GTI
5G-A Super Uplink Technology Evolution White Paper

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Preface

Driven by the rapid growth of emerging services such as digital assistants, embodied intelligence and connected vehicles, new types of terminals including AI smartphones, XR glasses and embodied robots are gaining widespread popularity at an accelerated pace. Characterized by intensive interaction, multi-modality and real-time sensing, these services impose higher requirements on the uplink capacity of mobile communication networks. The traditional service model dominated by downlink traffic is gradually evolving toward a balanced uplink-and-downlink architecture, bringing multiple challenges to communication networks in terms of uplink throughput and coverage.

GTI will continue to work hand in hand with industry partners to foster a mature ecosystem, accelerate the commercialization of technologies, and support high-quality development of the digital economy.

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1. Requirements and Objectives

1.1 Current Status of Network Services

Since 2010, mobile internet services have gradually evolved from symmetric communications, such as voice and SMS, to a "downlink-dominated" model represented by web browsing and video-on-demand (VoD). The service model in this phase generally exhibits a distinct asymmetric characteristic of "downlink-primary, uplink-secondary," with uplink traffic accounting for a relatively low proportion.

In recent years, with the explosive growth of services such as short video uploads, high-definition (HD) live streaming, XR real-time interactions, and AI Agents, user demand for active data uploading has increased rapidly, driving a continuous surge in uplink traffic. In certain high-density, highly interactive hotspot scenarios—such as the Guangzhou Spring Festival Fireworks display and the Harbin Asian Winter Games Opening Ceremony—uplink traffic has approached nearly half of the total traffic, resulting in a significant increase in uplink PRB Utilization.

These trends indicate that with the rapid development of heavy-uplink services like live video streaming, current network uplink capabilities are increasingly becoming the critical bottleneck affecting user experience. This necessitates the acceleration of research, verification, and commercialization of uplink enhancement technologies.

1.2 Service Development Trends

Driven by technologies such as artificial intelligence (AI), emerging applications including AI smartphones and PCs (hereafter referred to as AI Devices), AI smart glasses, Smart Connected New Energy Vehicles (hereafter referred to as Connected Vehicles), and smart robots (hereafter referred to as Embodied AI) are accelerating into a new phase of large-scale development. These emerging services generally feature strong interactivity, multi-modal sensing, and real-time synergy. They require the continuous uploading of HD audio/video, interactive environmental sensing data, and control commands, imposing higher requirements on network uplink capabilities.

(1) AI Devices: New Experiences with Smart Assistants AI Devices universally integrate AI Agents.

Intelligent systems capable of autonomous environmental sensing, intent understanding, decision-making, and execution. The current mainstream approach adopts a "Device-Cloud Synergy" architecture, where complex tasks are inferred by cloud-based large models, while raw data such as locally generated HD images, audio, and video streams must be uploaded to the cloud for real-time processing. Insufficient uplink capacity or limited data rates will cause AI Devices to experience cloud inference delays and unresponsive behavior, severely degrading the continuity and fluency of the interactive experience. It is projected that global AI Device shipments will reach 580 million units by 2030, introducing a requirement for a stable uplink guarantee of at least 4–5 Mbps in wide-area scenarios, which poses a tremendous challenge to existing network uplink capabilities. Therefore, the large-scale popularization of AI Devices urgently relies on the support of high-performance uplink networks to achieve an efficient, secure, and natural human-device-cloud closed-loop interactive experience.

(2) Connected Vehicles: New Scenarios for Wide-Area IoT As a new generation of mobile intelligent space.

Connected Vehicles integrate diverse functions such as autonomous driving, in-vehicle entertainment, and remote work, relying on mobile communication networks to achieve efficient vehicle-human-road-cloud synergy. Current intelligent driving systems for Connected Vehicles generally adopt a "data-driven + cloud training" development model. Vehicles must continuously upload sensing data, decision logs, and environmental information gathered during operation to optimize cloud-based large intelligent driving models. Looking ahead to the evolution of unmanned driving systems, real-time remote takeover will be necessary. This requires the backend to synchronously receive video streams from 4to 6n-vehicle 1080PHD cameras and strictly control the air-interface latency to within 20ms@99% to ensure the timely and reliable delivery of control commands. It is projected that global smart connected vehicle shipments will reach 27million units by 2030, introducing a wide-area uplink guarantee requirement of

5–20Mbps in complex scenarios such as urban areas, highways, and tunnels. Consequently, an uplink network that guarantees high data rates, high reliability, and high mobility is not only the foundational support for the continuous evolution of Connected Vehicles but also the critical prerequisite for achieving safe and controllable operations.

(3) Embodied AI: A New Form of Human-Machine Interaction Compared to traditional fixed-program robots.

Embodied AI utilizes general AI large models to achieve online cognitive reasoning and learning. Simultaneously, it must upload multi-modal sensor data—such as visual, tactile, and positional data—to the cloud in real-time for environmental modeling and decision optimization. This type of service is characterized by diverse data dimensions and strong transmission continuity, imposing higher requirements on network uplink data rates and reliability. Provided the network delivers continuous high-speed and stable-latency uplink capabilities, embodied AI can achieve ubiquitous cross-scenario deployment and efficient synergy, thereby propelling its transition from single-point demonstration to large-scale commercialization. Projections indicate global shipments will reach 270,000 units by 2030, with the majority requiring a wide-area uplink guarantee of at least 10Mbps in mixed indoor/outdoor scenarios.

1.3 Action Plan Objectives

To address the diversified development requirements of uplink service performance regarding system capacity, user data rates, and network coverage, as well as the rapid advancement of emerging services like AI devices, connected vehicles, and embodied AI, this white paper establishes a phased, tiered and progressive technical system.

The first level comprises technologies that have completed field test verification, including Frame Structure Adjustment, Supplementary Uplink (SUL), and Uplink 3-Component Carrier Aggregation (UL 3CC CA).

The second level involves technologies with established technical reserves that still require accelerated research and promotion, including 700MHz 2T+High Power and Uplink Data Compression (UDC).

The third level encompasses technologies currently in the standardization formulation or technical verification stage, geared towards long-term 6G evolution, including UE Aggregation, Millimeter Wave (mmWave), and Unified Time & Frequency Division Duplex (UDD).

2. Technology and Practice

2.1 Differentiated TDD Frame Structure

Compared to the fixed frame structure of 4G, the 5G flexible frame structure is a major innovation. It dynamically adjusts key parameters—such as subcarrier spacing, slot length, and the number of symbols—based on the service requirements of different application scenarios (eMBB, uRLLC, mMTC). This flexibility is the key for 5G to support diversified service scenarios.

In Time Division Duplex (TDD) mode, the network dynamically configures the downlink-to-uplink slot ratio (DL:UL=4:6, 6:4, or 7:3) according to service requirements. 3GPP defines various pre-configured frame structure options. The network selects these options on demand, shifting from a "one-size-fits-all network" to a "multi-purpose network driven by services," providing foundational support for diverse services.

2.1.1 Technical Principles

In response to the growing demand for uplink services, the network flexibly adjusts the proportion of uplink and downlink resources based on service needs.

For example, it can be adjusted to a 2.5ms single-period frame structure. Among these, the DDSUU frame structure (6D4U frame structure) is suitable for services with balanced uplink and downlink traffic, while the DSUUU frame structure (4D6U frame structure) is suitable for high-speed uplink services.

Adjusting the frame structure affects the single-user peak rates for both uplink and downlink, cell capacity, SSB configuration and coverage, scheduling and feedback timing, re-transmission mechanisms, and Carrier Aggregation (CA) relationships. Simultaneously, due to the increased volume of uplink data processed by the network side and the shortened time-domain interval of uplink frames, a situation may arise where previous uplink processing resources are not yet released before subsequent uplink data arrives. This causes delays in subsequent data processing, thereby imposing higher requirements on the baseband processing capabilities of the base station.

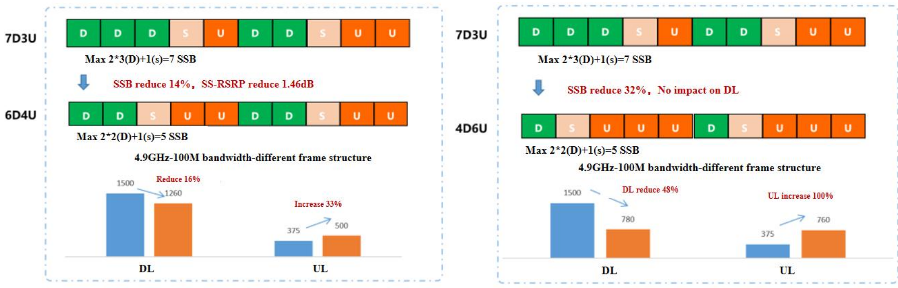

Figure 1. 4.9GHz Frame Structure Adjustment Impact

Table 1. 4.9GHz Frame Structure Adjustment Theoretical Performance

Frame Structure	Uplink Peak Rate (Mbps)	Downlink Peak Rate (Mbps)	Broadcast Coverage	Uplink Capacity	Downlink Capacity
2.5 ms dual-period: DDDSU DDSUU (7D3U)	375	1500	7 SSBs, 100%	Baseline	Baseline
2.5 ms single-period: DDSUU (6D4U)	500	1260	5 SSBs, 86%	+33%	-16%
2.5 ms single-period: DSUUU (4D6U)	750	780	2 SSBs, 68%	+100%	-48%

2.1.2 Application and Practice

In TDD networks, the frame structure determines the time-domain resource allocation ratio between uplink and downlink. Based on service requirements (such as uplink/downlink data asymmetry and latency requirements), a suitable frame structure configuration can be flexibly selected:

1. High-downlink service scenarios (primarily eMBB services): Typically uses the 2.5ms dual-period (DDDSU DDSUU, 7D3Uframe structure). This is suitable for HD video streaming, data downloads, and indoor hotspot coverage. It maximizes the downlink time-domain resource ratio to meet user demands for high-speed downloads.

2. Symmetric service scenarios (relatively balanced uplink and downlink): Typically uses the 2.5ms single-period (DDSUU, 6D4Uframe structure). This is suitable for bidirectional communications such as video conferencing and real-time collaboration. It provides a relatively balanced time-domain resource allocation, preventing either link from becoming a bottleneck and ensuring smooth interactions.

3. High-uplink service scenarios (uplink-intensive): Typically uses the 2.5ms single-period (DSUUU, 4D6Uframe structure). This is suitable for applications with robust uplink demands, such as video surveillance, cloud gaming, and Industrial IoT (IIoT) sensor data backhaul. It increases the uplink time-domain resource ratio to guarantee uplink service requirements.

2.2 Supplementary Uplink (SUL)

Current 5G networks primarily utilize NR TDD networking, where uplink and downlink time-division multiplex the same spectrum resources. Constrained by current downlink-to-uplink slot ratios, available uplink time-frequency resources are relatively limited, becoming a bottleneck for improving user uplink experience.

The 5G SUL technology transmits uplink data alternately across the NR TDD spectrum and the NR SUL spectrum. This significantly expands the user's uplink time-frequency resources without affecting downlink resources, thereby effectively enhancing the uplink user experience.

2.2.1 Technical Principles

In NR TDD cells, SUL technology introduces an independent Supplementary Uplink (SUL link) to form a synergistic complement with the original TDD uplink (also known as Normal Uplink, NUL link). Without reducing downlink resources, the network dynamically schedules the UE to use different uplinks based on timeslots. During the uplink timeslots of the NUL link, the UE transmits uplink data via the NUL link; during the downlink or mixed timeslots of the NUL link, the UE switches to the SUL link for uplink data transmission, achieving dynamic and optimized resource allocation, as shown in Figure 2.

Through SUL technology, uplink data can be carried in TDD downlink timeslots using the SUL frequency band without affecting downlink transmission. This enables full-slot uplink transmission, significantly expanding uplink time-frequency resources and effectively meeting the transmission demands of large-bandwidth uplink services such as HD live streaming.

Theoretically, the single-user uplink peak rates of 4.9GHz + F SUL and 4.9GHz + A SUL can reach 575Mbps and 475Mbps, respectively. In a 4.9GHz edge coverage scenario, using a baseline point where the 4.9GHz rate is 1Mbps, the theoretical uplink rates of 4.9GHz + F SUL and 4.9GHz + A SUL can reach 20Mbps and 14Mbps, respectively. This significantly enhances the uplink experience of 4.9GHz edge users and increases capacity by 60%and 30%.

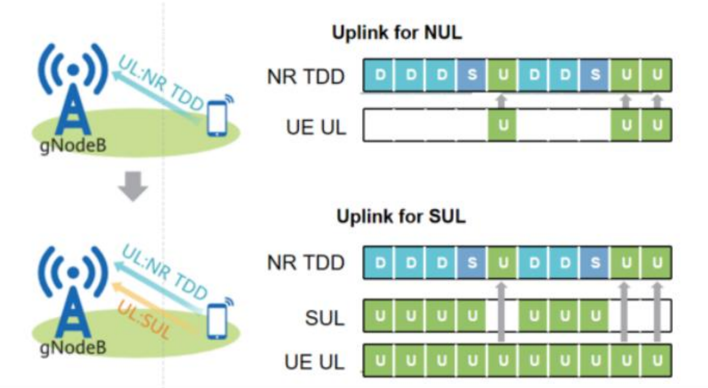

Figure 2. Supplementary Uplink Principle Diagram

2.2.2 Application and Practice

Through the complementation of high and low frequencies, SUL technology effectively enhances the uplink coverage capability of NR carriers (especially TDD carriers). It significantly improves the uplink rates for cell-edge users while further boosting uplink peak rates by increasing the spectrum resources available for single-user uplink transmission.

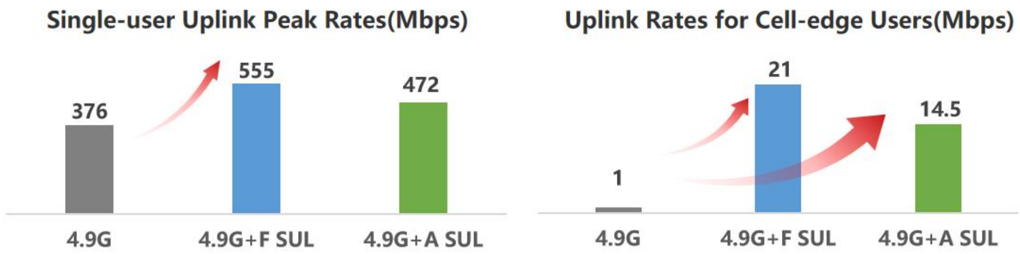

Figure 3. SUL Field Test Results

In 2025, industry's field test results show that the single-user uplink peak rates of 4.9GHz + F SUL and 4.9GHz + A SUL are approximately 555Mbps and 472Mbps, respectively. In a 4.9GHz edge coverage scenario, using a baseline point where the 4.9GHz rate is 1Mbps, the measured uplink rates of 4.9GHz + F SUL and 4.9GHz + A SUL reach 20Mbps and 14Mbps. This provides a foundation for subsequent commercial deployment.

2.3 Uplink 3-Component Carrier Aggregation

With the rapid development of applications such as ultra-high-definition (UHD) video backhaul and real-time network live streaming, user demand for high uplink rates is increasing daily. Uplink 3-Component Carrier Aggregation (UL 3CC CA) significantly improves the single-user uplink peak rate through cross-band and cross-RAT spectrum resource integration, demonstrating broad application prospects in hotspot areas and high-value scenarios.

2.3.1 Technical Principles

UL 3CC CA jointly schedules and performs parallel data transmission across multiple dispersed uplink carriers (including both TDD and FDD modes). This achieves bandwidth superposition for the terminal's uplink, substantially enhancing the single-user uplink peak rate performance.

5G introduced Carrier Aggregation (CA) technology in R15. However, due to constraints such as terminal power consumption and transmission channels, the uplink supports a maximum of two carriers for parallel transmission, resulting in relatively limited uplink CA gains. To improve uplink CA performance, 3GPP standards introduced the UL Tx Switching feature in subsequent releases. This supports the UL CA dual-carrier Time Division Multiplexing (TDM) transmission mode, achieving channel switching through uplink antenna alternate transmission to guarantee TDD uplink dual-stream capabilities, as shown in Figure 4. The R17release introduced UL 3CC CA, expanding the supported number of carriers from the previous two-carrier aggregation to two-band three-carrier aggregation.

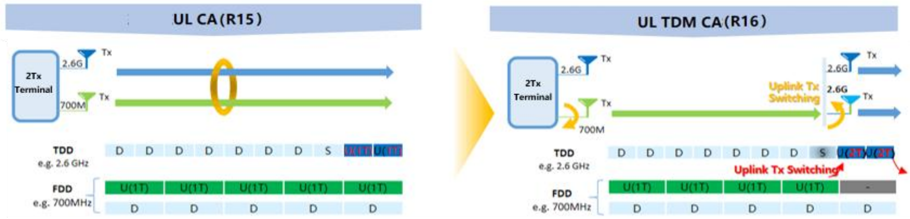

Figure 4. UL Tx switching feature

Depending on the networking mode, there are two primary typical configurations:

1. TDD+FDD UL 3CC CA: For instance, combining 2.6GHz (100MHz + 60MHz) with a 700MHz (30MHz) carrier. This balances the large bandwidth characteristics of high frequencies with the wide coverage characteristics of low frequencies, achieving balanced development of both uplink and downlink performance.

2. TDD+TDD UL 3CC CA: For instance, combining 2.6GHz (100MHz + 60MHz) with a 4.9GHz (100MHz) carrier. This leverages the large bandwidth advantages of high frequencies to effectively enhance single-user uplink peak capabilities.

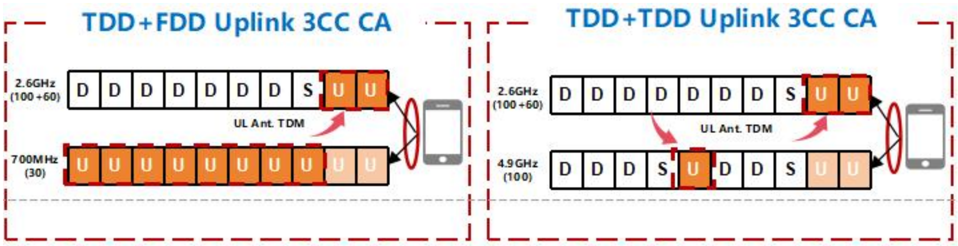

Figure 5. UL 3CC CA

Compared to a single 2.6GHz 100MHz carrier, a 3CC CA composed of 2.6GHz, 700MHz, and 4.9GHz can achieve a maximum aggregated bandwidth of 260MHz, and the theoretical single-user peak rate can be more than doubled.

2.3.2 Application and Practice

In scenarios such as live sports broadcasting and XR/VR immersive communications, users or devices must upload HD live video streams or perform real-time backhaul of massive data, demanding high single-user uplink rates from the network. UL 3CC CA offers the advantage of substantially boosting the single-user uplink peak rate. It effectively overcomes single-user uplink communication bottlenecks, guarantees the rapid backhaul of UHD video and massive data, and provides high-performance uplink experiences.

The tests in 2025 show that the 2.6GHz (160 MHz) + 4.9GHz (100MHz) combination improves uplink performance by 208.4%, and the 2.6GHz (160MHz) + 700MHz (30MHz) combination improves uplink performance by 161.1% (with the device supporting 700MHz dual transmission). This laid the foundation for subsequent commercial deployments.

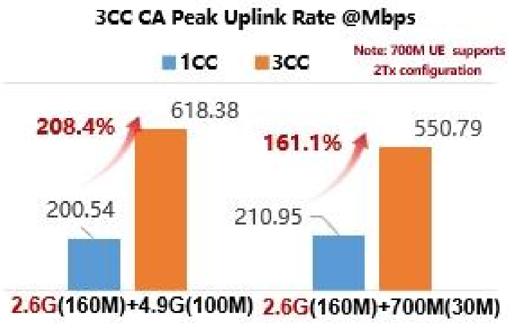

Figure 6. UL 3CC CA Field Test Results

2.4 700MHz High Power

The 700 MHz frequency band meets both deep coverage and wide-area coverage scenarios simultaneously. However, due to low-frequency characteristics, its antenna size is larger than that of other frequency bands, generally leading devices to adopt a single-transmit-antenna (1T) design. Simultaneously, constrained by Specific Absorption Rate (SAR) requirements for devices in FDD networks, devices typically use a 23dBm transmit power. This restricts further improvements in uplink coverage and user experience.

This significantly improves user data rates, expands coverage, and effectively enhances the uplink link performance of the 700 MHz band.

2.4.1 Technical Principles

The device transmit power is increased from 23dBm to 26dBm. Compared to 1T+26dBm capabilities at 700MHz, supporting 2T+26dBm requires an additional independent transmission path containing components such as a power amplifier, filter, switch, and power supply.

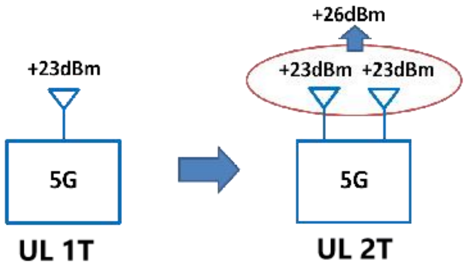

Figure 7. Device 2T+26 dBm Capabilities

Compared to single-antenna uplink transmission, dual-antenna transmission can increase the single-user uplink peak rate by 100% theoretically. The transmit diversity gain combined with the 26dBm high-power gain can improve uplink coverage by 4–5dB, bringing a significant enhancement to the service experience of users at the mid-to-far edges of the cell.

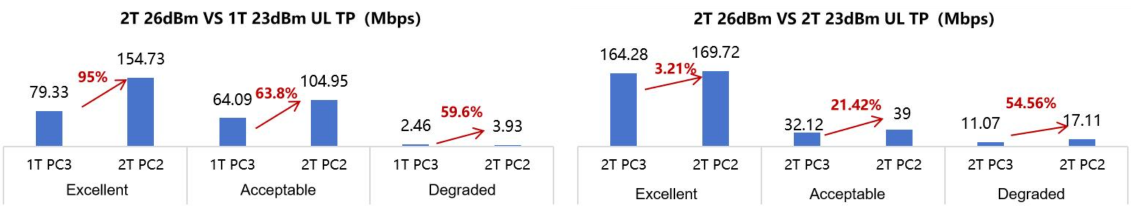

Figure 8. Performance Improvement Effects

2.4.2 Application and Practice

700 MHz 2T+26dBm devices offer high application value in deep coverage areas, wide-area coverage areas, and specific scenarios, such as indoor/outdoor coverage, rural/remote mountainous areas, and ultra-long-distance island coverage:

1. Outdoor-to-Indoor Coverage Scenarios: The 700MHz band possesses strong penetration capabilities. Combined with the device's 2T 26dBm high power, uplink capabilities are significantly enhanced. This improves VoNR voice and video call quality in weak coverage areas, reduces reliance on indoor distributed systems (DAS), and saves network construction costs.

2. Rural/Remote Mountainous Scenarios: In wide-area environments with sparse base stations, 26dBm devices provide higher transmit diversity and power gains. This further improves uplink performance and enhances edge coverage, providing reliable communication guarantees for digital services such as remote education, smart agriculture, and environmental monitoring.

3. Ultra-Long-Distance Maritime Coverage Scenarios: The 700MHz band features low

propagation loss and weak surface reflection, enabling continuous coverage over dozens of kilometers. The 2T+26dBm device capability provides additional uplink gain, significantly enhancing the uplink stability of mobile devices on fishing vessels and offshore platforms to support critical services like emergency communications and AIS positioning backhaul.

The test results in 2023 demonstrate that 700MHz 26dBm devices deliver remarkable effects in improving uplink service rates, edge service experiences, and coverage distance, comprehensively enhancing 700 MHz wide-area coverage capabilities.

2.5 Uplink Data Compression (UDC)

In high-density user scenarios such as football matches and concerts, a massive number of devices initiating service requests simultaneously causes network congestion, severely impacting user experience. The 3GPP R17 standard introduced the Uplink Data Compression (UDC) mechanism. By having the device compress repetitive data in uplink packets and the base station decompress them, this mechanism effectively saves uplink air-interface resources, reduces device transmit power, and achieves improvements in uplink transmission efficiency and coverage range.

2.5.1 Technical Principles

5G UDC technology introduces data compression and decompression mechanisms at the PDCP layer of both the device and the base station to compress repetitive data within the headers and payloads of uplink packets entirely. When transmitting the same service data, the UE can use less power and fewer air-interface resources. Particularly in edge areas, under the same signal and service experience requirements, the UE can be located further from the base station, thereby enhancing data transmission efficiency and cell uplink coverage.

Compression buffers are configured on both the device and base station sides to store repetitive data. The device adds data compression-related information to the PDCP layer packet header; the compression principle is shown in Figure 10. Based on the compression information in the PDCP header and the contents of the compression buffer, the base station decompresses the uplink data packets, reassembles them, and delivers them to higher layers. UDC can be configured at a Data Radio Bearer (DRB) granularity based on 5QI (5QI 5), or based on service types, where the base station activates the UDC function according to the identified service. UDC gain is reflected by compression efficiency — the ratio of compressible bytes to pre-compression bytes. Higher compression efficiency means fewer air-interface resources are required, resulting in extended uplink coverage.

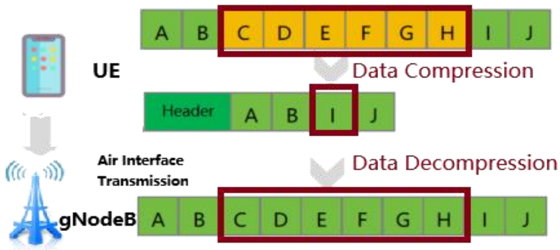

Figure 9. UDC Technical Principle Diagram

2.5.2 Application and Practice

Verification shows that for voice services, VoNR compression efficiency can reach 50% – 84%, with larger compression buffers yielding higher gains. For ViNR, when the compression buffer is configured to 4Kbytes, compression efficiency can reach 74%. Particularly at edge locations, VoNR setup latency, Invite signaling transmission duration, RTP latency, and jitter are all improved. Edge coverage can be enhanced by 1 – 3dB, the drop-call distance is extended by 50meters, and the service experience for edge users is improved.

For data services, such as instant messaging, live streaming, and video, the compression efficiency is approximately 10%-30%. For gaming services, uplink compression efficiency exceeds 40%. This saves air-interface resources, elevates the user edge experience, and lowers device power consumption.

Therefore, in hotspot and high-capacity scenarios like football matches and concerts, massive and concentrated user volumes easily cause voice service access congestion. Implementing UDC can save interaction time for voice service signaling, reduce access congestion, and lower resource occupation, allowing more users to complete voice communications. Concurrently, compressing a large volume of user data services frees up resources for heavy-traffic services without UDC gains, such as live video streaming, ensuring performance in high-capacity scenarios. Furthermore, in deep coverage scenarios like underground parking lots or wide-area coverage scenarios in remote regions, UDC technology protects the service quality of edge users from the impacts of weak coverage, guaranteeing service experience while extending network coverage.

Figure 10. UDC Application Scenario Diagram

Moving forward, UDC technology will focus on exploring application value in hotspot and high-capacity scenarios, such as sports and cultural events and transportation hubs, providing network support for innovative applications like the Metaverse, 4K/8K live streaming, and the Industrial Internet.

In September 2025, the test results demonstrate that UDC technology can significantly enhance uplink coverage and improve the edge user experience.

2.6 UE Aggregation

Facing multiple constraints in bandwidth, channels, and resources for single devices, which make it difficult to meet service requirements in certain scenarios, UE Aggregation technology establishes a direct link between a Remote UE experiencing poor channel quality and another UE. All or part of the data is "relayed" through the latter to the network, achieving joint data transmission and effectively improving transmission data rates and reliability.

2.6.1 Technical Principles

UE Aggregation technology transmits all or part of the Remote UE's data via the Relay UE's wireless link. The Remote UE and Relay UE can interact through methods such as Wi-Fi, Bluetooth, or wired connections to achieve data forwarding. This enhances the transmission data rate of the Remote UE or improves latency and reliability performance.

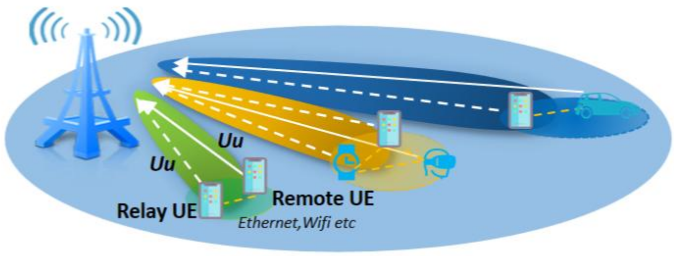

Figure 11. UE Aggregation Configuration Diagram

By performing data splitting, duplication, and merging at the PDCP layer, the base station achieves coordinated configuration across multiple devices, providing higher-layer applications with transmission capabilities several times greater than those of a single device. Its core mechanisms include:

1. Air Interface Selection: A Remote UE communicates with the base station via a direct path and an indirect path under the same gNB. The direct path communicates directly with the base station via the Uu interface. The indirect path forwards data through a non-3GPP Connection (N3C, such as Wi-Fi, Bluetooth, wired, etc., excluding PC5 links) to a Relay UE, which then communicates with the base station.

2. Aggregation UE Selection: The base station selects an appropriate Relay UE for aggregation configuration based on the capabilities of both the Remote UE and the Relay UE, as well as information such as the Remote UE's requests and the candidate Relay UE list.

3. Data Transmission Selection: Based on different service requirements, transmission is categorized into split mode and duplicate mode. For high data rate scenarios, data is split at the transmitter's PDCP layer and sent via direct and indirect paths, respectively; the receiver's PDCP layer merges them, thereby increasing service rates. For high-reliability scenarios, data is duplicated at the transmitter's PDCP layer and sent via direct and indirect paths; the receiver's PDCP layer merges them, thereby reducing transmission latency and improving reliability.

2.6.2 Application and Practice

Currently, real-time interactive services such as live streaming, video conferencing, and drones are demanding increasingly higher definitions for video uploads and strict latency requirements.

The split mode of UE Aggregation can boost uplink transmission bandwidth, satisfying the demands of real-time interactive services for high definition and low latency (1080P/4K/VR). UE Aggregation can also expand network coverage by leveraging the physical distance between aggregated devices, ensuring service continuity in outdoor edge scenarios. Simultaneously, the duplicate mode of UE Aggregation transmits the same data over two paths concurrently, enhancing the reliability of edge data transmission and improving the stability of the service experience.

Figure 12. UE Aggregation Live Demonstration and Edge Rate Performance Comparison

In October 2025, GTI members including China Mobile, MediaTek, vivo and ZTE jointly released the industry's first end-to-end capability verification results for UE Aggregation technology based on the 3GPP R18 standard. The verification completed end-to-end testing for video uploads and uplink live streaming. This marks a critical breakthrough for 5G-Advanced UE Aggregation technology, moving from "standard definition" to "industry realization." It provides broader application spaces and superior service experiences for the robust development of emerging services such as immersive communications, embodied AI, connected vehicles, and the low-altitude economy.

Preliminary verification shows that by employing the UE Aggregation split mode, the uplink rate for edge cell users can be improved by 2 to 10 times, transforming live video streaming quality for deep-indoor devices from stuttering to smooth. By employing the UE Aggregation duplicate mode, the latency of online gaming for edge cell devices is reduced, and reliability is improved by 5%-10%, guaranteeing the gaming experience, with further room for improvement in the future.

2.7 Millimeter Wave (mmWave)

Addressing the challenge that traditional low-frequency spectrum resources struggle to meet the requirements of certain services for ultra-high data rates and ultra-low latency, mmWave technology provides a critical solution. mmWave generally refers to electromagnetic waves with wavelengths ranging from 1 to 10 millimeters and frequencies from 30GHz to 300GHz. Compared to the 5G Frequency Range 1 (FR1) band below 6GHz, the available continuous bandwidth in the mmWave band increases by 10 times. It can provide a peak rate of over 7Gbps and millisecond-level latency, serving as a key enabling technology for building next-generation intelligent digital infrastructure.

2.7.1 Technical Principles

The single-carrier bandwidth of 5G mmWave reaches 200MHz and can support 2 to 4carriers, significantly enhancing user data rates by leveraging its ultra-large bandwidth. Theoretical calculations and field measurements demonstrate that mmWave can achieve a downlink user rate of over 7Gbps and an uplink user rate of over 2Gbps. Concurrently, by adopting a 120kHz subcarrier spacing, lower user latency can be achieved. Due to the high frequency band, mmWave typically employs an ultra-large-scale antenna array to obtain sufficient transmit power. This results in extremely narrow mmWave beams, which effectively reduce co-channel interference and improve link reliability. Furthermore, owing to the wide bandwidth, mmWave can achieve higher positioning accuracy.

2.7.2 Application and Practice

mmWave offers advantages such as large bandwidth, high data rates, low latency, and high-precision positioning. Under a 200MHz single-carrier configuration, the downlink peak rate can reach 1.68Gbps using the DDDSU frame structure, and the uplink peak rate can reach 1.04Gbps using the DSUUU frame structure. Under a 400MHz bandwidth 2-carrier configuration, the downlink peak rate can reach 3.37Gbps using the DDDSU frame structure, and the uplink peak rate can reach 2.09Gbps using the DSUUU frame structure. The Round-Trip Time (RTT) is approximately 4ms, the air-interface average latency is 2.5slots (0.3125ms), and cellular positioning can achieve sub-meter-level accuracy. Based on analysis, the primary application scenarios suitable for mmWave are:

1. Extreme Experience Areas: Such as landmarks and retail stores. Deploying mmWave provides an ultimate network experience, creates high-quality service benchmarks, and assists in elevating brand image.

2. High-Traffic Hotspot Areas: Such as stadiums, concerts, and transportation hubs. mmWave is utilized for precise coverage and traffic offloading to efficiently cope with instantaneous, massive concurrent traffic demands and guarantee users' high-speed access experience.

3. Industrial Sectors: Leveraging the low-latency and high-positioning-accuracy characteristics of mmWave to meet the stringent latency and reliability requirements of services such as Programmable Logic Controller (PLC) industrial control.

2.8 Unified Time & Frequency Division Duplex (UDD)

Unified Time & Frequency Division Duplex(UDD) integrates the large bandwidth advantage of TDD bands with the low latency advantage of FDD bands. By simultaneously performing uplink and downlink data transmission within a single subframe, it achieves improvements in uplink coverage and capacity, providing users with ultimate performance.

2.8.1 Technical Principles

The basic principle of UDD is dividing a TDD spectrum into frequency-domain non-overlapping subbands, including an Uplink Subband (UL subband) and a Downlink Subband (DL subband). The base station can simultaneously transmit downlink data in the DL subband and receive uplink data in the UL subband, achieving full-duplex transmission and reception. UDD combines the advantages of FDD and TDD. Compared to FDD, which requires symmetric spectrum with identical bandwidths, UDD can more flexibly configure the bandwidths of the uplink and downlink subbands to adapt to asymmetric service traffic without needing symmetric spectrum resources. Compared to TDD, because UDD can simultaneously transmit and receive on different subbands, transmission waiting latency is reduced. Moreover, due to the presence of more consecutive uplink slot resources, uplink coverage and throughput performance can be improved.

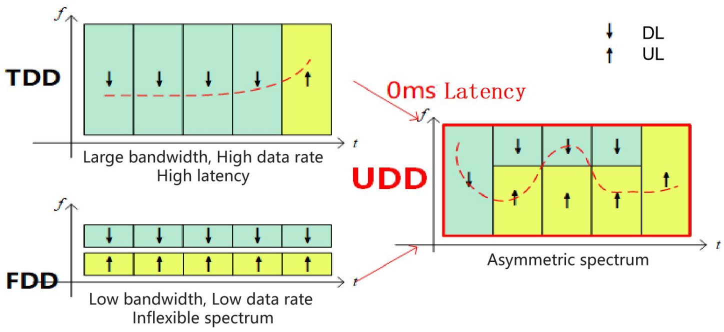

Figure 13. UDD Technical Principles

2.8.2 Application and Practice

Oriented towards ToC, UDD can address the uplink coverage shortfall of the U6G spectrum and overcome the challenges of 5G/6G co-site deployment. Oriented towards ToB, UDD can satisfy the stringent deployment requirements of industrial on-site networks for deterministic low latency and ultra-large uplink transmission.

In 2024, GTI members, China Mobile and ZTE, have jointly carried out research and development on key technologies and prototype products, and completed technology verification of the 4.9GHz expanded UDD prototype. This achieved a 1.7-fold increase in the uplink peak rate, a 15ms reduction in end-to-end latency, and a 5dB enhancement in uplink coverage.

3. Initiatives

To systematically enhance uplink capabilities and meet the diversified requirements of future services regarding capacity, network coverage, and user data rate, GTI is advancing technology and industry development in a phased, focused, and progressive manner.

Various technologies complement each other and work synergistically across different service scenarios, network loads, and coverage conditions. Together, they provide flexible and diverse technical paths and capability support for the network, effectively propelling the continuous development of uplink services and a comprehensive upgrade of the network experience.

Looking ahead, GTI calls on the industry to uphold the philosophy of openness and cooperation, with all parties jointly advancing the industrial development of uplink enhancement.Together, we will build an uplink enhancement industry ecosystem characterized by unified standards, open synergy, and joint value creation, accelerating the release of the development potential of emerging business formats such as AI devices, connected vehicles, and embodied AI, and providing solid support for promoting the high-quality development of the digital economy.