Dual PHY Layer Multiple Access Transceiver for Next Generation 6G Networks

Salman Ahmad
Dept. of IT Convergence Engineering
Kumoh National Institute of Technology
Gumi, South Korea
salman@kumoh.ac.kr

Muneeb Ahmad
Dept. of IT Convergence Engineering
Kumoh National Institute of Technology
Gumi, South Korea
muneeb.ahmad@kumoh.ac.kr

Soo Young Shin
Dept. of IT Convergence Engineering
Kumoh National Institute of Technology
Gumi, South Korea
wdragon@kumoh.ac.kr

***Abstract*—Orthogonal Chirp Division Multiplexing (OCDM) enhances digital communication by improving robustness against noise and adjacent channel interference, surpassing Orthogonal Frequency Division Multiplexing (OFDM) in spectral efficiency and multi-user capacity. While most 5G networks rely on OFDM with lower computational complexity and latency, this paper proposes a dual physical layer transceiver that integrates both OFDM and OCDM to meet the advanced requirements of 6G networks while ensuring backward compatibility with 5G. The system's performance is assessed based on bit error rate (BER) under channel impairments such as Rayleigh fading and IQ imbalance, and multi-user capacity is evaluated. The analysis demonstrates that OCDM offers significant advantages over OFDM, particularly under challenging channel conditions, making this architecture a promising candidate for future 6G systems.**

***Index Terms*—Data communication, OFDM, OCDM, PHY layer, ISI, Doppler Effect**

I. Introduction

Sixth-generation (6G) mobile communication systems aim to revolutionize the landscape of voice and data communications by integrating cutting-edge technologies and supporting a wide range of devices and use cases, each with specific needs [1]. The literature research aims to overcome the limitations of previous generations, significantly enhancing user capacity and network efficiency by leveraging cutting-edge multiple access methodologies [2]. These advancements promise unparalleled data rates, ultra-low latency, and support for many interconnected devices, paving the way for the future of global communication networks [3].

The fifth-generation (5G) networks extensively employ orthogonal frequency-division multiplexing (OFDM) as a multiple access approach to effectively manage resources among several users. To enable simultaneous transmission without interference, OFDM divides the available bandwidth into several orthogonal sub-carriers [4]. While there are certain disadvantages to this OFDM technique, such as inferior noise immunity from the use of rectangular pulse-shaped carriers and unused bandwidth due to cyclic prefixing, there are also some benefits, like lower latency and simpler channel equalization. [5]. Besides, the requirement for multi-user capacity is also multiplying due to applications like the Internet of Things (IoT) and the rising need for mobile connections, and the traditional OFDM sub-carriers-based approaches are unable to keep up with this demand [6]. Therefore, a great emphasis has been placed on developing unique waveforms and techniques for multiple access to building next-generation 6G wireless communication networks [7], [8]. OCDM has been getting more attention as an alternative for 5G networks lately. It uses chirp signals for pulse shaping, which makes it more resistant to multi-path fading and noise [9]. By employing chirp waveforms, OCDM can provide efficient bandwidth utilization and enhanced performance in high-mobility environments [10]. This makes OCDM a promising candidate for addressing the challenges of multi-user capacity and connectivity in the evolving landscape of mobile communication systems.

Among these features, OCDM is more reliable than OFDM and provides a higher data rate by offering resistance to channel noise and frequency-selective fading [11]. This study investigates the benefits offered by both discrete fast Fourier transform (FFT)-based OFDM and discrete Fresnel transform (DFnT)-based OCDM systems. The initial concept for a hybrid physical layer architecture did not work because it was based on older waveforms and did not consider the high Doppler tolerance, strict noise immunity, and resilience against multi-path fading [12]. Consequently, this research proposes a dual physical (PHY) layer architecture for developing next-generation 6G transceiver networks. This architecture allocates one layer to the traditional OFDM and another to the OCDM as multiple access techniques. This design is expected to enhance the system's resilience and improve frequency utilization efficiency while maintaining compatibility with current 5G networks.

II. System Model

The proposed architecture for the dual PHY layer OCDM/OFDM transceiver is illustrated in Fig. 1. On the transmitter side, data bits are adaptively loaded according to the channel's signal-to-noise ratio (SNR), leveraging the available channel state information (CSI). These bits are subsequently converted into symbols through M-ary modulation schemes. The resulting symbol sequence $x(i)$ is then organized into blocks of size N as $x(i) = [x(iN), x(iN+1), ..., x(iN+N-1)]^T$. For the OFDM system, the modulated symbols

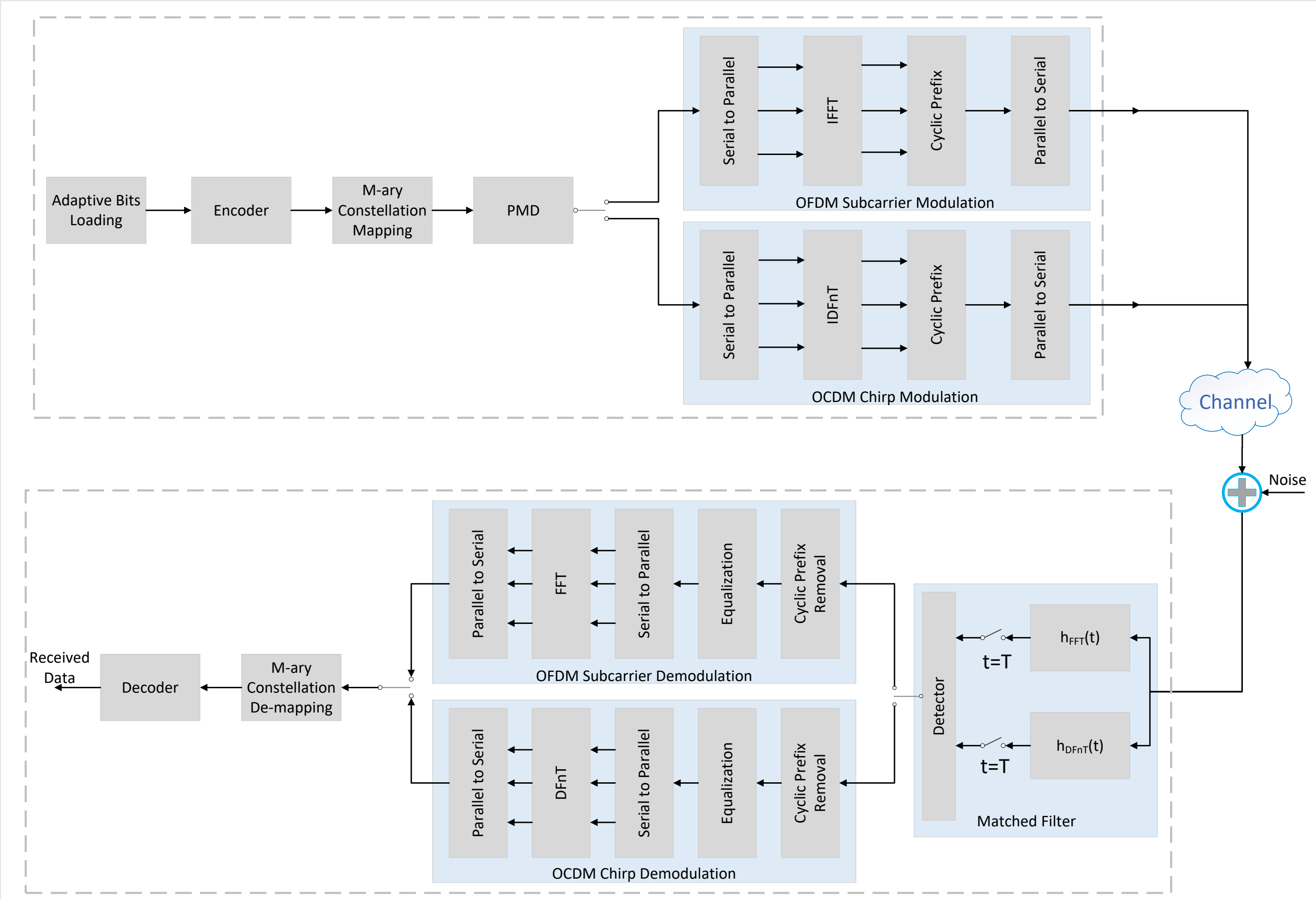


Fig. 1. Block diagram of proposed dual PHY layer transceiver

are transformed into the time domain using the Inverse-FFT expressed as

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j\frac{2\pi kn}{N}}, \quad n = 0, 1, ..., N-1 \tag{1}$$

where $X(k)$ and $x(n)$ represent the frequency domain symbols, and time domain samples, respectively. To mitigate inter-symbol interference (ISI), a cyclic prefix (CP) is appended to the OFDM signal. This prefix consists of a copy of the last L_{cp} samples of the block, which are then placed at the beginning of the signal $x(n)$ and making it $x_{\text{cp}}(n) = [x(N-L_{\text{cp}}), ..., x(N-1), x(0), ..., x(N-1)]$ with L_{cp} as the length of CP.

Given the extensive scope of exploring OCDM compared to OFDM, this paper focuses exclusively on OCDM signal calculations for clarity and precision. The expression for discrete Fresnel transform, an $N \times N$ DFnT matrix is given by [13]:

$$\Phi(m,n) = \frac{1}{\sqrt{N}} e^{-j\frac{\pi}{4}} \times \begin{cases} e^{j\frac{\pi}{N}(m-n)^2} & N \equiv 0(\text{mod}2) \\ e^{j\frac{\pi}{N}(m+\frac{1}{2}-n)^2} & N \equiv 1(\text{mod}2) \end{cases} \tag{2}$$

For the sake of simplicity, this paper restricts its analysis to the even N values only. For the input block $x(k)$, the n^{th} element of the modulated symbol $s(n)$ is represented by:

$$s(n) = e^{j\frac{\pi}{4}} \sum_{k=0}^{N-1} \text{x}(k) e^{-j\frac{\pi}{N}(n-k)^2} \tag{3}$$

where $e^{j\frac{\pi}{4}}$ is a complex exponential term representing phase rotation and $x(k)$ is the k^{th} element of the input sequence. After appending the cyclic prefix, the transmitting OCDM chirp-based symbols $s(n)$ can be represented in the form $\bar{s}(n) = [s(N-L_{\text{cp}}), ..., s(N-1), s(0), ..., s(N-1)]$. The resulting symbols are multiplied with the k^{th} term of a set of mutually orthogonal chirp signals (ψ_k). To specify the continuous-time signal $s(t)$, we first need to introduce the continuous-time root-chirp function $\psi_0(t) = e^{j\frac{\pi}{4}} e^{-j\pi\frac{N}{T^2}t^2} \Pi_T(t)$. Where $\Pi_T(t)$ is one for $0 \leq \text{t} < \text{T}$ and otherwise zero. The k^{th} chirp waveform can be defined as:

$$\psi_k(t) = e^{j\frac{\pi}{4}} e^{-j\pi\frac{N}{T^2}\left(t-k\frac{T}{N}\right)^2} \Pi_T(t) \tag{4}$$

By using (4), the periodic continuous time-domain signal can be represented as:

$$s(t) = \sum_{k=0}^{N-1} x(k)\psi_k(t), \tag{5}$$

$$s(t) = \sum_{k=0}^{N-1} \mathrm{x}(k) e^{j\frac{\pi}{4}} e^{-j\pi \frac{N}{T^2}\left(t-k\frac{T}{N}\right)^2} \Pi_T(t), \tag{6}$$

The terms $s(t)$ as a sum of input symbols $x(k)$ modulated by quadratic phase chirps, represented by $\psi_k(t)$. This modulation provides robustness to Doppler shifts, high time-frequency resolution, and improved SNR. Compared to OFDM, quadratic chirps offer simpler receiver designs and better multi-path resistance. While OFDM is easier to implement, it struggles with frequency-selective channels.

The received signal, influenced by multipath propagation and channel interference, undergoes processing to retrieve each user's transmitted data. This data reveals the pulse shaping method used at the transmitter, aiding in demodulation. Demodulation takes place in specific layers via matched filtering. Matched filters utilizing FFT and DFnT waveforms correlate the signals, and a detector identifies the type of pulse-shaped data received. At the receiver, the matched filter multiplies $s(t)$ by the complex conjugate of the transmitted signal's impulse response, selecting the appropriate window for the desired signal. The baseband discrete-time domain signal, sampled from $y(t)$ at $t = \frac{nT}{N}$, can be expressed as:

$$y(n) = e^{j2\pi \frac{\Delta_f T}{N} n} \sum h(n;l)\bar{s}(n-l) + \sigma(n). \tag{7}$$

where Δ_f is the carrier frequency offset (CFO) resulting from an oscillator or phase noise, $\sigma(n)$ is the channel noise, and $h(.)$ is the effect of the channel plus the transmit and receive filters added together.

A. PHY Medium Dependent (PMD) Layer

The open systems interconnection (OSI) model has a layer called medium access control (MAC) that controls how data packets are sent across the network. It connects the logical link control (LLC) layer to the physical layer for data transmission [14]. As seen in Fig. 2, the Physical Layer Convergence Protocol (PLCP) and the Physical Medium Dependent (PMD) sub-layers make up the physical layer. The PMD sub-layer is responsible for choosing the right transmission approach, depending on the channel conditions. It uses OCDM pulse-shaped data when the SINR is low and vice versa. The PLCP processes the data and converts it to a format compatible with the chosen PHY layer once the PMD selects the appropriate physical layer.

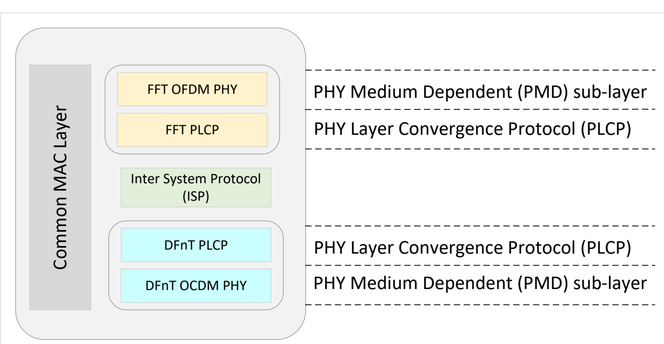


Fig. 2. PMD sub-layer architecture

III. Performance comparison of traditional OFDM and OCDM dual PHY layer

The development of future 6G applications must address multi-user capacity, mobility, Doppler fading, and quality of service in wireless data traffic. Nevertheless, devices that rely on the previous generation cannot be completely rendered useless. This necessitates multiple access techniques that support rising data rates while ensuring compatibility with current-generation devices and infrastructure. Consequently, the proposed dual PHY layer architecture, incorporating both OFDM and OCDM, aims to address the limitations. Evaluating its capabilities against a single PHY layer OFDM transceiver is vital to justifying its use. To appropriately evaluate the performance of each physical layer, we detailed the simulation findings and addressed many critical factors below.

A. Doppler Fading

The Doppler effect, sometimes referred to as the Doppler shift, is a phenomenon that happens when there is a difference in frequency between electromagnetic signals sent by a transmitter and received by a receiver due to their directions of movement. Wireless communication involves the transmission of signals through the air at a speed $(3 \times 10^8 m/s)$ far greater than the user's velocity. Therefore, in wireless communication, the movement of the transmitter and receiver is more apparent, and the Doppler shift may significantly impact the quality of communication.

Let's assume the frequency of the transmitted signal as f_0. The Doppler effect causes a shift in the frequency of the received signal. The observed frequency f is calculated based on the transmitted frequency f_0, the relative velocity v between the transmitter and receiver, and the speed of light c. The Doppler shift f_d is given by:

$$f_d = f - f_0 = \frac{v}{c} f_0 \tag{8}$$

This can be rearranged to:

$$f = \left(1 + \frac{v}{c}\right) f_0 = \beta f_0 \tag{9}$$

The Doppler effect also impacts the chirp signal received by the receiver, which can be described as:

$$c(t) = \cos\left(2\pi\beta f_c t + \pi\beta^2\mu t^2\right) \tag{10}$$

where f_c is the center frequency of the transmitted chirp signal and μ is the chirp rate. The equation indicates that the centre frequency of the received chirp signal becomes βf_c and the chirp rate becomes $\beta^2\mu$. To demonstrate the effect of the

TABLE I
SIMULATION PARAMETERS

Parameters	OFDM/OCDM Values
No. of Subcarriers/ Chirps	128
CP Length	8
Modulation Scheme	BPSK
Channel Estimation	ZF & MMSE
Channel	Rayleigh
Chirp Rate	20 GHz/s
Duration of Chirp	1 ms
User Speed	28 m/s or (100 Km/h)

Doppler shift on the chirp signal, we use a chirp signal with a duration of ($T = 1$ ms), a centre frequency of ($f_0 = 20$ kHz), and a sweep width of ($B = 20$ MHz). The relative velocity between the transmitter and receiver is set to 28 meters per second.

B. Robustness to Channel Impairments

In this subsection, the performance comparison of the proposed dual PHY layer in terms of bit error rate (BER) is presented. The chirp spread spectrum (CSS) technique used in OCDM modulates each data symbol with a chirp signal, which linearly sweeps through a range of frequencies, utilizing the entire allocated bandwidth to broadcast a signal. This approach distributes the signal energy across a wide frequency range, which enhances resistance to narrowband interference. By distributing the signal over a broader spectrum, the impact of frequency shifts and fading is mitigated, minimizing the risk of deep fades and maintaining robust communication, even under challenging conditions where traditional OFDM might be more susceptible. Furthermore, OCDM preserves orthogonality between chirp signals more effectively than subcarriers in OFDM, even under severe channel impairments. It minimizes inter-symbol interference (ISI) and inter-carrier interference (ICI), ensuring better signal recovery. Overall, these attributes contribute to OCDM's superior performance and reliability, making it a more reliable choice in environments with significant noise and interference.

C. Sum Capacity

To evaluate the spectral efficiency, which indicates the maximum achievable data rate within a specified bandwidth under certain SNR conditions, we utilized the concept of total capacity for multi-carrier systems. For a system with N sub-carriers or chirps, the total capacity C_{total} can be expressed as

$$C_{\text{total}} = \sum_{n=1}^{N} B_n \log_2 (1 + \text{SNR}_n) \quad (11)$$

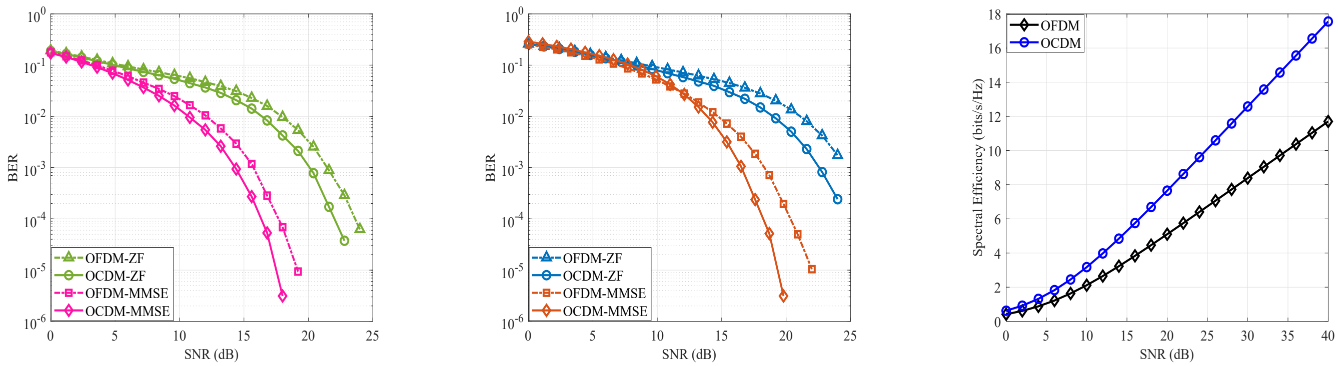
where B_n and SNR_n represent the bandwidth and signal-to-noise ratio respectively. In OFDM, orthogonal sub-carriers are used, which effectively manage multipath interference but can suffer from fixed sub-carrier spacing issues, particularly in dynamic environments with Doppler shifts and frequency offsets. OCDM, on the other hand, utilizes chirp signals with frequency variations over time. This approach allows for broader spectrum usage and better noise mitigation due to the time-frequency spreading characteristics of chirps. This enhancement in bandwidth and SNR results in significant differences in capacity, particularly under varying SNR conditions.

D. Complexity Analysis

In designing a dual PHY layer system incorporating two distinct layers, such as FFT-OFDM and DFnT-OCDM, increases both modem complexity and cost. For data modulated using OFDM pulse shapes, the computational complexity is primarily driven by the algorithm used to compute the Discrete Fourier Transform (DFT). The radix-2 Fast Fourier Transform (FFT) algorithm requires ($Nlog_2N$) multiplications and ($3Nlog_2N$) additions to process complex frequency components [15]. In contrast, OCDM introduces additional complexity due to its use of chirp signals. Besides the standard FFT operations, DFnT involves handling additional N quadratic phase factors for each chirp signal [13], leading to complex ($N(log_2N+2)$) multiplications and ($3N(log_2N+2)$) additions [13] to process. This added complexity contributes to higher computational demands compared to OFDM. Consequently, the integration of PMD sub-layer in the dual PHY transceiver faces higher computational complexity and latency. However, this trade-off offers enhanced reliability and spectral efficiency, which are critical for the evolving demands of future communication networks.
In summary, this section has evaluated key performance parameters, emphasizing the distinct advantages of each technique within the proposed system. The OCDM PHY layer excels in mitigating noise and enhancing spectral efficiency, making it ideal for applications such as industrial IoT and precision healthcare monitoring. In contrast, OFDM is better suited for low-latency, cost-effective scenarios like vehicle-to-vehicle (V2V) communications. By leveraging these complementary strengths, the dual PHY layer transceiver enables the system to adapt to diverse 6G application requirements. The next section analyzes simulation results to validate the system's performance and advantages.

IV. RESULTS DISCUSSION

In this section, we present and analyze the simulation results. Simulations, performed in Matlab, evaluate the BER performance, the impact of radio frequency (RF) impairments, and the sum capacity of the proposed dual PHY layer architecture integrating both OFDM and OCDM techniques. The specifications for the simulation are detailed in Table I. Fig. 3(a) illustrates the comparison of BER performance between OFDM and OCDM under zero-forcing (ZF) and minimum



(a) (b) (c)

Fig. 3. (a) Bit error rate (BER) comparison of OFDM and OCDM using ZF and MMSE equalization techniques. (b) BER comparison of OFDM and OCDM using ZF and MMSE under IQ imbalance conditions. (c) Sum capacity comparison.

mean square error (MMSE) equalization schemes. OCDM outperforms OFDM at all SNR levels, notably with MMSE providing up to a 5dB improvement in BER, highlighting OCDM's enhanced noise robustness and error-handling. Moreover, the performance evaluation of dual PHY transceiver system is further conducted under the RF impairments, specifically IQ imbalance. Here, the amplitude and phase distortions occur in the received signal during the conversion from radio frequency (RF) to intermediate frequency (IF). An IQ imbalance with a change in amplitude of less than 1 and a change in phase of about 3 degrees was used for this test. It deteriorates the BER performance of both PHY layers as illustrated in Fig. 3(b). Nevertheless, under these conditions, OCDM still performs better than OFDM. Therefore, for future 6G applications demanding high reliability, OCDM multiple access emerges as a more dependable and efficient technique compared to conventional OFDM.

Moreover, for capacity measurement as discussed in section III-C, Fig. 3(c) illustrates the comparison between OFDM and OCDM in terms of spectral efficiency across a range of SNR values, demonstrating that OCDM consistently outperforms OFDM. The improved capacity of OCDM can be attributed to its inherent resilience against channel impairments such as multipath fading and Doppler shifts, which allows it to maintain higher data rates under varying conditions. The chirp-based modulation in OCDM provides better time-frequency diversity, enhancing its ability to achieve closer to the theoretical channel capacity in practical scenarios, making it a more efficient choice for modern communication systems.

Conclusion

Future 6G systems are anticipated to deliver up to a thousand-fold increase in traffic capacity, tenfold improvements in spectral efficiency, and ultra-low latency on the order of milliseconds. Considering the distinct advantages of each technology, with OCDM offering superior spectral efficiency and interference immunity, and OFDM providing lower latency and simplified channel equalization, a dual PHY layer system that integrates both is proposed. This hybrid approach not only leverages the strengths of each technique but also ensures seamless compatibility with existing 5G infrastructure. Future research should focus on exploring the cutting-edge technologies such as terahertz communication and AI-driven network management.

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