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HF-Based NILE Network Configuration for Link-22 Operations on the Korean Peninsula

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ABSTRACT

The Republic of Korea Navy (ROKN), in collaboration with the North Atlantic Treaty Organization (NATO) and the United States Navy (USN), is preparing to deploy Link-22, a Beyond Line of Sight (BLOS) tactical data link. This deploy- ment aims to address the limitations of Link-11 and support more comprehensive Network-Centric Operations (NCO). De- termining the appropriate configuration of the Super Network (SN) and the NATO Improved Link Eleven (NILE) Networks (NNs) is crucial to ensure effective Link-22 operations in the Korean theater. This paper proposes a design methodology for the NNs, tailored to the geographic and operational requirements of the Korean Peninsula. Our analysis, which is based on High-Frequency (HF) communication and Near Vertical Incidence Skywave (NVIS) propagation, indicates that four HF-based NNs with a transmission power of 100W and up to 500W provide reliable coverage for short to medium-range communications. This configuration minimizes communication gaps and ensures continuous connectivity. These results offer practical guidelines for the ROKN's deployment of Link-22 networks.

Key Words : Link-22, NILE Network, Maritime HF Communication, Naval Tactical Network, Republic of Korea Navy

Ⅰ. Introduction

In modern naval warfare, tactical data links have become crucial components for ensuring real-time information sharing and enhancing decision-making across multiple platforms. These capabilities are central to the concept of Network-Centric Operations (NCO), which allow for more coordinated and effective responses to complex battlefield conditions. Historically, Link-11 has served an important role in tactical communication for the Republic of Korea Navy (ROKN) and other military organizations. However, the growing demands of 21st-century warfare have exposed the limitations of Link-11, particularly in terms of range, data throughput, and cryptographic security, prompting the need for a more advanced tactical data link system.[1]

In response, the North Atlantic Treaty Organization (NATO) developed Link-22 as part of the NATO Improved Link Eleven (NILE) project. Link-22 was designed to address the shortcomings of Link-11 while complementing the existing Link-16. One of its most significant enhancements is the ability to provide Beyond Line-Of-Sight (BLOS) communication without relying on satellite links as shown in Fig.1.[2] This capability ensures robust and secure communication in scenarios where satellite access is limited or denied. For the ROKN, adopting Link-22 is a crucial step in modernizing its communication infrastructure to meet the challenges of future naval operations.[3]

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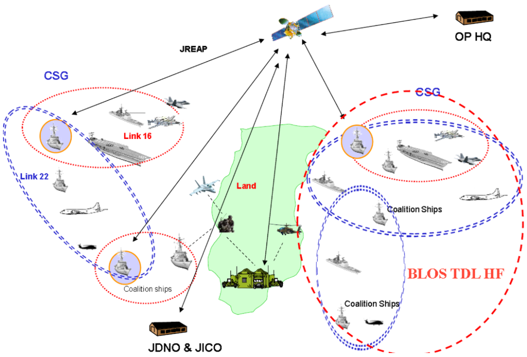

Fig. 1. MTN (Mobile Tactical Network) future concept

The deployment of Link-22 in South Korea necessitates a meticulous examination of the network configuration, with particular attention paid to the design of the Super Network (SN) and Nile Networks (NNs).

Given the complex geographical and climatic conditions of the Korean Peninsula, it is crucial to ensure the reliability of short-and medium-range communications networks, particularly those utilizing High-Frequency (HF) communications.

The Near Vertical Incidence Skywave (NVIS) propagation mode offers a reliable solution for distances up to 400km, effectively eliminating the 'skip zones' that are a common challenge with traditional HF communications. This is of particular importance with regard to the utilisation of Link-22's relay capabilities.

This paper presents a design methodology for the construction of Link-22 NNs in the Korean Peninsula, with a particular focus on HF-based NNs. We propose that a total of four NNs, utilizing HF communication and operating with a low transmission power of less than 1 KW, can provide the required coverage while simultaneously minimising network complexity.

By employing NVIS for short-to medium-range communication, this configuration ensures continuous communication without significant gaps, making it highly effective for the tactical needs of the ROKN.

The remainder of this paper is organized as follows: Section II provides an overview of Link-22 system components and communication characteristics. Section III outlines the specific configuration criteria for Link-22 operations on the Korean Peninsula. Section IV presents simulation results based on various network configurations and power settings. Finally, Section V concludes this paper and suggests directions for future research.

Ⅱ. Link-22 System Components and Communication Characteristics

This section analyzes the major system components and communication characteristics of Link-22 and summarizes its network structure and relay functionality.[1,4,5]

2.1 Link-22 System Components

Link-22 comprises the following primary components, as illustrated in Fig.2, which collectively facilitate the effective management of data communications across a range of network environments.

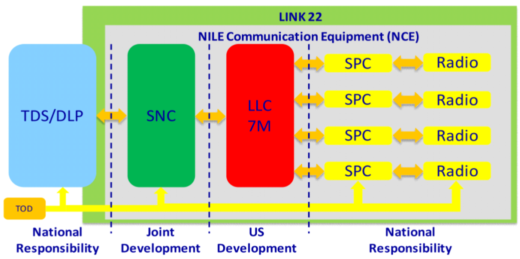

Fig. 2. Link-22 System Architecture

2.1.1 DLP (Data Link Processor)

The DLP is the central processing unit of the Link-22 system, managing the transmission and reception of communications data. Installed in each unit, the DLP performs functions such as message format conversion, data transmission, error checking, and processing of received data. The DLP generates data packets tailored to each unit's communication needs and enables effective exchange with other units on the network.

2.1.2 SNC (System Network Controller)

The SNC is a software component installed on the DLP that plays a vital role in Link-22 network management. It determines the necessity for relaying based on information about connections between Link-22 units and optimizes bandwidth usage by retransmitting tactical messages only when required.

Through these functions, the SNC enhances the overall efficiency and reliability of the Link-22 network, ensuring effective delivery of critical information while minimizing unnecessary network traffic. This management of message routing and transmission is crucial for maintaining robust communication in various operational scenarios.

2.1.3 LLC (Link Level COMSEC)

The LLC is responsible for communications security and performs encryption and decryption of tactical data. Link-22 ensures the confidentiality and integrity of data transmissions through COMSEC (Communication Security), preventing enemy eavesdropping and interference. The LLC adds a layer of security to each data packet, ensuring that transmitted data is properly protected and can only be decrypted by valid recipients.

2.1.4 SPC (Signal Processing Controller)

The SPC is responsible for communications signal processing functions, adjusting signals before transmission, and analyzing and restoring received signals.[6] The SPC performs modulation and demodulation of signals according to the propagation environment, which is critical for optimizing data transmission quality in HF and UHF (Ultra High Frequency) communications.

2.2 Link-22 Communication Methods

Link-22 supports both BLOS and LOS (Line-of-Sight) communication methods, each selected according to the operating environment.

2.2.1 BLOS Communication

BLOS communication utilizes the HF band, facilitating long-distance communication through the exploitation of ionospheric reflection of signals. This method circumvents the constraints of LOS communication, enabling connectivity beyond the horizon.

The capacity to overcome geographic impediments and curved terrain renders BLOS communication particularly advantageous in maritime and long-range operations. However, it is essential to acknowledge that RF communication quality may fluctuate based on multiple factors, including ionospheric conditions, time of day (TOD), and weather patterns. Furthermore, this form of communication is vulnerable to frequency interference.

2.2.2 LOS Communication

LOS communication uses the UHF band, with communication occurring in a straight line between two communication devices. It is generally effective within about 30-50km.

LOS communication is suitable for tactical situations requiring fast and accurate communication due to its high signal stability and data transmission speed. LOS communication can be blocked by geographical obstacles and has a relatively short communication distance.

2.3 Network Design and Relay Functionality

Link-22 integrates multiple networks into a SN to meet the communications requirements of complex tactical environments. The network structure and relay functionality are designed as follows.

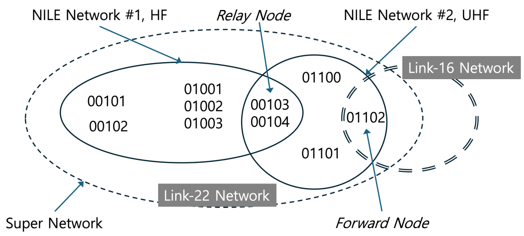

Fig. 3. Example of network design, relay and forward

2.3.1 Network Structure

As illustrated in Fig.3, the Link-22 network is constituted of two primary components: the Super Network (SN) and the NILE Network (NN).

The Link-22 network structure is defined by the following attributes:

- A single SN may comprise up to eight NNs. The SN assumes responsibility for network management and communication control, ensuring the efficient administration of communication resources across the entire network.
- Each NN is an independently operated subnetwork, tasked with the management of communications be-

tween units within its network.

NNs may utilise disparate frequency bands or channels, necessitating the implementation of frequency allocation and management strategies to minimise interference with other networks.

2.3.2 Relay Functionality

Link-22 is a communication facilitator that enables the connection or extension of communication pathways between BLOS and LOS via relay nodes. The function of relay nodes is to enhance connectivity or extend the communication range by facilitating the transfer of data between two networks. The role of relay functionality in BLOS communications is of particular importance, as it serves to offset the constraints of RF communications.

Although Link-22 does provide forwarding, which is analogous to relaying, this is not its primary function. The process of forwarding is defined as the transfer of data from one node to another as shown in Fig.4. This is accomplished by selecting a tactical data link message type, converting the data accordingly, and transmitting it. The distinction between forwarding and relaying lies in their respective objectives.

Forwarding focuses on transferring data between different message formats, while relaying aims to overcome physical limitations in communication. Essentially, relaying enhances physical network connectivity, whereas forwarding manages the logical flow of data.

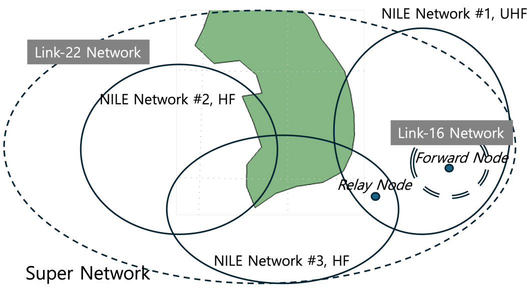

Fig. 4. Example of deploying in the Korean peninsula

Ⅲ. Designing a Link-22 Network

This section addresses design strategies to enhance the performance of Link-22 networks. We focus on network design methodologies that consider the characteristics of HF radio communications and issues related to communication range. The relationship between effective range and transmit power is examined, taking into account the specific geographical features of the Korean Peninsula region.

3.1 Communication Characteristics of Link-22

Link-22 is a versatile tactical data link that operates across both HF and UHF bands, offering a range of communication capabilities that are essential for modern naval operations. Understanding the specific characteristics of these frequency bands is crucial for the deployment and operation of Link-22.

3.1.1 HF Band Characteristics

Link-22 operates within the 2-30 MHz HF band, utilizing an Automatic Link Establishment (ALE) compliant with MIL-STD-188-141B/C for dynamic frequency selection.[7] Recent advancements outlined in MIL-STD-188-110D and MIL-STD-188-141D have significantly enhanced HF data communication capabilities.[8,9] While not replacing satellite networks, these improvements offer robust alternatives for scenarios where satellite communications are not supported.[1]

Link-22 also supports Wideband HF (WBHF), achieving bandwidths up to 24 kHz. This enables data-intensive operations while maintaining long-range capabilities, enhancing overall military communication resilience.

3.1.2 UHF Band Characteristics

The UHF band for Link-22 is situated within the 225-400 MHz frequency range. The total available bandwidth in this band is considerably more extensive, with each channel encompassing 25 kHz. The extended bandwidth of the UHF band allows data to be transmitted at higher rates than those achievable in the HF band, making it an effective choice for scenarios where rapid data transfer is required.

In the UHF band, Link-22 employs a total of seven channels, each with a bandwidth of 25 kHz. The aforementioned channels are distributed across the 225-400 MHz frequency range. Similarly to the HF band, UHF channels utilise frequency hopping, which serves to enhance the robustness of communications by mitigating the risks associated with jamming and interception.

3.2 Considerations for Link-22 Network

This subsection presents the methodology for designing the Link-22 network to be deployed on the Korean Peninsula, incorporating the effects of transmission power. Given the geographic constraints and operational requirements, the network will consist of a single SN that can support up to eight NNs. The design aims to minimize frequency interference while ensuring reliable communication across all regions.[10]

A key focus of this design is the use of HF communication to enable BLOS capabilities, especially in critical areas such as the East Sea, West Sea, South Sea, and the Busan region. To ensure continuous coverage and communication reliability, slight overlap between adjacent NNs is necessary to facilitate signal relaying.

The key design considerations include:

- A single SN is appropriate for covering the entire Korean Peninsula, given its geographic size and operational needs.
- Up to eight NNs will be deployed, with HF communication prioritized in key maritime and coastal regions.
- NNs will be strategically placed to avoid frequency interference, ensuring reliable communication without disruptions.
- HF communication will be used for long-range BLOS capability, especially in the East Sea, West Sea, South Sea, and Busan regions.
- Slight overlap between NNs will allow signal relaying, ensuring network continuity and robust communication across the entire coverage area.

3.2.1 Transmission Power for Communication

For HF communication, the range is significantly influenced by transmission power. The received power P_r at a distance d can be determined using the Friis transmission equation:

$$P_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda}{4\pi d} \right)^2, \quad (1)$$

where: P_r is the received power, P_t is the transmission power, G_t and G_r are the transmitter and receiver gains, λ is the wavelength of the signal, d is the communication distance.

The transmission power P_t directly affects the effective communication range, and must be adjusted based on the required BLOS communication distance.

The required transmission power for HF communication depends on the propagation conditions, including ionospheric reflection and noise levels. A typical transmission power for HF communication in Link-22 is in the range of 100-1000 W.

For UHF communication, which operates in a LOS range, the transmission power is usually lower, between 10-50 W, because UHF communication is less affected by atmospheric conditions.

The transmission range R can be approximated based on the output power P_t and propagation conditions:

$$R = \sqrt{\frac{P_t \cdot G_t \cdot G_r}{P_r}} \cdot \frac{\lambda}{4\pi}, \quad (2)$$

where R is the effective communication range.

3.2.2 Effective Range of HF Communication

For BLOS communication, the effective range of HF depends on ionospheric reflection height (h) and take-off angle (θ) of the transmitted signal:

$$R = \frac{2h}{\sin(\theta)} \quad (3)$$

In typical naval operations, an ionospheric height of 300 km and a takeoff angle of 30 degrees give an effective range of approximately 500 km.

3.2.3 HF Propagation Modes

In order to reflect realistic HF propagation characteristics in the simulation, this paper divides the propagation modes of HF communication into the following categories: Ground Wave, NVIS (Near Vertical Incidence Skywave), Single-hop (Skywave), and Multihop (Skywave).

Ground waves follow the surface of the Earth and enable short-range communication. However, the attenuation of ground waves with distance is significant, rendering communication impossible beyond a certain distance.[11,12]

The skywave is reflected back to Earth from the ionosphere, which is located in the atmosphere. At this time, no signal is received on the Earth's surface in areas where the skywave does not reach. This is due to the fact that the reflected wave does not reach the ground in these areas, which is referred to as the skip zone.[13,14]

In contrast, NVIS communications exhibit minimal or negligible skip zones. NVIS employs the lower HF bands (typically 3 to 10 MHz) to transmit radio waves almost vertically into the ionosphere, where they are then reflected back to the surface at a relatively short distance.[15]

Fig. 5 compares ground wave, NVIS, and skywave propagation at 100W and 1000W, showing how communication range and skip zones change with power. This reveals the relative strengths of each mode at different distances and how power affects overall performance.

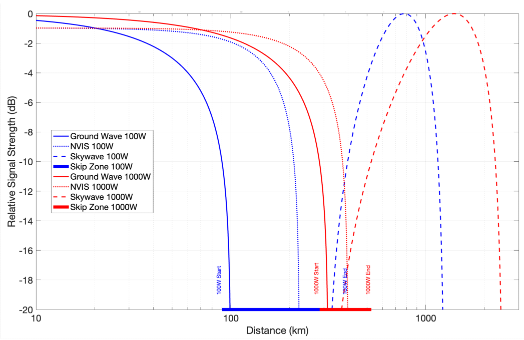

Fig. 5. HF Propagation Modes: Coverage and Skip Zone Comparison (100W vs 1000W)

3.2.4 HF Frequency Management

The HF band is divided into multiple narrowband channels of 3 kHz each. Each NN will use different channels to avoid frequency interference. The spacing between frequencies can be determined as:

$$\Delta f = \frac{B}{N}, \tag{4}$$

where B = 28 MHz is the total available HF bandwidth, and N = 15 is the number of channels per network. This ensures adequate separation between channels to prevent interference.

3.3 Link-22 NILE Networks Design Methodology

This design methodology for Link-22 networks on the Korean Peninsula incorporates transmission power considerations, ensuring that each NN achieves reliable BLOS communication with minimal frequency interference. The methodology can be presented as an algorithm, as referenced in the Algorithm 1.

The SN will cover the entire Korean Peninsula. The four key regions will be covered by HF-enabled NILE Networks with appropriate transmission power for long-range communication.

Algorithm 1 Link-22 NNs Design Methodology

```
Require: P_max, HF Band (2-30 MHz), B_c = 3 kHz, η, N
Ensure: Network coverage, overlap regions, frequency assignment, optimal N
Initialize geographic regions: East Sea, West Sea, South Sea, Busan
P_t ← {100, 200, 300, 500 W}                        ▷ Transmission power
R ← sqrt(P_t G_t G_r / P_r) · λ/(4π)                 ▷ HF range calculation
for i ∈ {East Sea, West Sea, South Sea, Busan} do
    Place network i at region center
    R_i ← f(P_t)                            ▷ Coverage radius based on P_t
    d_overlap ← η R_i
    Assign HF channels to i (no overlap)
end for
for adjacent networks (i, j) do
    if d(i, j) < R_i + R_j − d_overlap then
        Adjust P_t or reposition to maintain overlap
    end if
    Ensure channel separation between i and j
end for
Δf ← B/N                                             ▷ Channel bandwidth
for each network i do
    Assign unique channel set to i
end for
N ← min{N | full coverage and minimal interference}
P_t ← max{P_t | P_t ≤ P_max}                         ▷ Maximize range
Optimize overlap for continuous coverage
return Optimal configuration (N, coverage, overlap, channels)
```

By adjusting transmission power, network overlap, and channel allocation, we ensure that the Link-22 network can operate effectively across key maritime and coastal regions, providing robust communication for naval operations.

To ensure reliable communication between adjacent NNs, the overlap distance d_{overlap} is calculated based on a fraction η of the HF communication range R. The overlap ensures signal relay between the networks. Using $\eta = 0.1$, we calculate:

$$d_{\text{overlap}} = \eta \cdot R \tag{5}$$

Thus, for a communication range R = 500 km, the overlap distance d_{overlap} is 50 km, ensuring that adjacent networks can relay signals. Each NN must overlap with adjacent networks for signal relaying. The overlap distance d_{overlap} ensures that the networks can relay signals while maintaining distinct frequency allocations.

Ⅳ. Simulation of HF NILE Networks Coverage on Korean Peninsula

In this section, we simulate the coverage and BLOS transmission capabilities of the HF NNs deployed around the Korean Peninsula. The simulation examines the effect of varying transmission power levels and network configuration to ensure reliable long-range communication using the relaying capabilities of the NNs.

4.1 Simulation Conditions

4.1.1 Geographical Environments

The simulation covers an expanded area around the Korean Peninsula to analyze long-distance BLOS communication. The geographic bounds are defined as spanning from 20°N to 50°N in latitude and from 110°E to 145°E in longitude. This extended area enables simulation of HF transmission range over both land and sea, ensuring full coverage of critical maritime regions.

The four NNs are positioned at key geographic locations to provide complete maritime coverage while minimizing overlap, as shown in Table 1.

Table 1. Simulation Environment and Conditions

Parameter	Value
Geographic Area	20°N to 50°N, 110°E to 145°E
NILE Network Locations	East Sea (37.5°N, 129.0°E) West Sea (35.5°N, 125.5°E) South Sea (33.5°N, 126.5°E) Busan (35.1°N, 129.1°E)
Frequency	28 MHz (Fixed)
Transmission Power	100W, 200W, 300W, 500W
Time of Day	Noon (12:00)

4.1.2 Simulation Conditions

The simulation is conducted under fixed conditions, with specific transmission parameters as described in Table 1. These conditions provide a controlled environment to evaluate the impact of transmission power and geographic placement on network performance. The frequency is fixed at 28 MHz, representing a high-frequency channel suitable for long-range BLOS communication. Transmission powers of 100W, 200W, 300W, and 500W are used to evaluate the coverage area and effectiveness of each NILE Network under varying conditions.

The simulation time was fixed at noon; however, it should be acknowledged that the ionospheric conditions in HF communications can change over time. Although these changes can impact the propagation path and communication quality, the primary objective of this research is to present a network design and optimization methodology for HF communications in Link-22. The time at which the simulation is conducted does not affect the core purpose and results of the study.

4.1.3 Transmission Parameters

The selection of 28 MHz as the simulation frequency provides a balanced trade-off between bandwidth and propagation range for HF communication. By simulating the network at noon, when ionospheric conditions are relatively stable, we can effectively model the propagation characteristics of HF signals under optimal conditions. Transmission power is varied to assess how range and coverage are affected by increased power levels.

4.2 NILE Network Coverage

This simulation will help establish the practical transmission limits and optimal configuration for NILE Networks, ensuring continuous and reliable communication for naval operations in both coastal and opensea environments. In this simulation, we referred to the propagation models as followed.

4.2.1 Ground Wave Model

The ground wave propagation model is based on the work of [11], with modifications for HF frequencies:

$$R_g = 10\sqrt{P} \cdot \frac{50}{f} \cdot 0.9, \tag{6}$$

where R_g is the ground wave range, P is the transmission power in Watts, and f is the frequency in MHz.

4.2.2 Skywave Model

The Skywave model, based on the work of [13], calculates the transmission range for various modes of HF communication, specifically NVIS (Near Vertical Incidence Skywave), Single-Hop Skywave, and Multi-Hop Skywave. Each mode depends on transmission power, frequency, ionospheric conditions, and the time of day.

The transmission range for NVIS is primarily used for short-to medium-range communication, covering distances between 0 and 400 km. The formula for NVIS range is based on transmission power and time of day.[15]

$$R_{NVIS} = \left(300 + 100 \cdot \log_{10}\left(\frac{P}{100}\right)\right) \cdot \left(1 + 0.2 \cdot \sin\left(\frac{(t-12)\cdot\pi}{12}\right)\right), \tag{7}$$

where t is the time of day (in hours), $300 + 100 \cdot \log_{10}\left(\frac{P}{100}\right)$ represents the base range in kilometers, and - $\left(1 + 0.2 \cdot \sin\left(\frac{(t-12)\cdot\pi}{12}\right)\right)$ djusts the range based on the time factor.

Single-Hop Skywave mode enables medium-range communication by bouncing HF signals off the ionosphere. The maximum usable frequency (MUF) and ionospheric height are crucial in determining the effective range. Multi-Hop Skywave mode extends the communication range by allowing the signal to bounce multiple times between the ionosphere and the Earth's surface. The multi-hop range is derived from the singlehop distance and a multiplication factor.

$$R_s = d_{\text{hop}} \cdot (1 + 0.3\log_{10}(\frac{P}{100})) \tag{8}$$

$$R_m = 2.5 \cdot R_s, \tag{9}$$

where d_{hop} is calculated based on the ionosphere height and Maximum Usable Frequency (MUF).

The modeling of ionospheric conditions, particularly the critical frequency (f_{oF2}) and ionosphere height (h), draws from the research of [16] on the International Reference Ionosphere (IRI) model:

$$f_{\text{oF2}} = 12 + 4\sin(\frac{\pi(t-12)}{12}) \text{ MHz} \tag{10}$$

$$h = 300 + 50\sin(\frac{\pi(t-12)}{12}) \text{ km} \tag{11}$$

4.3 Analysis of NILE Network Coverage on the Korean Peninsula

The transmission ranges of the HF NILE network were simulated in Matlab for four different propagation modes while varying the transmission power. For convenience, the frequency was fixed at 28 MHz, and a model based on noon time was used for the analysis.

The simulation results are shown in Fig. 6. Only the Ground wave and NVIS modes are visible because ionospheric reflection waves have much larger transmission ranges, which are not displayed on the current map. This can be easily understood by comparing the transmission ranges shown in the following Table 2.

The figures illustrate HF transmission coverage for the NILE network at varying power levels (100W, 200W, 300W, and 500W) over the Korean Peninsula.

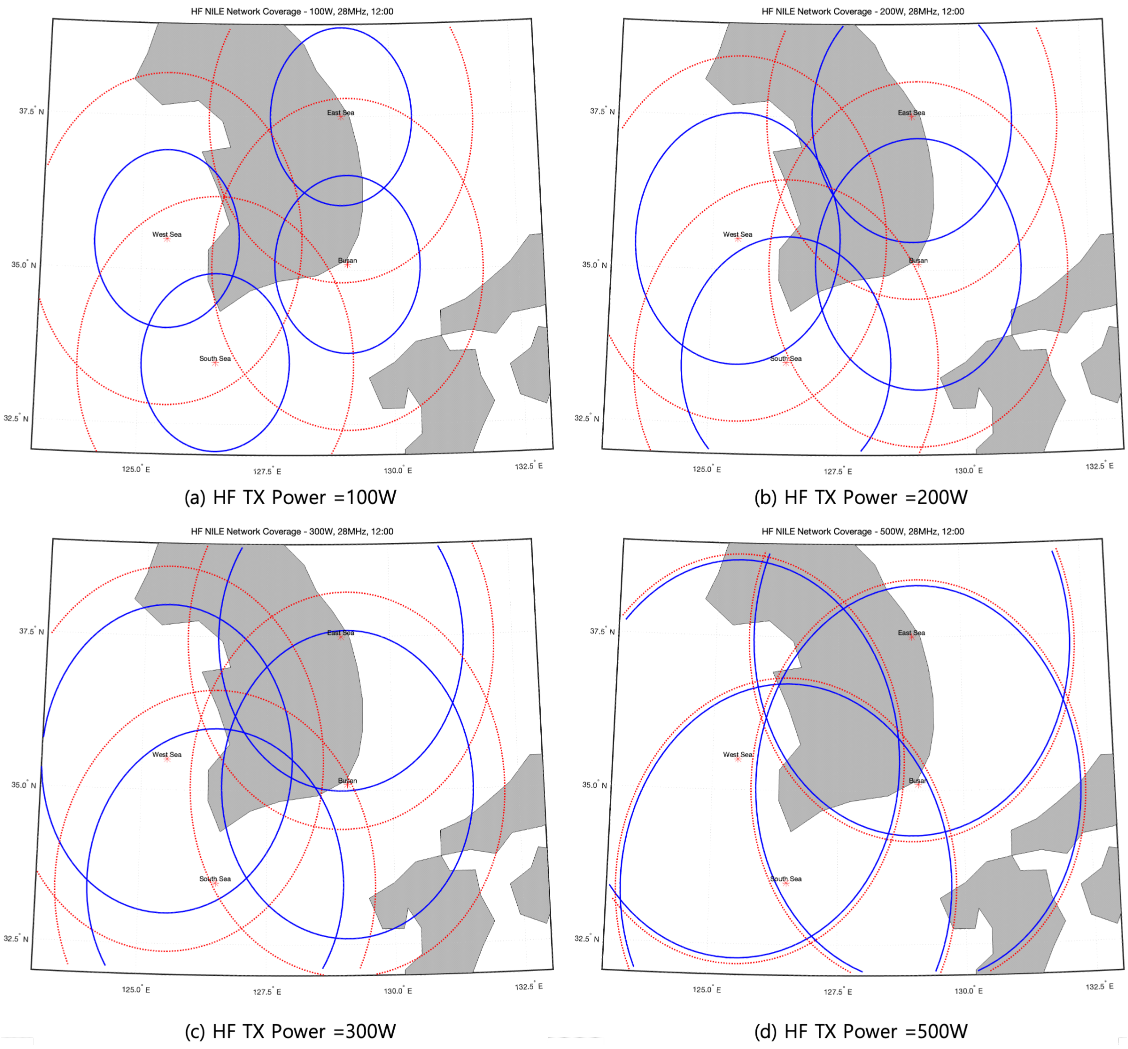

Fig. 6. HF Power Impact on NILE Network Coverage (Blue Line: Ground Wave, Red Line: NVIS)

Table 2. Maximum Transmission Ranges for Different Propagation Modes in HF NILE Network

Transmission Power (W)	Ground Wave (km)	NVIS (km)	Single Hop (km)	Multi (km)
100	158.7	321.5	1245.8	2987.4
200	224.5	352.3	1389.2	3342.1
300	275.1	371.8	1486.5	3567.6
500	355.2	398.6	1628.9	3909.4

The blue circles represent ”Ground wave” coverage, while the red dashed circles show ”NVIS” coverage. The simulation is set at 28 MHz frequency and 12:00 (noon) to reflect stable ionospheric conditions.

At 100W, both the ground wave and NVIS coverage are limited. Ground wave coverage remains small and localized, while NVIS extends up to 400 km, but without significant overlap between NILE nodes.

This power level is sufficient for short-range communication but leaves gaps for medium-range transmission.

At 200W, both ground wave and NVIS coverage improve. The NVIS areas overlap more between regions, particularly in the East Sea, West Sea, and Busan, allowing for better signal relay and fewer gaps in coverage. This configuration is more suitable for mediumrange operations along the coast.

At 300W, coverage expands further, with significant NVIS overlap across the regions, ensuring continuous medium-range communication. This setup effectively closes the skip zones, making it well-suited for tactical operations requiring robust mid-range coverage.

At 500W, both ground wave and NVIS cover a vast area. The NVIS regions overlap extensively, providing full coverage over the peninsula with minimal gaps. This power level maximizes relay potential between nodes, ensuring seamless communication over both short and long distances.

As transmission power increases, both "ground wave" and "NVIS" coverage expand, with significantly enhancing communication range and reducing gaps. The 500W configuration offers the most comprehensive coverage, making it ideal for continuous communication over the entire peninsula.

Ⅴ. Conclusions and future works

In this study, we proposed an optimal design methodology for the NILE network to effectively operate Link-22 on the Korean Peninsula. Given the unique geographic and operational requirements of the region, we identified that using four NNs based on HF communication would provide robust coverage across the East Sea, West Sea, South Sea, and Busan areas.

Future work will involve investigating the communication delay effects when using relay functions in a BLOS environment. This analysis will help to further refine the operational efficiency of Link-22 and ensure minimal latency in long-range communication scenarios, particularly in dynamic and high-demand tactical environments.

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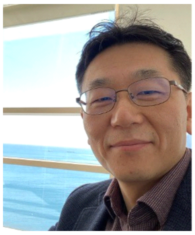

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