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ZTE TECHNOLOGIES

VIP Voice

EOLO: Bridging the Digital Divide with 5G FWA in Italy

Expert Views

Multi-Band Sensing: Empowering Industry Applications

Special Topic

5G-A mmWave

mmWave: Unlocking Infinite Possibilities of 5G-A Communication

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Bridging the Digital Divide with 5G FWA in Italy

Reporter: Zeng Yuwen

Guido Garrone
CEO of EOLO

EOLO, established in 1999, has been pioneering radio technology to deliver affordable, high-speed internet and has grown into Italy's largest fixed wireless access (FWA) provider, playing a crucial role in bridging the digital divide in the country. Guido Garrone, CEO of EOLO, talks about the company's unique advantages in the FWA sector, the significance of driving 5G FWA deployment, and the challenges of closing the digital gap nationwide. EOLO recently signed a multi-year collaboration agreement with ZTE to build a 5G millimeter wave (mmWave) FWA network, aiming to deliver superior connectivity services to households and businesses in small Italian towns, comparable to the quality delivered in major cities.

EOLO is a leading FWA broadband provider in Italy. What sets your company apart in this sector?

EOLO is the leading FWA provider in Italy, with the largest market share in the country. We have achieved this goal through continuous efforts to develop and improve our network, tested for the first time in 2007. Since then, our service has made several important technological progresses, becoming the most important FWA network using 28 GHz frequencies and mmWaves, reaching a maximum speed of 300 Mbps in download for residentials and 500 Mbps for businesses. With the work of several notable partners such as ZTE, in 2025 EOLO will be launching the first standalone FWA connectivity combining 5G and mmWave technologies, reaching a maximum download speed of 1 Gbps.

Our company has always been pioneering the use and deployment of FWA technology, identifying the best connectivity solution for rural areas and villages.

What's the significance of driving the expansion of 5G FWA in Italy?

Our mission has always been to enable economic and social inclusion for all Italian territories, focusing on areas affected by digital divide and digital speed divide. As FTTH fiber is already serving the major cities of our country, connecting them effectively, its deployment outside main urban areas will still be unfeasible in the upcoming years because of economic reasons. Indeed, the cost model for FTTH technology increases when the population density decreases.

mmWave FWA can bring ultrabroadband connectivity outside urban areas with costs that do not depend on population. Moreover, with 1 Gbps maximum speed in download and continuous quality improvements, we will play a pivotal role in complementing FTTH fiber and offering a fiber-like experience everywhere.

To successfully achieve this goal, ZTE plays a key role as a top-tier partner. Their cutting-edge technological solutions and exceptional ability to integrate with third-party platforms—such as 5G core network, RAN and terminals—set them apart as an indispensable ally. This unique capability makes ZTE a key enabler in building a truly future-proof infrastructure, ensuring the highest quality standards and fully meeting the expectations of end customers.

What are the challenges to connect underserved communities, and how are you addressing them?

Our nation has unique geographical features, including physical and orographic barriers that hinder ultrabroadband deployment.

Geographical barriers are not the only one to look at: there are cultural challenges to consider as well. Without having the possibility to access

ultrabroadband technology, several portions of our territory had not been used to receiving significant advantages from a solid and performing connectivity. Moreover, these areas have experienced a steady decline in population and business presence for several years, without sufficient interventions to reverse the trend. This means that an important share of our population doesn't see the role played by ultrabroadband connectivity as able to bring economic growth and inclusion. Despite all these factors, these territories still represent an important portion of our social and economic national heritage. It is important to reach a deep territorial capillarity, in order to effectively show connectivity advantages for all towns and villages.

Again, Italian telecommunications sector has been suffering from profit margin erosion during last decades. As a result, a general shrinking in resources addressing infrastructural investments has occurred. It is important to make operators' infrastructures available for common purposes, such as the digitalization process of our country.

What does the collaboration with ZTE mean for EOLO's growth and future direction?

Partnering with ZTE is an important recognition of EOLO's role in bridging digital divide and digital speed divide in Italy. We are extremely glad to have ZTE, one of the key players in the global telecommunications sector, as a companion on this ambitious journey.

How do you see the potential opportunities for EOLO in the coming years?

Our company can rely on an increasing customer base, today just over 700,000 households served nationwide. At the same time, seven million families of our country still lack adequate connectivity solutions, meant as broadband or ultrabroadband access. This means that, in order to align with national and international ambitious targets of digitalization for 2030, we still have room for a solid growth in terms of potential market. ZTE TECHNOLOGIES

Multi-Band Sensing: Empowering Industry Applications

Zhao Zhiyong
Director of ISAC Products, ZTE

Han Zhiqiang
Senior System Engineer, ZTE

China's 5G development has now moved beyond network construction and entered a new phase of application innovation. Building on further evolution and enhancement of 5G network capabilities, the introduction of revolutionary technologies such as integrated sensing and communication (ISAC) can better support scenarios such as low-altitude economy, intelligent driving, and high-end manufacturing.

In November 2023, the International Telecommunication Union Radiocommunication Sector (ITU-R) released the "Framework and Overall Objectives of the Future Development of IMT for 2030 and Beyond". This recommendation, also known as a global vision for 6G, serves as a blueprint for defining global 6G standards. It defines six major usage scenarios for 6G, three of which are enhanced communication scenarios that build upon 5G's eMBB, URLLC, and mMTC—namely, immersive communication, hyper reliable and low-latency communication, and massive communication. ISAC, AI and communication, and ubiquitous connectivity are three new scenarios introduced by 6G. Among these, ISAC enables 6G mobile communication networks to have dual engines: communication and sensing.

The traditional telecommunications industry has long focused on increasing the amount of information carried by each hertz of electromagnetic waves. Now, it has entered a new phase where electromagnetic waves are directly utilized for sensing purposes, leading to the integration of sensing and communication technologies, and opening a new dimension in the utilization of communication spectrum. Leveraging the abundant communication spectrum and infrastructure resources, a ubiquitous sensing network can be

constructed to better support various applications. Sensing capabilities serve as a bridge between the physical and digital world, providing richer content for generative AI models and facilitating the development of digital twins. These advancements represent crucial directions for development from 5G-Advanced (5G-A) towards 6G.

Throughout the evolution of mobile communication networks, both communication and sensing have relied on wireless electromagnetic waves as their medium, making radio spectrum a critical element essential for the survival and growth of mobile communications. Currently, the primary frequency band utilized by 5G systems is in the sub-6 GHz range. In the updated version of China's "Radio Frequency Allocation Regulations", the entire or part of the 6.425–7.125 GHz (U6G) band has been allocated for IMT systems. Additionally, 3GPP has initiated channel modeling research for the FR3 band (7–24 GHz). The use of millimeter wave (mmWave) bands in 5G applications is rapidly growing, and the mmWave bands will undoubtedly play a significant role in 5G-A and 6G systems. All these frequency bands will be crucial in shaping the future of 5G-A and 6G technologies.

This article analyzes the sensing applications in the aforementioned frequency bands and explores methods for collaborative sensing across different bands, aiming to provide insights for enabling sensing capabilities in more frequency bands.

Suitable Sensing Applications for Different Frequency Bands

Sensing is a technology that extracts features of targets or the environment by analyzing the reflections of wireless radios, with applications spanning consumer entertainment, industries, and beyond. Depending on the nature of the sensing targets, applications can be categorized into four major types:

- **Monitoring, localization, and tracking applications:** These applications detect entities such as pedestrians, UAVs, vehicles, automated guided vehicles (AGVs), animals, and ships in various use cases. They can be further divided into applications focused on detecting a target's presence, localizing it, and tracking its trajectory.
- **Motion monitoring applications:** These focus on detecting partial body movements, encompassing use cases like respiratory monitoring, sports monitoring, fall detection, and gesture recognition.
- **Environmental monitoring applications:** These involve monitoring environmental phenomena, such as rainfall, floods, and landslides.
- **Environment reconstruction and imaging applications:** These are designed for three-dimensional reconstruction or imaging of environments, including use cases such as 3D mapping, gaming, and network optimization.

Different use cases have varying requirements and correspond to suitable frequency bands. Based on the attributes of different frequency bands, Table 1 illustrates the potentially appropriate bands for each use case.

With the implementation of technologies such as wide bandwidth, multiple antennas, and mmWaves, 5G has acquired the initial sensing capabilities. ZTE, in collaboration with industry partners, is actively exploring 5G-A sensing applications based on sub-6 GHz and mmWave bands. Significant advancements have been made in low-altitude scenarios, where continuous detection and tracking of UAV intrusions have been realized. This technology has already been deployed at scale in commercial operations with carrier partners.

Multi-Band Collaboration Approaches

Future ISAC systems will collaborate across multiple frequency bands to perform both communication and sensing functions. There are three ways in which collaboration can occur across multiple bands:

- Different bands can play different roles, such as utilizing sub-6 GHz for communication and mmWave for sensing, as illustrated in Fig. 1 (a). Leveraging the extensive coverage of sub-6 GHz for communication

Use cases\Frequency bands	Sub-6 GHz	U6G	7–24 GHz	Millimeter wave
UAV intrusion detection	Y	Y	Y	Y
UAV tracking	Y	Y	Y	Y
UAV obstacle avoidance	P	P	Y	Y
Vehicle tracking	Y	Y	Y	Y
Intelligent driving	P	P	Y	Y
Ship detection	Y	Y	Y	Y
Rainfall monitoring	Y	Y	Y	Y
Flooding monitoring	P	P	Y	Y
Gesture recognition	—	—	—	Y
Sports monitoring	Y	Y	Y	Y
Micro-deformation monitoring	Y	Y	P	P
Outdoor health monitoring	Y	Y	Y	P
Emergency search and rescue	Y	Y	Complementing sub-6 GHz and U6G	Complementing sub-6 GHz and U6G
Sensing-aided communication	Complementing 7–24 GHz and >24 GHz	Complementing 7–24 GHz and >24 GHz	Y	Y
AGV tracking	—	—	—	Y
High-precision environmental reconstruction	—	—	—	Y
Low-precision environmental reconstruction	—	—	Y	Y
Imaging	—	—	—	Y

Table 1 Potential applicable frequency bands for sensing use cases (Y denotes applicable, P denotes potentially applicable).

and the high precision of mmWave for sensing, these two functions can be separately realized. However, this approach does not fully exploit the spectrum of both bands and keeps sensing and communication functions compartmentalized. It represents a compromise designed to minimize alterations to existing sub-6 GHz communication networks, which may not be the mainstream or widely deployed method for future integrated communication and sensing systems.

- Multiple bands collaborate to accomplish either sensing or communication tasks through carrier aggregation or multi-link approaches. For example, using a multi-link approach with both sub-6 GHz and mmWave bands to complete either communication or sensing functions, as depicted in Fig. 1 (b). When different bands work together to handle both communication and sensing services, the spectrum resources expand beyond a single band, significantly broadening the available bandwidth. A larger transmission bandwidth offers higher data rates for communication and higher resolution for sensing. However, there are coverage disparities across different bands. Moreover, supporting carrier aggregation or multi-link technologies across these bands increases terminal complexity and power consumption. In addition, multi-band carrier aggregation or multi-link technologies require precise power control and interference coordination mechanisms.
- Different bands assist each other, collaboratively completing a single communication or sensing task, as shown in Fig. 1 (c). For instance, in sensing scenarios, sub-6 GHz's wide beams can be initially used for scanning to roughly pinpoint the location of the sensing target. Subsequently, mmWave's narrow beams can be employed for precise scanning. This approach not only reduces the time required for mmWave beam scanning but also allows for the fusion of sub-6 GHz and mmWave sensing data to enhance overall sensing performance.

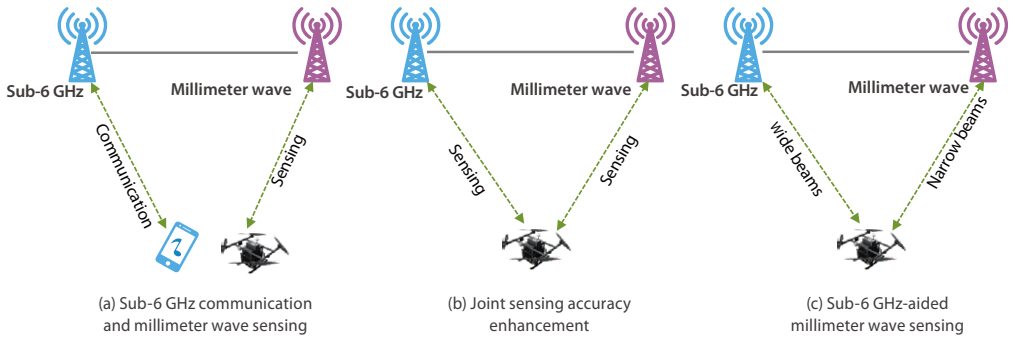

Fig. 1 An illustration of the multi-band collaboration approaches.

Potential Key Technologies

To support sensing capabilities in mobile communication systems, research into several potential key technologies is necessary.

- **Waveform, sequence, and pattern design:** Research is needed into waveforms, sequences, and patterns that support sensing across multiple bands while accommodating detection, localization, identification, imaging, and reconstruction of object targets—essential for delivering comprehensive sensing services. ZTE pioneered the industry's first solution that supplements linear frequency modulation (LFM) onto OFDM waveforms under the base station mono-static sensing, to address coverage challenges in sensing. This solution has been successfully implemented with favorable outcomes.
- **Sensing measurement reporting:** There are various levels of sensing measurement reporting involved. For applications such as detection, localization, and tracking, leveraging the computational power of base stations and their management of multiple AAUs enables the fusion of sensing data from multiple AAUs. Processing this data at the base station to derive sensing outcomes can significantly enhance sensing accuracy while reducing transmission overhead.
- **Multi-band sensing collaboration:** ISAC leverages the strengths and characteristics of different frequency bands to offer comprehensive, optimized solutions, facilitating a broader range of sensing applications and expanding possibilities for both end-users and industry stakeholders. Collaboration across multiple bands can enhance sensing accuracy or extend the sensing range; however, techniques for data fusion, synchronization issues, and beam management require further investigation.

Building on the foundation of technical research, it is necessary to develop communication-sensing prototypes to validate various ISAC technologies, advancing them from research to industry. Efforts should focus on identifying suitable scenarios for each frequency band, conducting effective commercial promotion, fostering related industrial chains, and laying the groundwork for ISAC to thrive in commercial applications by preparing the industrial landscape.

ZTE is actively exploring the applications of sensing across various frequency bands. Together with our operator partners, we have embarked on technical and application explorations for multiple sensing scenarios based on 5G networks in the sub-6 GHz and mmWave bands, encompassing network validation and testing for use cases such as detection and tracking of low-altitude UAVs, vehicles, pedestrians, as well as ship detection and tracking in rivers. These efforts have resulted in commercial deployments in several cities. ZTE is also delving into potential applications in bands like U6G, laying a solid foundation for future exploitation of these new spectrum opportunities. ZTE TECHNOLOGIES

mmWave Development and Evolution Overview

Wu Minghao

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Gao Bo

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Each iteration of communications technology has brought new experiences and opportunities to society. Millimeter wave (mmWave), a high-frequency-band communication technology, plays a vital role in the evolution from 5G-Advanced (5G-A) to 6G, promoting communication technologies to new heights.

mmWave Development in 5G-A

5G-A starts from Release 18 (R18), further advancing and expanding 5G technologies. As one of the key 5G-A technologies, mmWave operates at frequencies from 30 GHz to 300 GHz. Compared with traditional communication frequency bands, mmWave is characterized by short wavelengths and wide frequency bands. This allows more antenna elements to be packed within the same antenna size, providing favorable conditions for the application of large-scale multi-input multi-output (MIMO) technology.

Key mmWave applications in the 5G-A phase include:

- **Large, high-density gathering places:** mmWave supports huge data traffic demands in places such as large stadiums and commercial centers.
- **Industrial internet:** In factory workshops, mmWave enables high-precision equipment interconnection and real-time transmission of operational and monitoring data, facilitating intelligent production management and fault prediction.
- **XR applications:** In XR experience scenarios such as immersive VR games or AR navigation, mmWave ensures fast and stable data transmission, delivering extremely high definition and smooth virtual experiences.
- **Live broadcast of HD and 4K videos:** mmWave is ideal for live streaming large concerts and sports events. With high-speed transmission capabilities, mmWave base stations ensure the real-time and stable delivery of live HD and even 4K video signals to a wide audience on their devices.
- **mmWave integrated sensing and communication (ISAC):** With its high-precision sensing capabilities, mmWave can be widely used in low-altitude security and logistics. In waterways, mmWave technology enables effective ship detection and

tracking, assisting maritime departments in enriching supervision services. In addition, the high-precision feature of mmWave ISAC has been explored for applications such as vehicle-road coordination and micro-deformation detection of bridges and landslides.

mmWave Evolution from 5G-A to 6G

The evolution of mmWave from 5G-A to 6G is marked by continuous upgrades and enhancements, aimed at achieving an intelligent network with higher rates, lower latency and wider coverage.

Frequency Band Expansion: Towards Higher Frequencies

With communication technologies moving towards 6G, mmWave frequency bands will be further extended to higher frequencies. FR2-2, the frequency range beyond 52.6 GHz was introduced in 3GPP R17, and further spectrum expansion is expected in 6G. For example, initial exploration and applications in the 0.1-10 THz frequency range may be involved. Higher frequency bands will offer wider available bandwidth, enabling higher peak rates than those of 5G and 5G-A. This will meet extreme bandwidth requirements of future applications such as holographic communication and ultra-high-definition 8K/16K video transmission.

Technology Integration and Miniaturization

In the 6G era, mmWave communication equipment will evolve towards higher integration and smaller size. Base stations will become more compact and easier to deploy, reducing deployment costs. The continuous advancements in semiconductor and micro-nano processing technologies have enabled the internal components of base stations to be more tightly integrated, significantly reducing the size and weight of the equipment.

Similarly, terminal devices, such as smartphones, intelligent wearable devices, and drone communication modules, will integrate miniaturized mmWave communication modules, improving portability while giving full play to the communication performance of mmWave. This will drive the wide application of the mmWave technology across various terminal devices.

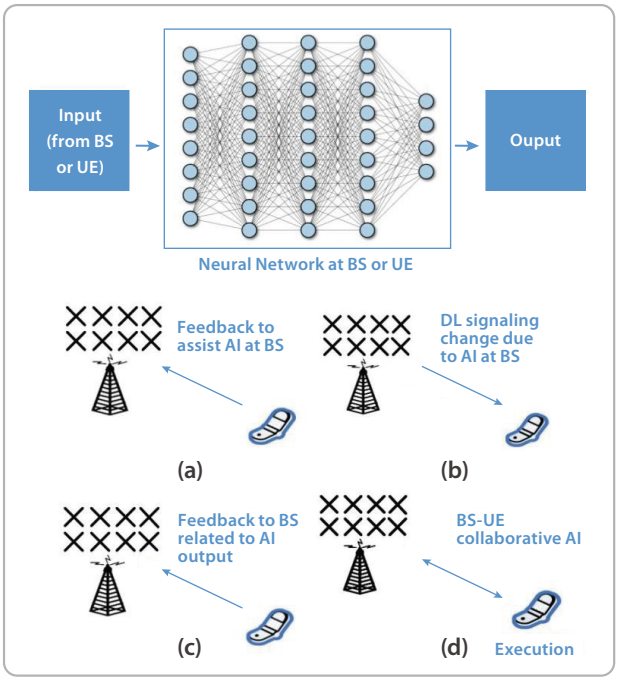


Fig. 1 6G native AI mmWave communication architecture.

Intelligent Beam Management and Adaptive Communication

To support 6G native AI communication, mmWave in 6G will use more intelligent beam management and adaptive communication technologies. Intelligent beam management can automatically adjust beam characteristics based on complicated environmental conditions—such as dynamically changing obstacles and user distribution—to optimize signal transmission. Base stations (BSs) or UEs can decide which AI algorithm to use.

Fig. 1 shows examples of how the 3GPP standard supports AI-based beam management through the signaling framework, without the need to standardize specific AI algorithms.

- Fig. 1a: The mechanism for UE to provide feedback on its mobility information is standardized so that the information can be used as an input to the neural network at BS for AI-based beam management.
- Fig. 1b: The BS performs AI-based beam management to predict the future beams and sends the future beam indication information with timestamps to the UE via signaling.
- Fig. 1c: The neural network is implemented at the UE side in this case. Feedback is standardized to support AI output results from the UE, such as beam prediction results or recommended demodulation pilot information.
- Fig. 1d: Collaborative AI is done between BS and UE. The BS is responsible for training and downloading the trained neural network to the UE. The UE

executes the neural network to generate the final beam prediction result.

Multi-Site Cooperative Communication

To further enhance the robustness and networking flexibility of 5G mmWave communication, multi-site joint transmission needs to be considered in the first version of 6G mmWave communication, including non-coherent multi-point coordination and coherent multi-point coordination. In addition to the multi-TRP based channel/RS repetition supported in 5G-A, a new topology structure needs to be considered, such as uplink and downlink decoupling. In this new topology, uplink and downlink services can be implemented through different physical sites: Downlink sites can be selected based on the best received signal power or SINR, while uplink sites can be selected based on path loss to achieve the best uplink reception.

Multi-Modal Sensing

In future 6G, ISAC technologies will rely on new frequency bands such as THz and visible light, as well as new technologies such as air-space-ground integration and native AI to endow 6G systems with native sensing capabilities. As an important evolution in sensing technologies, multi-modal sensing integrates multiple sensing technologies and data sources, including mobile communication signals, radars, sensors, cameras, Wi-Fi, ultrasonic waves, Bluetooth, and RFID. Different sensing technologies, combined with data fusion techniques, can significantly improve the accuracy and security of detection, positioning, identification, and estimation.

Key technologies in the future will focus on exploring advanced fusion methods for multi-granularity and multi-modal sensing information, the collaborative application of deep reinforcement learning tools, and the coordinated utilization of multi-source sensing information. The collaborative sensing of multi-modal information will provide powerful support for the wide-area expansion of 6G system capabilities.

Prospects for 6G mmWave Application Scenarios

6G mmWave has a wide range of application scenarios, including immersive communication, holographic communication, greater integration of XR in industrial design, AI perception, and high-precision positioning and tracking.

Holographic Communication and Immersive Experience

With the ultra-high communication rates and bandwidth of 6G mmWave, holographic communication becomes possible. Holographic images can be transmitted in real time over mmWave networks, allowing for remote activities such as holographic conferences and performances, and blurring the boundary between the virtual and real worlds.

Advancing and Expanding XR Applications

In the 6G era, with the further development of mmWave technologies, XR applications will expand further. For example, in building design and industrial maintenance, virtual design solutions or maintenance guidance information can be overlaid onto real-world scenarios or devices through AR/MR applications, improving work efficiency and accuracy.

Deepening and Expanding mmWave Sensing Scenarios

ITU-R has defined IMT-2030 to cover six major application scenarios, including new scenarios such as ISAC, AI and communication, and ubiquitous connectivity. In the future, ISAC systems will leverage a variety of features such as super-large-scale antenna array, large bandwidth, multi-band integration, network multi-point collaboration, AI perception with native computing power, and multi-modal sensing, providing high-precision positioning and tracking, target imaging and reconstruction, action recognition, and agent interaction. This will empower the development of intelligent transportation, low-altitude economy, smart factories, and smart medical services, thus promoting industrial transformation and upgrades.

mmWave technology, guided by new technologies such as THz, AI-driven MIMO beams, and air-space-ground integration, will greatly expand its service scope. It will bridge the physical and digital worlds, ushering a new era of ubiquitous sensing, ubiquitous connectivity, and ubiquitous intelligence. ZTE TECHNOLOGIES

mmWave: Unlocking Infinite Possibilities of 5G-A Communication

Liu Shuang

Vice President of RAN Products, ZTE

Guo Qing

RAN Solution Manager, ZTE

In the global 5G revolution, China stands at the forefront, with over 4 million base stations and over 1 billion 5G users. 5G technology has penetrated 22 key industries, including steel, power, and mining, with over 10,000 successful application cases. As demands for network capacity, latency, and connectivity continue to rise, wireless network technology is evolving towards 5G-Advanced (5G-A).

5G-A introduces new technologies and expands spectrum applications, delivering larger capacity, more connections, and lower latency. It enables all-domain sensing, ubiquitous intelligence, and seamless air-space-ground integration, pushing the boundaries of traditional wireless communication.

In this evolution, millimeter wave (mmWave) technology injects new impetus into 5G-A networks.

ZTE, a pioneer in mmWave product solutions, has been committed to advancing this technology and exploring its potential applications. This article delves into the characteristics and applicable scenarios of mmWave technology, uncovering how mmWave ushers in a new era of wireless communication.

mmWaves: Building Blocks of 5G-A

mmWaves refer to the electromagnetic spectrum from 30 GHz to 300 GHz, with wavelengths ranging from 1 mm to 10 mm. Compared to the traditional sub-6 GHz, mmWaves exhibit remarkable physical characteristics (Fig. 1), unlocking new possibilities for high-speed communication and precision services.

Ultra-Large Bandwidth: Gigabit-Level Capabilities

mmWave technology offers up to 26.75 GHz of available bandwidth, covering multiple key frequency bands. With 800 MHz of spectrum resources, the peak rate for a single user in the uplink and downlink can reach 2 Gbps and 6.8 Gbps, respectively, enabling an unprecedentedly smooth experience for large video downloads and real-time live-streaming uploads.

Millisecond-Level Latency: Extreme Response Speed

With a sub-carrier spacing of 120 kHz and a slot duration of only 0.125 ms—one-fourth that of sub-6G NR—mmWave significantly reduces the physical-layer latency. This provides strong support for business scenarios with extremely high latency requirements, such as industrial IoT, AR/VR, cloud gaming, and real-time computing.

Concentrated Beam Energy for Precise and Efficient Coverage

mmWaves have short wavelengths and small antenna elements, making them more suited for large-scale antenna array products. When combined with beamforming technology, they enable precise coverage and efficient transmission. This increases the concentration of energy, reduces the transmission power required from a single antenna, and improves energy efficiency.

Precise Sensing: Expanding Boundaries of Communication Applications

mmWave base stations can use the characteristics of direct, reflected, and scattered radio waves to achieve target ranging, speed measurement, and angle measurement, providing strong support for fields such as the low-altitude economy, waterway management, and intelligent transportation.

While mmWave offers remarkable advantages, it faces coverage challenges due to greater penetration loss and weaker diffraction compared to sub-6 GHz frequencies. Therefore, it is essential to maximize its potential in the most suitable scenarios. ZTE has found that mmWaves are not only applicable to scenarios without obstruction (LOS paths), such as outdoor squares, indoor hotspots, and large stadiums, but also in long and narrow spaces with obvious multipath effects, such as rail transit tunnels

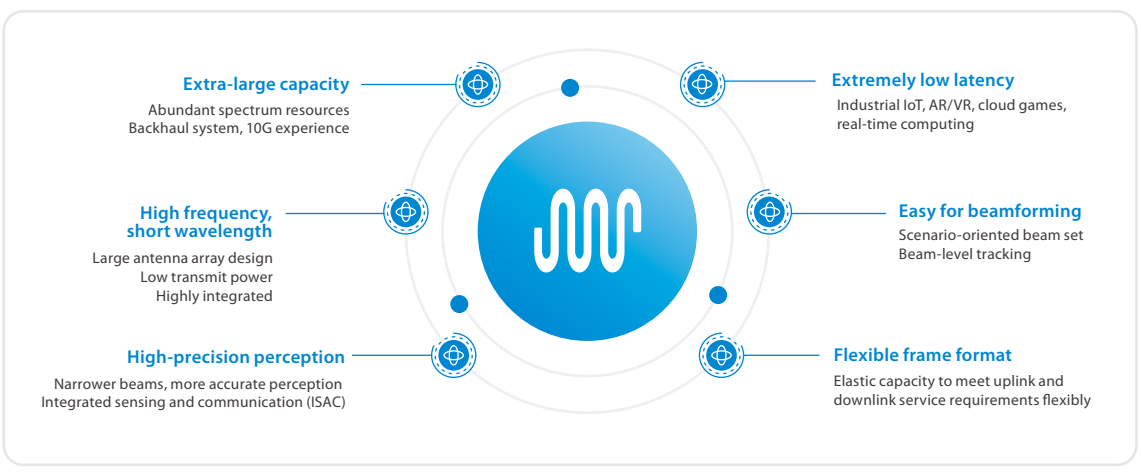


Fig. 1 Six technical advantages of mmWaves.

and outdoor streets. By utilizing multiple reflections and multipath superposition, mmWave can provide an excellent communication experience.

ZTE: Leading mmWave Innovation

As a leading provider of mmWave solutions, ZTE makes breakthroughs with innovations like flexible networking architectures and frame-format designs to meet diverse business needs across different scenarios. It also combines indoor and outdoor product models to support full-scenario deployments.

Multiple Networking Architectures to Ensure Coverage

The NSA architecture leverages existing 4G infrastructure for rapid deployment, while the SA architecture delivers excellent network performance with high data rates, low latency, and high reliability. ZTE's NSA and SA networking solutions have been commercially deployed on a large scale in Italy. Based on the SA infrastructure, ZTE further supports NR dual connectivity (DC) and NR carrier aggregation (CA), providing more configuration options while meeting diverse business needs and ensuring network performance.

Flexible Frame-Format Design to Meet Tidal Service Demands

ZTE has pioneered a flexible frame-format design for mmWave. Each 0.625 ms cycle contains one full downlink time slot and one full uplink time slot, and the remaining three time slots can be flexibly scheduled according to real-time service needs. This design enables the mmWave system to flexibly adjust uplink and downlink capacity, meeting the needs of diverse scenarios.

Large-Bandwidth Macro AAUs for Excellent Performance

In July 2024, ZTE achieved the industry's fastest mobile speed at 30.8 Gbps through NR-DC networking in Malaysia. In later September, it collaborated with Qualcomm to verify performance using a smartphone test terminal under NR-DC networking combined with 1024QAM modulation, achieving a peak single-user rate of 9.34 Gbps.

MiCell, the Distributed Micro-Cell Solution for Diverse Deployment Scenarios

ZTE took the lead in launching the mmWave distributed micro-station, MiCell, which uses intermediate frequency pooling technology to miniaturize the front-end equipment, supporting easy, quick deployment and expansion, and fulfilling the application requirements of large indoor spaces.

ZTE's mmWave Commercial Practice

ZTE's mmWave solutions have been commercially implemented since 2020 across multiple countries, including China, Italy, and Thailand, supporting various scenarios such as FWA, large-bandwidth backhaul, free-roam XR, and live streaming (Fig. 2).

mmWave FWA: Leading a New Era of Fixed Wireless Broadband Access

Fixed wireless access (FWA) uses wireless technology to achieve fixed-broadband access. It is characterized by rapid deployment, low cost, and wide coverage. The ultra-large bandwidth of mmWaves can provide higher system capacity and speeds, further enhancing the end-user experience. ZTE has successfully delivered mmWave FWA solutions for multiple operators in Italy, ensuring a 1 Gbps download speed for more than 20,000 household users, meeting their demand for high-speed internet access.

Gigabit-Level Backhaul for Shanghai Metro

In subway tunnels, traditional 5G leaky cable upgrades are costly, time-consuming and face practical problems such as insufficient space and limited power capacity. ZTE's "dual-use for train and ground" solution, implemented on Shanghai Metro Line 4, builds a a gigabit-level backhaul system without needing leaky cable renovation by deploying mmWave AAUs inside the subway tunnel. Meanwhile, a 5G digital indoor distribution system is deployed inside the carriages. With a downlink backhaul capacity of up to 15 Gbps, mmWave enables over 1,800 passengers to enjoy high-definition videos simultaneously.

Free-Roam XR: Enabling Immersive Experience

mmWave has rejuvenated free-roam XR by

Fig. 2 Multi-scenario applications of ZTE's mmWave solutions.

eliminating the need for the bulky backpack for local image rendering, allowing users to enjoy the high-definition immersive experience through cloud rendering. In November 2024, ZTE cooperated with USUNHOME Group to launch the world's first 5G-A VR immersive theater application called "Jimmy Picture Book Metaverse Drama—My World is All You." Leveraging the large capacity, low latency of mmWaves, and intelligent XR service guarantee technology, users can easily enjoy the ultimate XR experience. This innovation sets a milestone for the entertainment industry.

Gigabit-Level Production and Broadcasting: mmWave Revolutionizing Live Streaming

Traditional wired live streaming for large-scale events is limited by complex wiring, restricting camera placement and shooting ranges. ZTE's gigabit-level mmWave network offers a new wireless live streaming solution. During the 2024 Spring Festival Gala, ZTE's Micell mmWave micro-station guaranteed high-definition live streaming from multiple wireless mobile cameras throughout the event. In August of the same year, Malaysia's National Games adopted ZTE's mmWave macro AAU solution, successfully completing the first wireless live streaming of the event via Radio Televisyen Malaysia. This solution enabled photographers to travel light and shoot flexibly, while ultra-low latency realized seamless integration of wireless and wired footage for a multi-angle, immersive viewing experience. mmWave is ushering in a new era of live streaming with greater freedom and richer visuals.

mmWave: Unfolding a New Chapter in Innovative Applications

With ongoing improvements of the industrial chain, including chips, modules, and various types of terminals, along with the increasing maturity of network equipment technology, mmWave applications are expanding into more industries. Among these, integrated communication and sensing with mmWave has emerged as a key technology in the low-altitude economy.

Communication-sensing integration features tight integration of communication and sensing technologies, addressing two core demands of the low-altitude economy: communication and supervision. In addition to traditional communication functions, the mmWave communication-sensing integrated station can accurately track drones' flight trajectory, speed, longitude, and latitude in real time, report the data to a management platform for effective supervision, and ensure safe and orderly low-altitude flights.

As the industry continues to overcome technical challenges in mmWave propagation, cost, and integration, mmWave technology is gradually becoming a more practical and reliable commercial solution. We look forward to the new chapter that mmWave will bring to the future of wireless communication. ZTE TECHNOLOGIES

5G-A Minimalist Private Network: Unleashing Free-Roam VR

Song Shuli
RAN Solution Manager, ZTE

Free-roam VR, or location-based entertainment (LBE) VR, offers an immersive experience by creating virtual environments in large physical spaces where users can move and interact with dynamically changing virtual content. The LBE VR market has witnessed remarkable growth in recent years, with a projected compound annual growth rate (CAGR) of 28.3% from 2023 to 2030.

Free-Roam VR's Rapid Growth in China

As one of the world's leading metaverse markets, China is entering a rapid growth phase in the LBE VR sector. At present, more than 100 LBE VR projects based on popular intellectual properties (IPs) have been launched in the country, with 41% of these projects focused on the Chinese culture. Industry data indicates that the LBE VR market in China is expected to exceed 250 billion yuan by 2026, positioning LBE VR a landmark industry in the new-quality productivity sector.

The popularity of LBE VR can be attributed to its ability to combine exceptional narrative capabilities with well-known IPs. These LBE VR projects reduce the sense of unfamiliarity often associated with VR but also provide enhanced interactive experiences. The overall user experience is at the heart of VR market recognition. For example, the precision of graphics impacts user immersion, while narrative and interactivity determine user engagement and emotional connection.

Bottlenecks in LBE VR Development

While LBE VR is rapidly gaining market recognition, it still faces huge challenges in scaling and inconsistent technical standards, which affect content quality, user experience, and long-term profitability of VR providers. Currently, mainstream technical solutions present several shortcomings:

- **Backpack rendering solution:** Users must wear a heavy 5 kg backpack with a rendering laptop, which is tough for adults to endure 45-60 minutes, let alone for children and the elderly. Moreover, traditional backpacks face issues such as poor heat dissipation, short battery life, and high costs.
- **VR headset rendering solution:** Due to the limited computing power of VR headsets, graphic quality is seriously degraded, and positional tracking becomes inaccurate, failing to deliver an immersive experience.
- **Wi-Fi-based edge rendering solution:** Wi-Fi's limited bandwidth and spectrum interference restrict the number of simultaneous players, reducing video and graphic quality as player numbers increase, ultimately impacting revenue and user satisfaction.

Therefore, it is crucial to develop a solution that enhances the user experience by providing high-quality graphics while ensuring high operational efficiency for businesses.

ZTE's 5G-A Minimalist Private Network Leads Next-Generation LBE VR

ZTE's innovative 5G-A minimalist private network addresses these challenges by offering an all-in-one large-capacity and low-latency 5G-A network without requiring a core network. The solution combines edge computing with the powerful capabilities of 5G-A networks, creating a tailor-made,

Multi-user concurrency XR competitive gaming verification.

high-performance network for LBE VR applications.

Self-Sustained Deployment

Its deployment is self-sustained, requiring nothing from mobile operators other than spectrum. This makes it perfect for densely populated business areas where both people traffic and data traffic are off the charts, leaving little room for mobile operator to squeeze strained resources.

Streamlined, Secure, and Fast Network

All data remains on-site and is fully controlled by VR providers. The 5G-A base station, or more precisely, the baseband unit, do the "light-lifting" by the otherwise needed core network. This ensures not only data security but also extremely fast data processing.

mmWave to Support More Users

ZTE's MiCell, the industry's first millimeter wave (mmWave) distributed micro-cell and IF pooling solution, supports 800 MHz bandwidth and can achieve a peak data rate of 6 Gbps per single cell. Combined with the powerful computing board NodeEngine and SuperMicell's intelligent beam management solution, it enhances service coverage, meets the mobility needs of XR applications, and ensures the certainty of a large amount of concurrent XR data.

XR-Specific Solution Providing Deterministic Guarantees

Designed specifically for VR, this solution ensures end-to-end reliability for high-priority VR services. By optimizing resource scheduling based on real-time user experience and network conditions, it prioritizes either bandwidth efficiency or video quality, offering a future-proof solution tailored for the evolving needs of VR.

In 2024, ZTE teamed up with China Mobile, Qualcomm and Sky Limit Entertainment to complete the industry's first 5G-A multi-user concurrency XR competitive gaming services at Sky Limit Entertainment's SoReal Paradise in Shougang Park, Beijing. ZTE deployed the MiCell to provide high-capacity, low-latency network coverage. Clear pictures in gaming reached a high picture quality of 4K @90 fps, a mainstream level in the industry. The 5G-A XR-specific solution ensures XR services' performance with slot-level intelligent scheduling and optimization policy, achieving an average air interface latency of less than 15 ms. This verification demonstrated that this end-to-end solution delivers a wireless XR experience in a large space and can support more than 50 users enjoying XR gaming simultaneously. This innovation has won multiple industry accolades.

Looking ahead, ZTE will continue to work closely with strategic partners constantly enrich 5G-A solutions, drive the XR industry to thrive, and expand scenario-based application rollouts across industries. ZTE TECHNOLOGIES

5G-A Minimalist Private Network Reshapes Live Broadcasting

Cheng Xuman

RAN Solution Manager, ZTE

Following the commercial debut of 5G-Advanced (5G-A) in 2024, telecommunications carriers and industry stakeholders are focused on leveraging 5G-A networks to drive industrial innovation, facilitate industry transformation, and catalyze market monetization. ZTE's 5G-A minimalist private network solution for wireless production and broadcasting effectively overcomes the limitations of traditional wired broadcasting systems and the performance constraints of existing wireless alternatives, offering highlights such as efficient deployment, flexible customization, and scalability. This solution has been successfully applied in major broadcasting events, including the 2024 CCTV Spring Festival Gala and the 2024 Malaysia Games (Sukma), injecting fresh momentum into the media production and broadcasting sector.

Media Broadcasting Challenges

Traditional wired broadcasting solutions face multiple constraints, including complex cable deployment, high costs, difficult maintenance, and safety risks. Previous wireless attempts at video production and broadcasting using Wi-Fi and 4G have proven inadequate. Wi-Fi, operating on unauthorized spectrum, suffers from low security and vulnerability to interference. 4G systems, on the other hand, face limitations in capacity and latency, and strong interference. Traditional sub-6 GHz is constrained by bandwidth resources, and the number of wireless cameras supported by 100 MHz bandwidth is limited. It cannot evolve to meet the needs of 4K/8K or shallow compression, nor meet the end-to-end latency requirements of hundreds of milliseconds for live broadcast scenarios. 5G-A millimeter wave (mmWave), with its large capacity and low latency, has become the optimal choice for the wireless transformation of media production and broadcasting.

ZTE's 5G-A Minimalist Private Network Solution

Based on the large bandwidth and low latency of 5G-A mmWave, ZTE launched the 5G-A minimalist private network solution for wireless production and broadcasting. This solution combines multiple types of 5G-A RF equipment with the NodeEngine computing board to create a high-performance, ultra-reliable minimalist private network for media production and broadcasting (Fig. 1).

Cable-Free: High Integration and Compatibility

The solution uses a wireless backpack that integrates encoding, battery and 5G-A transmission equipment (CPE), allowing camera operators to pick up the camera and shoot freely without being encumbered by cables. The backpack features a lightweight design, with a volume of about 3 L and a weight of about 5 kg, enabling photographers to work for a long time without strain. In addition, the 5G-A wireless backpack is compatible with all camera equipment using standard open interfaces (SDI/HDMI), facilitating a smooth transition to a wireless mode.

High Performance: Ultra-High Capacity and Ultra-Low Latency

On the network side, the solution offers scenario-specific RF equipment. For outdoor deployments, the industry-leading 1.6 GHz 5G-A

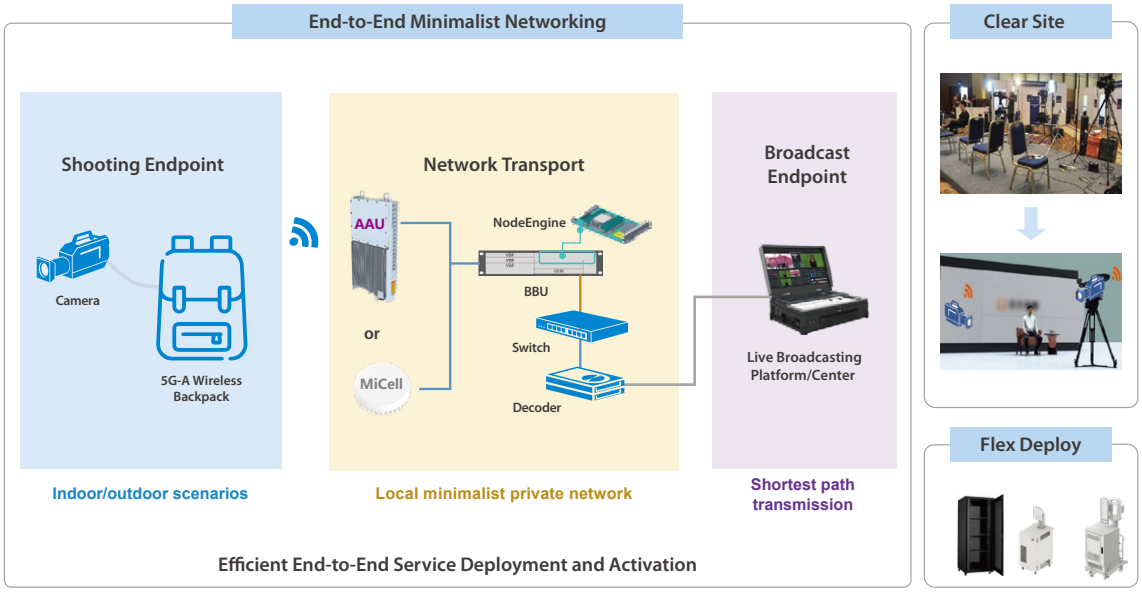


Fig. 1 ZTE's 5G-A end-to-end minimalist networking solution for media production and broadcasting.

mmWave AAU provides extensive, high-quality coverage. In indoor environments, the compact 5G-A mmWave MiCell micro-station can be used, featuring cascading capabilities through multiple head-ends to expand coverage.

Video data is wirelessly transmitted from cameras to RF units, then to the 5G-A BBU. The NodeEngine board, deployed on the same chassis as the BBU, identifies and locally offloads data, enabling direct transmission to the local broadcast center with minimal latency.

In the end-to-end transmission, the solution supports a maximum single-camera uplink rate of up to 2 Gbps, with just 4 ms wireless RTT latency. With end-to-end latency kept within 100 milliseconds, the solution enables seamless switching between wired and wireless camera feeds. This high performance meets current operational needs. supports near-term business evolution, and enables a smooth transition from wired systems.

High Reliability: Efficient Deployment with Enhanced Security

The solution requires only an on-site 5G-A network with a plug-and-play NodeEngine board on the BBU. After initial verification, a single technician can activate the network within two days. All data remains local for security, and flexible base station deployment options support various scenarios.

The 5G-A minimalist private network solution eliminates traditional cable constraints while maintaining high picture quality. It meets mobility demands, such as flexible capture, tracking shots, and close-up filming, and supports future features like AR overlays, higher resolutions, and cloud integration.

During the 2024 CCTV Spring Festival Gala, the 5G-A solution supported multiple wireless HD cameras with 99.99999% reliability throughout the over 5-hour broadcast. It achieved seamless switching between wireless and wired feeds, and was recognized by CCTV as a breakthrough achievement in the field of new media production and broadcasting. The midnight countdown live close-up shot, captured via the 5G-A wireless camera, proved the solution's stability. The vertical-screen broadcast garnered 420 million views—up 57.58% compared to the same period in 2023, marking a milestone in cable-free broadcasting.

The successful implementation of 5G-A technology in media broadcasting marks a pivotal advancement in the industry's transformation. By reshaping content production, streamlining workflows, and fostering new industrial chains, this breakthrough highlights the strong value of 5G-A in practical applications. ZTE TECHNOLOGIES

5G-A mmWave: Powering Grid Digitalization

Cao Ni

RAN Solution Manager, ZTE

The commercialization of 5G has injected strong momentum into digitalization across various industries, including the power industry, which has been exploring the concept of a "5G Smart Grid". As applications deepen, demands evolve. Millimeter wave (mmWave), a new spectrum introduced in 5G-Advanced (5G-A), offers unique advantages such as superior speed, ultra-low latency, and integrated sensing and communication (ISAC), providing more comprehensive support for the digital transformation of the power grid.

mmWave for Grid Digitalization

Since 2020, the power industry has been using 5G to empower smart grids. With characteristics such as low latency, high reliability, and slicing, 5G provides a ubiquitous communication network for power grids, benefiting remote control, data collection, and mobile inspections. As 5G applications deepen, grid demands evolve. For instance, with the expansion of visual O&M and the coexistence of diverse O&M methods, there is a growing demand for uplink (UL) throughput, requiring greater communication bandwidth. Furthermore, ensuring power grid security against threats like illegal drone intrusions has become a major concern.

mmWave, a new spectrum in 5G-A, offers key advantages. First, the mmWave band is isolated from the current public 5G network, facilitating private networks that meet the power grid's high security isolation requirements. Second, mmWave offers large bandwidth, supporting the power grid's increasing data transmission demands. Third, the wide carriers of mmWave enable shorter transmission time intervals and lower latency, fully meeting the requirements of ultra-low latency applications. Finally, mmWave enables high-precision sensing to allow power grids to more accurately identify and respond to external intrusions.

The use of mmWave in the power grid accelerates digital transformation, expanding the breadth and depth of power digitalization. mmWave demonstrates its advantages in the following power grid applications:

High Capacity Services

As intelligent O&M advances, power generation, transmission, and transformation require video surveillance and robot/drone inspection services, characterized by high capacity and high UL throughput. For example, substations may have hundreds of cameras, several mobile inspection terminals like robots, and multiple sensors transmitting monitoring data. For video transmission, the single uplink capacity demand ranges from 6 to 25 Mbps (for 1080p to 4K), and when multiple services transmit concurrently, the substation's uplink data volume can exceed 1 Gbps, which mmWaves can accommodate.

Low-Latency and High-Reliability Services

To enhance grid intelligence, there are numerous real-time data collection and control services, such as differential protection, requiring low latency and high reliability. For differential protection, real-time comparison of current values at both ends or multiple ends requires end-to-end latency under 20 ms and reliability of 99.999%. mmWave fulfills these ultra-low latency and

ultra-high reliability requirements.

Security Services

With increasingly severe security challenges, power grids need more intelligent and precise sensing capabilities for real-time monitoring and early threat warning. Common risks include unauthorized individuals, vehicles, and illegal drone intrusions into substation areas or other grid regions. mmWave supports ISAC, enabling a 24/7 precise sensing network to protect the power grid.


substation

ZTE's mmWave Solutions for Power Grid Application

For the power industry, ZTE provides a series of mmWave base station products, including high-performance outdoor macro stations and the industry's first distributed micro station, MiCell. ZTE also offers innovative scenario-based solutions to drive the digital transformation of power grids.

Flexible Frame Structure for Diversified Capacity Demands

Power grid services, such as video surveillance and drone inspection, are mostly uplink-oriented. ZTE supports the adjustment of frame structures to achieve high uplink data rates. Tests show that a peak uplink rate of 2 Gbps can be achieved with the "DSUUU" frame structure at 400 MHz bandwidth, fully meeting the power grid's demands. Furthermore, ZTE exclusively supports AI-powered dynamic frame structures that can quickly predict and adjust the frame structure based on real-time uplink and downlink loads, perfectly matching real-time service demands.

NodeEngine (NE) for Local Processing and Deterministic Guarantee

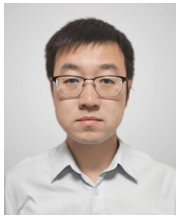
NE, the industry's first base station-level edge computing solution, enables plug-and-play in BBUs to support local service offloading and deterministic assurance. In substation scenarios, where local inspection video platforms are often required, NE enables lightweight deployment without the need for core network UPF offloading. Furthermore, for low-latency services such as differential protection, in addition to the reduced radio-interface brought about by mmWave itself, NE enables direct local communication between terminals across base stations, significantly reducing transmission latency. NE also supports precise service identification and intelligent scheduling, ensuring deterministic assurance for low-latency, high-reliability services.

ISAC Solution for a 24/7 Seamless Air-Ground Security Network

In the power grid, sensing rogue drones and monitoring the intrusion of ground vehicles and personnel is essential. ZTE's industry-first self-transmitting and self-receiving large-angle AAU can sense up to 600 m, creating an integrated air-ground "all-inclusive" network. Moreover, ZTE is the first in the industry to propose dual-waveform intelligent sensing technology, addressing both long-distance sensing and near-point blind spot elimination. Building on the basic sensing function, ZTE introduces an AI computing board into the BBU, equipping the base station with native AI capabilities to perform advanced functions such as identifying networked drone identities, thereby improving low-altitude airspace control. The sensing server can also be deployed lightly on the NE.

As a key element of 5G-A, mmWave technology holds enormous potential in the digital transformation of power grids. ZTE is committed to collaborating with industry partners to drive scenario exploration, technological R&D, and demonstration applications of mmWave in the power industry. ZTE TECHNOLOGIES

5G-A mmWave: A New Engine for Digital Transformation of Railways



Liu Jia
RAN Solution Manager, ZTE

In 2023, China State Railway Group Co., Ltd. (CHINA RAILWAY) set clear goals in the "Digital Railway Plan": By 2027, railway digitalization will be significantly improved, with key areas achieving intelligence, a landscape covering business scenarios at all levels, and significant progress in digital railway construction. The top priority in building a digital railway is to enhance the capabilities of digital infrastructure.

The 5G for railways (5G-R) system promoted by CHINA RAILWAY mainly carries critical services such as high-speed train control and command dispatch communications, which are essential for ensuring railway operation safety. However, the capacity of the 5G-R system is limited, focusing on high-priority voice and data services along the railway. While the application scenarios outlined in the "Digital Railway Plan" are abundant and cover all operational aspects of railway business, 5G-R can't fully meet the dedicated network application needs across all railway scenarios. Big data services, such as massive data transfers between locomotives and the ground, as well as intelligent maintenance based on digital twins, require a foundational network with greater capacity and richer spectrum. With its unique technological advantages, millimeter wave (mmWave) is expected to become another significant technology for railway dedicated networks.

mmWave Enables Massive Train-to-Ground Data Dump

Monitoring equipment and data recording for locomotives play a crucial role in ensuring safe train operations and enhancing transportation efficiency. By deploying a series of advanced monitoring systems such as the remote monitoring and diagnostics system, train operation monitoring and management system, and derailment monitoring system, staff at the locomotive depot can collect and analyze real-time data from locomotive operations. This enables them to promptly identify and address potential safety risks, ensuring the safe and stable operation of trains.

Multiple systems on locomotives generate massive amounts of data during daily operations, and dumping this data is a key challenge in railway digital transformation. For example, the locomotive on-board safety protection system (6A system) generates approximately 1 GB of data per camera per hour, meaning that a single locomotive can accumulate about 24 GB of data per day. For locomotives operating continuously for several days, this can amount to hundreds of GBs. Wi-Fi has relatively low transmission rates and cannot support cross-station data transfer. Currently, data dumping mainly relies on manual copying by locomotive depot staff, which is time-consuming, labor-intensive, and prone to errors, increasing safety risks.

To meet these challenges, wireless equipment can be deployed along tracks, leveraging the ultra-wide bandwidth of mmWaves to build an efficient and stable wireless train-to-ground communication system. In particular, the valuable time windows when locomotives are stationary at major stations and locomotive depots can be fully utilized to enable the rapid wireless transfer of

onboard equipment data.

ZTE has developed a comprehensive solution for railway bureaus, including a lightweight 5G dedicated core network, a series of wireless products, dedicated mmWave on-board terminals, and a network management system that integrates multiple products, meeting the unified end-to-end management of networks and services.

Data from multiple systems in the locomotive is aggregated and uniformly fed into the mmWave on-board terminal for transmission. Given that the transmission of the locomotive data spans multiple locations, such as stations and locomotive depots, the deployment of mmWave base stations need to be planned in advance to ensure that there are no significant obstructions between the on-board terminals and the base stations. For key locations where locomotives are stationed, 3D digital mapping of the site environment and channel model SLA simulation can be conducted to ensure optimal wireless network coverage and capacity.

In addition, since railway business data is primarily transmitted upwards, the system's frame structure can be adjusted to 1D3U, allocating more resources to the uplink and increasing the system's uplink throughput several times. After the locomotive data is relayed back to the dedicated core network via mmWave base stations, it can be directly docked to the data analysis system for processing. This innovative solution provides an efficient approach for the rapid transfer and storage of massive amounts of data between the locomotive and the ground.

Compared to traditional Wi-Fi solutions, mmWave offers a significant advantage in transmission speed, capable of transferring large volumes of data much faster—such as completing the transmission of 50 GB data in just 5 minutes. In addition, mmWave uses a dedicated frequency, ensuring that all data remains within the railway company, and guaranteeing data security. The contactless transmission of multiple data streams efficiently aggregates data from multiple systems on the locomotive and transmits it back through an on-board terminal mounted on the top of the locomotive. This innovative technology, which supports segmented data transmission across multiple locations, greatly saves time and labor, bringing unprecedented convenience to locomotive data transmission.

mmWave Creates a Digital Space for Railways

In traditional locomotive maintenance workshops, there are a large number of locomotives with complex workflows, and operators need to perform a series of tedious tasks, such as monitoring locomotive components and debugging various performance parameters. These tasks rely heavily on manual observation and experience, leading to long maintenance cycles and low efficiency. Building a digital twin of the maintenance workshop enables real-time monitoring and in-depth data analysis of operations within the workshop, thereby improving the efficiency of maintenance work. This is undoubtedly a significant step towards digitalization in the railway industry.

To construct a digital maintenance depot, the digital twin system needs to synchronize all workshop data in real time, ensuring consistency between the virtual and real worlds. This requires a wireless network capable of supporting high-speed data transmission and instant feedback, allowing virtual operations to immediately impact physical entities. Due to the relatively small area within the locomotive depot maintenance workshop, ZTE provides a workshop-level 5G minimalist private network solution without the need for a dedicated core network. This solution is centered around the NodeEngine computing base station and the mmWave indoor product Micell, enabling real-time feedback between on-site services and the digital twin platform. The NodeEngine also serves as a lightweight cloud foundation, providing computing resources and a runtime environment for the digital twin platform at a low cost, accelerating the setup, deployment, and capability opening of on-site applications. The physical environment of the locomotive depot maintenance workshop is shown in Fig. 1.

When transmitting complex 3D model data and massive real-time operational data from devices, mmWave, with its superior low-latency characteristics,

Fig. 1 Maintenance workshop of the locomotive depot.

ensures that the digital twin platform operates smoothly without lag or delay during control and operation. This not only effectively prevents operational errors but also ensures seamless integration and consistency between the virtual and physical worlds.

Combining mmWave with digital twin technology enables real-time acquisition of dynamic data from the entire maintenance workshop, which is then fed back to the digital twin platform as a high-precision 3D model. This provides operators with unprecedented visual insights, enabling them to easily understand the internal structure of locomotives and the complex relationships between the components, allowing them to accurately identify potential failure points and predict maintenance needs, thereby enhancing the efficiency of preparation operations.

mmWave Brings More Possibilities

In November 2024, China's Ministry of Industry and Information Technology and 11 other departments jointly launched an upgraded plan for the large-scale application of 5G. This second "set sail" action plan states that the construction of 5G dedicated networks will be promoted, and the innovative applications of 5G mmWave technology in key sectors such as manufacturing, railways, mining, and the defense industry will be explored. In this blueprint, mmWave is assigned a new mission to drive industry innovation and lead digital transformation. As mmWave technology and its industrial chain mature, its gigabit-level uplink transmission rate and millisecond-level network latency provide a solid technical foundation for the digital transformation and upgrade of railways.

In the railway industry, the application prospects of mmWave are extremely broad. It not only significantly improves the efficiency and security of locomotive data transmission, but also demonstrates enormous potential in key areas such as intelligent maintenance and automated inspections, driving the railway industry toward a smarter, more efficient, and safer future. ZTE TECHNOLOGIES

Application and Prospects of mmWave in the Industrial Sector

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RAN Solution Manager, ZTE

Han Ying

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In the wave of transformation towards intelligence in today's industrial enterprises, the introduction of 5G wireless technology has undoubtedly provided a powerful boost, opening up new development paths and infinite possibilities. This transformation is not only a technological innovation, but also a profound reshaping of traditional production models and ways of thinking. Amidst this tide of change, millimeter wave (mmWave) technology, with its outstanding high bandwidth and low latency characteristics, has emerged as a key enabler for building an efficient and stable industrial dedicated network system.

Characteristics of 5G mmWave

Compared to traditional sub-6 GHz 5G technology, 5G mmWave technology demonstrates significant advantages in terms of bandwidth, latency, capacity, and directivity, laying a solid foundation for the extensive application and in-depth development of mmWave in the industrial sector.

- **Large Bandwidth: Highway of Data Transmission**

The mmWave band boasts an abundance of spectral resources, with a single carrier bandwidth easily spanning a vast range from 400 MHz to even 800 MHz. This characteristic endows mmWave with the capability to deliver ultra-high data transmission rates, where the peak downlink rate for a single user can soar to 7 Gbps, and the uplink peak rate can also reach 2 Gbps. In contrast, the bandwidth of the sub-6 GHz band appears rather limited, typically confined within a range of just a few hundred megahertz. Consequently, when dealing with large-scale, high-frequency data transmission tasks, mmWave demonstrates a more prominent advantage. In industrial scenarios, this feature enables mmWave to effortlessly support critical applications such as high-definition video transmission, big data processing, and real-time control, providing robust technological support for the transformation towards industrial automation and intelligence.

- **Low latency: Guardian of Swift Response**

Another highlight of mmWave is its ultra-low latency. Thanks to the larger subcarrier spacing and shorter slot duration, its air interface latency is approximately one-quarter that of sub-6 GHz. This characteristic shines in industrial applications requiring rapid response, such as industrial automation control and remote real-time monitoring. In the field of industrial automation, millisecond-level latency differences can significantly impact the smooth operation of production lines and product quality. mmWave, with its low latency feature, ensures the real-time data transmission and accuracy, thereby significantly improving production efficiency and product quality.

- **Beamforming: Precise Focus, Reduced Interference**

The narrow beam of mmWave signals has strong directivity, allowing mmWave to better focus signals, effectively reducing interference and improving spatial reuse rates. In industrial scenarios, the beamforming feature of mmWave technology makes communication between devices more stable and reliable, reducing the impact of signal attenuation and interference on communication quality. At the same time, the clear propagation path of mmWave signals, due to their ease of being blocked, enhances communication security to a certain extent, reducing

the risk of data interception. Therefore, mmWave provides a safer and more stable guarantee for communication between devices in industrial environments.

- **High Integration: Flexible Deployment, Convenient Application**

The compact size of mmWave device antennas greatly facilitates the widespread application of mmWave technology. This feature allows mmWave technology to be easily integrated into various terminal devices, opening up new possibilities for flexible deployment and convenient application in industrial internet scenarios. In smart factories, mmWave devices can be deployed in large numbers to achieve high-density connectivity and real-time data transmission, providing technical support for industrial automation and high-definition video surveillance. In addition, the miniaturization of mmWave devices also makes their application possible in fields such as telemedicine and intelligent transportation.

mmWave in Industrial Scenarios

- **Factories**

In the factory, mmWave, with its high bandwidth and low latency characteristics, becomes a capable assistant for industrial automation and intelligent production. mmWave enables precise remote control of robotic arms, real-time monitoring of production line operation, and efficient transmission of industrial data. These applications not only significantly improve production efficiency but also ensure the safety and stability of the production line. At the same time, mmWave supports key applications such as high-definition video surveillance and quality inspection, providing technical assurance for product quality control.

- **Telemedicine**

The application of mmWave technology in the field of telemedicine is also highly promising. Leveraging its high bandwidth and low latency characteristics, high-definition video transmission and real-time diagnosis applications can be realized, improving the efficiency and quality of medical services. In telemedicine, doctors can engage in real-time communication with patients through high-definition video, providing remote consultations and surgical guidance, effectively reducing patient wait times and enhancing the accessibility and convenience of medical services.

- **Intelligent Transportation Systems**

In intelligent transportation systems, mmWave, with its high-precision positioning and low latency characteristics, becomes crucial for autonomous driving and traffic management. For autonomous driving, mmWave provides high-precision vehicle

With its notable advantages of high bandwidth, low latency, high directivity, and miniaturized devices, 5G mmWave technology has demonstrated signifcant potential and prospects in the industrial sector.

positioning and speed measurement data, offering a reliable basis for decision-making of the autonomous driving system. In traffic management, mmWave enables real-time monitoring and intelligent scheduling of traffic flow, significantly improving the efficiency and safety of traffic operations.

- **Steel Smelting Plants**

In steel smelting plants, mmWave is transforming applications such as machine vision and unmanned transportation. For machine vision, mmWave technology supports the real-time transmission and processing of high-definition video, enabling precise detection of parameters such as the color and quality of molten steel. In unmanned transportation, mmWave achieves precise positioning and remote monitoring of unmanned molten steel transport vehicles, ensuring the safety and efficiency of molten steel transportation. In addition, mmWave can also be applied in scenarios such as crane remote control, by retrofitting traditional cranes with high-definition cameras and other equipment to achieve unmanned operation, providing workers with a safer and more comfortable working environment.

- **Mines**

In the mining field, mmWave provides strong technical support for unmanned mining trucks in open-pit mines. There are a large number of mining trucks in open-pit mines, with urgent needs for automation upgrades. Leveraging the characteristics of mmWave, such as large bandwidth, high-precision positioning, and low latency, autonomous navigation and remote monitoring of unmanned mining trucks can be achieved. This significantly improves the safety and efficiency of mining operations while reducing labor costs and environmental risks, contributing to the sustainable development of the mining industry.

- **Ports**

In the port scenario, mmWave provides strong technical support for applications such as shore bridge remote control, gantry crane remote control, and waterway communication and sensing. Port equipment is densely deployed, with extremely high requirements for high-definition video return transmission and remote operation monitoring. mmWave, with its large bandwidth capability, can achieve real-time return transmission of high-definition video and remote operation monitoring, improving the efficiency and safety of port loading and unloading operations. In waterway communication and sensing, mmWave can support functions such as ship mooring perception and collision avoidance warnings, ensuring the smoothness and safety of waterway traffic.

With its notable advantages of high bandwidth, low latency, high directivity, and miniaturized devices, 5G mmWave technology has demonstrated significant potential and prospects in the industrial sector. As it matures, mmWave will find broader applications in various fields, providing more efficient, secure, and intelligent support for industrial scenarios such as industrial automation, high-definition video surveillance, remote healthcare, steel plants, open-pit mines, and ports. Looking ahead, mmWave will play an even more critical role in the industrial sector, contributing further to the intelligent transformation and sustainable development of society, and ushering in a new chapter in the sector's development. ZTE TECHNOLOGIES

mmWave: Enabling 10-Gigabit Backhaul for Superior Network Performance

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With the rapid advancements in communication technologies, the demand for data, faster internet speed, and reliable service is growing, especially in popular attractions, business districts, transportation systems, and large-scale event venues. The current network infrastructure is facing considerable challenges in maintaining its performance.

Millimeter wave (mmWave) technology offers a key solution for future high-density communication scenarios and varied service requirements. Specifically, it enables "10-gigabit backhaul"—the transmission of substantial data from end devices to the core network—thanks to its abundant bandwidth resources and outstanding data transmission rates. These features complement the current 5G spectrum, reduce network congestion in densely populated places, and enhance overall efficiency and service quality, providing customers with a smoother and faster internet experience.

How mmWave Empowers 10-Gigabit Backhaul

The extensive frequency resources and substantial bandwidth capacity of mmWave position it as a fundamental technology for achieving 5G's "10-gigabit speed." Compared to conventional sub-6 GHz bands, mmWave provides significantly more spectrum (Fig. 1). For example, by using continuous 800 MHz spectrum in the 26 GHz band, along with multi-carrier aggregation technology, mmWave provides highly efficient data transmission. According to 3GPP specifications, utilizing advanced antenna design and radio-frequency processing, a single mmWave device can achieve peak throughput of over 7 Gbps.

In September 2024, ZTE partnered with China Unicom and Qualcomm to conduct a high- and low-frequency new radio-dual connectivity (NR-DC) speed test on smartphones, attaining a peak downlink rate of 9.3 Gbps on a single device and a cell-level peak capacity surpassing 30 Gbps. This accomplishment established a new benchmark for ultra-high-speed network performance.

With its high frequency and short wavelength properties, mmWave is highly compatible with beamforming technology. Beamforming enhances signal strength in targeted directions while reducing interference in non-targeted regions, making mmWave systems ideal for implementation in high-density areas, such as popular attractions, central business districts (CBDs), stadiums, and metro lines.

Currently, ZTE's mmWave AAU equipment comprises 1,536 antenna elements, and can be further scaled for greater beamforming gain. This technology significantly enhances both uplink and downlink performance.

10-Gigabit Backhaul Scenarios and Use Cases

In high-traffic hotspots, heavy user data traffic during peak hours put considerable pressure on network resources. Implementing 5G mmWave in these areas with its "10-gigabit backhaul" capabilities enables accurate data offloading and reduces network congestion. Outdoor hotspot areas include

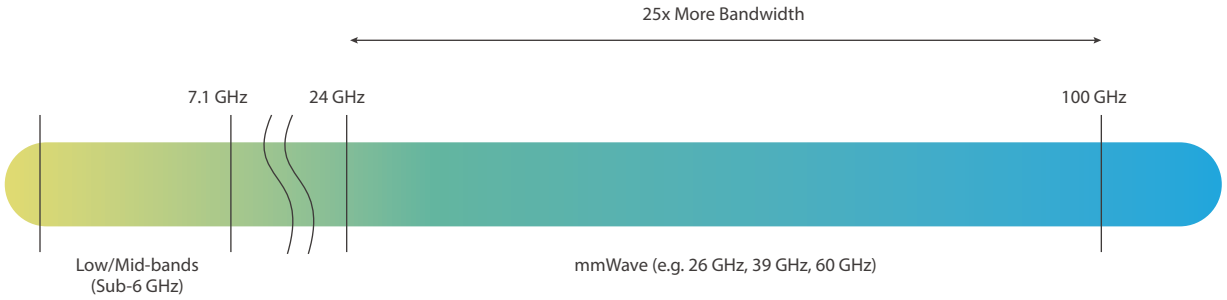


Fig. 1 mmWave spectrum.

public squares, stadiums, and main avenues, while indoor hotspots consist of transportation hubs, business buildings, and shopping malls.

Empowering Metro Systems with Faster Internet and Smart Operations

In major cities like Beijing, Shanghai, and Guangzhou, metros account for about 70% of public transportation usage. For instance, the metro lines in Shanghai span approximately 936.17 km, serving around 13 million passengers daily. Passengers require stable, high-speed internet access during their average 40-minute commutes for social interaction and entertainment. However, while outdoor 5G coverage exceeds 95%, metro systems remain less connected, with only 20% coverage. A key limitation is the existing cables that support frequencies between 800 MHz and 2.3 GHz, while 5G requires higher bands like 2.6 GHz and 3.5 GHz. Additionally, space constraints in tunnels, power supply limitations, and the need to upgrade existing infrastructure further slow down deployment.

ZTE has introduced the "Smart 5G-Powered Metro" solution to address these challenges: mmWave AAUs are installed in tunnels for 10-gigabit backhaul, and a complete 5G micro-station (QCell) system is deployed on each train. This solution meets passenger internet demands and supports the digital and intelligent transformation of metro system.

- **In the tunnel: mmWave 10-gigabit backhaul.** mmWave provides up to 15 Gbps in downlink backhaul, supporting seamless HD video streaming for over 1,800 passengers simultaneously. The integration of beamforming significantly decreases the need for AAU output power within the tunnel, hence reducing total energy usage. In the Shanghai Metro Line 4 project, the total power consumption of 5G system was reduced by 78%, saving 3.7 million kWh of electricity annually.
- **Inside train carriages: 5G QCell for enhanced passenger experience.** The 5G Qcell system aboard the train minimizes spatial limitations, where installing new 5G cables in tunnels is restricted or unfeasible, while also resolving signal loss problems induced by the train's metal body and Doppler shifts from high-speed travel. The maximum per-user throughput in the carriage can increase from 600 Mbps to 2.1 Gbps.

Supporting a 100,000-Person Music Festival

Thailand's "Big Mountain Music Festival" is a popular music event in Southeast Asia, drawing over 100,000 visitors annually. As attendance grew, network connectivity issues—particularly during peak periods—became more evident, resulting in network congestion and reduced audience satisfaction. To enhance network quality and customer satisfaction, mmWave sites were deployed at a 1.5 km line-of-sight (LoS) from the festival grounds, achieving a cell-level peak rate of 22 Gbps and offering ultra-fast, low-latency connectivity throughout the event.

During the festival, the backhaul site accommodated over 3,600 concurrent users at peak times, generating total data traffic of nearly 2,400 GB. Participants could share images and videos on social media at any time. Social media engagement surged by 300%, and audience satisfaction with network performance far exceeded that that of previous years.

mmWave technology is ushering in a new age of communications, offering substantial benefits in crowded attractions, commercial zones, metro transit systems, as well as for live streaming and virtual reality applications. As technology advances, mmWave will facilitate the development of a more intelligent and efficient society, providing unparalleled connectivity for users. ZTE TECHNOLOGIES

mmWave FWA: Leading the Future of Broadband Access and Maximizing the Value of 5G-A Networks

Wei Tao

RAN Solution Manager, ZTE

With the widespread adoption of 5G communication technology, fixed wireless access (FWA) has emerged as the first successful business scenario in the 5G era. In the 5G-A era, with the enhanced end-to-end capabilities of the network, this service will generate substantial returns on investment for operators. Global FWA connections are expected to grow from 160 million in 2024 to 350 million by 2030—an increase of over 118%—with the total number of connections accounting for nearly 20% of global fixed broadband connections. Among these, 80% of connections will be supported by 5G-A networks, revealing huge market potential.

Currently, FWA deployment relies predominantly on mid-to-low bands. The data usage of FWA users is usually several times higher than that of mobile users, making network capacity improvement crucial to ensure service quality for both FWA and mobile users. Millimeter wave (mmWave)-based FWA is the most effective way to enhance capacity. Data from a major sports event shows that low bands carried 8% of the data traffic, mid-frequency bands handled 41%, while high-frequency bands carried as much as 51%, demonstrating exceptional capacity support.

mmWave is characterized by large bandwidth, high transmission rates, and low interference, and the global end-to-end industry chain is relatively mature. mmWave FWA is gradually becoming the mainstream form of fixed broadband access.

mmWave FWA: Leading the Ultimate Performance and User Experience

The large bandwidth and serialized solutions of mmWave effectively enhance network performance, providing users with a better experience.

- **Ultra-Broadband, Ultra-High Speed**

With the strong support of large bandwidth and massive antenna technology, mmWave FWA is capable of delivering exceptionally high transmission speeds. ZTE, in collaboration with Malaysian operators, achieved field test speeds exceeding 30 Gbps. This remarkable performance pushes the user's online experience to new heights, providing robust support for home and small-to-medium business applications. For bandwidth-intensive applications such as high-definition video streaming, online gaming, and video conferencing, where broadband demands are extremely high, mmWave FWA undoubtedly offers unparalleled performance.

- **End-to-End Collaboration, Overcoming Coverage Challenges**

Due to its higher frequencies, mmWave has weaker physical propagation characteristics than lower frequencies, making mmWave network coverage a challenging issue. Leveraging its latest end-to-end system solutions, ZTE is able to effectively compensate for the coverage limitations of mmWave, significantly enhancing coverage capabilities. This

ZTE, in collaboration with Malaysian operators, achieved a peak speed exceeding 30 Gbps in field tests, which was recognized by the Malaysia Book of Records.

reduces costs and improves efficiency for mmWave FWA's commercial applications and also accelerates its deployment.

In 2023, ZTE conducted field tests of mmWave ultra-long coverage performance with a leading Thai operator, achieving an impressive 2.25 Gbps downlink speed over a distance of 11 km.

Furthermore, mmWave FWA does not require acquiring right-of-way, digging trenches, or penetrating walls. Deploying 5G mmWave FWA can dramatically shorten deployment times, which is crucial for connecting remote areas and quickly meeting market demands.

- **A Series of Solutions Ensuring Optimal Performance**

Through continuous exploration and validation, ZTE has developed a comprehensive mmWave FWA deployment solution, successfully transitioning from best-effort performance to deterministic performance assurance. By leveraging intelligent solutions such as DeepEdge, smart PBR, and Smart Steering within the base station, ZTE ensures deterministic assurance for FWA services and an exceptional user experience.

- **Multiple Product Series to Fulfill the Varied Needs of Customers**

After years of research and development, ZTE now offers multiple mmWave products series for various scenarios: the macro base station for outdoor macro coverage, supporting 1.6 GHz ultra-large bandwidth, which is the industry's first; the innovative intermediate-frequency pooled small cell solution MiCell, designed for indoor coverage in factories, offices, and CBDs; and the mobile CampSite base station, tailored for high-heat and emergency scenarios, enabling rapid deployment within one hour and supporting large-capacity installations.

ZTE Facilitating Scaled mmWave FWA Deployment

ZTE has successfully achieved large-scale 5G deployment globally. In Europe, we have supported an operator in actively developing mmWave FWA services, resulting in a steady 2% annual increase in average revenue per user (ARPU) over the past three years. ZTE is dedicated to helping operators use mmWave FWA to provide convenient broadband services for users, while driving strong commercial returns and enhancing brand value.

With its remarkable features such as high speeds and large bandwidth, mmWave FWA is well-positioned to meet the strong growth demands of future services like high-definition video and big data. Through continuous innovation in end-to-end solutions, ZTE has rapidly deployed mmWave FWA and significantly improved network performance. mmWave FWA will serve society more effectively, spreading digital value, transforming lifestyles, and opening new commercial avenues. ZTE TECHNOLOGIES

mmWave ISAC: Driving Low-Altitude Economy

Ren Tao

RAN Solution Manager, ZTE

Driven by supportive policies, the continuous expansion of application scenarios, and the rapid evolution of technology, the low-altitude economy—an ecosystem of diverse new industries and business models fueled by the growth of general aviation and unmanned aerial vehicle (UAV) industries—is emerging as a new engine for China's economic growth.

The Rise of the Low-Altitude Economy

The concept of the "low-altitude economy" was first introduced in China's "National Comprehensive Three-dimensional Transportation Network Planning Outline" in February 2021. In March 2024, the Government Work Report released at the annual "two sessions" meetings proposed proactively fostering new growth engines such as bio-manufacturing, commercial aerospace, and the low-altitude economy. This marked the first time the low-altitude economy was mentioned in the Government Work Report and categorized as part of new quality productive forces.

Since 2024, nearly 30 provinces have incorporated the development of the low-altitude economy into their government work reports or issued related policies. The favorable national policies have created an environment conductive to the development of the low-altitude economy. According to the "China Low-Altitude Economy Development Research Report (2024)" released by the CCID Research Institute of the Ministry of Industry and Information Technology, the scale of China's low-altitude economy reached 505.95 billion yuan in 2023, and it is expected to exceed 1 trillion yuan by 2026.

Key Requirements of the Low-Altitude Economy for Low-Altitude Networks

With the gradual maturation of low-altitude flight technologies, such as drones and electric vertical take-off and landing (eVTOL) vehicles, the low-altitude economy has expanded beyond traditional air transportation into diverse fields such as logistics, emergency rescue, aerial inspection, and aerial tourism. However, this diversification has also brought stricter requirements and challenges to network infrastructure, particularly in low-altitude communications and low-altitude surveillance.

In low-altitude communications, the core requirements focus on data transmission and video transmission between UAVs and ground stations. For data transmission, the network must ensure continuous, stable, highly reliable, and low-latency communication during low-altitude operations, enabling UAVs to receive operational instructions while allowing ground stations to track the flight status of UAVs in real-time and provide immediate feedback.

Video transmission, on the other hand, emphasizes the efficient transmission of high-definition images and videos captured by UAV cameras to the ground. This requires high uplink bandwidth; for example, the uplink rate requirement for 1080P videos is approximately 5 Mbps, while for 4K videos, it can reach up to 25 Mbps.

In low-altitude surveillance, it is necessary to monitor and provide services for cooperative UAVs to ensure orderly and controllable flight, as well as to detect and counteract non-cooperative UAVs to guarantee airspace safety.

However, traditional low-altitude communication

and surveillance technologies face numerous limitations, such as limited coverage for point-to-point communication, insufficient positioning accuracy in spectrum monitoring, and the difficulty of continuously networking low-altitude radars, all of which restrict the in-depth development of the low-altitude economy. The emergence of integrated sensing and communication (ISAC) technology in the 5G-Advanced (5G-A) phase has become a key solution to address these issues.

mmWave ISAC: Enabling Ubiquitous Connectivity and Easy Management in Low-Altitude Spaces

ISAC achieves a deep integration of communication and sensing technologies. In traditional technological architectures, communication and sensing are two distinct functional domains. Communication primarily handles the transmission of information, serving as the core function of 4G/5G cellular networks. In contrast, sensing focuses on monitoring and identifying the surrounding environment and objects, typically undertaken by sensing devices such as radars and cameras. The introduction of ISAC in the 5G-A phase equips communication base stations with unprecedented "visual" capabilities, similar to radar-like object detection and sensing functions.

The core of the ISAC base station lies in its dual capabilities of "communication" and "sensing," both realized using electromagnetic waves within the same frequency band. Specifically, the communication function modulates electromagnetic waves to carry and transmit information such as voice and data. In contrast, the sensing function focuses on analyzing echo signals of electromagnetic waves to accurately locate, measure distance, and determine the speed of target objects. This breakthrough enables communication base stations not only to transmit information but also to "see" and understand their surroundings, significantly broadening their application scenarios.

When selecting the frequency band for ISAC technology, millimeter wave (mmWave) has emerged as an ideal choice for achieving high-precision detection, due to its superior bandwidth advantages and beam narrowing characteristics. The large bandwidth of mmWave enables high-speed information transmission, while the narrow beamwidth facilitates more precise detection and positioning, bringing revolutionary changes to drone communication and surveillance in the low-altitude economy.

Key Technology of ZTE's Integrated Sensing, Communication, Computing and Intelligence

ZTE, with its profound expertise in cellular communication technology and exceptional innovative capabilities, has successfully launched multiple industry-leading core technologies for ISAC, leading industry development and providing strong technical support for the growth of the low-altitude economy.

In communication technology, to address challenges in low-altitude communication, such as severe interference, frequent handovers, and network jitter, ZTE has introduced the user-centric dynamic, distributed, and deterministic extremely large antenna array (D^3-ELAA) solution. This solution leverages dynamic coordination and distributed beamforming technologies to ensure stability and certainty in user experience, successfully pushing the boundaries of cellular networks and achieving ultra-stable communication in low-altitude environments. It provides reliable communication for low-altitude flying devices, such as drones.

In sensing technology, ZTE has also demonstrated its powerful innovative capabilities. To address the issue of insufficient coverage height of traditional base stations, ZTE has launched the industry's first monostatic ISAC AAU with a vertical scanning angle exceeding 60 degrees. Furthermore, to tackle the tradeoff between long-distance sensing and close-range blind zones in traditional radar technology, ZTE has creatively proposed dual-waveform intelligent sensing technology. By transmitting pulsed and continuous waves in a time-division manner, this technology achieves a perfect balance between long-distance sensing and close-range, blind-zone-free operation, further enhancing the practicality of sensing technology.

Building on basic sensing capabilities, ZTE has

The largest-scale mmWave ISAC network in Binjiang Economic Development Zone, Nanjing.

taken a step further by introducing an intelligent computing board into the baseband unit (BBU) of the base station, equipping it with native AI capabilities. This innovative measure enables the base station to perform advanced functions such as classifying and identifying sensing targets like drones and birds, as well as recognizing the identities of network-connected drones. This provides more precise and efficient technical support for low-altitude management and control.

ZTE Actively Drives Commercial Applications in the Low-Altitude Economy

Currently, ZTE has collaborated with operators and third-party partners to complete over 80 low-altitude communication and sensing pilot projects in 25 provinces and municipalities, covering a wide range of application scenarios such as logistics and delivery, low-altitude inspection, and low-altitude security in critical facilities.

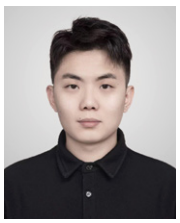
At the Talent Park in Nanshan District, Shenzhen, ZTE has completed the construction of 5G-A ISAC base stations, successfully validating applications such as electronic fence intrusion warning for low-altitude security, multi-target drone trajectory tracking, and route sensing for Meituan's food delivery drones. These applications essentially cover the full range of low-altitude sensing scenarios.

In Nanjing Binjiang Economic Development Zone, ZTE has implemented the largest-scale 5G-A mmWave ISAC network for low-altitude applications, deploying 10 mmWave ISAC base stations in a coordinated manner to cover 10 square kilometers of low-altitude space above Binjiang. Various low-altitude communication and sensing services have been validated, including simulations of complex air routes, low-altitude logistics feeder routes, and low-altitude air quality monitoring. This represents a significant step towards commercialization of 5G-A ISAC technology.

In Anyang, Henan Province, a large-scale UAV fleet test for 5G-A low-altitude communication and sensing was successfully completed. During the test, a fleet of 20 UAVs flew simultaneously, and multiple rounds of precise detection were conducted using mmWave ISAC base stations, with zero missed detections. This validates the stability and reliability of 5G-A mmWave low-altitude ISAC technology in complex environments, paving the way for future practical applications.

Looking ahead, ZTE will continue to deepen its involvement in the low-altitude economy. This sector will not only revolutionize transportation but also profoundly impact daily life and manufacturing processes. In this journey, 5G-A ISAC technology will pave the digital "skyway" for the high-quality development of the low-altitude economy, safeguarding it and helping to create a brilliant future. ZTE TECHNOLOGIES

mmWave ISAC: Pioneering a New Era in Water Area Development



Hai Zhenkun

RAN Solution Manager, ZTE

Wang Qinghong

Manager of mmWave ISAC Product Planning, ZTE

China is rich in water resources, with over 500,000 rivers totaling 430,000 kilometers. Among them, approximately 1,500 rivers cover an area exceeding 1,000 square kilometers. The country also has an 18,000-kilometer coastline and a total maritime area of over 4.73 million square kilometers. These vast water resources provide significant opportunities for industries such as shipping, fisheries, and tourism. In 2023, China's marine economy output surpassed 10 trillion yuan. With the rapid development of next-generation information and communication technologies, such as 5G, information infrastructure and digital applications in aquatic sectors have accelerated. Traditional water area industries are undergoing digital, green, and intelligent upgrades, giving rise to new industries, business models, and innovations.

Waterway Safety Urgently Requires Cost-Effective Regulatory Solutions

China's rapid development in the water economy calls for effective and economical solutions to ensure safety and compliance.

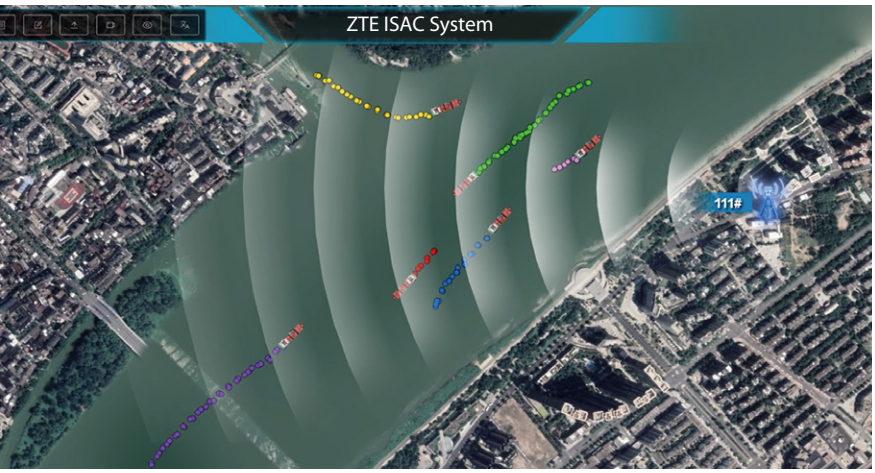
In waterway transportation, smart ports require comprehensive monitoring of vessels, cargo, and other operational elements to ensure waterway safety and regulatory compliance. With the continued growth of tourism, the number of lakes has been steadily increasing, requiring effective management, such as enforcing fishing bans during designated periods.

Current monitoring of waterways primarily rely on four systems: automatic identification system (AIS), vessel traffic services (VTS), closed circuit television (CCTV), and BeiDou navigation satellite system (BDS). These systems depend on vessels receiving GPS or Beidou satellite positioning signals and actively reporting their location via communication networks. However, adverse weather conditions, such as heavy rain or fog, can impair satellite positioning accuracy. Additionally, vessels without communication or positioning functions and floating debris on the water surface often go undetected, as active reporting technologies can't effectively identify such situations.

In maritime regulation, monitoring focuses on three key scenarios: nearshore law enforcement, illegal fishing detection, and unauthorized intrusion prevention. Vessels engaged in illegal activities generally avoid connecting to GPS systems, making monitoring more challenging.

Current maritime surveillance predominantly relies on radar systems combined with infrared cameras, but these methods have significant limitations, such as high deployment costs, fragmented network coverage, and weak real-time performance. Infrared thermal imaging technology, which operates within the 750–2500 nm wavelength range, cannot penetrate opaque obstacles, and its detection range is constrained by the curvature of the sea surface. Additionally, deploying optical cables for data transmission is difficult and costly.

Similarly, shore-based radar systems monitor isolated islands, ports, and offshore drilling



platforms, detecting small vessels within a 10 km range. However, the deployment cost is high and full-scenario coverage is diffcult. Moreover, data transmission via third-party interfaces often results in delays. As a result, by the time an alert is received, the vessel may have already left the monitored area. Mobile surveillance ships integrate multiple sensing technologies but are the most expensive option and cannot provide 24/7 continuous monitoring, limiting their use to high-priority maritime zones.

mmWave ISAC Empowers Water Area Regulation

Millimeter wave integrated sensing and communication (mmWave ISAC) technology offers significant potential for water area monitoring and regulation. By integrating communication, sensing, and computation within the mmWave spectrum, ISAC enhances resource utilization and sensing precision. Compared to traditional systems, ISAC reduces the need for additional sensing hardware, lowering costs and energy consumption, aligning with green and sustainable development goals. mmWave, with its rich bandwidth and high-speed transmission capabilities, enables precise distance measurement, speed detection, and real-time positioning. In dynamic water area scenarios, ISAC supports accurate vessel trajectory tracking and comprehensive monitoring of surface activities. Additionally, ISAC's networkable design ensures continuous and seamless coverage under various environmental conditions, making it suitable for diverse regulatory requirements.

ZTE Actively Promotes Research and Application of mmWave ISAC in Water Areas

ZTE has taken a leading role in the development and application of ISAC technology for water areas. It introduced the industry's first monostatic mmWave ISAC AAU, which integrates sensing signal transmission and reception into a single unit. ZTE's ISAC AAU employs a unique combination of continuous and pulsed waves, achieving high precision and long-range sensing capabilities. Real-time signal processing and trajectory analysis are performed using BBU computing, enabling fast and accurate data reporting with low latency. This cost-effective system offers a reliable solution for extensive water area monitoring.

ZTE has explored the application of mmWave ISAC technology in waterway regulation. For instance, in the Huangpu River, ZTE deployed ISAC technology for real-time monitoring of vessel trajectories, speeds, and other data, even in foggy and rainy conditions. This significantly enhances waterway safety and vessel management efficiency.

In the Wuhan section of the Yangtze River, ZTE has built a waterway electronic fence system that allows precise detection and real-time alerts for vessels illegally entering restricted zones, ensuring legal waterway safety. Additionally, in the Sun Island area of Harbin, ZTE implemented a system for synchronous detection of multiple vessels, achieving millisecond-level sensing delay to support collision avoidance, laying the foundation for creating a high-tech"Smart Winter Games."

As mmWave technology evolves, ISAC is expected to deliver expanded coverage, reduced costs, and simplified deployment. The deployment of ISAC systems will unlock greater value from 5G networks, enabling multi-functional applications and promoting sustainable development in water area management. ZTE TECHNOLOGIES

CelcomDigi, U Mobile and ZTE Achieve 5G-A Live Broadcast for Malaysia Games

Sukma (Sukan Malaysia or Malaysia Games) is a biennial sporting event and the highest-level competition in Malaysia. Covering all states and federal territories, it brings together top athletes from all over the country and attracts global attention. It is also known as the "Mini Olympic Games" of Malaysia. In Sukma 2024, Malaysian mobile network operators CelcomDigi and U Mobile, together with ZTE, launched a 5G-A wireless live broadcast solution, enabling a high-quality, multi-perspective, and highly interactive live broadcast of the opening ceremony and the sports games through national broadcaster Radio Televisyen Malaysia (RTM). This marked the world's first commercial use of 5G-A for event wireless live broadcasting.

Sukma 2024: World's First 5G-A Wireless Sports Broadcast

On August 17, 2024, the highly anticipated Sukma 2024 opened at Stadium Sarawak. RTM, CelcomDigi, U Mobile and ZTE jointly launched the "5G-A minimalist private network wireless live broadcast" solution, which successfully guaranteed high-quality live broadcast throughout the entire event.

At Stadium Sarawak, which accommodates 40,000 spectators, the solution deployed four 5G-A AAUs, providing full-venue signal coverage for two high-definition wireless live broadcast cameras. During the opening ceremony and subsequent live broadcasts, the two wireless cameras were deployed flexibly throughout the stadium, and videographers quickly positioned themselves as needed to ensure timely, accurate and efficient shot capture. The live camera feed was wirelessly sent back to the BBU, locally diverted by NodeEngine on the base station, and directly transmitted to the local OB Van. The overall solution achieved the shortest end-to-end data transmission, ensuring low latency performance and data security. It has effectively improved the experience for multiple parties, as outlined below:

Cheng Xuman

RAN Solution Manager, ZTE

Tey Khang Lian

CMO of ZTE Malaysia

Enhanced Viewing: Improving Online & Offline Experience

Online audiences can enjoy multi-angle live broadcasts, close-up camera interactions as well as stable mixing via 5G-A wireless cameras. Meanwhile, global audiences could use VR to "teleport" into the stadium, immersing themselves in the best perspective. On-site audiences benefited from high-speed data and seamless large-screen viewing, supported by a reliable network. 5G-A technology successfully provided wireless support for diverse cameras with varying specifications, resolutions, and transmission speeds. This integration with different equipment enabled novel perspective capture, scene exploration, and dynamic shot interactions, delivering a more immersive and engaging experience to all viewers. The active sharing and discussion on social media boosted audience viewership.

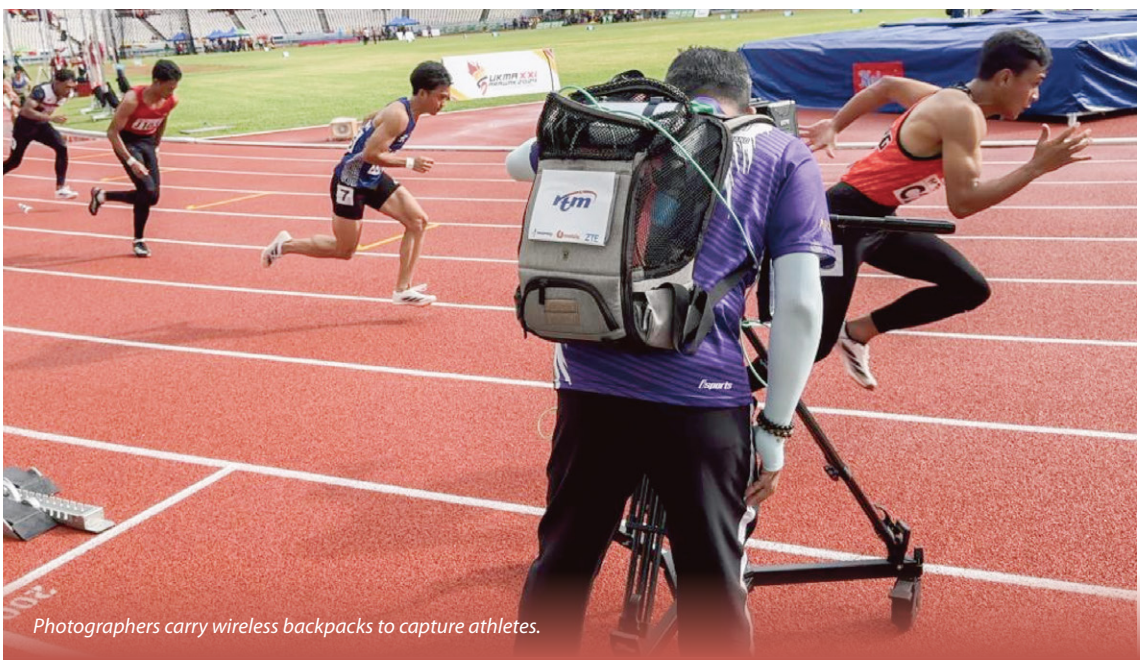
Enhanced Application Experience: New Perspectives for Premium Live Broadcasts

At Sukma 2024, RTM enhanced both deployment efficiency and the broadcasting experience through 5G-A. The wireless solution simplified on-site camera deployment while enabling camera operators to move freely throughout the venue. Videographers achieved precise shot capture while delivering compelling live broadcasts. Compared to traditional wired solutions, the wireless approach significantly improved operational convenience, filming safety, and live broadcast image quality. The flexibility of wireless cameras enabled the capture of many iconic shots during the event. The enhanced interactivity was well received by the audience, and the video quality, along with seamless integration with wired feeds, was highly recognized by RTM.

Enhanced Efficiency: Flexible and Reusable Deployment

After successful docking tests in the early stage, the on-site 5G-A deployment was completed in just one day. The solution is self-sustained and requires no changes to the existing network, greatly reducing the construction period and manpower investment. In terms of network deployment, the comprehensive 5G-A solution achieved a 36% reduction in labor costs, a 23% decrease in deployment cycles, and a 67% increase in equipment reusability. This represents a new application paradigm for live sports broadcasts, enhancing both efficiency and sustainability in event-based infrastructure.

As the first post-COVID Sukma, the 2024 event carried heightened expectations for a full return to



Photographers carry wireless backpacks to capture athletes.

ZTE's industry-exclusive mmWave AAU supporting 1.6 GHz deployed in stadiums.

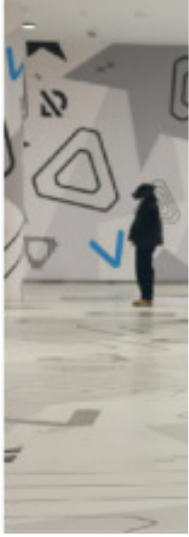
pre-pandemic scale. The 5G-A wireless live broadcast solution successfully presented high-quality live broadcasts of sports events to audiences around the world, providing a new, high-reliability commercial solution for live broadcasts of sports events. It also offered new directions for the future evolution of the live broadcast industry. Official data revealed a remarkable surge in Sukma viewership: the total audience across TV and social media platforms reached 85 million, marking an increase of 32.66% from the previous event. The video presentation effect and flexible mobility advantages were highly recognized by event organizers, broadcasters, athletes, and on-site audiences.

Shaping the Future of Sports Broadcasting with 5G-A

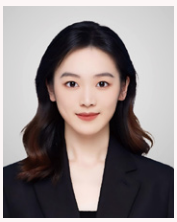
The journey of wireless transformation has been gradual, and using communication technology to drive industry development has always been ZTE's goal. When traditional wired solutions couldn't meet business requirements, and previous attempts with 4G, Wi-Fi, and conventional 5G for wireless transformation fell short, ZTE turned to 5G-A millimeter wave (mmWave), which offers large bandwidth and low latency. At the 2023 Hangzhou Asian Games, ZTE used 5G-A technology to improve the image quality and stability of wireless live broadcasts. During the 2024 CCTV Spring Festival Gala, the 5G-A minimalist private network wireless production and broadcasting solution guaranteed stable live broadcasts with multiple cameras. At Sukma 2024, ZTE further optimized its technical solution to achieve full-field roaming of multiple wireless cameras across large outdoor venues. Throughout the 6-hour opening ceremony and 7 days of event live broadcasts (12 hours per day), it delivered multi-perspective, highly interactive, and high-quality live coverage.

The global sports broadcasting technology market is experiencing explosive growth, projected to surge from $75.14 billion in 2023 to $114.21 billion by 2030. During the Paris Olympics, telecommunications technology demonstrated enormous potential in enhancing spectator experiences and innovating viewing modes, introducing new application scenarios and visual perspectives to live broadcasting. As the market expand, audiences are raising expectations for live experiences, further promoting the integrated application of new technologies in sports event broadcasting. It can be foreseen that using communication technology to enable wireless production and broadcasting of events will be a key direction for the future of live sports event broadcasting.

In response to the growing demand for wireless live event broadcasting, 5G-A has proved to be a perfect solution. ZTE will continue to deepen its involvement in the media production and broadcasting industry, driving development and innovation, enabling business applications and transformation, and bringing new possibilities to global users. ZTE TECHNOLOGIES



ZTE Supports USUNHOME to Complete World's First Commercial 5G-A Immersive VR Theater



Song Shuli

RAN Solution Manager, ZTE

Jimmy's works have illuminated countless youthful memories. These picture books, renowned for their distinctive artistic style and profound emotional resonance, have comforted generations. Now, this warmth and inspiration have arrived in Chengdu in the form of location-based entertainment (LBE) VR.

On October 31, 2024, "Jimmy Picture Book Metaverse Drama—My World is All You" opened at East Lake Park, Chengdu. This project is based on the classic picture book metaverse drama adaptation of Jimmy, carefully crafted by USUNHOME Group in partnership with ZTE, China Electronic Cloud, and China Telecom Sichuan Branch. By deploying a 5G-A minimalist private network, USUNHOME Group has completed the world's first commercial 5G-A immersive VR theater. This innovative solution not only achieves a highly immersive experience under lightweight equipment but also brings warm spiritual journeys to the audience.

The play presents a heartwarming story about pets, loss, and farewells. As the narrative progresses, players will experience the story physically unfolding around them, with VR technology enabling sensations like flying and rising within the expansive virtual space. The whimsical aesthetic, paired with a pure and simple storyline, resonates uniquely with audiences across different age groups, inviting diverse interpretations and emotional connections to the tale.

At the beginning of this project's design, traditional solutions faced many challenges in balancing commercial operational efficiency with an immersive user experience. First, if a backpack-based local rendering solution is used, the players need to carry a heavy backpack (up to 5 kg) for 45-60 minutes, which is quite difficult for adults, let alone children and the elderly. While the industry has shifted from backpack rendering to VR headset rendering, the limited computing power of VR headsets greatly affects graphic details and real-time interactive experience, making it difficult to show the high-quality content.

USUNHOME Group shifted its focus to "cloud

rendering" and deployed computing resources at the "edge" of the network. Through wireless streaming, high-quality content is delivered in real time. However, using Wi-Fi for wireless streaming brings significant signal interference as the number of users increases, severely restricting player capacity and impacting both operational efficiency and user satisfaction.

Under these circumstances, ZTE's 5G-A minimalist private network perfectly meets USUNHOME Group's requirements. This solution integrates edge computing with the robust capabilities of 5G-A networks, delivering high-speed, low-latency network coverage and intelligent XR service assurance. It solves the critical pain points in traditional technology solutions, ensuring a superior immersive experience for players.

ZTE has deployed a minimalist network within the 500-square-meter space. With the ZTE XRExplore platform, rendering resources can be flexibly scheduled, and service data is transmitted via the 5G-A network. Leveraging the high-speed and low-latency advantages of 5G-A networks, data transmission for edge computing becomes more reliable. The deployment features ZTE's innovative lightweight indoor millimeter wave (mmWave) micro base station, MiCell, enhanced by NodeEngine and SuperMicell's intelligent beam management solution. This improves network coverage, meets the mobility demands of XR applications, and provides deterministic assurance for a large volume of concurrent VR service data.

In addition, through the slot-level intelligent scheduling and optimization policy of 5G-A XR service, combined with XRExplore for network and media integration, the end-to-end stability and reliability of XR service are ensured. The air interface latency is less than 15 ms, guaranteeing high image quality during gaming at 4K @90 fps—a mainstream level in the industry, which addresses the headset's computing power limitations that cause degraded image quality and lag. Additionally, the issue of limited concurrent players in Wi-Fi-based VR headsets has been resolved.

At present, "My World is All You" has been officially put into commercial operation, offering

HD graphics and real-time data interaction for a multiplayer experience. Players step into a "comic book world," enjoying the freedom of immersive free-roam VR. Among the players are many years of Jimmy fans bringing their families to experience the game. One visitor, Ms. Wang from Chengdu, brought her child to play. After removing her VR headset, she was deeply moved. "It felt like stepping into the books I read years ago," she said. "I was fully immersed for 30 minutes." Notably, this lightweight solution is especially friendly to children and women, with the youngest players being just six years old. A seasoned VR enthusiast remarked, "I used to worry about network latency and stuttering, but the mmWave technology has eliminated those concerns. Now, I can fully focus on the experience itself."

The introduction of mmWave technology is leading an industrial revolution, heralding a new era of VR. With the power of mmWave, LBE VR not only solves the challenge of efficient operation, but also elevates the user experience to new heights, making a movie-like immersive experience a reality. With immense market potential, LBE VR is expected to become a pioneer in the large-scale commercial application of VR, opening a new era of business and entertainment. ZTE TECHNOLOGIES

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