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Data Transmission Method Using SATIN-based NOMA to Enhance Future Combat Capabilities

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Abstract

Herein, an innovative transmission technique that utilizes the satellite aerial terrestrial integrated network (SATIN) architecture in combination with non-orthogonal multiple access (NOMA) communications is proposed. This approach is designed to significantly enhance communication rates, which is critical for modern and future combat capabilities. The effectiveness of the proposed transmission system is validated by conducting a comparative analysis of the sum-throughput results, considering various numbers of transmission nodes within the SATIN structure. The results and analyses reveal that the proposed method outperforms traditional methods such as spatial division multiple access (SDMA) and time division multiple access (TDMA), especially in terms of reducing data loss. This superior performance is primarily due to the advanced capability of NOMA in minimizing interference between signals, resulting in improved sum-throughput outcomes. The implementation of this method is expected to significantly enhance command communications in manned-unmanned combat systems, thereby bolstering overall combat effectiveness through improved transmission rates.

Index Terms: Future Combat System, SATIN, NOMA, Sum-throughput

I. INTRODUCTION

Modern weapon systems has been rapidly evolving due to various factors, including advancements in science and technology such as artificial intelligence (AI), big data, robotics, and the Internet of Things (IoT), as well as shifts in policy as we undergo the Fourth Industrial Revolution. The South Korean military is preparing for these paradigm shifts by transitioning to manned unmanned-teaming (MUM-T) combat systems to prepare for future warfare. The battlefield environment of the South Korean military is pivoting towards MUM-T systems because of rising societal issues like low birth rates and an aging population leading to reduced enlistment resources, as well as an amplified emphasis on the value of human life in modern combat scenarios.

A. Future Combat System

The MUM-T combat system integrates traditional manned combat units with unmanned apparatus using a sophisticated command and control network. This synergy is tailored to enhance combat effectiveness while simultaneously minimizing human casualties. Within this context, unmanned combat systems deploy a variety of equipment, such as unmanned ground vehicles (UGV), unmanned surface vehicles (USV), unmanned underwater vehicles (UUV), and unmanned aerial vehicles (UAV), augmenting the capabilities of the manned units.

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The strategic roadmap of the South Korean military for the phased deployment of the MUM-T system is outlined as follows [1]:

- Phase 1 (Remote-Control): This stage is characterized by the performance of combat support tasks under the direct remote guidance of human operators.
- Phase 2 (Semi-Autonomous): Here, operations are executed based on a semi-autonomous framework, yet they remain contingent upon directives from human operators.
- Phase 3 (Autonomous): As the pinnacle of this development trajectory, the objective is to facilitate collaboration between wholly autonomous unmanned entities. An actionable plan has been formulated to actualize this vision.

To maximize the autonomous efficiency in the MUM-T combat system, innovations in command-and-control capabilities, which are closely tied to advancements in communications technologies, are essential. Notably, in the tactical on-the-move (OTM) environment, moving nodes form a network without the fixed communication infrastructures typically found in conventional wireless networks. Consequently, combat communication networks face various challenges due to frequent changes in network topology, such as poor transmission environments, channel interference, and communication breakdowns. Given these constraints, communication technologies utilizing satellite communication are preferred.

B. Characteristics of The Military Communication System

The South Korean military is aiming to secure core military capabilities for the transition to wartime operational control. However, compared to neighboring countries, South Korean operational control systems remain inadequate. It is anticipated that the command and communication capabilities of the South Korean military will largely rely on weapon systems using the global positioning system (GPS) and other satellite communication systems. There is a pressing need to ensure a reliable and survivable information distribution capability between surveillance, decision-making, and strike systems by building a high-speed, high-capacity network based on satellite communications for the South Korean military [1].

Analyzing the status of South Korean communication networks, both fixed and mobile, several challenges emerge. For fixed communication networks, the transmission of high-capacity video information is limited, and there is no infrastructure in the rear areas, leading to the use of leased lines. The existing military broadband convergence network (M-BcN) uses aging and near-obsolete equipment and must be urgently updated. Furthermore, M-BcN, constrained by transmission capacity limits, cannot meet significantly increasing data demands. Leased lines are communication channels rented from and controlled by civilian communication service providers. Compared to M-BcN, they have a relatively low transmission capacity, restricting data communication. Microwaves (M/W), which transmit large data capacities of 45 Mbps and 155 Mbps over long distances, face issues of capacity saturation. These limitations raise concerns about their effectiveness as a backup communication system, especially in supporting major “command, control, communications, computers, and intelligence” (C4I) operations.

The mobile communication network serves as the core communication network operated by units below the corps level, and it is capable of forming dynamic communication networks by moving and switching. However, the installation and operation of communication equipment can be somewhat limited depending on the terrain and weather conditions, posing vulnerabilities in terms of survivability. The mobile communication network includes the tactical communication system (SPIDER), tactical information communication network (TICN), and the military satellite communication system. The SPIDER system, which was operational from the late 1990s to the mid-2000s. The tactical multichannel radio (TMR), a component of the SPIDER system, has a maximum line-of-sight communication distance of 48 km, constraining long-distance operations in vast operational zones. The TICN system is a mobile communication network that circulates data, voice, and video information. TICN also links surveillance and detection assets to the battlefield management information system. It comprises subsystems like the high capacity trunk radio system (HCTRS), low capacity trunk radio system (LCTRS), tactical Internet protocol system (TIPS), combat network radio system (CNRS), tactical mobile communication system (TMCS), and network control system (NCS). The limitations of the TICN system include a shortage of TICN node communication stations due to wide operational areas and challenges with data communication services for tactical multi-function terminals using the mobile subscriber access point system (MASP). Software and hardware performance improvements are needed for broader coverage. The operational environment of the Korean Peninsula, with 70% mountainous terrain, causes communication dead zones, and there are survival vulnerabilities when installing communication stations in high-altitude areas.

The Army, Navy, and Air Force Satellite Information System (ANASIS) complements the ground communication system in terms of mobility and survivability by utilizing the Korean Mugunghwa satellites, Iridium satellites, and other international communication satellites. However, its weak points include limited high-speed, high-capacity information transmission, and extended satellite communication due to low bandwidth. Furthermore, commercial satellite phones currently in use store information on servers located overseas, leading to security vulnerabilities.

C. Satellite Communication System in Future Warfare

Satellite network utilization by the South Korean military is anticipated to increase significantly in the coming years. As operational areas expand and timely command and communication support becomes crucial, the satellite communication capabilities must be enhanced. Presently, the Korean military is developing a next-generation military satellite communication system. This forthcoming system will ensure reliable and robust information distribution capabilities among surveillance, decision-making, and strike systems. To achieve this, the long-term plan involves progressing from expensive geostationary satellites to a global communication network comprised of cost-effective low-Earth orbit (LEO) satellites [1].

LEO satellites travel at altitudes between 160 to 2,000 km, enabling mobile communication from anywhere in the world. Comprising both satellite and ground systems, the LEO network predominantly uses the Ku and Ka bands. A fundamental feature of LEO satellites is their low latency of 0.025 s, which is significantly shorter than the 0.5 s offered by geostationary satellite communication. The lower orbits of LEO satellites result in shorter radio wave round-trip times and reduced signal loss. Therefore, the LEO communication system is of immense military value in modern and future warfare, applicable in coastal and general outpost border operations as well as diverse battlefield environments.

Taking recent examples from the Russia-Ukraine conflict, the absence of indigenous Ukrainian satellites degraded Ukraine's real-time battlefield situation awareness, and their inability to form a satellite-based communication network posed various constraints. Moreover, the future of warfare, based on the expansion of combat zones, will likely operate under a network-centric operational environment (NCOE). NCOE integrates air, land, and sea operations into a singular, network-centric platform, facilitating the swift provision of large-scale battlefield information, which can ultimately secure battlefield dominance.

D. SATIN Architecture

The satellite aerial terrestrial integrated network (SATIN) architecture integrates terrestrial networks with aerial and satellite networks, enhancing channel access environments and network coverage [2]. The features of SATIN include: (a) Interference mitigation considering the characteristics of terrestrial, aerial, and satellite RANs and efficient wireless resource management through joint SATIN resource scheduling. (b) Orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA) to multiplex signals from different users. (c) Spectrum sensing of cognitive radio communication to minimize interference between satellite, aerial, and terrestrial networks. (d) Sophisticated and efficient horizontal and vertical handovers for quick transitions of terminals in terrestrial and aerial areas.

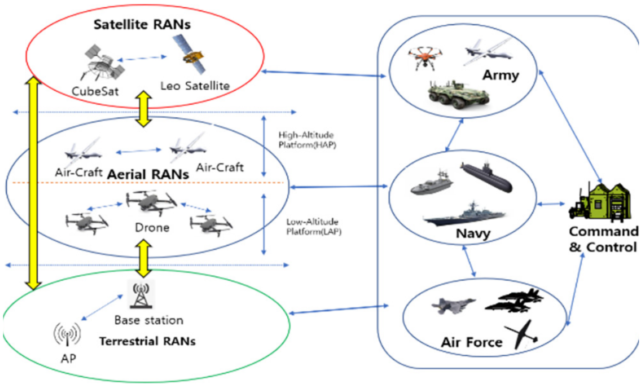

Fig. 1. The satellite aerial terrestrial integrated network (SATIN) architecture.

Given these attributes, SATIN is essential for advancing military communication systems. As depicted in Fig. 1, SATIN consists of the terrestrial radio access network (RAN), aerial RAN, and satellite RAN, forming an inter-layered structure.

The terrestrial RAN can encompass established mobile communication infrastructures like 3G, 4G, 5G, and WiFi, as well as other communication network infrastructures. The aerial RAN is divided into low altitude platforms (LAP) and high altitude platforms (HAP). LAP uses UAVs situated 0-10 km above ground to offer wireless services to users, while HAP employs larger UAVs located 20-50 km above ground for the same purpose. The satellite RAN can include CubeSats, LEO, medium-Earth orbit (MEO), and GEO satellites. Although satellite RAN provides extended area services to users, it serves them through ground stations, distinct from terrestrial and aerial RANs. LAP has the capability to configure dynamic networks using UAVs, while HAP can use aircraft to serve as base stations for broadband services. The terrestrial RAN serves as a gateway between the aerial RAN and satellite RAN, providing inter-layer communication services. This 6G-based SATIN architecture is crucial for future manned and unmanned integrated combat systems, offering high capacity and rapid information dissemination.

Therefore, to address the limitations in transmission capacity and speed of existing communication systems, the surveillance data collection rate for manned and unmanned integrated combat systems was enhanced by applying a transmission method based on the SATIN architecture and non-orthogonal multiple access (NOMA).

II. RELATED WORKS

Various standardization bodies are actively examining the use-cases, requirements, and technical issues of SATIN. As the coverage of such an integrated network structure expands, the number of users simultaneously accessing the network is bound to surge, highlighting the growing interest in NOMA technologies. Wu et al. [3] proposed a navigation-based positioning system applicable to military systems using satellites. They analyzed the functional characteristics of the Beidou satellite navigation and positioning system and the military geo-graphic information system (MGIS) and suggested a design method for naval equipment support command automation systems. This approach combines computer technology, MGIS, and Beidou satellite positioning and communication technologies to automate and digitize equipment support commands. Ruan et al. [2] applied the SATIN architecture to weapons systems. To accommodate the high demands of IoT within a congested spectrum, they analyzed the potential of integrating cooperation into cognitive SATIN for IoT communications. The proposed cognitive SATIN architecture demonstrated high throughput, cost-efficiency, and flexibility through simulation results, especially in the aspects of 3D spatial-temporal deployment of UAVs, interference management, and physical layer security. Khan et al. [4] applied NOMA to device-to-device (D2D) communication, aiming to maximize sum-throughput by mitigating cross-channel and co-channel interference between D2D users. Shen et al. [5] designed a beamforming method using a closed-form expression to maximize the sum-rate for a multiple-input multiple-output and non-orthogonal multiple access (MIMO-NOMA) system. Chen et al. [6] optimized user selection and power allocation in a NOMA system equipped with multiple antennas, aiming to enhance the sum capacity.

III. METHODS

A. Multiple Access (MA)

Multiple access enables several nodes to share the spectrum simultaneously. Through spectrum sharing, the system capacity is enhanced [8]. However, when two or more nodes transmit data concurrently, node collisions can occur, leading to data loss. Consequently, throughput diminishes. Such access permits multiple nodes to use channels — which are shared resources — at the same time. These methods can be categorized into those that allocate resources to each node in a fixed manner and those that do so in a variable manner. Fixed allocation schemes include frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and non-orthogonal multiple access (NOMA).

As illustrated in Fig. 2, FDMA segments the frequency spectrum into smaller bands. Each segmented band acts as a channel, with each node being allocated a distinct channel. Since data is transmitted and received through separate channels, collision-induced data loss is minimized. However, even if a node is inactive, a designated channel can only be used by that particular node at a given time. Thus, no other node can utilize the channel when it is idle. This leads to reduced channel utilization when data transmission and reception are irregular.

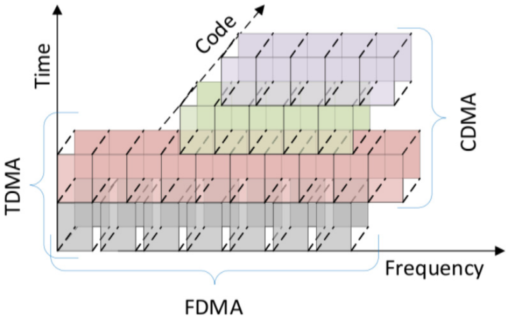

Fig. 2. Frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA) comparison.

TDMA partitions channels temporally into sub-channels, allocating different time slots to various nodes. As data is transmitted at separate intervals, collisions are avoided, potentially enhancing throughput. Nevertheless, simultaneous data transmissions can result in conflicts, necessitating synchronization management to evade interference.

CDMA facilitates data transmission and reception through unique codes assigned to individual nodes while they share frequencies and channels. The signal of a specific node, when coded, appears as noise to another node, enhancing the signal security of every node. However, the CDMA setup can be very intricate.

NOMA is a promising scheme that can meet the needs of future wireless communication networks, such as increasing the number of users and improving utilization rates [7]. NOMA segments the channel into sub-channels based on power, and nodes transmit and receive data at varying power levels. With several nodes transmitting concurrently using the same channel, time, and code, both channel utilization and throughput are improved. Yet, processing is essential to distinguish the received signals [8].

Carrier sense multiple access (CSMA), CSMA with collision detection (CSMA-CD), and CSMA with collision avoidance (CSMA-CA) are schemes that allocate resources in a variable manner. Before transmitting data, CSMA first ascertains whether the channel is vacant. Often referred to as “listen-before-talk” or “sense-before-transmit” multiple access, this system checks the state of the channel before using it.

The primary parameters of CSMA include detection delay and propagation delay. The former pertains to the time needed to identify a channel's idle status, while the latter refers to the data transmission duration from the sender to the receiver [8]. Since CSMA can use an unoccupied channel, channel utilization is enhanced. However, channel status checking adds to the transmission delay.

CSMA-CD halts transmission when a collision arises from multiple nodes transmitting data simultaneously. Consequently, collisions can increase data loss. This approach is prevalent in wired systems like IEEE 802.3 (Ethernet). In contrast, CSMA-CA, utilized in wireless systems like IEEE 802.11b (WLAN) [8], uses an acknowledgment (ACK) post-signal reception to diminish node collisions, potentially rendering it unsuitable for real-time networks.

B. Non-Orthogonal Multiple Access (NOMA)

Unlike traditional multiple access methods that depend on time, frequency, and code domains, NOMA operates in novel domains, such as power, as depicted in Figs. 3 and 4. The primary NOMA schemes are categorized into power-domain NOMA and code-domain NOMA. Multiple nodes utilize the same time and frequency, and signals from each node overlap after channel coding and modulation. A receiving node detects signals from each transmitting node using successive interference cancellation (SIC). While NOMA enhances spectral efficiency, it also increases the complexity of the receiver [9].

When there are two nodes, the channel capacity, which represents the throughput for each node, is given by Eqs. (1) and (2). r_i represents the channel capacity of node i. p_i is the power strength transmitted by node i, while h_i denotes the channel gain. The noise power of node i is represented by n_i.

$$r_1 = \log_2\left(1+\frac{p_1|h_1|^2}{n_1}\right) \tag{1}$$

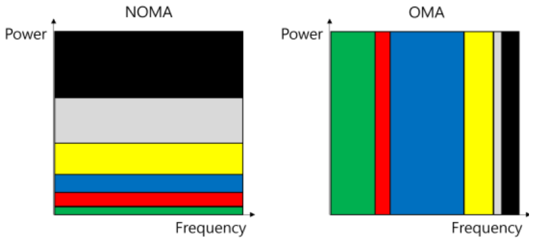

Fig. 3. Comparison between non-orthogonal multiple access (NOMA) and orthogonal multiple access (OMA).

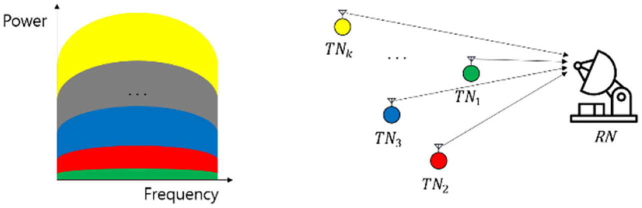

Fig. 4. Signal multiplexing based on NOMA. TN is a transmitting node while RN is a receiving node.

$$r_2 = \log_2\left(1+\frac{p_2|h_2|^2}{p_1|h_2|^2+n_1}\right) \tag{2}$$

C. Data Transmission Method Based on NOMA

Data transmission based on power-domain NOMA is illustrated in Fig. 5. A receiving node is centrally located within a cell, surrounded by k transmitting nodes. These transmitting nodes are strategically positioned, either randomly or at consistent distances or angles from one another. Each node is equipped with a single antenna and operates in a half-duplex transmission mode. The receiving node possesses full knowledge of the channel status information (CSI). Moreover, each transmitting node sends data to the receiving node with distinct power levels, leading to overlapping data from multiple nodes. The node that receives this overlapped signal deciphers the data for each node using the SIC process.

As depicted in Eq. (3), the channel gain of node i + 1 will be smaller than that of node i due to signal attenuation resulting from the differences in distance. The channel gain for each node is represented as h_i, and n_i stands for the noise power.

$$\frac{|h_i|^2}{n_i} > \frac{|h_{i+1}|^2}{n_{i+1}}, \ \forall i \in \{1,2,3,\ldots,k\} \tag{3}$$

To enhance the signal-to-interference and noise ratio (SINR), node $i+1$, which has a lower channel gain, transmits data with greater strength compared to node i. The overlapping signal, y_1, captured by the receiving node is defined by Eq. (4). A signal dispatched by each node k is represented as x_i, and h_i indicates the channel gain. Additionally, n_i designates the noise power.

$$y_1 = h_i x_i + n_i, \ \forall i \in \{1,2,3,\ldots,k\} \tag{4}$$

From the overlapped signal, the receiving node isolates the signal from node i, which is transmitted with the highest strength. Here, signals other than that of node i are regarded

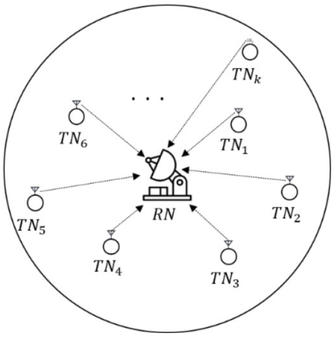

Fig. 5. System model. TN is a transmitting node, while RN is a receiving node.

as interference. The sum-throughput is articulated in Eq. (7). The signal-to-noise ratio (SNR) for each node is detailed in Eq. (5). In this context, d_i represents the distance between the transmitting node i and the receiving node. The cumulative SNR for each node is outlined in Eq. (6).

$$SNR_i = \frac{p_i h_i}{n_i d_i} \tag{5}$$

$$SNR_{sum} = \sum_{i=1}^{k} \frac{p_i h_i}{n_i d_i} \tag{6}$$

$$Sum-throughput = \log_2\left(1 + \sum_{i=1}^{k} \frac{SNR_i}{SNR_{sum} - SNR_i}\right) \tag{7}$$

IV. PERFORMANCE EVALUATION

The performance of NOMA-based data transmission was assessed. For this purpose, the proposed scheme was implemented in MATLAB (ver. R2022b) and tested as outlined in Table 1. The analysis centered on the quality of data gathered by the receiving node situated at the center of the cell. After conducting 100 experiments, results were presented as average values.

The sum-throughput varies depending on how the transmitting node was deployed. This is because if another transmitting node is positioned between the receiving node and one transmitting node, interference may occur, and the data transmitted by each node may be lost. Also, if many transmitting nodes are deployed far from the receiving node, the loss may increase due to signal attenuation. Therefore, a method of deploying the transmitting node around the receiving node should be considered in order to increase the sum-throughput. In this study, experiments were conducted for each method of randomly deploying or evenly deploying the transmitting node around the receiving node. All sending nodes deployed around the receiving node transmit data to it. The sum-throughput was evaluated using NOMA, space division multiple access (SDMA), and TDMA, based on the number of transmitting nodes.

Fig. 6 presents the sum-throughput results for each protocol as the number of transmitting nodes randomly deployed around the receiving node increases. Regardless of the number of transmitting nodes, the sum-throughput of the proposed power-domain NOMA-based data transmission technique is higher than other protocols. This confirms that there was a reduction in data loss due to decreased interference among the transmitting nodes. The reason SDMA performs lower than TDMA can be attributed to the increased data loss resulting from enhanced interference between transmitting nodes.

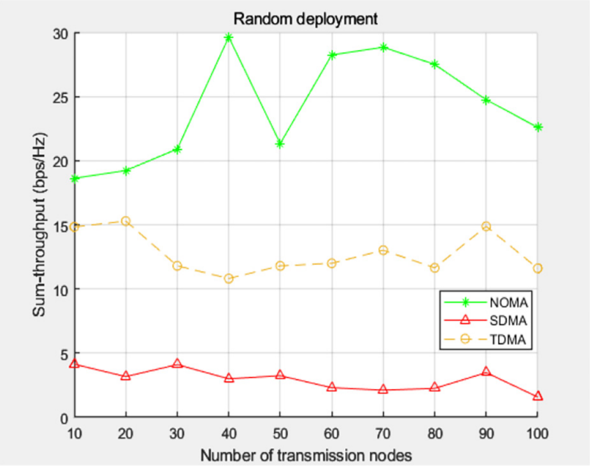

Fig. 6. Sum-throughput measurements for randomly deployed transmitting nodes.

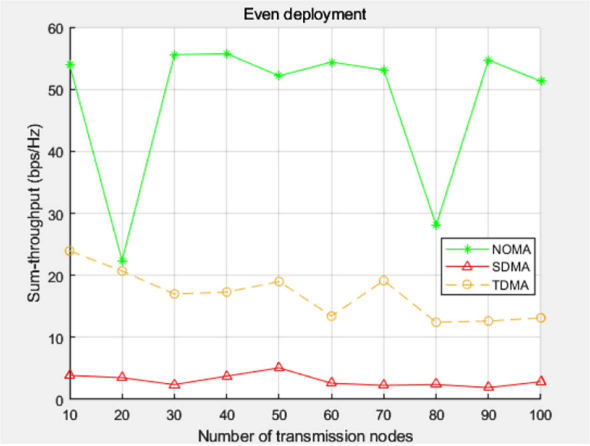

Fig. 7. Sum-throughput measurements based on the number of evenly deployed transmitting nodes.

Table 1. Simulation parameter values

Parameter	Value
Number of transmission nodes	Maximum 100
Transmit power strength	30 dBm
Channel gain	$10^{-3}\ d_i^{-2}$
Noise power	-30 dBm X Random numbers

Fig. 7 presents the sum-throughput results for each protocol as the number of transmitting nodes evenly deployed around the receiving node increases. Like the random deployment of transmitting nodes, the proposed power-domain NOMA-based data transmission technique consistently improves the sum-throughput. The proposed method reduces data loss compared to other protocols by minimizing interference among transmitting nodes. TDMA outperforms SDMA likely because it varies the timing of data transmission, thus reducing interference between the transmitting nodes.

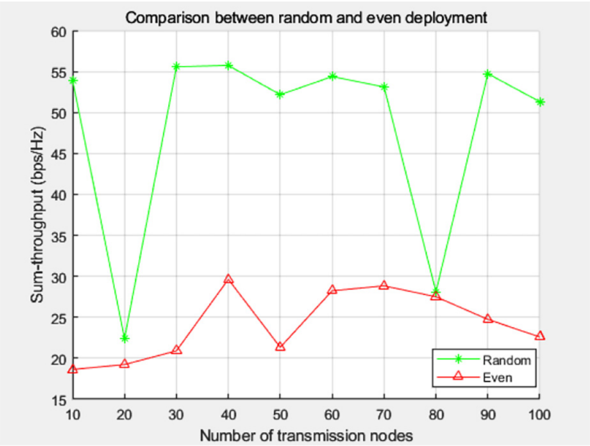

Fig. 8. Sum-throughput comparison by transmission node deployment method.

Fig. 8 presents the sum-throughput of different deployment methods as the number of transmission nodes around the receiving node is increased. Regardless of the number of transmission nodes, the sum-throughput of the random deployment method is higher than that of the regular deployment. This can be attributed to the fact that the regular deployment method can have more transmission nodes at a greater distance from the receiving node compared to random deployment. As a result, data loss due to signal attenuation is inevitable. Therefore, it can be inferred that randomly deploying transmission nodes around the receiving node enhances the sum-throughput.

V. DISCUSSION AND CONCLUSIONS

In this research, a transmission technique applying NOMA within the SATIN architecture was designed and evaluated. To validate the proposed approach, we compared the sum-throughput results according to the number of transmission nodes in the SATIN structure. The sum-throughput results by protocol confirm that the proposed transmission method exhibits significantly superior results in terms of data loss compared to SDMA and TDMA. This improvement in sum-throughput can be attributed to the ability of NOMA to reduce interference between signals. However, as the number of transmission nodes increases, the error probability can rise due to error propagation in SIC [9]. Therefore, improving SIC with an increased number of transmission nodes is essential.

The NOMA technology within the SATIN structure boasts high capacity and swift transmission speeds and enables high spectrum resource efficiency, thus enhancing the command-and-control communication capabilities in manned-unmanned integrated combat systems. This is possible because users in the same cell are allowed to utilize identical network resources simultaneously. As such, the proposed technique can boost combat capabilities through enhanced transmission rates in the command communications of the manned-unmanned combat system. Detailed findings are not disclosed in this paper due to security concerns. Nevertheless, our work highlights the potential of NOMA under the SATIN structure for enhancing command-and-control communications in a manned-unmanned combat system. Moreover, recent studies have utilized deep learning to predict future user demands and mobility trajectories, learning optimal strategies for spectrum sharing, thereby maximizing spectrum efficiency.

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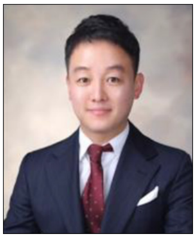

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