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상용 기성부품을 이용한 O-RAN 호환 기지국 시스템 구현*

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Implementation of an O-RAN-Compliant Base Station System Using Commercial Off-the-Shelf Components

Du Hongxin · Zhang Zhongfeng · Choi Seungwon · Lee Taehoon

<Abstract>

Open Radio Access Network (O-RAN) standard has been proposed to separate the baseband signal processing unit from the Radio Frequency (RF) unit at base station system mainly for reducing the cost of base station systems through open-source interfaces between the two units. To satisfy the performance metrics in various scenarios, several fronthaul functional split options were presented by O-RAN. Amongst these options, the split option 7-2x is widely adopted in practical applications due to its excellent trade-off between the required bandwidth and RU overhead. In this paper, we present a hardware implementation of a base station system that is compliant with the Category B of O-RAN split option 7-2x. It consists of O-DU and O-RU implemented with a commercial off-the-shelf Digital Signal Processor and RF transceiver, respectively. The performance of the proposed base station system is evaluated in terms of Bit Error Rate and received signal power as well as the required fronthaul bandwidth. Through various experimental tests, we have observed that the proposed system reduces the fronthaul bandwidth nearly by 89.7% compared to the conventional system that dose not employ the O-RAN standard.

Key Words : O-RAN, Category B, Split Option 7-2x, DSP, USRP

Ⅰ. INTRODUCTION

Over the past few decades, wireless mobile communications have been constantly evolving. From the beginning of communication technologies, Radio Access Network (RAN) has always worked using a monolithic architecture[1]. This means that the Baseband Unit (BBU) and the Remote Radio Unit (RRU) had to be placed together in a single body. However, as wireless communications evolve, the cost based on this architecture has been tremendously increased due to the large number of

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base station systems required[2]. In the process of Long Term Evolution (LTE) base station construction, Cloud RAN (C-RAN)[3] has been adopted to separate the base station systems into 2 parts, BBU and RRU, where RRU includes the functions of Digital Front End (DFE) and Radio Frequency Front End (RFFE) while the other functions, for example, Media Access Control and Physical Layer (PHY), are implemented in BBU. The main problem in the C-RAN standard is that the fronthaul between BBU and RRU is implemented by Common Public Radio Interface (CPRI), which is not a completely open source to third parties[4].

In the Fifth Generation New Radio (5G NR), there arises very strict requirements, extremely large bandwidth and low latency[2]. This means that the size of each 5G NR base station should be a lot smaller than that of LTE base station, which consequently requires the number of 5G NR base stations to be considerably increased compared to that of LTE ones. In addition to the need of increasing the total number of base station systems, due to the high cost of each 5G NR base station system, there arises an extremely keen need to reduce down the cost of each base station system as much as possible.

In order to reduce the cost of base station systems, the base station markets need to be open to small- or medium-sized companies as well as to a few selected large-sized vendors. For that purpose, the Open RAN (O-RAN) standard has been provided in such a way that each base station system is split into 3 units, i.e., O-RAN Control Unit (O-CU), O-RAN Distributed Unit (O-DU) and O-RAN Radio Unit (O-RU)[5], while the interface between neighboring units is open to third parties as an international standard. Consequently, each of these 3 units can be provided by small- or medium-sized companies as well as large-sized vendors. With the emergence of O-RAN, both the installation and operation cost of base stations can be tremendously reduced in this perspective. It particularly means that the 5G NR base station systems with the O-RAN standard can now be built with a mixture of multi-vendor units.

In addition to the abovementioned effort of reducing the base station cost, O-RAN has adopted the Enhanced CPRI (eCPRI) protocol to solve the problem of Fronthaul bandwidth limitations. For instance, with the massive Multiple-Input Multiple-Output (mMIMO) systems introduced in the 5G NR enhanced Mobile Broadband, the Fronthaul bandwidth is significantly increased due to the number of antenna elements at the transceiver[2, 6]. In this signal environment of mMIMO, a large number of CPRI fiber optic cables would be required due to the extremely wide bandwidth of the many antenna ports at the mMIMO transceiver if each antenna port at the O-DU transmits its digital data obtained at the endpoint of the Low-PHY. eCPRI instead of CPRI has been introduced to resolve this problem of too wide bandwidth required between O-DU and O-RU especially when the data are to be transmitted using the system of mMIMO. The O-RAN standard provides a few split options between O-DU and O-RU among which eCPRI that uses split option 7-2x is most frequently adopted in practical applications. In option 7-2x, the PHY is divided into High-PHY and Low-PHY. where High-PHY remains in O-DU, and Low-PHY is moved to O-RU. As the digital data transmitted from the O-DU have been processed only for the High-PHY, the data rate is much lower than that processed for the entire physical layer including the Low-PHY as well as High-PHY[4, 5].

In this paper, we introduce a hardware implementation of the base station system that is compliant with O-RAN adopting the Category B of eCPRI (split option 7-2x) using the commercial off-the-shelf devices, TMS320C6670 and USRP X310, where the O-DU and O-RU are implemented with the former and latter, respectively[6, 7]. In our implementation of O-RU using USRP X310, we have employed the Radio Frequency Network on Chip (RFNoC) framework in order to fully exploit the built-in functionalities such as Fast Fourier Transform (FFT), Digital Up Conversion (DUC) and Digital Down Conversion (DDC)[8].

The main contributions of this paper can be summarized as follows:

1. Hardware implementation of a base station system that is compliant with the O-RAN standard adopting Category B of split option 7-2x using COTS devices.
2. Connecting and controlling the Digital Signal Processor (DSP) module and Universal Software Radio Peripheral (USRP) module using a modified USRP Hardware Driver (UHD).
3. Adaptive beamforming where the main lobe can be arbitrarily steered by selecting the desired beam identifier according to Category B of split option 7-2x.

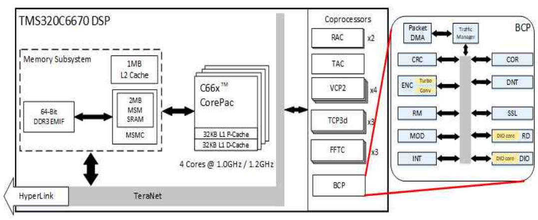
This paper is organized as follows. The second section describes the hardware structure of the O-RAN compliant base station system. The third section illustrates the software structure of the implemented base station system. The fourth section presents the experimental results and analysis. Finally, the conclusion is presented in the fifth section.

II. HARDWARE STRUCTURE

2.1 O-DU Structure

O-DU is to process baseband signals of the base station system. In order to support real-time processing for both Downlink and Uplink data transmissions, we have employed a high-speed DSP, TMS320C6670, for implementing the O-DU. Figure 1 is a photograph of the evaluation board of the DSP used to implement our O-DU. Figure 2

<Fig. 1> Photograph of the DSP evaluation board used to implement O-DU



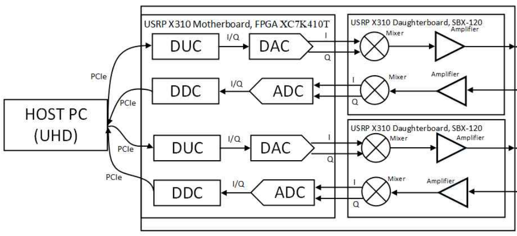
<Fig. 2> DSP structure including 4 cores, coprocessors and memory blocks[9, 10]

llustrates a block diagram of the DSP which includes 4 cores, for multi-tasking and simultaneous processing of the baseband signals required in the O-DU.

As shown in the figure, several coprocessors are provided within the DSP for supporting frequently used functional blocks. For example, the coprocessor labeled as Bit Rate Coprocessor (BCP) provides the functionalities of Cyclic Redundancy Check (CRC), Turbo encoding, Rate Matching, interleaving and modulation[9], which are core functions for both LTE and 5G NR. In addition, memory blocks are also provided in this DSP with 3 different priority levels. The memory block of L1 cache and L2 cache provided within the DSP core responses much faster (but smaller in size) than Multicore Shared Memory (MSM). In our implementation, the MSM has been used to store all the signal data generated during the procedure of baseband signal processing within the O-DU. The configuration information needed to set up each of all the functional blocks in each of the coprocessors are also stored in the MSM. It is noteworthy that the capacity as well as the read/write speed of the MSM, fully satisfies the timing requirement for the real-time processing of the baseband signals for both LTE and 5G NR[10, 11].

2.2 O-RU Structure

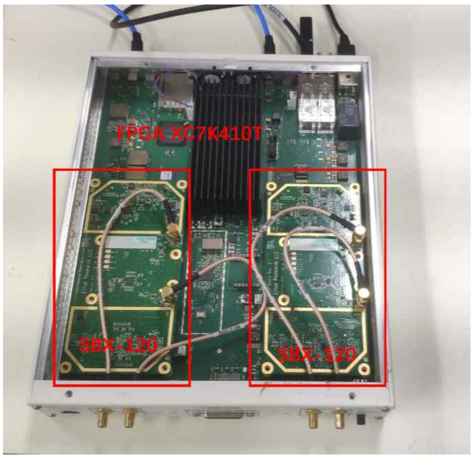
In the O-RAN functional split option 7-2x, Low-PHY of the baseband signal should be implemented in O-RU. For real-time processing of both Downlink and Uplink data, the signal processing of Low-PHY within O-RU which includes FFT/Inverse FFT (IFFT), Beamforming, DFE and RFFE should be done fast enough for each data packet. In order to support the timing requirement, we have employed the Field Programmable Gate Arrays (FPGA), XC7K410T, which is provided within the RF transceiver, USRP X310, for implementing the O-RU. Figure 3 is a block diagram representing the structure of USRP X310. The functional block labeled as DFE consists of DUC and DDC, while the other functional block labeled as RFFE contains Analog-to-Digital (ADC) and Digital-to-Analog (DAC).



<Fig. 3> Block diagram of USRP X310 structure

Figure 4 is a photograph of the proposed O-RU implemented with USRP X310, which supports a maximum sampling rate of 200M/800M samples per second for its ADC/DAC[12]. USRP X310 employs 2 master clocks, 184.32MHz and 200MHz, while the clock rate of 184.32MHz is the integer multiple of the sampling rate of both LTE and 5G NR, i.e., 15.36MHz. With these capabilities, it can be well applied to both LTE and 5G NR.

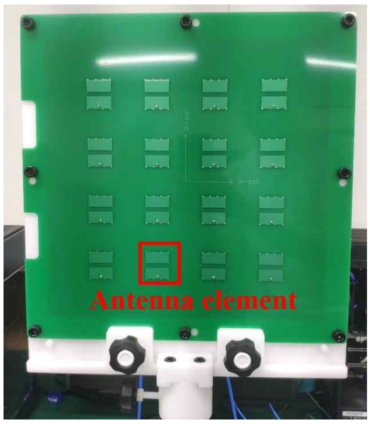
The USRP X310 consists of two daughterboards and one motherboard, where the motherboard is an evaluation board containing the FPGA XC7K410T, which performs the abovementioned functionalities of Low-PHY. Out of a variety of daughterboard



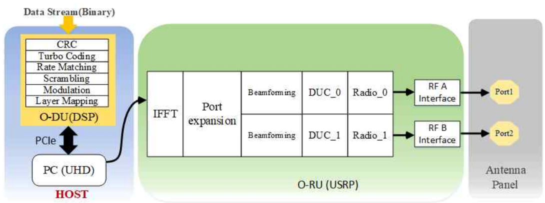
<Fig. 4> Photograph of USRP board including an FPGA (XC7K410T) and two daughterboards (SBX-120)

models, we have employed SBX-120 daughterboard in order to support LTE signals with 10MHz bandwidth at the carrier frequency of 2.4GHz, while the maximum bandwidth supported by SBX-120 is 120MHz with its up-conversion rate range being 400MHz ~ 4400MHz.

Meanwhile, in order to support the beamforming functionality, a 4x4 planar array antenna has been employed in our O-RU implementation. Figure 5 is a photograph of the array antenna used for the implementation of the RF front end of O-RU. Since the USRP X310 supports only 2 transmit antenna ports, however, the proposed O-RU uses only 2 antenna ports located at the center of the bottom line of the planar array. The number of antenna elements could be increased arbitrarily by employing more USRPs as desired. It is noteworthy that the center frequency, bandwidth and transmit power at each antenna port can also be arbitrarily reconfigured through the modified UHD introduced in the following section.



<Fig. 5> Photograph of 4x4 planar array antenna used for the implementation of O-RU



<Fig. 6> Conceptual Block Diagram of the implemented base station system consisting of O-DU, O-RU and array antenna

III. SOFTWARE IMPLEMENTATION

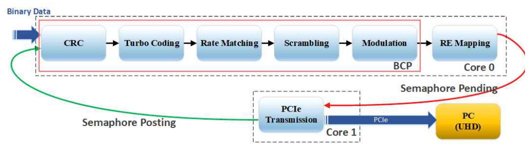
In this section, we introduce a software implementation for both O-DU and O-RU. Figure 6 shows the overall framework of the base station system implemented with the COTS platform of DSP, USRP and array antenna for O-DU, O-RU and RF front end, respectively. As mentioned earlier, the implemented base station system is compliant with the Category B of split option 7-2x of the O-RAN standard.

For simplicity but without loss of generality, the implemented base station system includes 2 transmit antennas and a single receive antenna. The key point is to demonstrate the beamforming capability that is one of the keenest requirements of the Category B of O-RAN standard. Although the O-RAN standard is proposed to address the large bandwidth and low latency requirements of 5G NR, in this paper, we use LTE signals instead of 5G NR signals as test data. The reason is that the main objective of this paper is to implement a base station system that is compliant with the O-RAN standard where the radio access technology of the transmission data is not the main interest.

3.1 Software Implementation for O-DU

As the O-DU is implemented with the TMSC320C6670 DSP, it is possible to exploit the coprocessors provided within the DSP for baseband signal processing of either LTE or 5G NR signals. Especially, the coprocessor labeled as BCP provides various useful functionalities required in LTE and 5G NR such as CRC, Turbo Coding, Rate Matching, interleaving and modulation. Besides the merits of using the coprocessors, the advantages of employing multiple cores within the DSP can also be fully exploited. Figure 7 is a block diagram showing the signal flow chart for the High-PHY signal processing in the implemented O-DU. While processing the baseband signals, the DSP is connected to the Host PC through the Peripheral Component Interconnect Express (PCIe), which facilitates fast data transfers between the DSP and USRP.

The signal flow chart for the Downlink transmission in the implemented O-DU can be summarized as follows. Firstly, binary data of the test signal is imported into the DSP. Then, the binary data of all the physical layer channels defined in LTE standard such as Physical Downlink Shared Channel, Physical Downlink Control Channel, Physical Broadcast Channel and Physical Downlink Format Indicator Channel are encoded in the Core 0 using the coprocessor BCP, which provides the functionalities of CRC, Turbo Coding, Rate Matching, Scrambling (Interleaving), Modulation, and RE Mapping. Note that input data to the BCP coprocessor should be formatted in such a way that each data packet contains configuration parameters for each functional block. In the proposed O-DU, 240 bits of configuration parameters are reserved for each data packet for the functional blocks of the BCP coprocessor.



<Fig. 7> High-PHY signal flow chart of O-DU implemented with DSP

In order to activate the baseband signal processing, the Core 0 should first be connected to BCP. Then, LTE Downlink parameters is to be sent to the BCP coprocessor through the send function in the BCP_common header file, after which the processed Downlink data are finally received at the Core 0 (from BCP) through the receive function in the BCP_common header file.

The configuration parameters have been set in such a way that the transmission mode is TM1, CRC size is 24bits, Turbo Encoding rate is 3/4, and modulation is set to 64QAM[9]. Meanwhile, the function that calls the BCP interface is placed in Core 0, while the PCIe interface is implemented in Core 1.

Semaphore has been used to avoid overwriting the processed data before the USRP reads them. After the execution of Resource Element mapping, Core 0 enters a short waiting cycle by pending Semaphore. When USRP finishes reading the processed data, Core 1 posts the corresponding semaphore which was generated by Core 0. Then, Core 0 may re-enter the working cycle. USRP reads the modulated signal from Core 1 via PCIe. Through the Semaphore mechanism, the signal processing rate can be well controlled.

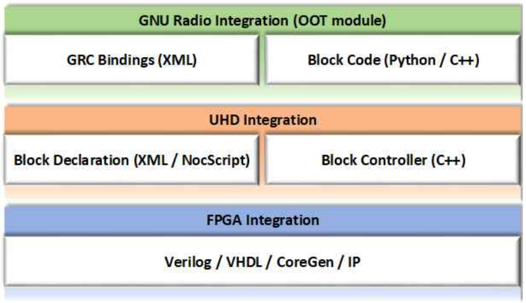
3.2 Software Implementation for O-RU

3.2.1 RFNoC Framework

RFNoC is an open-source framework that provides various useful functional blocks such as FFT, DUC and DDC[8, 13]. Configuration of each functional block provided by RFNoC can be set very easily by setting the corresponding parameters, for example, FFT size, center frequency and bandwidth. Besides the above-written built-in functional blocks, RFNoC allows creating customized blocks for user-desired functionalities.

Figure 8 shows the components of the RFNoC block. The components consists of 3 layers as follows:

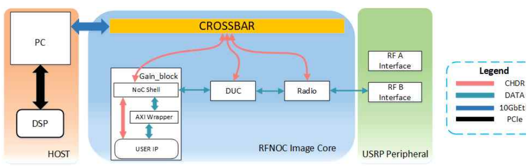
1. The layer of FPGA Integration, to be developed by user, includes the functions to set up the FPGA hardware.
2. The layer of UHD Integration, which allows the Host PC to access the USRP, connects each of the functional blocks in a given FPGA code in accordance with the execution order.
3. The layer of GNU Radio Integration, with the Out-of-Tree (OOT) module generated in the RFNoC block, allows FPGA code to be executed directly through GNU Radio. Note that FPGA code can be executed either through UHD or directly through GNU Radio.



<Fig. 8> Components of the RFNoC block[14]

After completing the development of RFNoC block, it is appended into the RFNoC image builder to generate a new image. The new image then is imported into USRP to complete the whole development process.

Figure 9 is a simplified architecture diagram of O-RU which includes RFNoC image Core connected with USRP peripheral and Host PC. Firstly, RFNoC receives the transmission data from the Host PC through the 10 Gigabit Ethernet transport adapter. Then, two main streams are generated in the framework, i.e., Condensed Hierarchical Datagram for RFNoC (CHDR) stream and data stream. The stream of CHDR, like a highly flexible dynamic router, handles the connections among RFNoC blocks. By using the UHD, CHDR can be controlled to connect or disconnect any two blocks through the NoC shell without rebuilding the FPGA image. The data stream consists of the data transferred between the connected blocks, which includes the process of packing and unpacking. Data processing is completed as the data are transmitted through the radio block to the USRP peripheral via RF interface on the daughterboard.

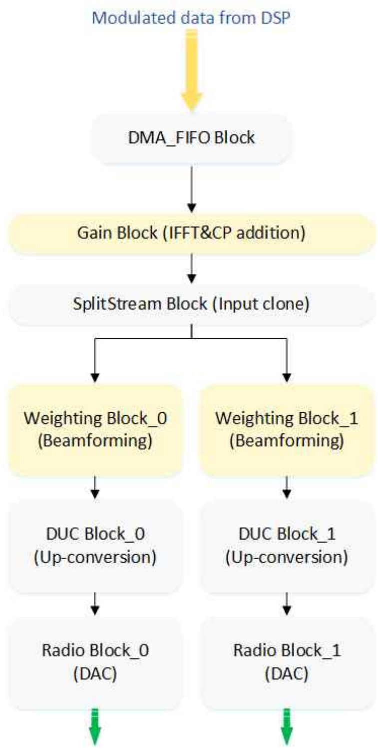


<Fig. 9> RFNoC image Core connected with USRP peripheral and Host PC

3.2.2 O-RU implementation Using RFNoC

In this subsection, O-RU is implemented with USRP X310 based on RFNoC framework. Besides the useful capabilities of RFNoC described in the preceding subsection, as RFNoC framework provides some built-in functional blocks, such as FFT, SplitStream, FIFO, DDC and DUC, it greatly reduces the development complexity[14].

In our system, the connection and control between the DSP and USRP are performed via UHD. As briefly mentioned in Subsection 3.2.1, the original UHD code, version 4.0[15], has been modified in this paper to provide some external functionalities such as initializing the RFNoC framework, transferring the DSP data into the USRP via PCIe, and controlling the stream of CHDR to connect and manage all the required functional blocks.



<Fig. 10> Signal flowchart in the implemented O-RU based on RFNoC

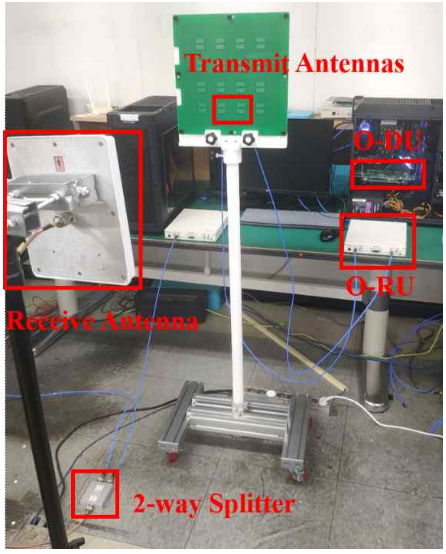
Figure 10 illustrates the signal flowchart in the functional blocks required in the implemented O-RU. When using the RFNoC framework, each functional block can select 1 clock signal out of 2 choices, i.e., the radio clock and computation engine (CE) clock. Since the signal transmission speed within the radio blocks (which include Up/Down converter and DAC) in the implemented O-RU is much faster than the CE clock, we have selected the radio clock instead of the CE clock as the clock signal for all the functional blocks to unify the data processing speed of the RFNoC blocks and the signal transmission speed of radio blocks. The first block labeled as Direct Memory Access First-Input-First-Output block (DMA-FIFO) block in Figure 10 is to read the modulated data from the DSP and transfer them into the Gain Block. The DMA-FIFO block resolves the underflow problem which may occur when the reading speed of the next functional block, Gain Block, ever becomes faster than the importing speed of the DSP input data. When the DMA-FIFO reaches a half of its full capacity, it starts sending the stored data to the Gain Block. Then, the functionalities of IFFT and Cyclic Prefix (CP) addition are activated upon the data in the Gain Block. Since the RFNoC framework provides only the FFT Intellectual Property (IP), meaning that the IFFT block is not provided, we have implemented the IFFT functional block using the FFT IP in such a way that the resultant IFFT functional block satisfies the requirement of LTE system bandwidth of 10MHz with 1024 IFFT points. After taking the IFFT, CP is added in such a way that every 0^{th} and 7^{th} Orthogonal Frequency Division Multiplexing (OFDM) symbols at every subframe contain 80 CPs while all the other symbols contain 72 CPs. After finishing the IFFT and CP addition, the Gain Block transfers the processed data into the next functional block, SplitStream Block, which splits the Gain Block output port into 2. Since the beamforming functionality of our O-RU is supported with 2 antenna ports, each of the 2 outputs of SplitStream Block is provided as an input of each of the 2 Weighting Blocks, which multiplies a proper beamforming weight onto the incoming data values.

In order to be compliant with the requirement of O-RAN Category B, we have implemented the Weighing Blocks in such a way that the desired beam pattern can be accomplished by selecting a corresponding beam ID[5]. More specifically, we can select 1 out of 10 beam patterns by choosing 1 weight value out of 10 different weight values stored in the Weighting Block. After multiplying the transmit data with the desired weight value at each of the 2 Weighting Blocks, each data sequence passes through the DUC Block and Radio Block for digital up-conversion and digital-to-analog conversion, respectively. Finally, the output of the Radio Block is imposed to the corresponding transmit antenna port of the array antenna.

IV. EXPERIMENTAL RESULTS

In order to verify the feasibility and performance of the implemented O-RAN-compliant base station system, we have conducted indoor RF tests with the implemented O-DU and O-RU as shown in Figure 11. In our experimental tests, for simplicity but without loss of generality, only 2 ports of the 4x4 planar array antenna has been activated as transmit antennas of the base station system while a single antenna has been used as receive antenna of the mobile terminal.

For the RF test, the UHD activates the DSP through the PCIe connection function, which allows the transmit data generated from the DSP to be transferred into the USRP. Note that the DSP and USRP emulate the O-DU and O-RU, respectively, as mentioned earlier. The transmit data are first transferred to the Host PC via PCIe, then, transferred from the Host PC to the USRP via 10 Gigabit Ethernet cable. As the Beam ID is set, the transmit data with a specific beam pattern are radiated through the transmit antennas.



<Fig. 11> RF test environment

Table 1 shows the PHY layer parameters of the implemented base station system. For our system, Sampling Rate is 15.36MHz, Bit width for QAM is 6 bits for both In-phase (I) and Quadrature (Q) components, the number of antenna ports is 2, the number of active subcarriers is 600, the number of symbols per subframe is 14, the number of layers is 1, and Bit width of IFFT-processed data is 16 bits for both I and Q.

By fully exploiting the merit of the O-RAN split 7-2x Category B architecture in the implemented base station system, the Fronthaul bandwidth is reduced down to 100.8Mbps, while the conventional base station system without the O-RAN architecture

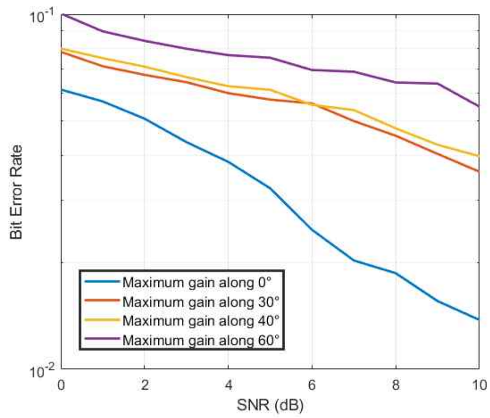
<TABLE 1> PHY-LAYER PARAMETERS

Parameters	Values
Center Frequency	2.4GHz
System Bandwidth	10MHz
Modulation	64 QAM
Number of Subcarriers	600
Symbols per Subframe	14
Transmission Mode	TM1
Beam ID	0 ~ 9 (10° per beam ID, 0 ~ 90°)

suffers from very high bandwidth requirement, i.e., 983.04Mbps [16].

Consequently, the Fronthaul bandwidth is approximately 89.7% reduced, i.e., from 983.04Mbps to 100.8Mbps, by applying the O-RAN architecture where the supported data throughput remains unchanged.

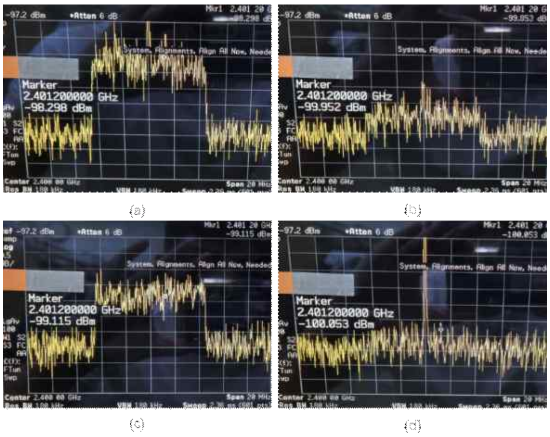
In order to evaluate the transmit performance of the implemented base station system, we implemented an emulator for the receiving mobile terminal as well as the base station system itself. In the emulator, the RF signals received through a signal antenna are first frequency-down converted



<Fig. 12> Received BER with various main-lobe angles

and analog-to-digital converted using another USRP. Then, the resultant receive digital data are stored as a data file to be processed using standard functional blocks given in Matlab[17].

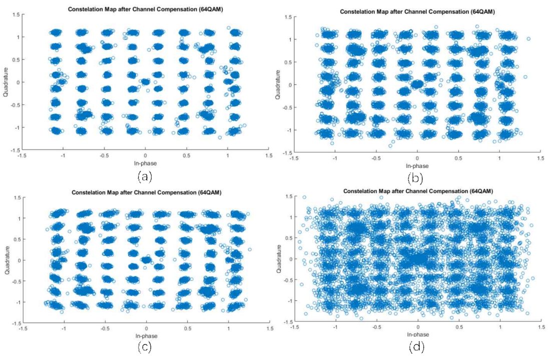
Figure 12 illustrates a Bit-Error-Rate performance of the implemented base station system when the receiving mobile terminal is located with the incident angle being 0° and separation from the base station system being approximately 2 meters. As shown in the figure, the BER performance is considerably enhanced when the transmit beam pattern is matched with the location of the receiving mobile terminal. As mentioned earlier, the base station system can provide a proper beam pattern by selecting the correct beam ID from the USRP through the UHD which has been modified in this paper as shown in Section III.



<Fig. 13> Received RF signal power (a) Transmit angle is matched with the terminal position, i.e., 0° (Beam ID set to 0), (b) Transmit angle is mismatched with the terminal position, i.e., 0° (Beam ID set to 4), (c) Transmit angle is matched with the terminal position, i.e., 40° (Beam ID set to 4), (d) Transmit angle is mismatched with the terminal position, i.e., 40° (Beam ID set to 0)

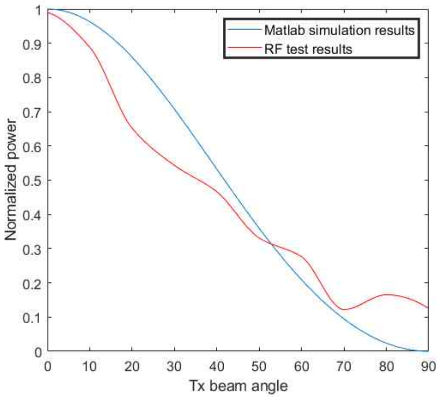
Figure 13 illustrates the received signal power of RF data measured at the receiving mobile terminal measured at a spectrum analyzer. As shown in Figure 13 (a)~(d), the received RF signal power is considerably increased when the transmit beam pattern is well matched with the mobile terminal position by selecting the correct beam ID.

Figure 14 illustrates the constellations of the received 64QAM data. Similarly to the case of Figure 13, the constellation is greatly improved as the transmit beam pattern is well matched with the position of the receiving mobile terminal by selecting the correct beam ID.



<Fig. 14> Received constellations (a) Transmit angle is matched with the terminal position, i.e., 0° (Beam ID set to 0), (b) Transmit angle is mismatched with the terminal position, i.e., 0° (Beam ID set to 4), (c) Transmit angle is matched with the terminal position, i.e., 40° (Beam ID set to 4), (d) Transmit angle is mismatched with the terminal position, i.e., 40° (Beam ID set to 0)

Figure 15 illustrates the beam pattern provided by the proposed base station system when the receiving mobile terminal is located at the position of the incident angle being 0°. As shown in the figure, the experimental test results are pretty well coincident with the simulation results, while there exist some erroneous fluctuations probably due to the multipath effects in the indoor signal environment.



<Fig. 15> Beam pattern with TA fixed at 0°

V. CONCLUSIONS

In this paper, we have implemented a transmit base station system and receive mobile terminal using COTS components where the base station system is fully compliant with the O-RAN standard. More specifically, the implemented base station system, of which the O-DU and O-RU have been implemented with the TMS320C6670 DSP and USRP X310, respectively, supports the standard of Category B of split option 7-2x. We have adopted PCIe to interface between the Host PC and DSP, while 10 Gigabit Ethernet has been employed for the connection between the Host PC and USRP. The feasibility and performance of the proposed base station system have been verified through various experimental indoor tests from which we observed significant performance enhancements in terms of both receiving capability and fronthaul bandwidth. In fact, the fronthaul bandwidth has been saved nearly by 89.7% through the adoption of the O-RAN standard compared to the case of the conventional base station system without the merit of the Category B of split option 7-2x. Meanwhile, the beamforming gain provided by the implemented base station system has tremendously enhanced the BER performance at the receive mobile terminal.

REFERENCES

[1] A. Checko et al., "Cloud RAN for Mobile Networks -A Technology Overview," IEEE Communications Surveys & Tutorials, vol.17, no.1, 2015, pp.405-426.

[2] C. N. Tadros, M. R. M. Rizk and B. M. Mokhtar, "Software Defined Network-Based Management for Enhanced 5G Network Services," IEEE Access, vol.8, 2020, pp.53997-54008.

[3] C. -L. I, J. Huang, R. Duan, C. Cui, J. Jiang and L. Li, "Recent Progress on C-RAN Centralization and Cloudification," IEEE Access, vol.2, 2014, pp.1030-1039.

[4] S. K. Singh, R. Singh and B. Kumbhani, "The Evolution of Radio Access Network Towards Open-RAN: Challenges and Opportunities," 2020 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), 2020, pp.1-6.

[5] O-RAN Fronthaul Control, User and Synchronization Plane 2.0, July, 2019, o-ran.org/specifications.

[6] Mohsin, Mustafa, Jordi M. Batalla, Evangelos

Pallis, George Mastorakis, Evangelos K. Markakis, and Constandinos X. Mavromoustakis. "On Analyzing Beamforming Implementation in O-RAN 5G," Electronics, vol.10, no.17, 2021, 2162. https://doi.org/10.3390/electronics10172162.
[7] 나용 · 안흥섭 · 최승원, “멀티코어 DSP를 이용한 다중 안테나를 지원하는 SDR 기반 LTE-A PDSCH 디코더 구현,” 디지털산업정보학회 논문지, 제15권, 제4호, pp.85~92.
[8] Kreinar, E. (2017). "RFNoC Neural Network Library using Vivado HLS," Proceedings Of The GNU Radio Conference, vol.2, no.1, 2017, pp.7.
[9] Texas Instruments, KeyStone Architecture Bit Rate Coprocessor (BCP) User's Guide, SPRUGZIA, Mar. 2015, https://www.ti.com/lit/ug/sprugz1a/sprugz1a.pdf?ts=1642657224278.
[10] Texas Instruments, TMS320C6670 Multicore Fixed and Floating-point System-On-Chip Data Manual, SPRS689D, March 2012, https://www.ti.com/lit/ds/symlink/tms320c6670.pdf.
[11] 장중봉 · 안흥섭 · 최승원, “멀티코어 DSP를 사용한 SDR 기반 IEEE 802.11ac 인코더의 설계 및 구현,” 디지털산업정보학회 논문지, 제15권, 제4호, pp.93~101.
[12] Ettus Knowledge Base contributors, "X300/X310" Ettus Knowledge Base, https://kb.ettus.com/X300/X310
[13] Braun, M., Pendlum, J., & Ettus, M. "RFNoC: RF Network-on-Chip," Proceedings Of The GNU Radio Conference, vol.1, no.1, 2016. https://pubs.gnuradio.org/index.php/grcon/article/view/3.
[14] Ettus Knowledge Base contributors, Getting Started with RFNoC Development, Ettus Knowledge Base, https://kb.ettus.com/index.php?title=Getting_Started_with_RFNoC_Development&oldid=4994.
[15] Ettus Knowledge Base contributors, Getting Started with RFNoC in UHD 4.0, Ettus Knowledge Base, https://kb.ettus.com/index.php?title=Getting_Started_with_RFNoC_in_UHD_4.0&oldid=5114.
[16] NTT DOCOMO, R3-162102: CU-DU Spsit: Refinement for Annex A, 3GPP, Sophia Antipolis, France, Oct. 2016, https://www.3gpp.org/ftp/tsg_ran/WG3_Iu/TSGR3_93bis/Docs/
[17] MATLAB, LTE Toolbox User's Guide, R2019, https://www.mathworks.com/help/pdf_doc/lte/lte_ug.pdf

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