O-RAN next Generation Research Group (nGRG) Contributed Research Report

Requirements and Design Principles on RAN Architecture for Next Generation Antenna Distribution System

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Executive summary

Mobile traffic has been increasing at an approximate annual growth rate of 1.3 times [1]. Based on this growth rate, it is predicted that the traffic volume in 2030 will be 14 times that of 2020 when 5G was introduced. By 2040, it is expected to reach 190 times the 2020 volume. To support this surge in mobile traffic, effective strategies to accommodate this traffic, such as enhancing frequency utilization efficiency and using higher order modulation schemes, are crucial. Additionally, these expansions must consider the principles of green communication.

From 2022 to 2024, nGRG conducted use case analyses and gap analyses of 6G use cases requirements and existing 5G system [3]. The findings indicate that antenna distribution is effective in enhancing capacity by improving resource utilization.

Distributed antenna systems (DAS) have been used for many years However, with the recent changes in the frequencies handled by RAN and the advancements in RAN functionality, there is a need for DAS to adapt to these developments with new designs.

This report clarifies the requirements and design principles for the next generation antenna distribution systems (nGADS).

In terms of requirements, eight key aspects have been defined, including capacity expansion, infrastructure sharing, and energy saving. Additionally, for design principles, eight elements have been outlined, including compliance with 3GPP and O-RAN ALLIANCE specifications, as well as ensuring high reliability.

To achieve these key principles, this report introduces analog radio over fiber (A-RoF) as an effective technology. When introducing A-RoF, there are multiple options for various aspects, including frequency conversion, multiplexing techniques, and network topology. These options are introduced in this research report.

Furthermore, this research report highlights the challenge of appropriate synchronization signals/physical broadcasting channel (SS/PBCH) when transmitting the same signal from multiple antennas to a single user equipment (UE).

Therefore, when considering the architecture of nGADS, it is essential to take the SS/PBCH issue into account and devise a reasonable solution as well as requirements and principles.

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List of abbreviations

3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
AI	Artificial Intelligence
A-RoF	Analog Radio over Fiber
B5G	Beyond 5G
CA	Carrier Aggregation
C-plane	Control plane
CPRI	Common Public Radio Interface
DAS	Distributed Antenna System
D-MIMO	Distributed MIMO
D-RoF	Digital Radio over Fiber
E2E	End to End
eMBB	Enhanced Mobile Broadband
FDD	Frequency Division Duplex
IF	Intermediate Frequency
IFoF	Intermediate Frequency over Fiber
I/F	Interface
IMDD	Intensity Modulation and Direct Detection
LOS	Line of Sight
MIMO	Multiple Input Multiple Output
mmWave	Millimeter wave
M-plane	Management plane
mWAD	mmWave Antenna Distribution
nGADS	Next Generation Antenna Distribution System
nGADS-CN	Next Generation Antenna Distribution System Center Node
nGADS-dAN	Next Generation Antenna Distribution System disaggregated Antenna Node
nGADS-dRN	Next Generation Antenna Distribution System disaggregated Remote Node
nGADS-RN	Next Generation Antenna Distribution System Remote Node
nGRG	Next Generation Research Group
NLOS	Non Line of Sight
OBSAI	Open Base Station Architecture Initiative
O-RAN	Open Radio Access Network
O-CU	O-RAN Central Unit
O-DU	O-RAN Distributed Unit
O-RU	O-RAN Radio Unit
OTA	Over-the-Air
OTRx	Optical Transceivers
PON	Passive Optical Network
PtMP	Point to Multipoint
PtP	Point to Point
RAN	Radio Access Network
RF	Radio Frequency
RFoF	Radio Frequency over Fiber
RoF	Radio over Fiber
SCM	Subcarrier Multiplexing
S-plane	Synchronization plane
SS/PBCH	Synchronization Signals/Physical Broadcasting Channel
Sub6	Sub 6GHz
TDD	Time Division Duplex
TDD-SW	TDD Switches
UDRAT	User Data Rate
UE	User Equipment
U-plane	User plane

WDM	Wavelength Division Multiplexing

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1 Introduction

1.1 Background

Mobile traffic has been increasing at an approximate annual growth rate of 1.3 times [1]. Based on this growth rate, it is predicted that the traffic volume in 2030 will be 14 times that of 2020 when 5G was introduced. By 2040, it is expected to reach 190 times the 2020 volume. To support this surge in mobile traffic, technological innovations, such as the utilization of millimeter waves to terahertz waves, are underway [1], [2]. Effective strategies to accommodate this traffic include expanding the mobile network capacity by increasing the frequency spectrum allocation for mobile communication as discussed in world radiocommunication conference 2023, and enhancing frequency utilization efficiency. Additionally, these expansions must consider the principles of green communication.

From 2022 to 2024, O-RAN ALLIANCE’s nGRG conducted use case and gap analyses of the existing architectures for mmWave antenna distribution (mWAD) [3]. The findings indicate that antenna distribution is effective in enhancing resource utilization efficiency. For instance, improving radio wave quality through optimal antenna placement enables the use of higher order modulation schemes [3]. Furthermore, sharing digital processing across multiple antennas, rather than each antenna having its own digital processing, can improve energy efficiency [3].

1.2 What is nGADS

The antenna distribution technique is integrated in a system so-called “Distributed Antenna System (DAS)”. DAS has a long history and has been widely used to extend coverage in 4G and previous networks [4]. In the past, DAS required simple connection with base station, since it redistributed RF signals transmitted by base stations. However, 6G networks, which are expected to utilize higher frequency bands, will require more advanced connectivity, including beamforming control [5], precise clock synchronization between base stations and DAS, and high-precision synchronization between multiple antennas as required by distributed MIMO [6] In this research report, we call DAS with above mentioned advanced connectivity next-generation antenna distribution system (nGADS). To enable operators and infrastructure sharing providers to select appropriate nGADS based on specific use cases, defining an open interface is essential, because the signals to control the array antennas could be propriety [7]. Nonetheless, the interface between base station and DAS has not been extensively discussed in O-RAN ALLIANCE, necessitating further investigation in this area.

1.3 Scope and objectives

The overall scope of this research report is to study the requirements and design policies which are required to realize nGADS in an open architecture. Therefore, the focus will be primarily on the architecture that disaggregates antennas from the O-RU.

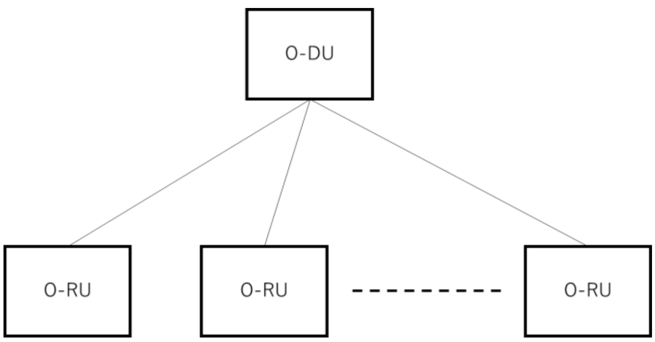
2 Definitions

2.1 Installation approaches

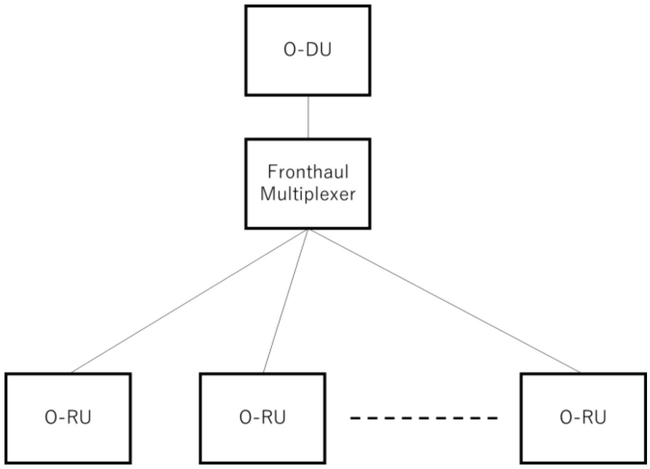
In this chapter, we discuss on the architecture from the functional perspective. There are three abstracted approaches to distributing the nodes which contains antennas. Figure 2-1 (a)(b)(c) represents the conceptual view to highlight the differences between these approaches. The first approach simply distributes O-RUs (Figure 2-1 (a)). This method is the basic approach for distributing O-RUs defined by the O-RAN ALLIANCE [7]. The second approach distributes O-RUs using fronthaul multiplexer defined by O-RAN ALLIANCE [7] (Figure 2-1 (b)), which serve a cell across multiple antennas. The final approach distributes disaggregated antenna nodes rather than the entire O-RU (Figure 2-1 (c)). The third configuration is known as distributed antenna systems (DAS), which show up in the traditional networks such as 3G or 4G [4], [8], [9].

In Figure 2-1 (C), “Center Node” and “Remote Node w/ antenna” are represented. The “Center Node” and “Remote Node w/ antenna” are abstracted equipment correspondent to “nGADS Center Node” and “nGADS Remote Node” introduced in 2.2 respectively. The detailed function are introduced in 2.2.

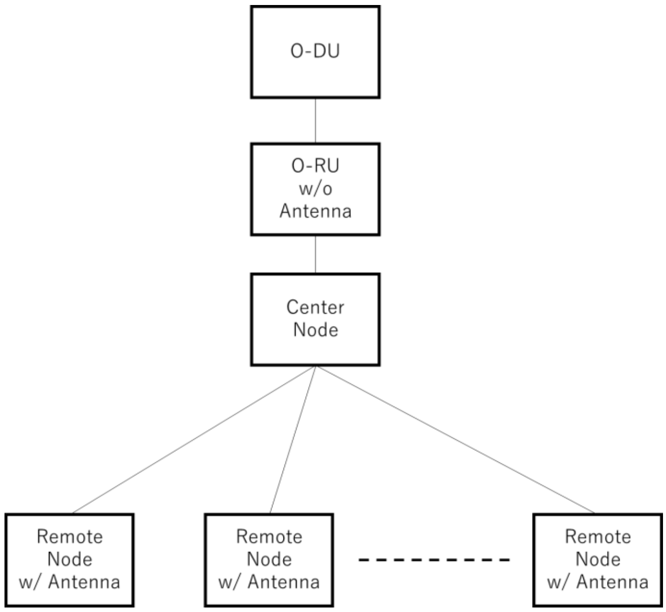
The approach of distributing O-RU (Figure 2-1 (a)) and distributing O-RUs using a fronthaul multiplexer (Figure 2-1 (b)) is out of the scope of this research report, as they have already been defined by the O-RAN ALLIANCE. Regarding to the approach of distributing the disaggregated antennas, it has not required detailed specification, as it simply redistributes the RF signal which are transmitted from O-RU in the 3G or 4G networks. However, in 5G and 6G networks, antennas are much more intelligent than in 4G and pervious networks as mentioned in 1.2. This will require more information to provide additional enhanced functions like beamforming for more efficient and value-added utilization. Therefore, this research report mainly focuses on the approach of distributing the disaggregated antennas.



(a) O-RU distribution



(b) Fronthaul Multiplexer



(c) Distributing disaggregated antennas

Figure 2-1 Installation approaches

2.2 nGADS nodes and interfaces

When delving into the components of nGADS based on existing distributed disaggregated antennas [9], we define three types of nodes and three key interfaces (I/Fs) that compose nGADS. This chapter discusses the nodes and I/Fs as shown in Figure 2-2.

Referring to Figure 2-2, definitions of these are described below.

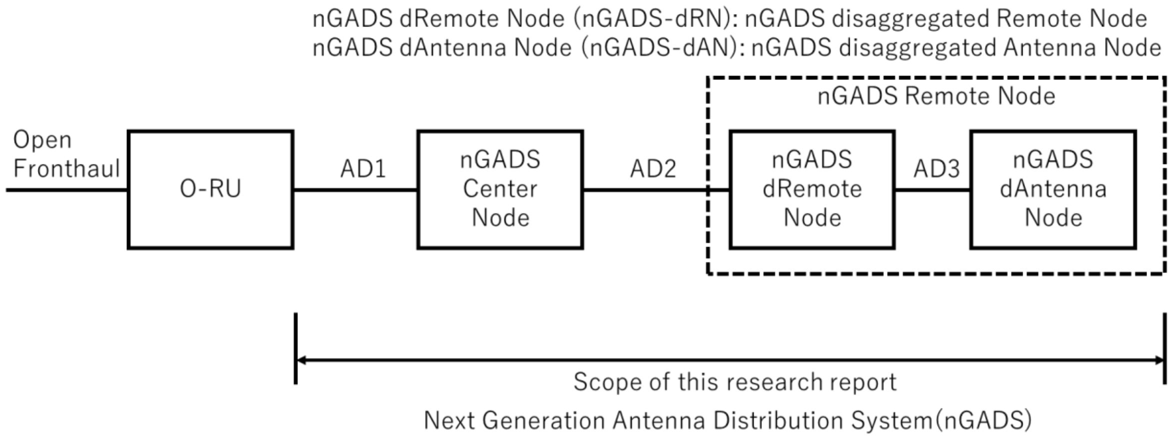


Figure 2-2 Detailed architecture of nGADS

Nodes

- nGADS Center Node (nGADS-CN): An Edge device on O-RU side, connecting to the O-RU via an AD1 interface as shown in Figure 2-2-2. The primary function of nGADS-CN is dispatching input signal from the O-RU to appropriate nGADS-RNs and vice versa.
- nGADS Remote Node (nGADS-RN): This node connects nGADS-CN to transmit RF signals into the air. Multiple nGADS-RNs connect to single nGADS-CN. When the GADS-RN receives multiple RF signals from different operators through the nGADS-CN, it transmits multiple RFs.
- nGADS disaggregated Remote Node (nGADS-dRN): Sometimes, the antenna function is disaggregated from the nGADS-RN, e.g., when the installation areas are smaller than nGADS-RN. This node retains remaining functions of the nGADS-RN other than disaggregated antenna.
- nGADS disaggregated Antenna Node (nGADS-dAN): This node retains the function to transmit the RF signals into the air. This node is generally smaller than the nGADS-RN, as it retains only a part of the nGADS-RN's functions. The integration of nGADS-dRN and nGADS-dAN is nGADS-RN.

Interfaces

- AD1: This I/F connects an O-RU and nGADS-CN. We assume that this connection coax cable for this I/F.
- AD2: This I/F connects the nGADS-CN and the nGADS-RN or nGADS-dRN.
- AD3: This I/F connects the nGADS-dRN and the nGADS-dAN. This I/F is used when the nGADS-RN is too large to place on the intended installation space Since the purpose of nGADS-dAN is allowing smaller antenna equipment, the propagated signal should not require further process on nGADS-dAN level as far as possible. Therefore, we assume for simplicity that coax cable is used for this I/F.

2.3 Possible installation scenarios

In this research report, the building where the remote node is called installation site, while the specific area where the remote node is installed is called the antenna site.

There are various nGADS installation scenarios. Possible installation scenarios are represented in Figure 2-3; examples include shopping malls, stadiums, and exhibition venues.

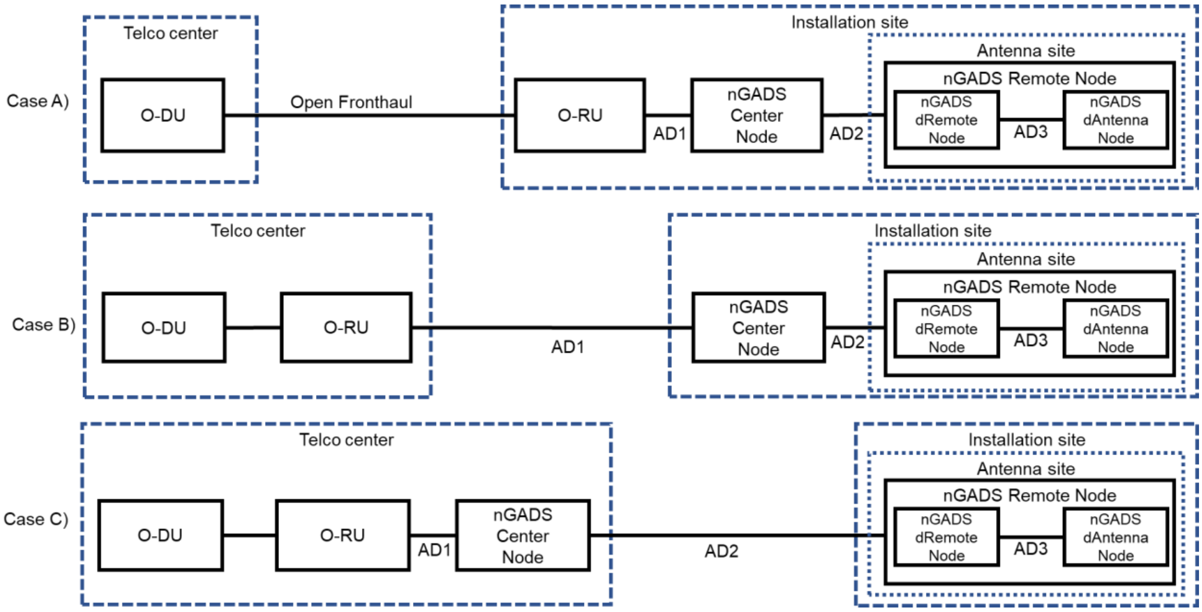


Figure 2-3 Possible installation scenarios

- Case A) Both the O-RU and all nGADS equipment are placed on-site at the “Installation site”.
- Case B) The O-RU is located at a “Telco center”, while all nGADS equipment is installed in the “Installation site”. This scenario has been observed if the AD1 is Over-the-Air (OTA) [9]. Although this case is a potential solution, it is less preferred when Case A and Case C are available, when using co-ax cable for AD1, since co-ax cable has bigger attenuation especially for high frequency radio, such as 28GHz.
- Case C) Both the O-RU and nGADS-CN are placed in the “Telco center”, and nGADS-RN is placed in the “installation site”. This scenario would be taken when the "Installation site” does not have enough space to place the nGADS-CN. The advantage of this case is only the smaller, distributed nGADS-RNs are installed on-site at various locations. As previously mentioned in 2.2, the nGADS-dAN is a relatively simple piece of equipment. The nGADS-dRN and nGADS-dAN will be placed in close proximity to each other, such as on the same floor [9] Therefore, deploying nGADS-dRN and nGADS-dAN at separate sites would not be practical.

For use cases such as music events, disaster recovery, or pop-up installations, a temporary, portable nGADS configuration could provide rapid deployment and high-bandwidth support. In such cases, lightweight, battery-operated equipment is particularly advantageous. Based on the survey to the operators conducted by authors, Case C seems to be widely utilized, since it requires less space and energy on-site. However, Case C may necessitate additional wiring. Therefore, the installation topology should be selected based on specific conditions and requirements.

3 Requirements

In a previous nGRG research report [3] we investigated 6G use cases and identified gaps in 5G networks. Many of these gaps are related to bandwidth and latency.

In this chapter, we will discuss the architecture requirements for nGADS.

3.1 Capacity expansion

The mWAD use case analysis [3] indicates that uplink data rates of 14–230 Gbps per object and downlink rates of 48–200 Gbps are necessary. Achieving these requirements is expected to involve a combination of multiple techniques, such as carrier aggregation and dual connectivity, alongside capacity expansion via nGADS. Consequently, nGADS is expected to operate with other capacity-expanding technologies, e.g., beamforming.

Regarding the maximum number of UEs, this is controlled by the gNB. Therefore, nGADS should not impose limitations on the maximum number of UEs, further restricting the number of channels available at the gNB.

3.2 Minimum latency impact

While 5G targeted a 1 ms latency in the wireless access network, applications requiring sub-millisecond end-to-end (E2E) latency have emerged [3], making delay reduction within the wireless access network a critical challenge. However, since E2E communication paths involve multiple network devices and mediums, defining a specific delay requirement within nGADS is not feasible. As a baseline requirement, nGADS is expected to meet the allowable delay thresholds defined for the O-RU.

3.3 Multiple nGADS-RNs per nGADS-CN

Line-of-sight (LOS) is particularly important for high-frequency radio communications, such as mmWave (e.g., 28GHz, 40GHz), to avoid propagation losses. However, maintaining LOS can be challenging when the UE or obstacles are in motion. To address this, distributing multiple nGADS-RNs transmitting identical signals is an effective approach to provide redundancy and maintain connectivity at the cost of capacity.

3.4 Distance between nGADS-CN and nGADS-RN

Traditionally, the central node of a DAS is located within the same building as the DAS [9]. However, server rooms in buildings often have limited space. In such cases, it is preferable to place the central node outside the building housing the distributed antennas, for instance, in a telecom center building as illustrated in Figure 2-3, Case C.

Therefore, in addition to traditional DAS configurations, nGADS-RNs must be capable of being installed at a distance from the central node to enable optimal placement and flexibility in dense urban or remote areas. Radio over fiber (RoF) and Intermediate frequency over fiber (IFoF) technologies [3] are critical for extending nGADS deployment distances without compromising signal integrity. RoF and IFoF ensure low-latency, high-quality connections over significant distances, supporting flexible node placement.

3.5 Beamforming for link budget enhancement

nGADS can carry the RF through the medium to targeted place. In this perspective, nGADS provides an effect similar to beamforming. As a result, beamforming is not always necessary in nGADS. However, incorporating adaptive beamforming is more effective for improving gain, particularly for mmWave frequencies, which have large propagation losses. Consequently, nGADS architecture must take into account both cases: with and without beamforming.

3.6 Multiple MIMO layers

User data rates (UDRAT) are expected to increase ongoingly [3]. Transmitting and receiving individual signals from multiple antennas, known as multiple-input and multiple-output (MIMO), is one of effective technique to achieve the required UDRAT. Additionally, distributed MIMO (D-MIMO), which transmits signals from different antenna nodes to a single node, is being widely studied as a key technology to improve UDRAT [10]. Therefore, supporting multiple MIMO layers with nGADS is crucial for enhancing UDRAT in any environment regardless of whether it is LOS or NLOS.

3.7 Multiple operator support

Due to the significant propagation loss and less-diffracting nature of high-frequency radio waves, such as mmWave, the number of antennas required for high-frequency bands are expected to increase. To alleviate the burden on facility owners and reduce installation costs and time for operators, the sharing functionality of nGADS is critical [3]. By enabling equipment sharing, nGADS can improve lower the cost per bit.

To achieve this, nGADS must support the range of frequencies assigned to the sharing operators. It is also essential to ensure isolation that enables multiple operators to coexist on a single infrastructure while maintaining their own dedicated resources and network policies. Furthermore, nGADS must include resource allocation adjustment capabilities to minimize interference among multiple operators.

3.8 Energy-saving

Sustainability is one of the most pressing challenges facing the Earth, making energy-saving features critical. Additionally, energy savings can reduce operating costs for operators [11]. Therefore, nGADS should be deployed in an energy-efficient manner.

nGADS-RN is configured with minimal functions, while certain O-RU functions are shared among multiple nGADS-RNs. This configuration allows nGADS to achieve greater energy efficiency per unit area compared to RU distribution. The energy-saving effect becomes more pronounced as the number of connected nGADS-RNs increases.

4 General principles of nGADS architecture

This chapter introduces the general principles to design the nGADS architecture.

4.1 3GPP and O-RAN ALLIANCE specification compliant

nGADS is expected to be seamlessly integrated within the mobile network, which is compliant to both 3GPP and O-RAN ALLIANCE’s specifications. This compliance ensures interoperability and compatibility across multi-vendor and multi-operator environments, which is crucial for supporting scalable and future-ready network deployments. For instance, compliance to O-RAN ALLIANCE's specifications facilitate the adoption of open interfaces and intelligent RAN functionalities [12].

4.2 Time synchronization

To operate a Time Division Duplex (TDD) system in synchronous or semi-synchronous mode, nGADS must align with the TDD timing at the specified points. Additionally, the synchronization requirements between antennas, as established by 3GPP, must be satisfied when supporting MIMO or D-MIMO [6]. Furthermore, if there are additional time synchronization accuracy requirements for the system, nGADS must comply with them.

4.3 Target-planes

nGADS needs to handle the transmission of traffic across all key planes: control-plane (C-plane), management-plane (M-plane), synchronization-plane (S-plane), and user-plane (U-plane). nGADS? must propagate these signals without altering their core context or structure to ensure integrity and reliability in signal distribution.

4.4 Infrastructure sharing

As mentioned in chapter 3.7, the installation of antennas imposes a significant burden on both operators and facility owners in terms of cost, time, and installation space). To alleviate these burdens, sharing installed antennas among multiple operators is an effective approach. Therefore, the nGADS architecture shall include features that enable sharing among multiple operators.

4.5 Deployability

One of the primary purposes of nGADS is to enable the flexible deployment of antennas. In many cases, the location where an antenna is installed faces various constraints, such as limited space, weight restrictions, long-distance requirements, or the need to ensure LOS propagation. To optimize antenna placement in such environments, nGADS-RNs must feature compact and lightweight designs, as well as the capability for extended distances from O-RU equipment. This flexibility ensures feasibility even in constrained or challenging installation sites.

Additionally, ensuring that nGADS-RNs operate reliably under a wide range of environmental conditions (e.g., temperature and humidity) is critical for their deployment in diverse locations.

4.6 High reliability and fault tolerance

As a system integral to the 6G RAN infrastructure, nGADS must have the capability to provide high reliability and fault tolerance to minimize service interruptions. This capability is particularly crucial for applications requiring ultra-reliable low-latency communication (URLLC), such as autonomous driving, remote surgery, and industrial automation [13]. For instance, nGADS could incorporate redundant data pathways to backup connectivity options to prevent single point of failure, enabling automatic rerouting in the event of a failure. Furthermore, by leveraging AI-driven diagnostics, nGADS can be used to predict, detect, isolate, and recover from faults without external intervention.

4.7 Authentication

Trustworthiness is crucial for mobile networks. nGADS must achieve the same level of security and reliability as other components of the mobile network. In particular, mutual authentication between nGADS-CN and nGADS-RN is essential.

4.8 Future proofing

Nowadays, innovative activities are taking place everywhere. Some of these, such as the rapid deployment of generative AI and immersive entertainment, significantly influence network traffic patterns. These developments may require enhancements in network quality, throughput, lower latency, and the addition of new signaling features and duplexing techniques (e.g., Frequency Division Duplex (FDD), TDD). To support these emerging requirements with minimal modifications, the nGADS architecture shall be designed to accommodate new demands without necessitating the redesign of the architecture.

5 Enabling Technologies

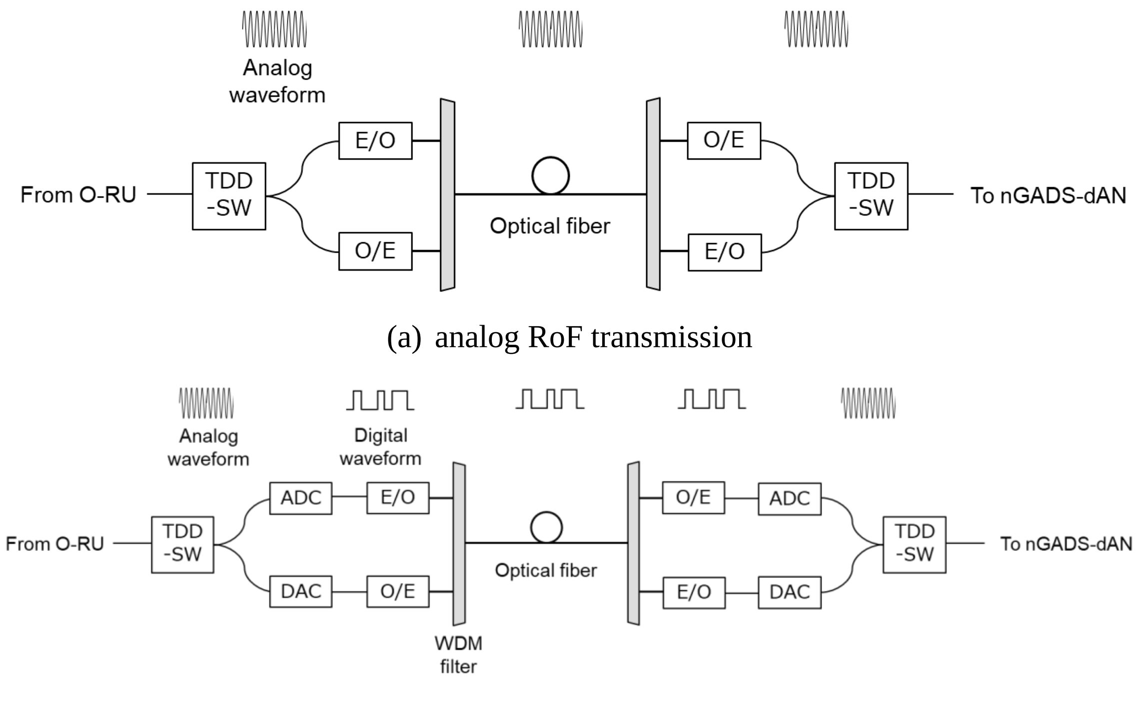
In Ref. [3], bare radio and tunneled radio are described as mmWave coverage extension techniques. The tunneled radio is also subcategorized into RU distribution and antenna distribution. The tunneled radio can transmit radio signals over cable to remote sites, regardless of obstacles or radio conditions in the path. The transmission distance can be extended to up to tens of kilometers by using optical fibers [3]. Therefore, the tunneled radio with optical fiber can be an effective technology for signal distribution to nGADS. This chapter presents technologies for the tunneled radio that meet the requirements for distributed antennas shown in chapter 3. Enabling technologies for AD2 interface defined in Figure 2-2 are mainly discussed.

5.1 O-RU distribution and antenna distribution for distributed antennas

Distributed antennas can be configured with both O-RU distribution and antenna distribution. In O-RU distribution, multiple O-RUs with antennas are placed in different sites from a O-DU site whereas, in antenna distribution, antennas are in different sites from an RU site. Therefore, in an antenna distribution, the functions and equipment in nGADS -RN can be simplified, and the power consumption and the deployment space are expected to be saved. The area where nGADS-RN is placed is referred to as an antenna site in the following text as defined in Figure 2-3. The optical transmission between O-DU and O-RU is based on digital Ethernet frame transmission scheme [7]. Such transmission scheme has been discussed a lot, and many standardization documents have been released in IEEE [14], [15] and ITU-T [16]. On the other hand, the optical transmission between O-RU and antennas is based on RoF technologies. Few standardization documents have described RoF technologies for distributed antennas [17], [18]. The following part of this chapter describes representative technologies for RoF systems between O-RU and antennas in antenna distribution.

5.2 Analog RoF and Digitized RoF technologies

RoF technologies are categorized in analog RoF technology and digitized RoF technology. Figure 5-1 (a) and (b) show examples of the configurations for analog RoF transmission and digitized RoF transmission, respectively. For bidirectional optical transmission, widely prevalent wavelength division multiplexing (WDM) technology can be used [19]. TDD switches (TDD-SW) are also used for TDD-based mobile communication. Such RoF links can coexist with existing F1 and O-RAN FH links without impacting them because they are only for RF functions and do not require specific configuration in upper layers. . In analog RoF transmission, the waveforms of radio signals are transmitted over fiber without changing the radio signal format. Electrical-to-optical converter (E/O) and optical-to-electrical converter (O/E) are required before and after optical fiber transmission, respectively. Most of the commercially available analog RoF systems use simple intensity modulation and direct detection (IMDD) scheme for the optical fiber transmission. To avoid the signal deterioration due to fiber transmission, the input power to the E/O should be adjusted to an appropriate range. In digital RoF transmission, the waveforms of radio signals are digitized by sampling and quantization, and the digital data is transmitted over fiber. Therefore, in comparison with analog RoF transmission, analog-to-digital converter (ADC) and digital-to-analog converter (DAC) are additionally required before and after transmission, respectively. When an O-RU can directly output the digitized waveform data, the ADC before transmission can be removed. Conventional common public radio interface (CPRI) and open base station architecture Initiative (OBSAI) for 4G services are based on D-RoF technology. The pros and cons of analog RoF transmission and digitized RoF transmission are summarized in Table 5-1. Compared to D-RoF systems, A-RoF systems are expected to simplify the equipment in antenna sites. Additionally, optical transmission with high spectral efficiency can be easily achieved in IMDD scheme. These features will be more important in 6G era because more small cells are formed for higher spectral efficiency and larger capacity in wireless communications. The following parts of this chapter are mainly related to analog RoF transmission. Table 5-2 briefly summarizes options of analog RoF implementation described in detail in the following chapters.



(a) analog RoF transmission

(b) digitized RoF transmission

Figure 5-1 Examples of the configurations for RoF type

Table 5-1 Pros and cons of analog RoF transmission and digitized RoF transmission.

Technique	Pros	Cons
Analog RoF	- Low power consumption and small deployment space in antenna sites - Optical transmission with high spectral-efficiency in IMDD scheme - Very low latency	- Susceptible to signal degradation due to fiber transmission
Digitized RoF	- Less susceptible to signal degradation caused by fiber transmission - Mature digital transmission scheme utilized	- High power consumption and large deployment space in antenna sites - Optical transmission with low spectral-efficiency in IMDD scheme

Table 5-2 Options of analog RoF implementation

Chapter No.	Perspective
5.2, 5.3	Analog transmission technologies: - Radio over fiber (RoF) - Intermediate frequency over fiber (IFoF)
5.4	Frequency conversion technologies for IFoF systems: - Without reference clock and local oscillator (LO) distribution to antenna sites - With reference clock distribution to antenna sites - With LO distribution to antenna sites
5.5	Multiplexing technologies for large-capacity transmission: - Subcarrier multiplexing (SCM) - Wavelength division multiplexing (WDM)
5.6	Analog beamforming (BF) technologies: - Analog BF processed in an O-RU site - Analog BF processed in each antenna site
5.7	Network Architectures: - Point-to-point (PtP) - Point-to-multipoint (PtMP)
5.8	Signals transmitted between O-RU and antenna equipment for control-plane (C-plane) and management-plane (M-plane): - Ethernet PHY - Digitally modulated signals for synchronization-plane (S-plane): - Reference clock - Precision time protocol (PTP) over Ethernet - Time division duplex (TDD) timing for user-plane (U-plane): - Analog radio frequency (RF) - Analog intermediate frequency (IF)
5.9	Resources for infrastructure sharing: - Optical fiber - Antenna site - nGADS-RN - O-RU

5.3 IFoF technology

As described in chapter 5.2, analog waveforms of radio signals are transmitted over fiber by analog RoF technology. The frequencies of the radio signals that are transmitted over fiber can be set to the RF itself or the intermediate frequencies (IF) of the radio signals. The analog RoF systems that use IF for fiber transmission are often referred to as IFoF systems, distinguished from the analog RoF systems that use RF for fiber transmission. Figure 5-2 depicts an example of a bidirectional IFoF system. WDM filters and TDD-SW are used for bidirectional optical transmission and TDD-based mobile communication, respectively. In comparison with RoF systems, IFoF systems require frequency converters (FC) for down-conversion and up-conversion of radio signals in both before and after fiber transmission. The configuration of the optical transmission equipment is complicated due to the additional frequency converters, whereas relatively low-cost E/O and O/E for narrower bandwidths and lower frequencies can be utilized. As described in chapter 5.5, using various frequencies, IFoF systems can simultaneously transmit multiple RF signals over fiber with a single wavelength.

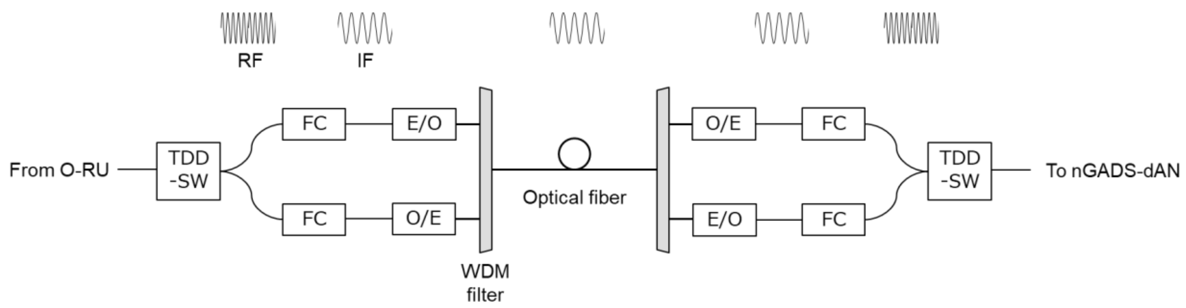
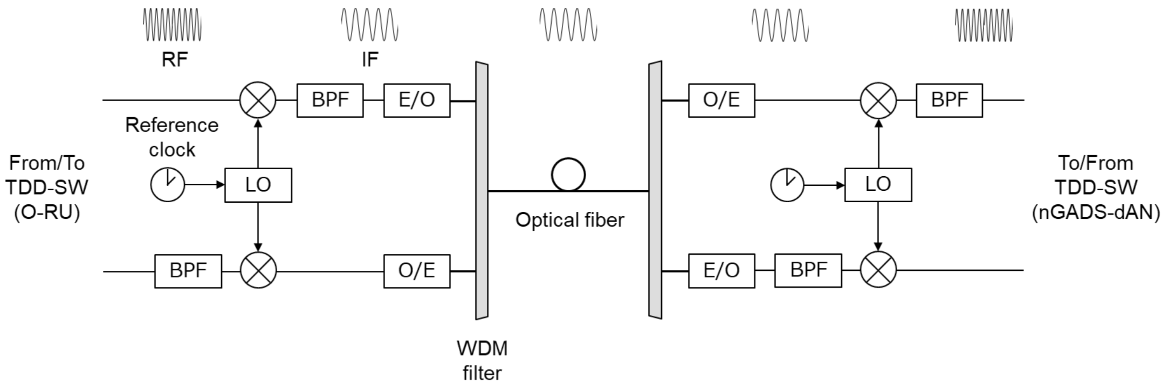


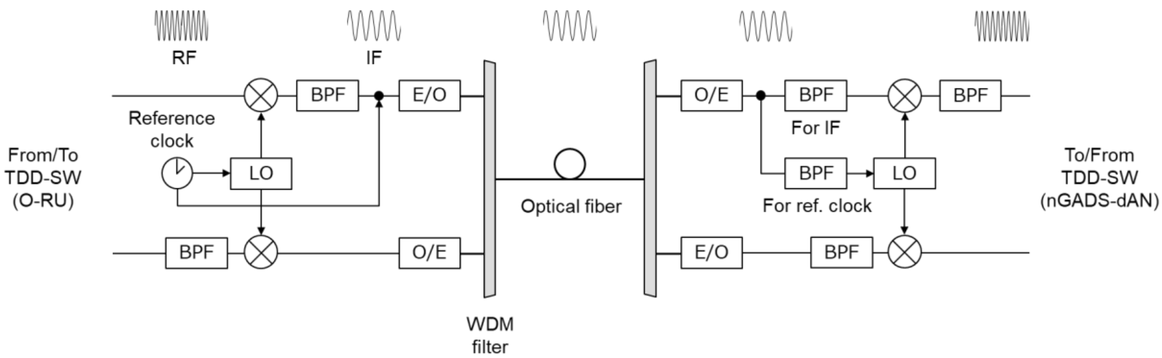
Figure 5-2 Example of the configuration for IFoF transmission system

5.4 Frequency conversions for IFoF systems

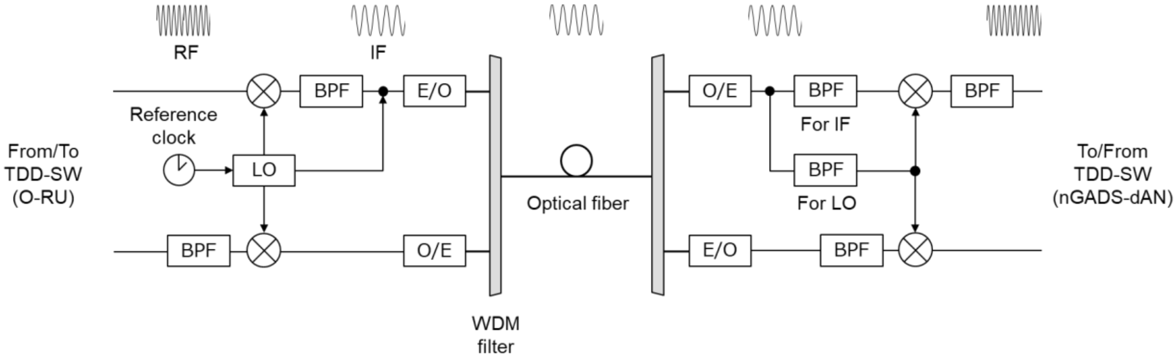
Figure 5-3 describes examples of configurations for frequency conversions from IF/RF to RF/IF in IFoF systems. A frequency converter basically consists of mixer, local oscillator (LO), and RF filter like band-pass filter (BPF). The LO sources for downlink (DL) transmission can be simultaneously used for uplink (UL) transmission. Additionally, RF amplifiers are used when the input RF power to the mixer is lower than the required value.. Reference clocks can also be used to stabilize the LO frequency and phase. Depending on the deployment sites and distribution schemes of the LO sources and reference clocks, several configurations for frequency conversions can be considered. In Figure 5-3 (a), an LO source is placed in each antenna site, and the reference clock is provided from a GPS signal via GPS antenna and GPS receiver in each antenna site. In Figure 5-3 (b), an LO source exists in each antenna site whereas the reference clock is distributed from the O-RU site to the antenna site over fiber transmission link. In comparison with Figure 5-3 (a), the deployment process in each antenna site can be simplified because a GPS antenna, a GPS receiver, and the RF cable between them are not needed. However, if the reference clock is used by multiple antenna sites and experiences some failure, all the antenna sites may encounter communication errors after a certain period of time. In Figure 5-3 (c), the LO source is placed in an O-RU site and the LO output signal is transmitted to multiple antenna sites over fiber links. The reference clock is provided from a GPS signal via GPS antenna and GPS receiver in the RU site or transmitted from different sites to the RU site over fiber links. In comparison with Figure 5-3 (b), the configuration for frequency conversions in each antenna site can be further simplified because the LO source is not required in each antenna site. However, if the LO has some failure, each antenna site immediately has communication errors. All the frequency conversion schemes in Figure 5-3 have advantages and disadvantages. Therefore, depending on the system design of mobile operators, appropriate frequency conversion schemes should be selected. Furthermore, not only frequency conversions with RF components but also frequency conversions with optical components are effective for high radio frequencies such as millimeter, sub-terahertz, and terahertz waves. In frequency conversions with optical components, an optical LO source is used whereas the RF mixer and LO are not needed. Especially for sub-terahertz and terahertz waves, such frequency conversions may need to be considered.



(a) without reference clock and LO distribution



(b) with reference clock and without LO distribution

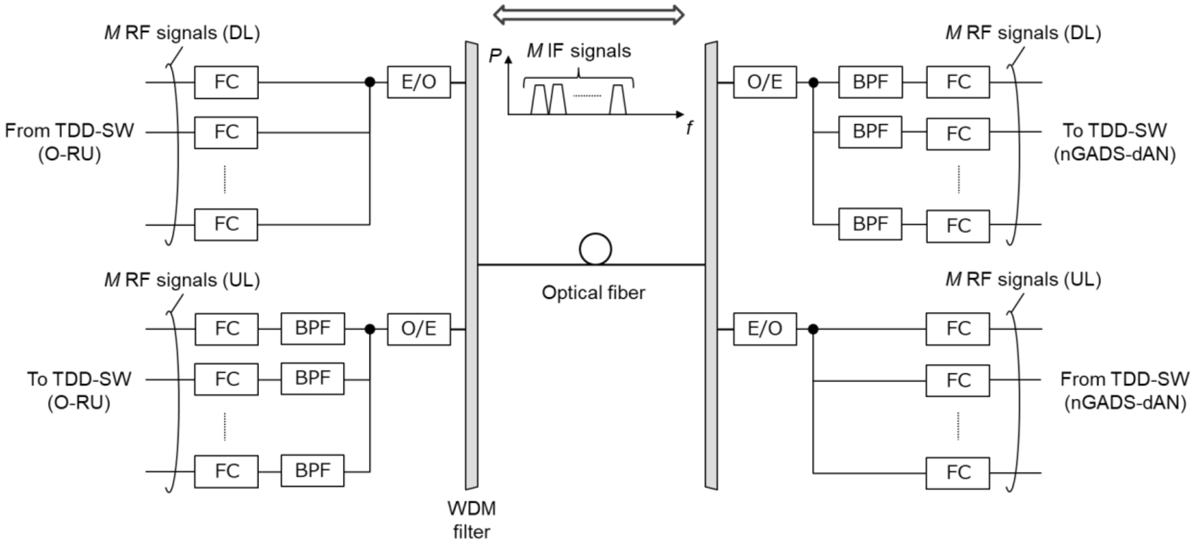


(c) with LO distribution

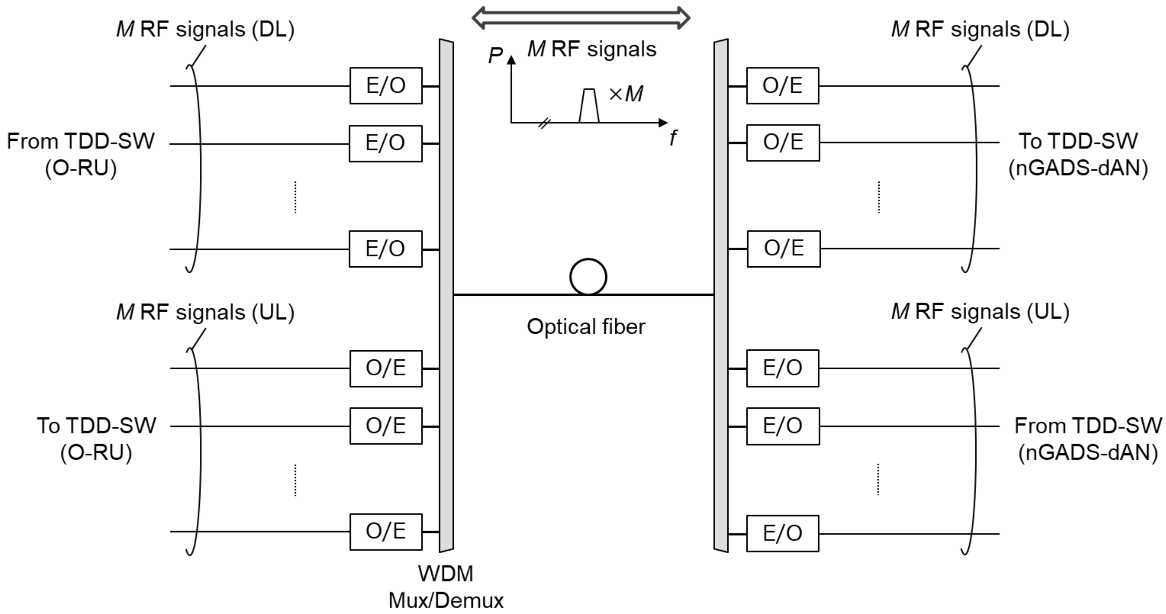
Figure 5-3 Examples of frequency conversion technologies for IFoF transmission systems

5.5 Multiplexing technologies for large-capacity analog RoF/IFoF systems

This chapter describes two technologies for increasing transmission capacities of analog RoF/IFoF systems. These technologies can support the increase of MIMO layers. The first one is subcarrier multiplexing (SCM). Figure 5-4 (a) shows an example of bidirectional IFoF transmission with SCM. The number of RF signals transmitted over fiber is assumed to be *M* for each direction. When each radio signal is converted to a different IF from the other radio signals, plural radio signals can be multiplexed in the electric frequency domain. The multiplexed IF signals are converted to an optical signal by an E/O and simultaneously transmitted over fiber with one optical wavelength for each direction. After transmission, the optical signal is converted to the original IF signals by an O/E. The output signal from the O/E is split into *M*, and each of the IF signal is separated by a BPF. The IF signals are finally converted to the RF signals by FCs. In the other case, when antennas for multiple mobile networks that use different radio frequencies are placed in an antenna site, multiple RF signals with different radio frequencies can also be transmitted over fiber with SCM technology. The second technology is wavelength division multiplexing (WDM). Figure 5-4 (b) depicts an example of WDM-based RoF system. *M* RF signals for each direction are converted to optical signals with different wavelengths by E/Os, and the optical signals are multiplexed by a WDM multiplexer (Mux). The WDM signals are transmitted over fiber and, after transmission, demultiplexed by a WDM demultiplexer (Demux). Each of the optical signal is converted to the RF signal by an O/E. Bidirectional transmission can be achieved by WDM technology with different wavelengths for DL and UL. The multiplexing technologies shown in Figure 5-4 (a) and (b) can be simultaneously used for further increasing the capacities of RoF/IFoF systems.



(a) with SCM technology

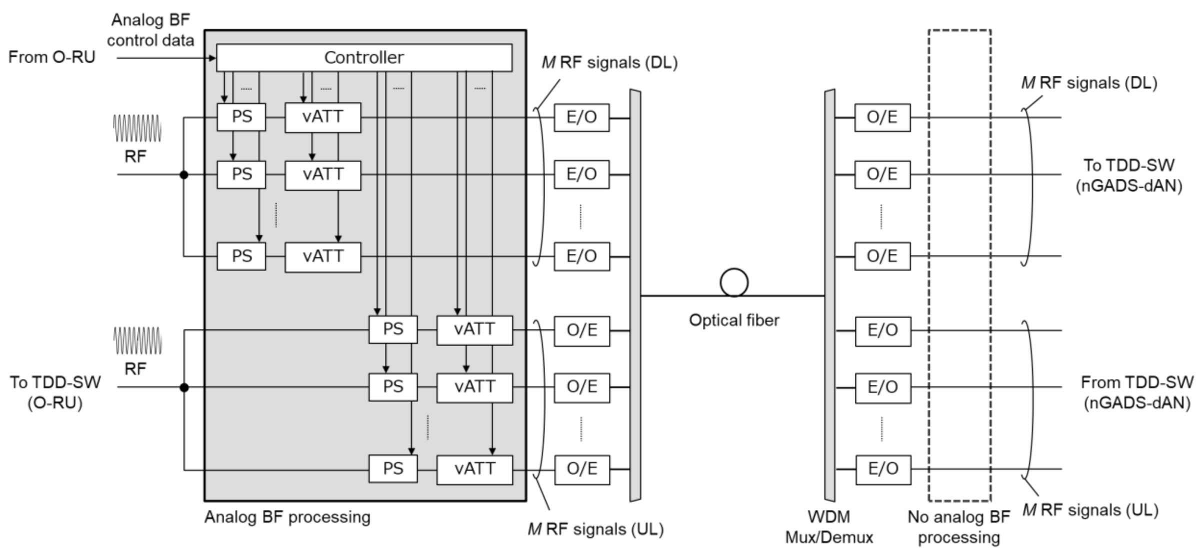


(b) with WDM technology

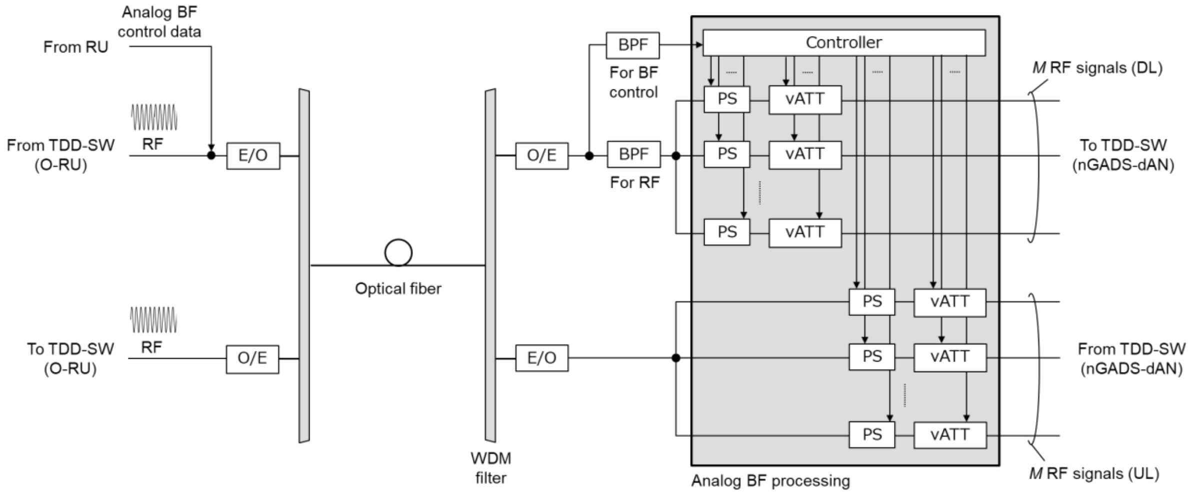
Figure 5-4 Examples of Large-capacity RoF/IFoF systems for downlink

5.6 Analog beamforming schemes for analog RoF/IFoF systems

Beamforming technology is effective for properly forming the service coverage especially for high frequencies such as millimeter waves. When analog RoF/IFoF technologies are used for antenna distribution systems, the processing of the analog beamforming can be performed in O-RU sites or in antenna sites. Figure 5-5 (a) shows an example of analog beamforming processed in an O-RU site. For downlink analog beamforming, an RF signal is split into multiple signals, and the phase and amplitude of each RF signal are adjusted by phase shifter (PS) and variable attenuator (vATT), respectively. The PS and vATT are managed by control data from the O-RU via the controller. After the analog beamforming processing, the number of RF signals is equal to the number of antennas or antenna elements in an antenna site. The number of RF signals after beamforming processing is assumed to be *M* in Figure 5-5. In WDM-based RoF transmission, the relationship of the relative phase and amplitude among the RF signals should be maintained if the beamforming process is conducted without considering phase and amplitude changes on the fiber transmission. In the antenna site, no complicated signal processing is required, and the RF signals can be directly emitted from each antenna or each antenna element. When IFoF technology is applied to the antenna distribution, as described in chapter 5.3, the frequency conversion process is required before and after optical transmission. For uplink analog beamforming, the opposite processing to the downlink beamforming is taken. Figure 5-5 (b) describes an example of analog beamforming processed in an antenna site. The number of RF signals transmitted over fiber is much less than that of antennas or antenna elements, which can drastically simplify the configuration of the optical transmission. However, control data signals for analog beamforming should be sent from the O-RU site to the antenna site. After analog RoF transmission for downlink, the output signal from the O/E is split into two signals. Both signals pass through BPFs for filtering control data signal and RF signal, respectively. The following analog beamforming process is the same as in Figure 5-5 (a). However, the beamforming process should be carefully performed at the appropriate timing for generating expected RF beams. The analog beamforming processing can also be conducted in optical domain for both schemes in Figure 5-5 (a) and (b). In such cases, optical phase shifters, variable optical attenuators, and multiple O/Es are used instead of the electrical components for analog beamforming.



(a) processed in an O-RU site

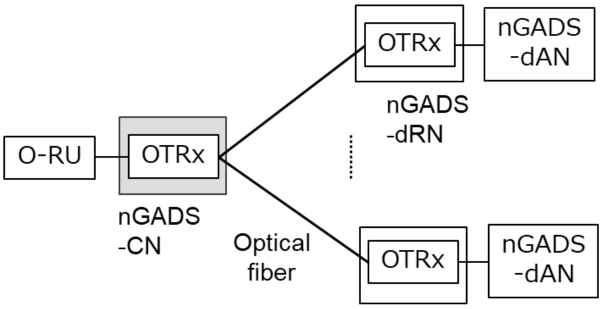


(b) processed in an antenna site

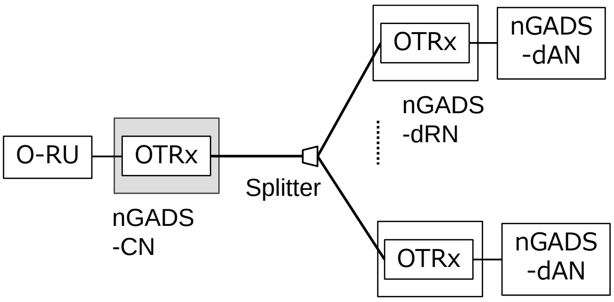
Figure 5-5 Examples of configurations for analog beamforming

5.7 Network topologies for analog RoF/IFoF systems

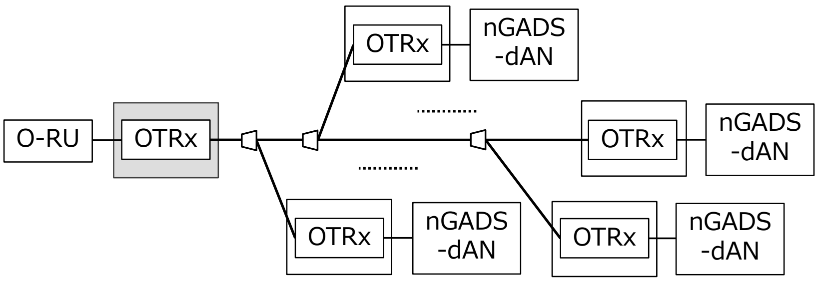
Analog RoF/IFoF systems for antenna distribution are mainly categorized in point-to-point (PtP) and point-to-multipoint (PtMP) access from the perspective of optical network architecture [18]. Figure 5-6 (a) shows an example of PtP architecture for star topology in RoF/IFoF systems. Optical fibers are deployed for connecting the O-RU site and antenna sites. RF/IF signals are bidirectionally transmitted over each of the fiber by optical transceivers (OTRx) with E/O, O/E, and WDM coupler. Each optical fiber is independent of the other fibers. Therefore, even when an optical fiber has some failure, the other links can work well without any impacts. However, the total fiber deployment cost is clearly increased. Figure 5-6 (b) and (c) illustrate two examples of PtMP architecture for analog RoF/IFoF systems. The first one described in Figure 5-6 (b) is a passive optical network (PON) that is widely used in current optical access networks [20], [21]. At least one optical splitter that connects multiple antenna sites is placed between the O-RU site and the antenna sites. Depending on the multiplexing technologies, the splitter can be a power splitter/coupler and/or WDM Demux/Mux. An optical fiber between the O-RU site and the splitter site is shared by multiple antenna sites. Using the PON architecture, the fiber deployment cost is expected to be reduced compared to the star topology. However, when the shared fiber between O-RU site and splitter site has some failure, all antenna sites may have difficulty in communicating with the O-RU site. The second PtMP architecture shown in Fig. 5-6 (c) is similar to the PON architecture in Fig. 5-6 (b). However, an antenna site is connected to each splitter whereas two antenna sites are connected to the farthest splitter from the O-RU. In comparison with the PON architecture in Fig. 5-6 (b), this architecture is suitable for connecting antenna sites with wide ranges of transmission distances from the O-RU.



(a) PtP topology (star)



(b) PtMP topology (PON)



(c) PtMP topology (hierarchical PON)

Figure 5-6 Examples of topologies for analog RoF/IFoF systems

5.8 C/M/S-plane signals for analog RoF/IFoF systems

As described in chapter 4.3, for antenna distribution with analog RoF/IFoF systems, newly defined control-plane (C-plane) and management-plane (M-plane), synchronization-plane (S-plane), and user-plane (U-plane), mobile wireless RF/IF signals should be transmitted over fiber between O-RU and antennas. Examples of transmitting reference clock or LO as S-plane signal and BF control signal as C/M-plane data have been described in chapter 5.4 and 5.6, respectively. This chapter presents the assumed signal types for C/M/S-plane data and how to send C/M/S-plane signals, including reference clock, LO, and BF control signal, from O-RU/antenna to antenna/RU. Figure 5-7 depicts the assumed signal types, transmission schemes, and functions required in antenna sites. Depending on the system design, all or part of the C/M/S-plane signals will be used. BPSK and QPSK signals can be assumed as digitally modulated signals for C-plane and M-plane. Sine waves such as 10-MHz and 100 MHz tone signals are considered as reference clocks. IEEE 1588 Precision Time Protocol (PTP) is also known as one of the time and frequency synchronization techniques via transmission networks [22], [23], [24]. For TDD-based mobile network, TDD timing signals for switching downlink and uplink transmission in antenna sites are essential. In antenna sites, transmission equipment should also be monitored and controlled from the O-RU side. C/M/S-plane signals are transmitted between the O-RU and the antenna sites along with U-plane signals using SCM, WDM, and/or SDM technologies. Dedicated fibers can also be used for transmitting the C/M/S-plane signals.

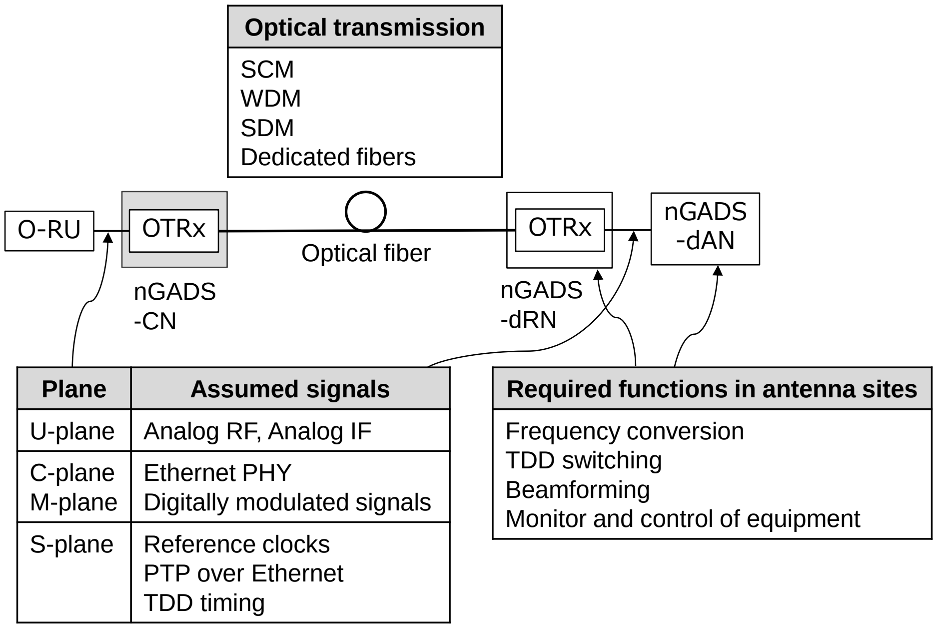


Figure 5-7 Assumed C/M/S-plane signals and required functions in antenna sites for antenna distribution with analog RoF/IFoF systems

5.9 Infrastructure sharing in antenna distribution with analog RoF/IFoF systems

For large-capacity 6G services, more antennas will be densely deployed, and more small cells will be formed. This causes a major problem for most operators due to higher deployment and operational costs. Therefore, infrastructure sharing for analog RoF/IFoF systems and the other resources such as nGADS-RN and antenna site will be more important in the future. In this chapter, some kinds of infrastructure sharing are assumed, depending on the scope of shared equipment and resources. Figure 5-8 briefly illustrates a RAN architecture that consists of O-CU, O-DU, O-RU [7], antenna, and analog RoF/IFoF system for antenna distribution. Table 5-3 outlines the infrastructure sharing scenarios that can be considered within the scope of antenna distribution. In general, the broader the scope, the more difficult infrastructure sharing becomes. In case #2, resources needed in antenna sites such as deployment spaces and power equipment are shared among multiple operators. When the optical fiber #3 used for the AD2 interface is shared by several mobile operators for the cases #1, #4, and #5, SCM, WDM, and/or SDM technologies are applied to the optical transmission between the O-RU and antenna sites.

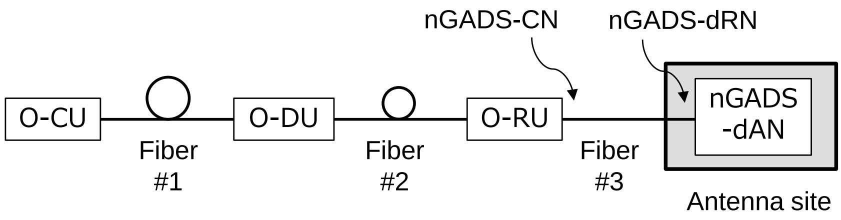


Figure 5-8 RAN architecture.

Table 5-3 Infrastructure sharing scenarios for antenna distribution.

Case	Shared infrastructure			
	O-RU	Fiber #3	nGADS-RN	Antenna site
#1		X		
#2				X
#3			X	X
#4		X	X	X
#5	X	X	X	X

6 Challenges

When nGADS transmits copied RF from multiple nGADS-RNs to a single UE with beamforming technique, there are some challenges due to the varying relative position of the UE with respect to each nGADS-RN. As an instance, when transmiting RF to UE(x) from two nGADS-RNs, such as nGADS-RN(a) and nGADS-RN(b), appropriate synchronization signals/physical broadcasting channel (SS/PBCH) block for nGADS-RN(a) may be 1 while for nGADS-RN(b) may be 9. gNB needs to select the appropriate SS/PBCH block for UE(x).

The architecture must address how to reconcile these differences effectively.

7 Conclusions

Systems of distributing antennas have been in use for a long time. However, recent RAN have seen advancements in functionality, such as support for multiple frequencies, particularly high frequencies like mmWave, and beamforming capabilities As these demands are expected to expand further with the advent of 6G, different technologies for distributed antennas will also need to adapt to meet these requirements.

To enable the design of nGADS, this research report has identified requirements and architecture principles relevant for nGADS, which will be required in 6G network. We defined eight (8) requirements for nGADS, focusing on aspects such as communication capacity extension, multi-operator coexistence, and energy efficiency.

Additionally, we outlined eight (8) design principles for nGADS to ensure compliance with 3GPP specifications and to achieve a highly reliable and secure system. We introduced the A-RoF technique, an enabling technology that ensures the stable transmission of high-frequency radio signals, including 40 GHz mmWave.

We also highlight the further challenge of handling beamforming between two antennas transmitting the same radio signals to a single UE. This issue should be addressed during the architecture design phase. While it may impact 3GPP and/or O-RAN specifications, such a scenario is expected to occur as part of D-MIMO.

We believe this research report will serve as valuable input for the standardization of the 6G RAN functional architecture, protocols, and interfaces in 3GPP and O-RAN ALLIANCE. It is also expected to inspire further research into the detailed impacts and requirements for future standardization, implementation, and deployment architectures.

Finally, the authors would like to thank all the reviewers for all the feedback to the research report.

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