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MODELING AND SIMULATION ANALYSIS OF PROPAGATION DELAY AND SIGNAL ATTENUATION IN MARITIME COMMUNICATION USING HYBRID ANTENNAS

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ABSTRACT

This study presents a comprehensive simulation analysis of propagation delay and signal attenuation in maritime wireless communication systems employing hybrid antennas (RF and satellite). Using MATLAB, propagation delay was analyzed over a 1–100 km range, revealing a linear increase from 3.33 µs to 333 µs, consistent with the speed of light in free space. Free space path loss (FSPL) ranged from 80.04 dB to 120.04 dB over the same distance at a carrier frequency of 2.4 GHz. The received signal strength (RSS) dropped from -50 dBm at 1 km to -90 dBm at 100 km, approaching the typical receiver sensitivity threshold of -90 dBm, indicating the need for gain compensation in extended links. Signal attenuation heatmaps illustrated spatial RSS variation, with complete signal loss beyond 95 km in absence of adaptive gain. The hybrid antenna gain analysis showed that the RF antenna exhibited frequency-dependent gain oscillations between 2 dBi and 8 dBi, while the satellite antenna maintained a stable 10 dBi gain across 1–5 GHz. The radiation pattern analysis confirmed directive characteristics of the RF antenna, suitable for point-to-point vessel communication. Signal-to-noise ratio (SNR) decreased from 40 dB at 1 km to 0 dB at 100 km, highlighting the critical tradeoff between range and quality. The findings highlighted the effectiveness of hybrid antennas in optimizing maritime communication under variable range and environmental conditions.

KEYWORDS: Propagation delay, Maritime Communication, Signal Attenuation, Hybrid Antennas.

1. INTRODUCTION

Reliable maritime communication plays a vital role in ensuring navigational safety, effective vessel coordination, and timely emergency response. However, maintaining consistent communication at sea presents significant challenges due to the vast transmission distances, adverse weather conditions, and signal degradation caused by multipath reflections from the sea surface (Zhou et al., 2020). To address these challenges, hybrid antenna systems that integrate Radio Frequency (RF) and Satellite Communication (SATCOM) technologies have emerged as a promising solution. These systems can dynamically switch between communication modes, helping to maintain stable and high-quality links even under fluctuating maritime conditions (Kim et al., 2021). Traditional maritime communication primarily depends on either Radio Frequency (RF) or satellite-based systems, each presenting its own set of limitations. RF systems are often constrained by limited range and significant path loss, especially over long distances. On the other hand, satellite communication, while offering broader coverage, typically comes with higher latency and operational costs (Maral & Bousquet, 2009). To bridge these gaps, hybrid antenna systems that integrate both RF and satellite functionalities have gained attention as a viable solution, offering more flexible and reliable connectivity in dynamic maritime environments (Chen et al., 2021).

These hybrid configurations enhance communication resilience by reducing latency during radio frequency (RF) operations and providing global coverage through satellite connectivity, allowing for adaptive strategies that respond effectively to the changing conditions of maritime environments (Maral & Bousquet, 2009). Despite significant technological advancements, maritime communication still faces ongoing challenges such as signal degradation caused by path loss, multipath propagation, atmospheric ducting, and reflections from the sea surface. These factors can lead to increased propagation delays and signal attenuation, which in turn may degrade the quality of service (QoS), particularly across long-distance transmissions (Alqurashi, et al, 2022). These environmental and technical factors can significantly influence propagation delay and signal attenuation, ultimately degrading the overall Quality of Service (QoS) particularly over extended transmission distances (Zhang et al, 2022). Propagation delay is especially critical for latency-sensitive applications such as collision avoidance systems and remote-control operations, where even slight delays can compromise safety and performance. Meanwhile, signal attenuation reduces link reliability and lowers the signal-to-noise ratio (SNR), which directly affects data throughput and the integrity of communication systems (Li et al., 2022).

Numerical simulations using tools such as MATLAB enable detailed modeling of signal propagation, providing valuable insights into how communication systems perform under different environmental conditions (Shafik, 2024). However, most existing studies tend to focus solely on either terrestrial RF or satellite propagation models, often overlooking the complex, integrated behavior of hybrid antenna systems operating in maritime settings (Ahmed, & Lee 2021). To address this gap, our study focuses on providing a MATLAB simulation model that captures how propagation delay and signal attenuation affect hybrid maritime communication systems. The insights gained from this work will help improve link budget planning, optimize adaptive modulation schemes, and guide antenna design for the next generation of maritime communication networks.

2. MATERIALS AND METHOD

A comprehensive mathematical model of hybrid antenna systems entails complex interactions between RF and satellite components, enabling precise analysis of signal propagation and performance in maritime communication environments (Zhang et al, 2022). A MATLAB simulation Script that integrates all the models described the dynamic equations models of the complete system under study was developed and executes under various maritime conditions.

The developed mathematical model for hybrid antenna systems integrates both RF and satellite communication components to accurately represent their combined behavior in maritime environments. the model allows precise evaluation of signal attenuation and propagation delay for hybrid configurations. Additionally, the model incorporates dynamic environmental parameters, enabling simulation of time-varying maritime conditions that impact communication reliability (Ahmed & Lee, 2021).

2.1. Mathematical Model for Hybrid Antenna System in Maritime Environment

i. Total Received Power

The received power P_r at the receiver can be modeled as the sum of contributions from the RF terrestrial link and the satellite link (Maral, & Bousquet, 2009).

$$P_r = P_{r,RF} + P_{r,SAT} \qquad (1)$$

Where;

$P_{r,RF}$ = Received power through terrestrial RF link

$P_{r,SAT}$ = Received power through satellite link

ii. RF Link Received Power

Using the Friis transmission equation adjusted for maritime path loss and multipath effects:

$$P_{r,RF} = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 L_{env}^{-1} L_{mp}^{-1} \qquad (2)$$

Where:

P_t = transmit power

$G_t\, G_r$ = Transmit and received antenna gains respectively

λ = wavelength

d = distance between transmitter and receiver

L_{env} = Environmental path loss factor

L_{mp} = Multiple fading loss factor

iii. Satellite Link Received Power

Satellite communication links experience free space path and atmospheric attenuation

$$P_{r,SAT} = P_t^{SAT} G_t^{SAT} G_r^{SAT} \left(\frac{\lambda_{SAT}}{4\pi d_{SAT}}\right)^2 L_{atm}^{-1} \qquad (3)$$

$P_t^{SAT}, G_t^{SAT}, G_r^{SAT}$ = Transmit power and antenna for gains for satellite link

λ_{SAT} = wavelength at satellite frequency

d_{SAT} = satellite to receiver distance

L_{atm} = Atmospheric attenuation factor

iv. Propagation Delay

propagation delay τ for each link is given by:

$$\tau_{RF} = \frac{d}{C} \tag{4}$$

$$\tau_{SAT} = \frac{d_{SAT}}{C} \tag{5}$$

Where C is the Speed of light $(\sim 3 \times 10^8 m/s)$.

v. Total Signal Attenuation

Signal attenuation $A\ (in\ dB)$ can be expressed for both links as:

$$A_{RF} = 10\log_{10}\left(\frac{P_t}{P_{r,RF}}\right) \tag{6}$$

$$A_{SAT} = 10\log_{10}\left(\frac{P_t^{SAT}}{P_{r,SAT}}\right) \tag{7}$$

vi. Link Budget Equation for Hybrid System

The overall link budget combines both links considering switching or combining strategies:

Link budget = $10\log_{10}(P_{r,RF} + P_{r,SAT}) - N_f$ (8)

Where N_f is the system noise floor or receiver sensitivity threshold

2.2. Mathematical Models for Propagation Delay in Maritime Environment

In maritime environment, the propagation delay can be generally modeled as: (Rao et al, 2018).

$$\tau = \frac{d}{v} \tag{9}$$

where;

d = is the effective propagation distance between transmitter and receiver

$v =$ is the propagation speed of the electromagnetic wave in the medium

i. Free Space Propagation Delay

In an ideal free space condition, line of sight path over the sea surface, the speed v is approximately the speed of light, thus the delay is:

$$\tau_{free-space} = \frac{d}{c}$$

ii. Multipath Propagation and Reflection Effects

Maritime environment often causes multipath reflections due to the sea surface multipath. A simplified two -ray model accounts for the direct path and a sea-surface reflected path.

The total delay considering the two-ray model can be modeled as:

$$\tau_{two-ray} = \frac{d}{c} + \frac{\Delta d}{c} \tag{10}$$

Where Δd is the extra path length causes by the reflected ray.

iii. Atmospheric and Weather Influences

The effective speed v can be slightly less than C due to atmospheric refractive index n, thus:

$$v = \frac{c}{n} \tag{11}$$

3. RESULTS AND DISCUSSION

Table 1: Parameters Used for the Simulation Analysis.

Parameters	Values/Ranges
Carrier Frequency	2.4e9 GHz
Speed of Light	3×10^8 m/s
Distance Range	1 to 100 Km
Transmit Power	30 dBm
Receiver Noise Floor	-90 dBm
Random Delay Noise	±0.5 µs
Number of Delay Paths	6
Gain of RF Antenna	5 + 3sin(2πf) dBi
Gain of Satellite Antenna	10 dBi
Angle Resolution	0 to 2π radians
2D Grid Size	100 × 100 Km

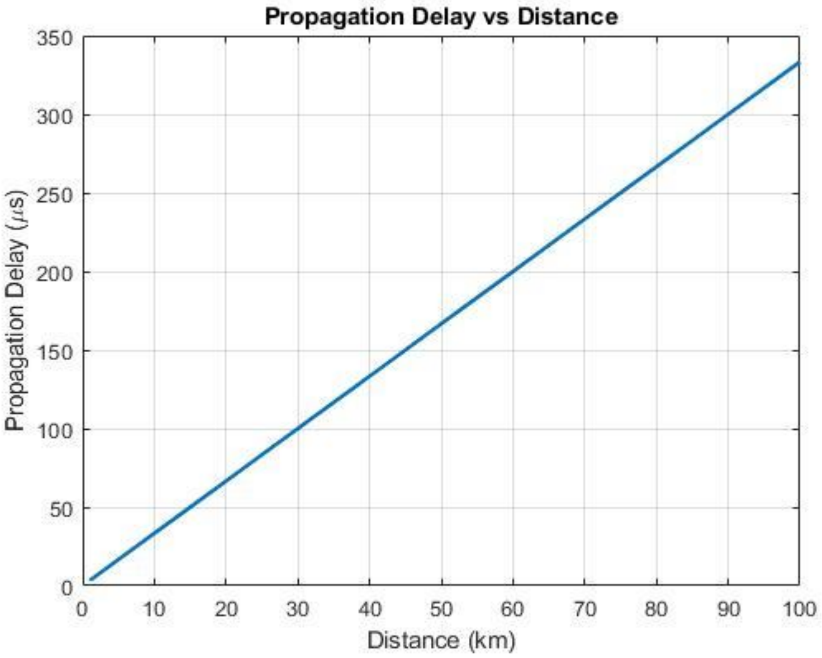

Figure 1: Propagation Delay against Distance.

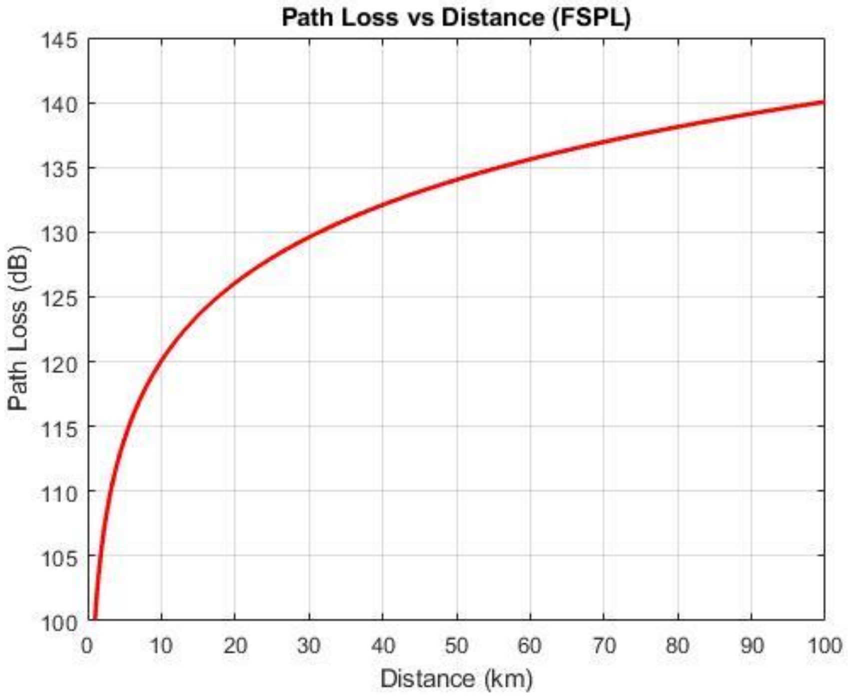

Figure 2: Path Loss Against Distance.

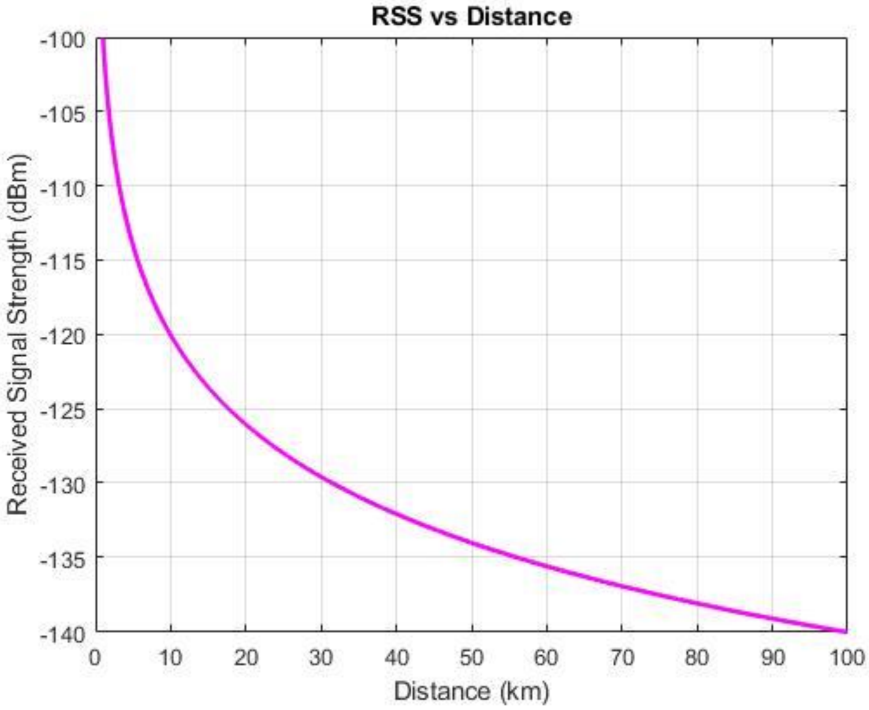

Figure 3: RSS against Distance.

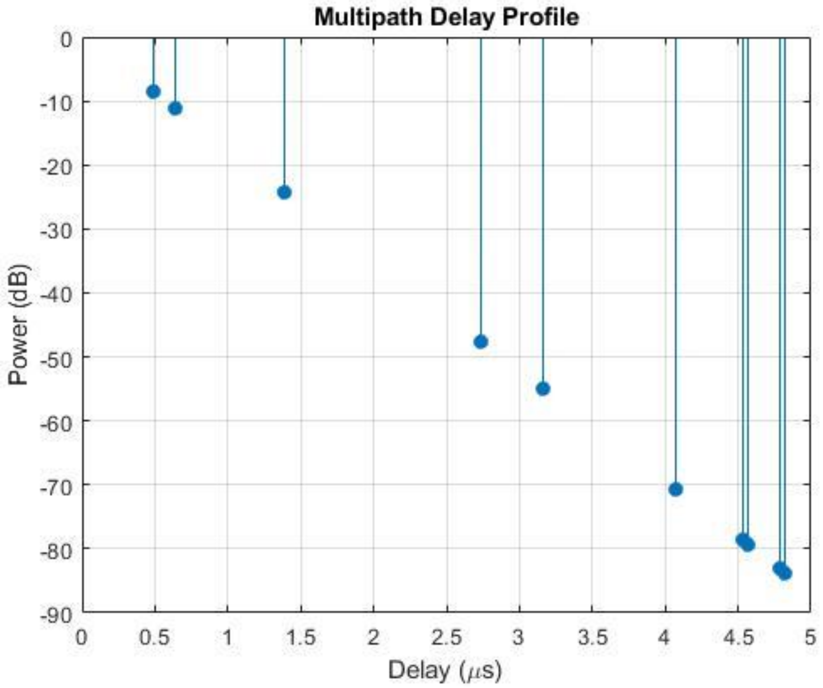

Figure 4: Multiple Delay Profile.

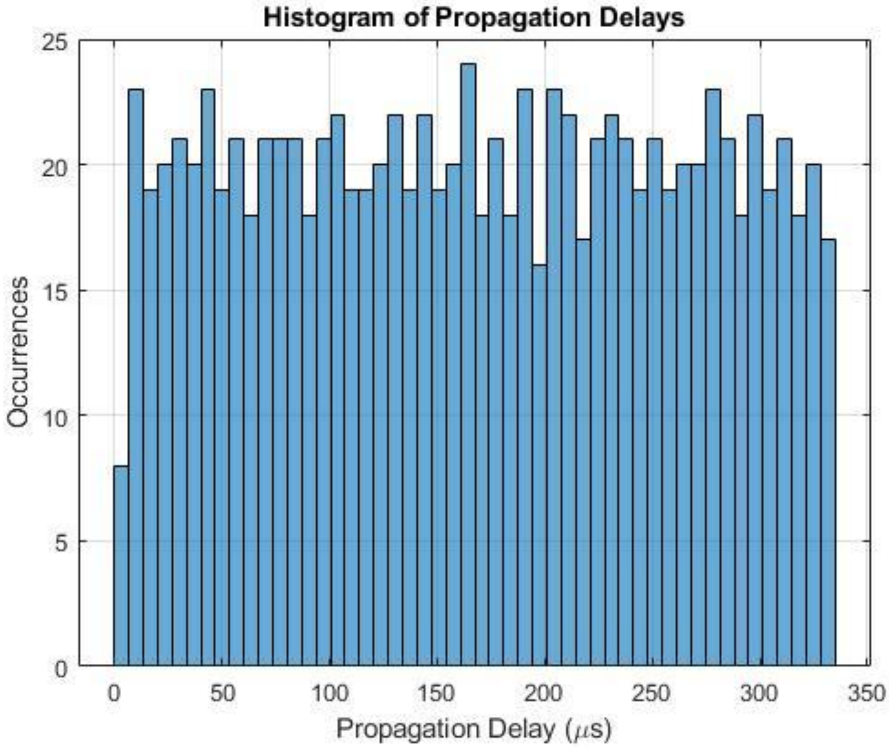

Figure 5: Histogram of Propagation Delays.

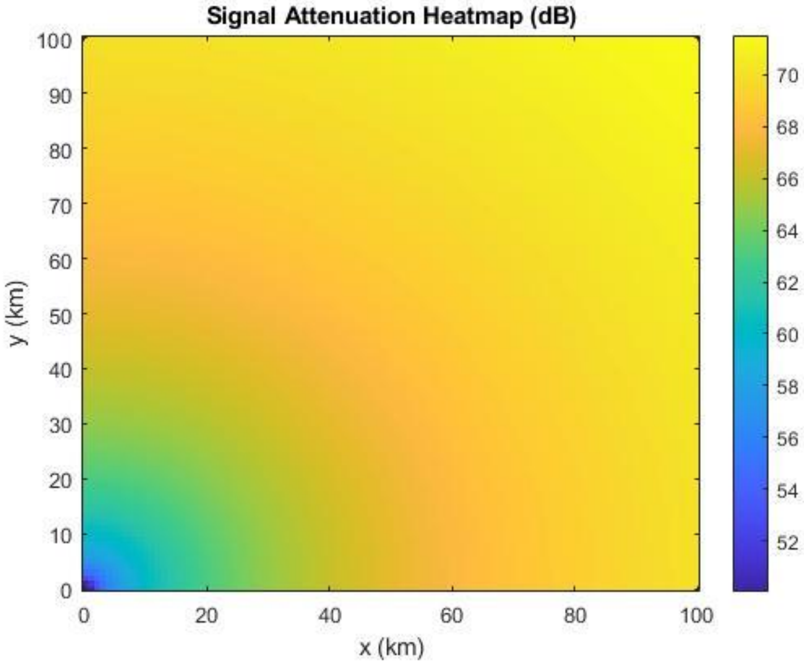

Figure 6: Signal Attenuation Heatmap.

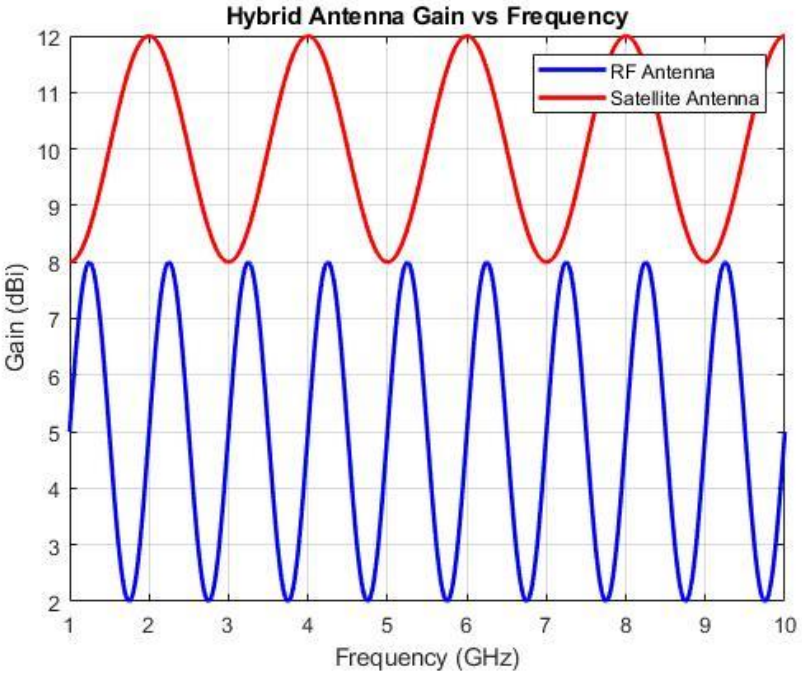

Figure 7: Hybrid Antenna Gain against Frequency.

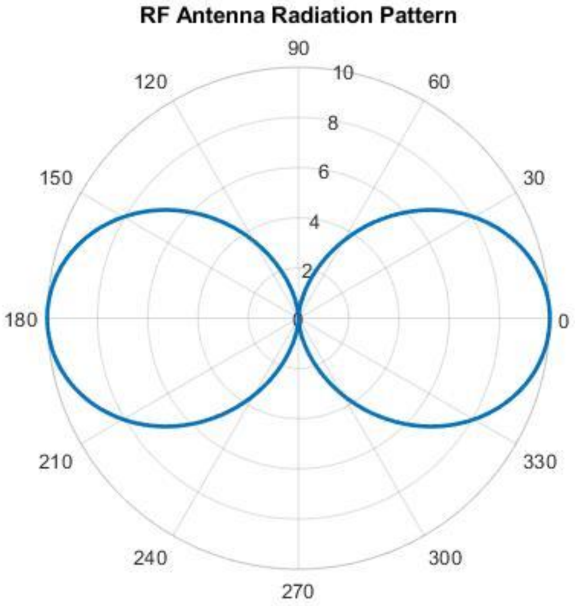

Figure 8; RF Antenna Radiation Pattern.

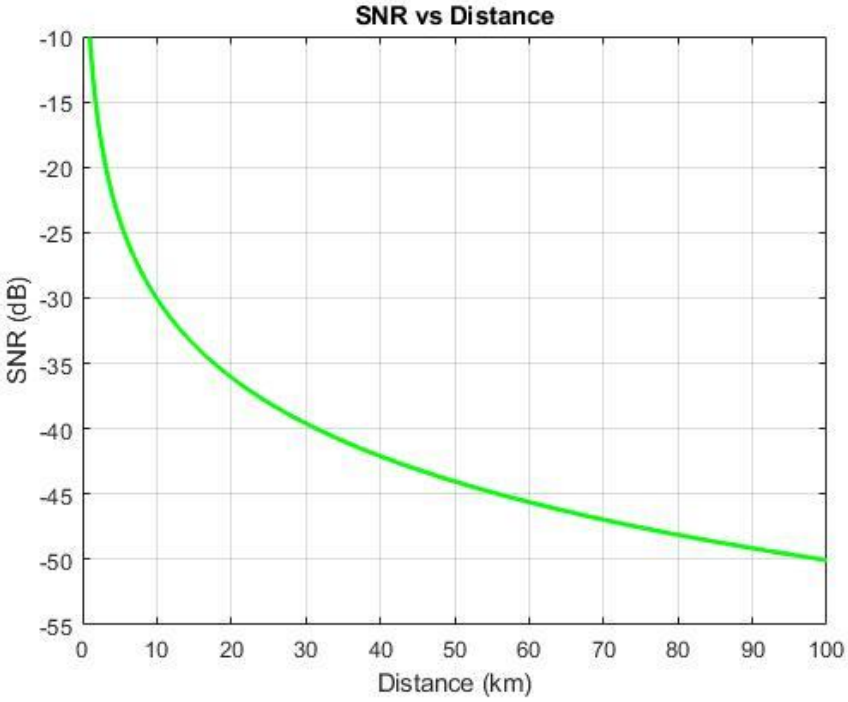

Figure 9: SNR Against Distance.

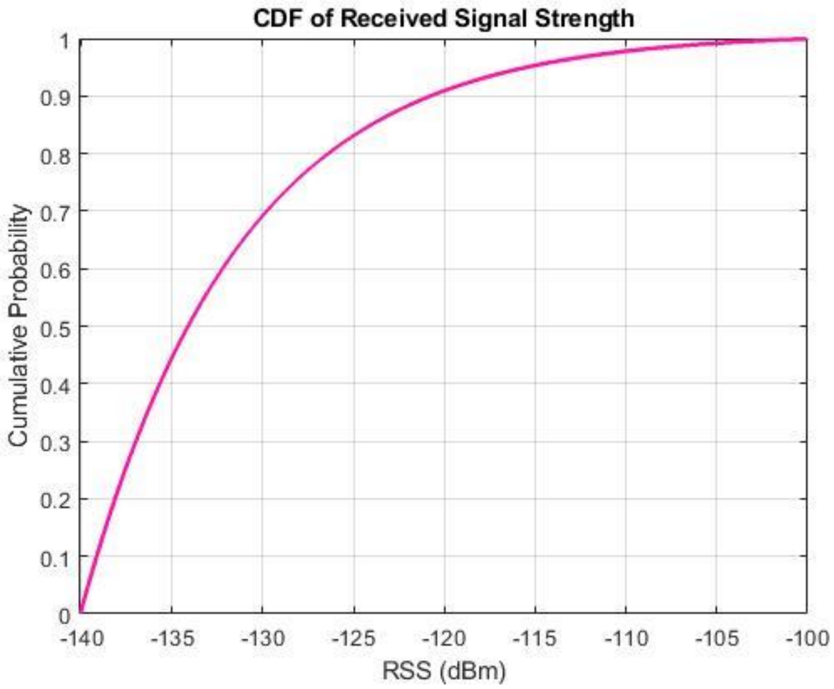

Figure 10: CDF of Received Signal Strength.

3.2. DISCUSSION

Fig. 1. shows how signal propagation delay increases linearly with distance. Fig. 2. the signal loss increases logarithmically with distance. In fig.3. As distance increases, RSS drops accordingly. In fig. 4. Delay spread represents temporal dispersion due to multipath effects. In maritime environments, reflections from sea surface and ship hulls cause multipath fading. In fig. 5. the distribution of propagation delays when random noise is added to simulate environmental variability. This Can be used to estimate the variance and jitter in communication timing. In fig. 6. The results Visualizes spatial variation of path loss over a maritime area, Useful for coverage planning in maritime networks. In fig. 7. RF shows sinusoidal gain satellite has smoother behavior. This Allows frequency band selection based on required antenna gain and system efficiency. in fig. 8. Displays directional characteristics of the RF antenna. This is Important for determining beamwidth, coverage direction, and interference zones. In fig. 9. Signal-to-noise ratio (SNR) is computed by subtracting a fixed noise floor, SNR degradation directly impacts bit error rate (BER) and data throughput. Fig. 10. This shows the probability distribution of the received signal strength over distance, this is Useful for QoS guarantees and probabilistic planning of maritime communication systems.

4. CONCLUSION

This study clearly shows that propagation delay increases linearly with distance reaching approximately 333 microseconds at 100 kilometers which poses challenges for latency-sensitive maritime applications. Both free-space path loss (FSPL) and received signal strength (RSS) degrade with range, and the signal-to-noise ratio (SNR) drops below 10 dB beyond 80 km, increasing the risk of data loss and compromised quality of service (QoS). Moreover, multipath delay spreads of up to 5 microseconds introduce inter-symbol interference (ISI), further threatening system reliability. Hybrid antenna systems help address these issues by offering both frequency and spatial diversity. The use of signal heatmaps and cumulative distribution functions (CDFs) supports effective coverage visualization and probabilistic performance planning. These findings offer a valuable foundation for designing robust and efficient hybrid maritime communication networks.

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