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Original Article

Development of New Hybrid Optical CDMA COARSE Radio over Fiber for 5G Capacity Improvement

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Abstract *- Recently, the application of Radio over Fiber (RoF) has grown such that the whole industry would benefit from a crucial element of it through the link between the base station and the central home. Integrated optical CDMA with Coarse WDM is essential, particularly when the market expands toward ultra-high-speed communication products like 5G applications. This article presents a design framework of RoF based on Wavelength Division Multiplexing (WDM) techniques, including the two main types, namely, Optical CDMA and Coarse WDM. The RoF-based Optical CDMA and Coarse WDM systems are verified and implemented at ultra-high data transmission of 10 Gbps, 8 channels each. We outline the performance comparison between both systems-based evaluations, which were conducted through eye diagram analysis, transmission distance, power levels, and minimum Bit-Error-Rate (BER) of* 10^{-9}*. The article concludes with a result showing that the new hybrid RoF system delivered a trade-off performance at 10 Gbps; these outcomes highlight Coase WDM as a cost-efficient approach that maximizes the use of existing fiber optic bandwidth. This study presents a new joint application-based Coarse WDM system used for distributed radio units, while the Optical CDMA system will be used for massive centralized baseband units associated with (5G/6G) network expansion up to 90 channels.*

Keywords *- Optical CDMA, SAC, Coarse, 5G/6G, BER.*

1. Introduction

Current telecommunication networks are mainly based on optical communication systems that integrate the frequency domain into the existing optical communication infrastructure, including various Free-Space Optics (FSO) access networks in smart city applications [1]. Radio over Fiber (RoF) is acknowledged as a particularly engaging system that allows millimeter waves to be transmitted over fiber optics [2]. Furthermore, a central location distributes microwave signals via fiber optic links to distant microwave units. The RoF can be defined as an analog optical link that broadcasts modulated radio frequency signals; as well as transmitting an RF signal uplink and downlink, the Base Station (BS) carries modulated RF energy to the main unit.

Consequently, it provides significant benefit in terms of adaptability and gain in the flexible features of telecommunication systems to support the cellular mobile communication systems when it comes to the terabit data rates required for 5G applications [3]. The RoF is an excellent choice for wireless network communication due to its characteristics, such as increasing channel capacity, reducing power consumption, and reducing implementation costs, since it increases channel capacity and reduces power consumption when applied to this type of network [1, 2]. Spectral Amplitude Coding (SAC)- The Optical CDMA technique is considered one of the multiple access techniques used in optical communication. [4, 5]. It has an enormous advantage as it can support many users, improve the BER, and system reliability with low Multiple Access Interference (MAI) [5]. Our proposed Optical CDMA system is based on Multiservice (MS) code, which has been proven to have a lot of features, such as low cross-correlation, Maintains MAI suppression, is suitable for high bit rates, and better BER performance than many existing SAC codes. Table 1 shows the proposed setup wavelength for each user of the MS code. It has been shown from the code structure that the cross-correlation is always equal to one.

Table 1. MS code signature with weight (W) of 4 and code length (L) of 9

L	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_9
Ch 1	1	1	0	1	0	0	1	0	0
Ch 2	1	0	1	0	1	0	0	1	0
Ch 3	0	1	1	0	0	1	0	0	1
nm	1548.8	1549.6	1550.4	1551.2	1552.0	1552.8	1553.6	1554.4	1555.2

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For Coarse WDM, wavelength separations between 1270-1610 nm are 20 nm in accordance with ITU-T G.694.2 [2]. There are 4-16 wavelengths that can be transmitted over a single Coarse WDM transmission network. Each wavelength transmits a different signal[4]. Because Coarse WDM systems do not amplify wavelengths, they cannot transmit data over long distances [6]. The Coarse WDM typically transmits data up to 160 km. Coarse WDM-based passive optical networks (Coarse WDM-PONs) are point-to-multipoint optical networks that use existing fiber. They are very economical for bringing bandwidth to end users on the last mile. Rather than using expensive active electronics, it uses passive devices such as couplers and splitters. In PON, endpoints and fiber capacity are expanded, but bandwidth is limited. When using Coarse WDM, a central office can connect to an end user via a virtual point-to-point connection over each additional wavelength when combined with another. A virtual fiber is created for an end user if the PON fiber needs to be extended to create their own fiber. This will maximize fiber efficiency for the access system because the bandwidth taken from the PON will now be available for other end users. The RoF systems are classified into analog and digital types based on their signal transmission method [9-12]. Analog RoF transmits radio signals directly in analog form, suitable for low-latency and wideband applications. Digital RoF converts signals into digital data, which offers better error correction, improved performance, and integration with digital networks. The choice depends on factors like data rate, distance, cost, and application needs. Both types support diverse uses, including mobile networks, broadband, and smart city technologies. The previous proposed RoF based on optical CDMA alone suffers from various limitations; for example, using an optical CDMA system alone is considered costly[11]. Moreover, focusing solely on Coarse-WDM has limitations regarding the number of channels and the maximum transmission distance. Thus, combining Coarse WDM and optical CDMA significantly reduces cost, as the Coarse WDM hardware is cheaper [12]. In addition, optical CDMA can increase capacity with suppressed MAI, and it can ideally be used for secured access networks and 5G/FTTx front-haul.

In this study, we reviewed contributions from researchers and industry experts in the field of Radio over Fiber (RoF) utilizing various WDM technologies[15-18]. It has been widely reported that most researchers have been integrating ROF with WDM and Orthogonal Frequency Division Multiple Access (OFDM) [13]. In some of these studies, the main focus is on simplifying the electronic-photonic-electronic conversion, which is implemented using a low-power and low-cost RoF scheme that modulates commercially available between 1344 nm and 1547 nm using Vertical-Cavity Surface-Emitting Lasers (VCSELs) by band-group of one ultra-wide band wireless signals (ECMA-368) at near broadcast power [14]. Also, M. T. Rahman et al. present a unique hybrid network employing mmWave-based RoF backhaul and Coarse WDM-VLC for indoor communication to generate the appropriate mmW signal. Utilizing optical heterodyning, in which one source conveys modulated information, and the other two provide unmodulated carriers [15]. None of the above-mentioned studies deals with the comparison of Coarse WDM and optical CDMA- based RoF systems, especially the cost-effective based higher data rates in implementing such systems. The following sections of this paper will investigate and compare the performance of the proposed Hybrid RoF system in terms of transmission distance, received power, bit-error rate, and number of active users. The basic concept behind RoF technology is modulating light using an RF signal and then sending it via an optical fiber connection.

2. Research Methods

The proposed RoF system setup is presented in the block diagram of Figure 2, where the Agilent programmable 2.5GHz RoF units with the C-band 1550 nm generator are used to deliver via radio interface to integrate with the Laser source (Ando AQ4321A) driver. The Mach-Zehnder encodes and converts the laser’s output to an intensity amplitude at the output, which is then modulated by radio frequency to produce a signal. The signal received from the Mach-Zehnder is then collected via the optical spectrum analyzer ANDO AQ6317B. This involves the use of an optical fiber link to transport the RF signal, with baseband signal construction and modulation taking place at the control office.

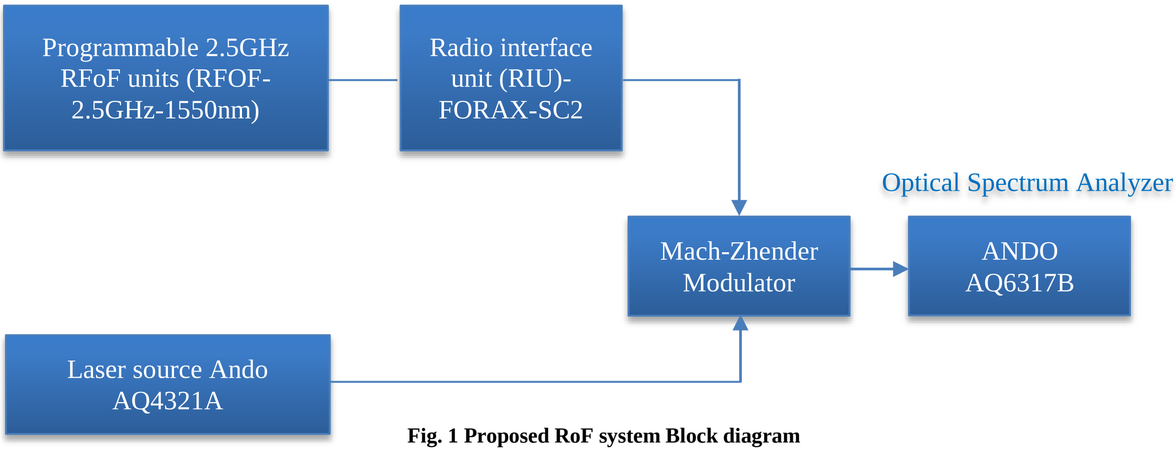


Fig. 1 Proposed RoF system Block diagram

We suggest using eight subcarrier-radio frequency channels; the multiplexing is used to collect the wavelengths from various transmitters in our system to send signals across Single-Mode Fiber (SMF) at various distances. The proposed (8 × 10 Gbps) system is designed as shown in Figure 3; in the transmitter part, there are 8 optical laser elements. Each transmitter has a channel with its associated operational optical spectrum. Through the external modulation block, which comprises pseudo-random bit sequences for generating Random Binary Sequences (RBSs), the electrical signal was generated. We demonstrate the use of Continuous Wave (CW) laser arrays as laser sources, and for each channel, we utilized a Mach-Zehnder Modulator to combine electrical and optical signal sources. CW lasers were operated using -10 dBm power at 0.1 MHz linewidth, with frequency spacing of 0.2 THz, starting at 1550 nm [6]. Additionally, the selected bit rate for each channel is 10 G bps, and the bandwidth for each link is 10 GHz, accommodating 8 subcarrier RF signals, with each link connecting to individual inputs. Other system parameters are mainly based on the previously published ITU-G652 reported in Ref [7-9]. The OptiSystem software would be used to simulate the proposed receiver, which contains 8 remote stations.

Hence, the Signal-to-Noise Ratio of the Hybrid system can be represented as

$$SNR = \frac{\frac{\Re^2 P_{Sr}^2 (W-N_B+1)^2}{L^2}}{\frac{eB\,\Re P_{Sr}\left(W+3N_B-3\right)}{L}+\frac{B\Re^2 P_{Sr}^2 NW}{2L^2\Delta v}[W+3N_B-3]+\frac{4K_b T_n B}{R_L}} \tag{1}$$

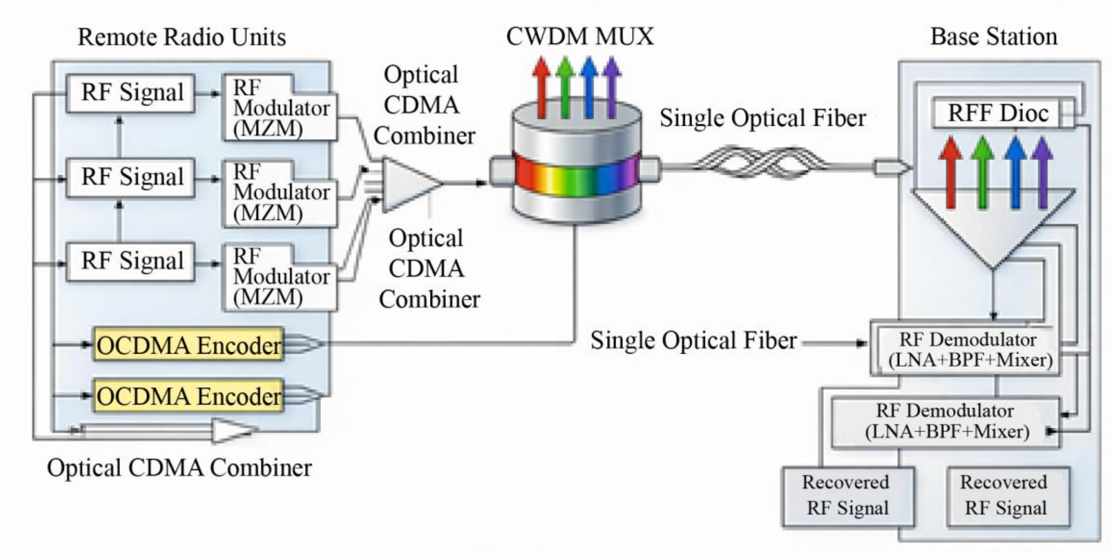


Fig. 2 System block diagram of the Transceiver RoF Optical -Coarse WDM system

The MS code parameters are based on the previously published article [5]. The hybrid system parameters presented in Eq. (1) are shown in Table 2.

Table 2. System parameters [17]

Symbol	Parameter	Value
η	Photodetector Quantum Efficiency	0.6
Δv	Linewidth Broadband Source	3.75 THz
P_{sr}	Broadband Effective power	-10 dBm
B	Electrical Bandwidth	311 MHz
λ_o	Operating Wavelength	1550 nm
T_n	Receiver Noise Temperature	300 K
R_L	Receiver Load Resistor	1030 Ω
e	Electron Charge	1.6×10^{-19} C
h	Planck’s Constant	6.66×10^{-34} Js
K_b	Boltzmann’s Constant	1.38×10^{-23} J/K

3. Results and Discussion

In this section, the BER variation against Fiber length for the hybrid RoF system is displayed in Figure 3. The system is tested for a various number of simultaneous channels at a transmission rate of 1.25Gbps each. Results indicate that when the number of channels is 4, there is a significant BER improvement compared with other users of 8 and 12. Also, at an optimum BER of 10-9, the system with a smaller number of users can support higher transmission distances. For example, at a transmission distance of 68 km, the BERs are 1.6×10^{-18}, 1.3×10^{-12}, and 1.8×10^{-9}, respectively.

The hybrid system has been used to demonstrate and execute the service differentiation strategy in optical domain networks in this section. Based on our assumptions, consumers who have access to Video-on-Demand (VoD), data, and audio services employ the triple play services that must be present in a single system. Thus, the hybrid system, as illustrated in Figure 3, can maintain an average BER across multiple qualities of service requirements. (VoD date rate of 1.25Gbps, 2.5Gbps, 5 Gbps, and 10 Gbps per channel for Netflix/YouTube HD streams).

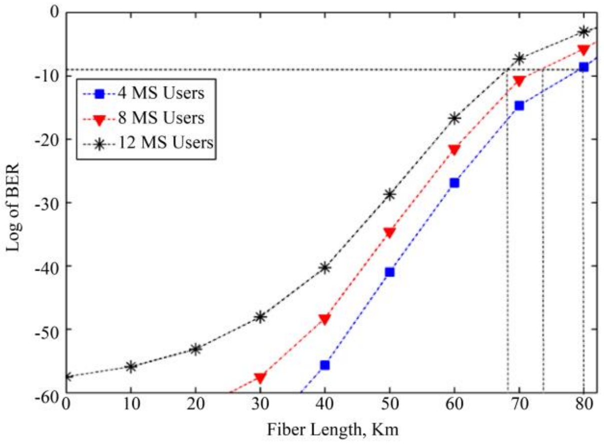


Fig. 3 BER as a function of Fiber Length of Hybrid RoF system at 1.25 Gbps under different numbers of channels

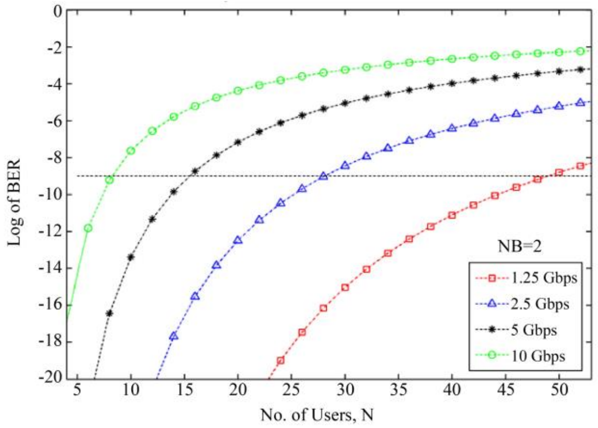
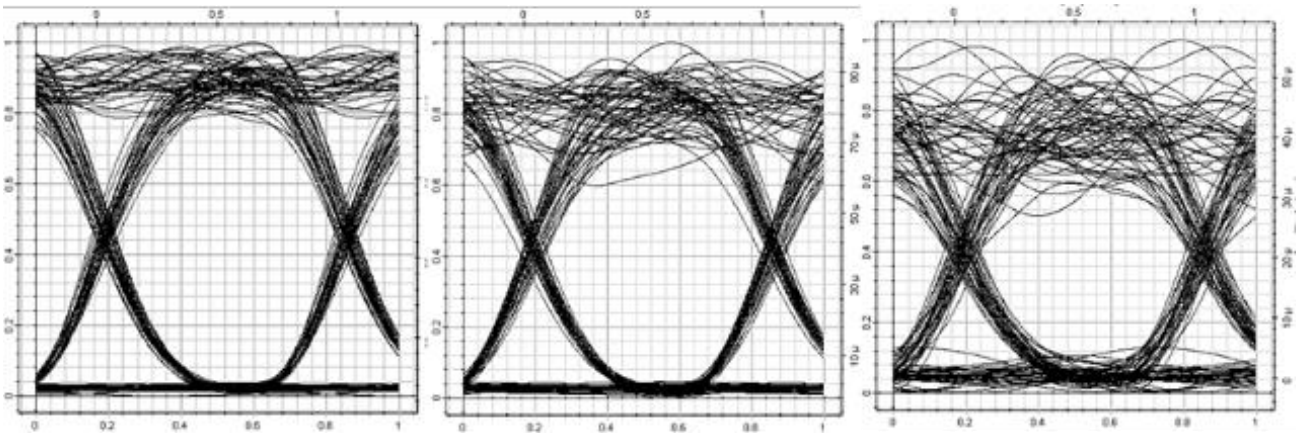


Fig. 4 BER Variation against the number of active users based on service differentiation



(a) **(b)** **(c)**

Fig. 5 Eye Diagrams for various numbers of channels (N), (a) N=2 with QF=15.83, (b) N=3 with QF=10.18, (c) N=4 with QF=5.19.

For further analysis, the worst eye diagram of the hybrid RoF system subscribers at a transmission length of 40 km under a data rate of 1.25Gbps is shown in Figures 5(a) through (c). Results indicate that users with subcarrier 2 perform more effectively than those with subcarriers (Sub) of 3 and 4, even at decreased received power. The system's performance improves significantly due to higher received power, as the figure reveals (i.e., services with subcarrier 2 have a higher Q-factor (lower BER) as opposed to subcarriers 3 and 4, and so on for subcarriers 3 and 4).

As a function of received power, Figure 6 displays the BER for different subcarrier users. The overall system performance is significantly increased by increasing the amount of received power. The code feature is used to support

Table 3. Comparison of the proposed hybrid system with standalone optical CDMA and CWDM systems

Aspect	Optical CDMA	Coarse WDM (CWDM)	Hybrid system
Cost-effectiveness	× Less cost-effective (complex hardware, MS coding/decoding)	√ Highly cost-effective (simple, wide spacing, cheaper components)	√
Noise	× Sensitive to MAI and receiver noise	√ Lower noise	√
Security	√ Strong inherent security (MS code-based access)	× Limited security (easy interception via wavelength separation)	√
Capacity	√ Potentially high capacity (50 multi-user codes)	× Moderate capacity (~18 channels, limited scalability)	√

Multiservice applications, for example, at BER $>10^{-6}$, the application operates at low Quality of Service (QoS), will be a promising candidate for higher subcarriers at a number of channel N=4. Moreover, for high Quality of Service at BER$<10^{-6}$, applications that support a low number of channesl will be a promising solution for a few channels (N=2, and N= 3). The amount of various received power values has a significant impact on the BER performance (i.e., at -12 dBm), N=4, 1.77×10^{-4}, N=3, 2.45×10^{-11}, and N=2, 3.21×10^{-23}, respectively.

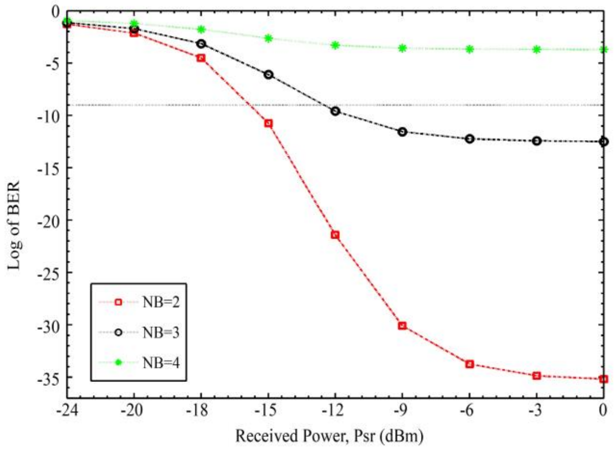


Fig. 6 BER as a function of received power operates at various Quality of Service (QoS) capacities

Figure 7 shows the output spectrum shape, which is a superposition of all individual channel shapes, as measured via Optical Spectrum Analyzer (OSA). It can be seen that each channel (user) has a specific wavelength based on the width allocated for each system type and has almost the same power level.

It can be seen that within each Coarse WDM waveform, a group of optical CDMA with a unique code signature is transmitted to achieve a higher power output (-5.5 dBm). The Coarse WDM spectrum shape is defined by a wider (20 nm) spacing.

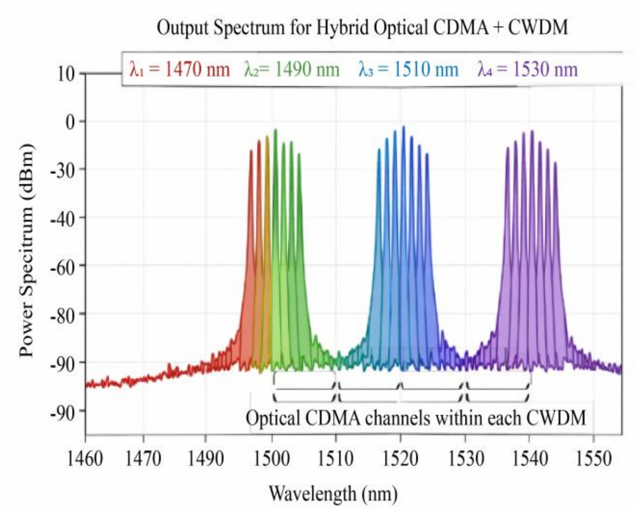


Fig. 7 Output spectrum shape

4. Application Scenario

A new hybrid design based on an optical CDMA-coarse WDM has been developed for a joint application aimed at expanding 5G and 6G networks[16-18]. The proposed system could be highly recommended for hybrid WDM in next-generation fronthaul, where the Coarse WDM system will be used for distributed radio units, while the optical CDMA system will be used for aggregation for massive centralized baseband units. The new joint hybrid technology has emerged as a significant impact for addressing the increasing need for ultra-high speed of 10 Gbps, long-distance, and cost-effective communication. The Hybrid system enables the transmission of multiple Radio Frequency (RF) signals over a single optical fiber, which simplifies network architecture and reduces the need for complex electronic components at base stations. This makes it highly suitable for C-RAN (centralized radio access networks) in which a baseband RoF processing is consolidated to improve efficiency. The ability to add more wavelengths to existing fiber lines without laying new cables allows for scalable and economical network growth. Finally, Table 3 shows a comparative analysis of the proposed Hybrid system versus conventional optical CDMA and coarse WDM systems operating independently.

5. Conclusion

The proposed system could be highly recommended for hybrid WDM in next-generation fronthaul, where the Coarse WDM system will be used for distributed radio units, while the optical CDMA system will be used for aggregation for massive centralized baseband units up to 90 channels. The Hybrid system enables the transmission of multiple Radio Frequency (RF) signals over a single optical fiber with a BER of 2.1×10^{-23}, which simplifies network architecture and reduces the need for complex electronic components at base stations with low quality of service. The ability to add more wavelengths to existing fiber lines without laying new cables allows for scalable and economical network growth.

The technology also supports in-building wireless coverage and distributed antenna systems, improving connectivity in airports, stadiums, hospitals, and corporate campuses. In urban environments and smart cities, Optical CDMA-RoF facilitates real-time communication among Internet of Things (IoT) devices, enabling effective control of traffic systems, MAI & noise suppression, and secured utility services.

It also plays a critical role in mission-critical communications, offering secure and reliable links for public safety networks, military operations, and emergency response systems. Furthermore, its resistance to electromagnetic interference and low signal loss over long distances make it ideal for aerospace and defense applications. Overall, a hybrid system is a scalable, efficient, and future-ready solution for modern communication challenges.

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