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Conceptual Verification of Integrated Heterogeneous Network Based on 5G Millimeter Wave Use in Gymnasium

Wanlin Yang

Department of Physical Education, Jining University, Jining 273155, China; yangwanlin345@163.com

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Abstract: Aiming at the problem that the optical link may be too expensive or even impossible to achieve in a large number of locations in the central part of the backhaul line, the proof-of-concept (PoC) verification of a millimeter-wave integrated heterogeneous network (HetNet) is proposed. HetNet includes a traditional macrocell network and a new small unit that uses a millimeter wave for backhaul line and link access. The concept of a segmentation control plane and user plane was introduced. In the HetNet integrated millimeter wave, the control plane and the user plane were segmented to support the uninterrupted connection and enhance the capacity of the millimeter wave small base station. Millimeter wave communication could be used not only for access links, but also for wireless backhaul links, which will facilitate the installation of small millimeter wave cells. Through conceptual verification (PoC), the feasibility of millimeter-wave integrated HetNet prototype with millimeter wave technology used for return lines and link access is proved.

Keywords: 5G cellular networks; millimeter wave; heterogeneous networks; backhaul; conceptual verification

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1. Introduction

The fifth generation mobile network [1] (5G) that is expected to be deployed in 2020 will become the main source of Internet connectivity thereafter. With the dramatic increase in the number of mobile connected devices and the endless emergence of new services, 5G research and development has also been extended [2]. 5G can increase mobile bandwidth [3] and provide a large number of machine-type communications for wireless sensors, meters, and drives. 5G should have the capacity to support a large number of connected devices and various types of traffic.

5G requirements include extremely high data rates, very low latency, the ability to handle large numbers of devices, high reliability, energy efficiency, and reasonable cost [4]. To cope with the growing traffic demand, 5G needs to take a heterogeneous network (HetNet) architecture, as well as multiple radio access technologies [5] (RAT). Researchers have done a lot of work for this. Literature [6] designed a network selection algorithm for message transmission in security applications. Starting from the message transmission quality requirements in security application, the algorithm comprehensively considers multiple parameter indicators of message transmission service quality in security application, including end-to-end delay, packet loss rate, and transmission rate. The Communications Research Laboratory (CRL) [7] developed 60-GHz access technology in 2000, enabling the world's then-fastest data rate of 128 Mbps. Intel subsequently released the first WiGig [8] chipset. In 2014, Qualcomm released a processor combining LTE (Long Term Evolution) and WiGig standards [9]. The first wireless local area networks (WLAN) AP (Associated Press) product with WiGig standard was released in 2016 [10]. InterDigital studied a 60-GHz mesh backhaul line for junior unit base stations [11], realizing self-organizing functions through phased arrays [12]. NEC (NEC Corporation) released an E-band

(71–86 GHz) transceiver that supports 10-Gbps backhaul lines to form a centralized radio frequency access network (C-RAN) [13–15]. The literature [16] proposed an optimization scheme that adopts integrated optimization ideas so that various optimization mechanisms can work cooperatively, which improves optimization efficiency by repeated utilization of network resources and information. The analog simulation results also verify the effectiveness of the optimization scheme. The related literature studies the selection and switching of ultra-dense heterogeneous networks in 5G wireless communication systems. This paper proposes a joint vertical handover method based on region-aware Bayesian decision-making, which is optimized by selecting ultra-dense heterogeneous access networks, and switching the probability to solve the problem of ultra-dense network handover. By simulating and analyzing mobile users from macro base stations entering ultra-dense service cells and different scenarios of intra-cell and inter-cell mobility, the method can accurately select the network to be switched. Thus, this solution can be applied to the application scenarios of ultra-dense networks.

This paper presents a proof-of-concept (PoC) of millimeter-wave integrated HetNet. The study looks at millimeter-wave technology in HetNet, especially the effective utilization of 60-GHz technology. HetNet includes a traditional macrocellular network and new junior units that use millimeter waves for backhaul and link access. In addition, the concept of split control plane (CP) and user plane (UP) is introduced in HetNet [17–20]. In CP/UP split HetNet, the traditional macrocell provides the CP with a large area coverage, while UP data is provided by the millimeter wave junior unit. This architecture supports uninterrupted connectivity and increases capacity by leveraging the advantages of both macro and junior cells.

2. Millimeter-Wave Integrated Cellular Network

2.1. HetNet Control Plane and User Plane Segmentation

CP/UP segmentation [17] is also referred to as a “phantom unit” or “soft unit” in which CP and UP are processed separately. In a CP/UP-segmented HetNet, a mobile station (MS), which is also known as user equipment (UE), is capable of maintaining a logical link with a macrocell and a plurality of junior units. This capability is referred to as dual connectivity (DC), and can handle CP and UP separately and flexibly. A single CP also supports efficient, centralized radio resource control (RRC). Since UE must start multiple RF devices at the same time, DC will affect the peak power consumption of UE. However, a higher throughput reduces the download time, allowing the device to shift to sleep status shortly after the download ends.

To achieve CP/UP segmentation, macrocells and junior units are linked together through a backhaul line interface and controlled by the same RRC entity, as shown in Figure 1. The backhaul line, as the intermediate link between the unit and the centralized network, constitutes the core part of the CP/UP-segmented HetNet.

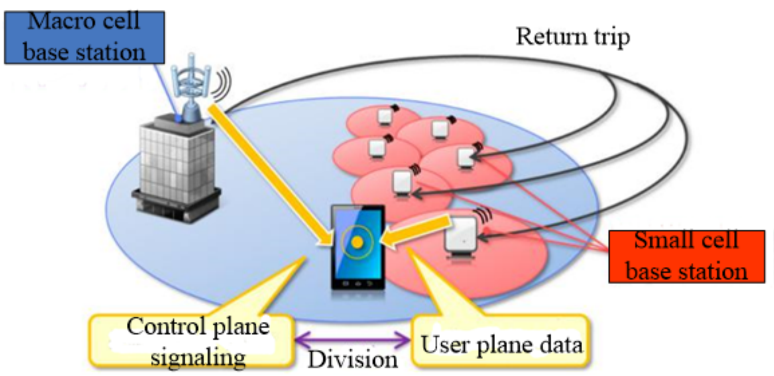


Figure 1. Control plane/user plane (CP/UP) segmentation based on heterogeneous network (HetNet) architecture in a centralized radio frequency access network (C-RAN).

DC and CP/UP segmentation features are introduced in Release 12 of the 3GPP LTE standard. In Release 13, it is extended to support DC (dual connectivity) between LTE and IEEE 802.11 wireless local area networks (WLAN).

2.2. 60-GHz Millimeter Wave WLAN

The IEEE (Institute of Electrical and Electronics Engineers) 802.11ad WLAN, also known as WiGig (8-Gigabit) [8], handles the unlicensed 60-GHz frequency band, which has at least 5 GHz of continuous bandwidth in several countries. WiGig adopts 2.16 GHz continuous band per channel in transmission, and is capable of transmitting at multiple Gbps rates. WiGig supports three different modulation methods: spread spectrum, single carrier (SC), and orthogonal frequency division multiplexing (OFDM) modulation. Spread spectrum modulation is used exclusively to control message transmission. SC modulation is mandatory and is applicable to low-power devices due to its lower peak-to-average power ratio (PAPR). OFDM modulation is optional, and is applicable to loose power devices. It is more robust to multipath effects than SC modulation. Table 1 gives an example of WiGig's Modulation and Coding Scheme (MCS), in which BOSK represents binary phase shift keying; QPSK represents quadrature phase shift keying; QAM represents quadrature amplitude modulation; and SQPSK represents extended QPSK. Here, the physical (PHY) layer has a maximum data rate of approximately 7 Gbps, while the next-generation IEEE 802.11ay 60-GHz WLAN is designed to support a maximum throughput of 20 Gbps in the Media Access Control (MAC) layer by space multiplexing or further enhanced MAC (Media Access Control) efficiency.

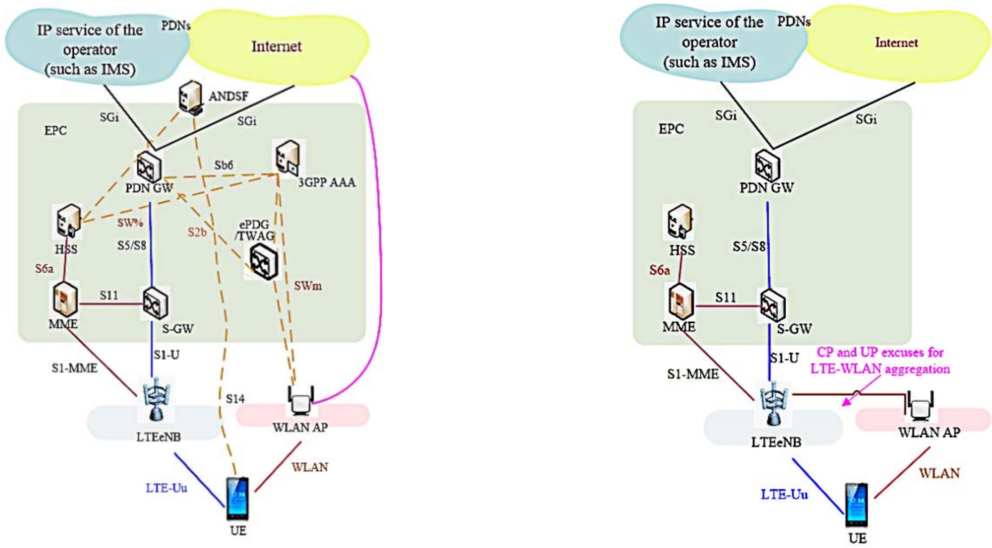
Table 1. Example of modulation and coding scheme for IEEE 802.11ad. BPSK: binary phase shift keying, MCS: Modulation and Coding Scheme, OFDM: orthogonal frequency division multiplexing, PHY: physical, QAM: quadrature amplitude modulation, QPSK: quadrature phase shift keying, SC: single carrier, SQPSK: represents extended QPSK.

MCS Index	PHY Pattern	Modulation	Coding Rate	PHY Data Rate (Mbps)
1	SC	π/2-BPSK	1/2	385
6	SC	π/2-QPSK	1/2	1540
9	SC	π/2-QPSK	13/16	2502.5
10	SC	π/2-16QAM	1/2	3080
12	SC	π/2-16QAM	5/8	4620
13	OFDM	SQPSK	1/2	693.00
15	OFDM	QPSK	1/2	1386.00
18	OFDM	16QAM	1/2	2772.00
22	OFDM	64QAM	5/8	5197.50
24	OFDM	64QAM	13/16	6756.75

The latest semiconductor technology applies 60-GHz communications to small handheld devices.

2.3. LTE-WLAN Interconnection and Aggregation

The Discovery and Selection Function of the Access Network (ANDSF) is a Core Network (CN) function that controls UP data offload between the 3GPP RAT and the non-3GPP RAT. The ANDSF is located in the Evolved Packet Core (EPC), which is part of the 3GPP CN. The ANDSF conveys UE context-based assistance information that is required for the discovery and selection of the RAT to the UE. The UE selects an appropriate RAT based on the delivered policy to connect to the network. Figure 2a shows an ANDSF-based LTE-WLAN interconnection architecture. In the LTE network, UE is connected to a base station (BS) through an LTE air interface. Wherein, the LTE air interface is referred to as the Uu interface, and the base station is referred to as an evolved Node B (eNB). When processed from the external packet data network (PDN) by the LTE-Uu interface, the traffic is transmitted to the UE through PDN Gateway (PDN GW), Service Gateway (S-GW), and eNB. There are two options available when traffic is offloaded to WLAN: (1) non-seamless WLAN offloading (NSWO); and (2) seamless WLAN offloading.



(**a**) ANDSF-based LTE-WLAN interconnection architecture

(**b**) RAN (Radio Access Network)-class LTE-WLAN integrated architecture

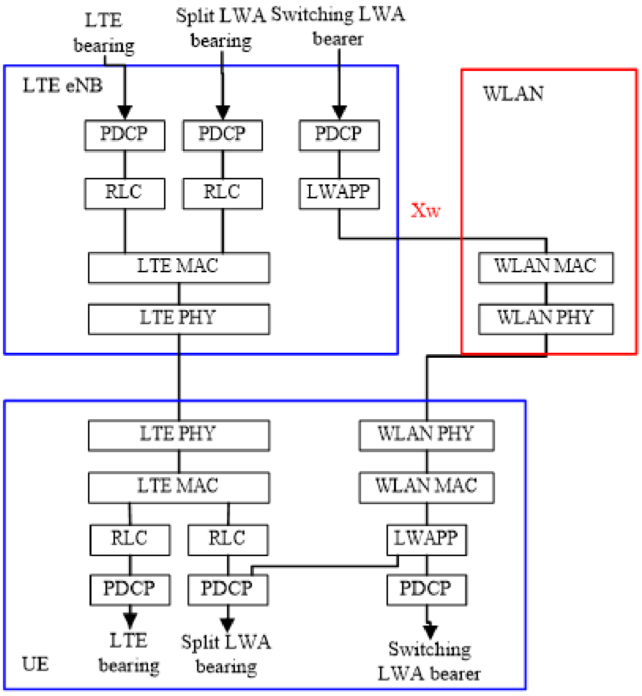
Figure 2. LTE (Long Term Evolution)-WLAN (wireless local area networks) system and integrated architecture. ANDSF: Discovery and Selection Function of the Access Network.

ANDSF is an efficient and scalable mechanism for controlling UE discovery and the selection of RATs in the network. However, ANDSF cannot control UP offloading in an ultra-dense HetNet.

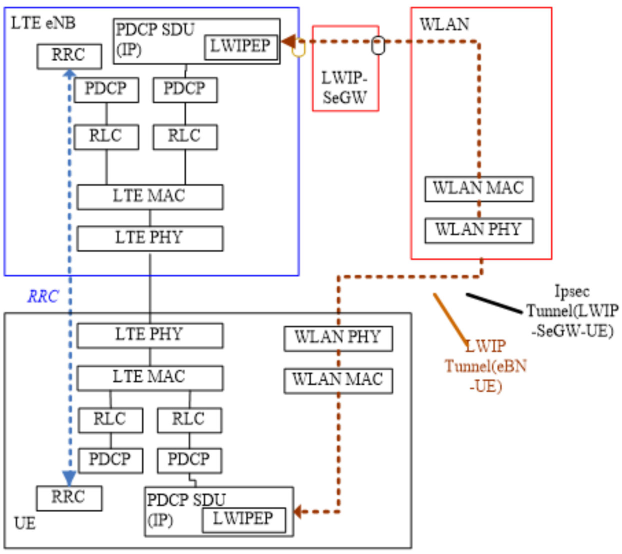
Figure 2b shows RAN-level LTE-WLAN integration architecture. In this architecture, UP and CP, LTE eNB, and the WLAN AP are all directly connected through a cooperative interface that transmits real-time traffic and radio information. The mobile anchor point resides in eNB, minimizing the interruption time during the handover process. The architecture supports CP/UP segmentation between LTE and WLAN.

The LTE-WLAN integration architecture was proposed and studied in the process of 3GPP(3rd Generation Partnership Project) standardization. Thus, two types of LTE-WLAN integration architectures are defined in Release 13: LTE-WLAN Integration (LWA) and LTE-WLAN Radio Integration (LWIP) using IPsec tunnel. Figure 3 provides the protocol stack for these architectures.

The main difference between the two architectures lies in the forwarding packet layer. In LWA, eNB forwards Packet Data Convergence Protocol (PDCP) Data Units (PDUs) to the WLAN AP. The PDCP PDU encapsulated in the LWA Adaptation Protocol (LWAAP) can be transmitted over the WLAN. In LWIP, eNB forwards PDCP Service Data Units (SDUs), i.e., IP packets, to WLAN AP. The forwarded IP packets are encapsulated in the Generic Routing Encapsulation (GRE) protocol and are protected by IP Security (IPsec). Therefore, the IWIP (Light Weight IP Protocol) bearer has a more complicated setting than LWA.



(a) LTE-WLAN integration



(b) LTE-WLAN radio integration using IPsec tunnel

Figure 3. LTE-WLAN interconnection architecture in Release 13. IPsec: IP Security.

3. Beamforming Antenna and Backhaul Line of Millimeter

The path loss of millimeter wave propagation is higher than that of low-frequency band communication systems such as LTE or Wi-Fi, so it is necessary to compensate with a highly directional antenna. These antennas should also have directional control to support access and reconfigurable backhaul links.

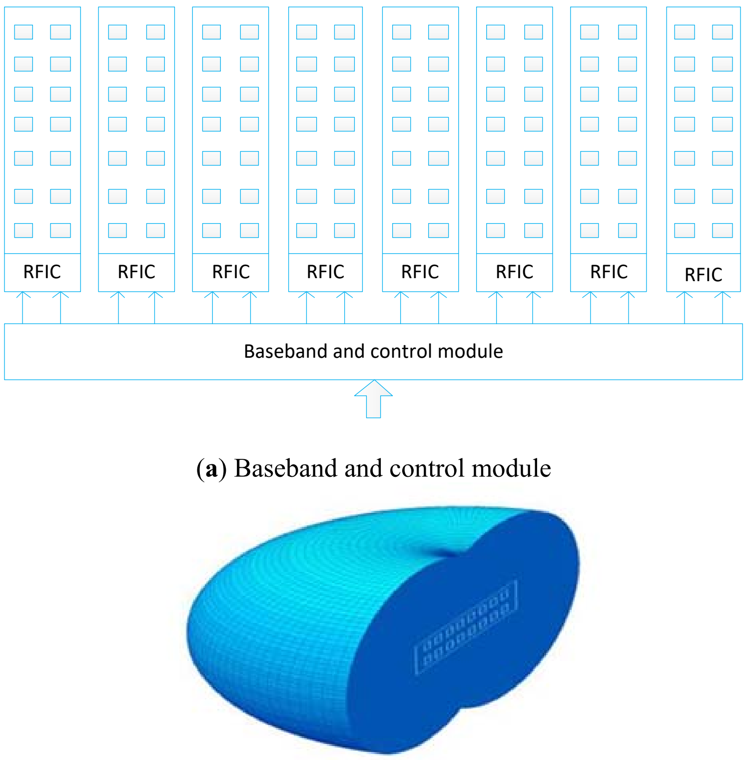
3.1. Passive Reflective Array Antenna

The static millimeter wave backhaul link implemented herein is based on the use of passive reflection facility [21,22]. The reflective array includes an array of specially designed dipole antenna elements on a printed circuit board (PCB) and a metallization layer on the opposite side of the ground. The dipole elements can be polarization-dependent, thus allowing the reflective array to use different focal points for orthogonal polarization. The shape of the collimated beam can be controlled by phase configuration.

In this paper, an integrated millimeter-wave transceiver is combined with an on-chip antenna in a reflective array structure to increase the antenna gain to achieve a longer link distance. The integrated transceiver can operate at 60 GHz based on the IEEE 802.11ad standard. The RF(Radio Frequency) feed structure and its associated losses can be minimized because the on-chip antenna requires only a lower gain. Installation costs can be reduced by implementing mechanical fine-tuning.

3.2. Highly Directional Steerable Millimeter Wave Antenna

A phased antenna array represents a perfect and mature electronically controlled antenna technology. However, highly directional arrays with larger apertures may encounter various problems in implementation. These problems have a greater impact on small millimeter wave antennas. Two solutions are proposed in literature [23]: modular antenna array (MAA) architecture and lens array antenna (LAA). The first is to create a large-aperture, high-gain antenna array from a small phased antenna array (PAA) module. Hybrid beamforming can be implemented in MAA by coarse analog phase shifting in the RFIC (Radio Frequency Integrated Circuit) circuit and fine digital beamforming in the baseband (BB) (Figure 4a). Since the feed line is short in each sub-array and the feed is typically implemented at intermediate frequency (IF), this design can significantly reduce feeder power loss.



(**a**) Baseband and control module

(**b**) Transmitting phased antenna array

Figure 4. Highly directional steerable millimeter wave antenna.

The LAA architecture forms a highly directional phased antenna array using different methods. The array aperture is increased by using a dielectric lens in a particular geometrical shape. In order to efficiently perform azimuth plane beam steering, the literature [23] proposed an elliptical toroidal lens array antenna, including a transmitting phased antenna array module placed on the back (Figure 4b). In this antenna design, the antenna aperture is determined by: (a) vertical dimension of the lens; and (b) horizontal dimension of the phased array antenna.

In order to prove the feasibility of the proposed LAA in access and backhaul applications, this paper performs real packet transmission with different MCS under field conditions. This paper examines three experimental scenarios: device-to-device (D2D) links (transmission of a single PAA module to a single PAA module); access links (LAA to a single PAA module) and long-range backhaul (LAA to LAA).

The use of a single lensless module allows transmission at the highest data rate up to a 15-m distance in the SC mode (MCS#12: 4.7 Gbps physical layer rate, 16-QAM (Quadrature Amplitude Modulation), and 3/4 encoding rate). The application of the lens at the transmitting end makes a maximum data rate (4.7 Gbps) possible, so that 16-QAM modulation is practical in outdoor communication within a distance of 30 to 35 m, which is suitable for millimeter wave access links.

The second experiment investigated the backhaul link based on two LAA antennas. Figure 5 presents the constellation diagram obtained in MCS #12 transmission at 100 m, 150 m, and 200 m, where the backhaul link with two LAAs achieves a maximum data transmission rate of 4.7 Gbps at a distance of up to 200 m, and the packet error rate is negligible.

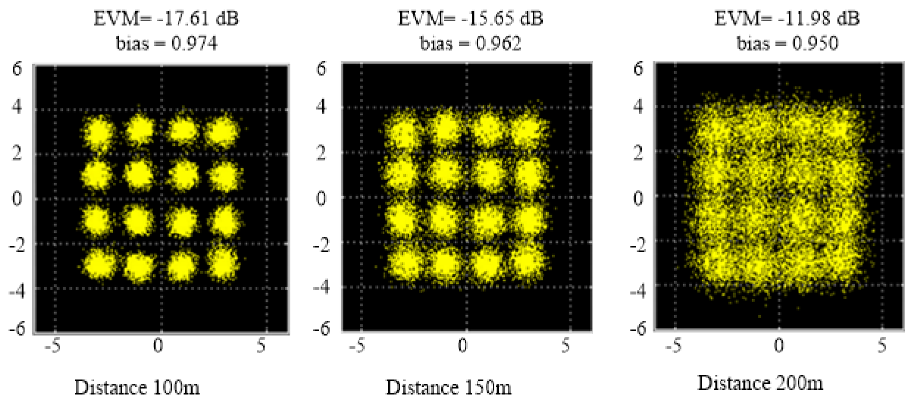


Figure 5. Constellation diagram of backhaul link with one lens array antenna (LAA) at the TX (transport)and RX (receive) ends.

In this paper, a 2×8 element antenna array module is used in LAA, which includes an RFIC chip and a BB module for digital signal processing. The total power consumption is about 4 to 6 Watts, depending on the working pattern. For the MAA prototype, eight antenna array modules as well as one BB module for digital signal processing were used. Accordingly, the total power consumption of the eight-module MAA is estimated to be 20 to 25 Watts. Therefore, both LAA and MAA devices can be powered by PoE (Power Over Ethernet).

4. Proof of Concept (Poc) of Implementation and Integration

PoC hardware includes backhaul and access devices. An IP (Internet Protocol Address)-based wireless backhaul link is established using a reflective array antenna with an integrated WiGig transceiver. One HetNet access network is used in this paper. CP/UP segmentation is introduced into HetNet. A multi-RAT CP application implemented in the LTE eNB manages UP traffic offload between LTE and WiGig.

The proposed PoC hardware for millimeter-wave integrated HetNet uses one LTE eNB as a macrocell and uses WiGig AP as a junior unit. The LTE baseband I/Q signal (In-phase/Quadrature signal) can be transmitted at a 50% compressed data rate. WiGig AP is connected to an LTE eNB through Ethernet. UE has an LTE modem and implements a WiGig device. The WiGig device supports MCS with the highest index #9, as shown in Table 1.

The protocol stack of PoC is shown in Figure 6. An LTE-WiGig Integrated CP (multi-RAT CP) application is implemented on the top of the CP protocol stack. The multi-RAT CP monitors real-time traffic load and radio link status. The link status measured on UE is reported to eNB through CP signaling of LTE. The multi-RAT CP on eNB manages UP data processing based on the monitoring information. The UP data path between LTE and WiGig is switched by Open vSwitch (OVS). During WiGig usage, the multi-RAT CP controls WiGig activation and authentication. The PDCP SDU is sent over a WiGig or LTE link. Since the interface between LTE–eNB and WiGig–AP is IP-based, the various Layer 2 media can be used for backhaul, including 1-Gigabit, 2.5-Gigabit, 5-Gigabit, or 10-Gigabit Ethernet.

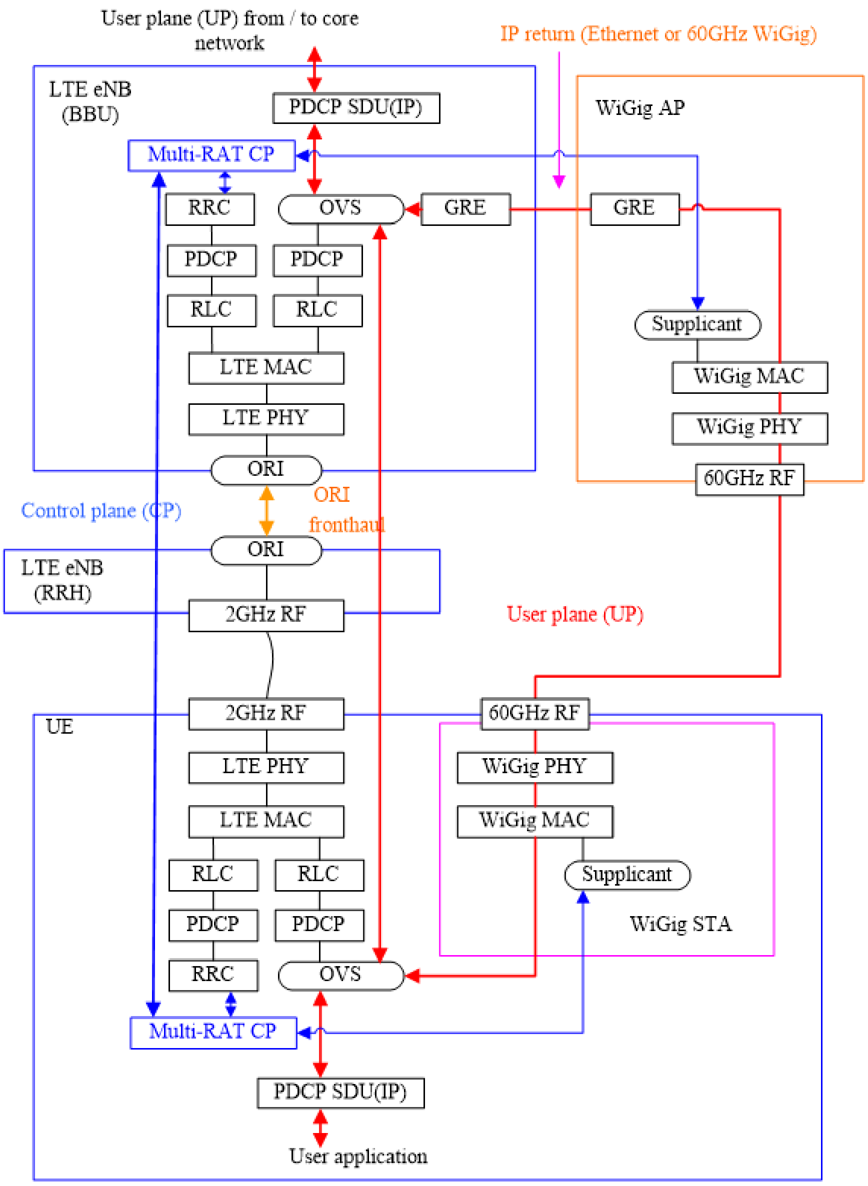


Figure 6. LTE-WiGig integrated HetNet proof-of-concept (PoC) protocol stack.

To prove the concept of CP/UP segmentation, performance of LTE–WiGig handover is evaluated herein. The WiGig station (STA (Single-threaded apartment)) device attached to a linear drive moves horizontally at a constant speed of 80 mm/s. The vertical distance between the AP and STA antennas is set to 200 mm so that the STA enters (or leaves) WiGig coverage. The UP data path handover is based on the availability of the WiGig link and reported RSSI (Received Signal Strength Indication). If the WiGig link is available and the RSSI exceeds the threshold $RSSI_{th}$, the UP data is then offloaded to the WiGig link. Otherwise, the UP data will be carried by the LTE link.

Figure 7 shows the transition of instantaneous UP throughput during an LTE–WiGig handover. Downlink UP data is transmitted from eNB using Iperf in TCP (Notes:Iperf is a network performance testing tool and TCP is a network transmission protocol.). The handover decision threshold RSSIth is set to −60 dBm, while throughput is measured in the MAC layer. It can be observed from the figure that the data path achieves smooth handover based on the UE location and achieves a throughput of more than 1 Gbps when the UP path is switched to WiGig.

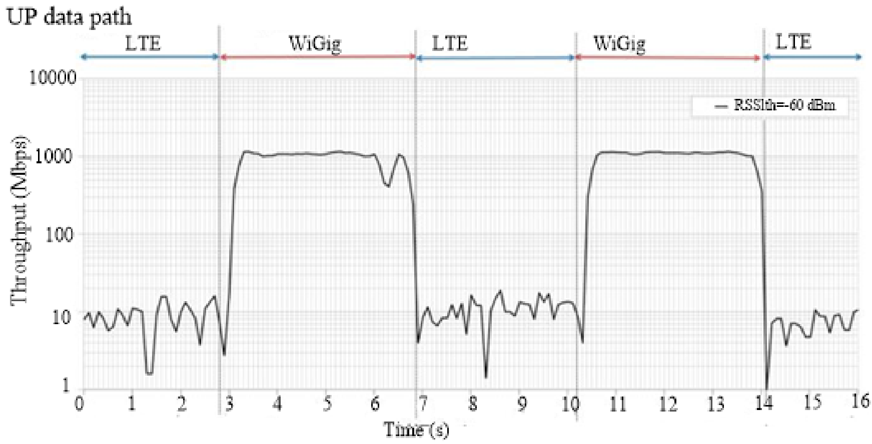


Figure 7. Transition of instantaneous UP throughput during LTE–WiGig handover.

5. Discussions

In order to verify the effectiveness of the proposed method, two applications are selected to give the benefits of the MMW (Millimeter Wave) integrated cellular network proposed by MiWEBA (Millimetre-Wave Evolution for Backhaul and Access): "context-aware cache" and "small cell on/off". The "Context Aware Cache" consists of dual connectivity user equipment, a macro base station (LTE eNB), and a millimeter wave junior unit. The client side runs a video streaming application while on the move. As a context-aware cache entity of the intermediate layer between the video application and network connection, it adopts the connection status as context information to perform data requests.

The video file is extracted from the content server and provided to the video player. When in the coverage of a millimeter wave cell, the cache pre-extracts and saves the video file chunks at the local maximum available rate. For this end, the cache creates a database of all the chunks in the currently playing video. Each chunk is associated with a state to indicate whether it is available locally, being downloaded, or not locally available. The recently played chunk is saved as an indicator and used to determine the next chunk to be downloaded. When outside the scope of the junior unit, the cache extracts the content on a timely basis to reduce the load on the LTE link. The content is seamlessly available from the user's perspective.

Next, f5G and WLAN convergence mechanisms, such as the 5G and WLAN convergence network switching mechanism, 5G and WLAN convergence, sister network wireless resource management strategy, 5G and WLAN convergence network access control strategy, etc. need further research.

6. Conclusions

This paper proposes a proof-of-concept (PoC) for integration into cellular networks by using millimeter-wave technology for backhaul and access in millimeter-wave integrated heterogeneous networks (HetNet). CP/UP segmentation is implemented in HetNet to allow the user plane to access the millimeter wave junior unit while retaining a reliable control plane connected to the macrocell. The wireless backhaul of junior units is performed using passive high-gain antenna technology in millimeter waves. In this paper, a beam directional steerable lens antenna is used for millimeter wave access. The practicality of millimeter-wave integrated HetNet is demonstrated through PoC. This paper presents successful CP/UP segmentation between traditional LTE and millimeter-wave WiGig and achieves seamless connection between two different technologies. It also demonstrates that high-throughput performance can be achieved in long-haul backhaul links using passive reflective arrays. Although the goal of millimeter wave access is high-speed data communication in the first phase of 5G, the architecture can be applied to the ultra-real-time and low-latency sensor networks that are required for future unmanned driving and will be implemented in the subsequent stages of 5G. 5G is confronted with the coexistence of many heterogeneous networks. How to use software to define network convergence and give full play to the advantages of each network system in data, capacity, and frequency has become a key issue. Therefore, this paper fully utilizes 60-GHz technology to elaborate the functions and workflow of the main modules, providing a research idea for the future 5G network structure.

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