetic field communication technology in extreme environments).

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

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How to cite this article: W.-Y. Song, S.-B. Hyun, and S. Jang, *Feasibility evaluation and performance enhancement of surface-wave-based communication in metallic structures*, ETRI Journal (2026), e70123, DOI [10.4218/etrij.2025-0510](https://doi.org/10.4218/etrij.2025-0510)