5G C-RAN Architecture: A Comparison of Multiple Optical Fronthaul Networks

Chathurika Ranaweera, Elaine Wong, Ampalavanapillai Nirmalathas, Chamil Jayasundara, and Christina Lim
Department of Electrical and Electronic Engineering
The University of Melbourne, Australia
Email: chathurika.sharmile@gmail.com

***Abstract*—The development of the fifth generation (5G) wireless technology is in progress to address the increasing demands for high capacity, low latency, and ubiquitous mobile access instigated by next-generation mobile and machine-centric applications. The Centralized/Cloud-Radio Access Network (C-RAN) architecture exploiting the small-cell paradigm has been identified as a promising approach to address the benchmarks of 5G networks. However, providing a reliable, cost-effective, and quality of service guaranteed end-to-end connectivity is one of the major challenges in 5G C-RAN. To identify the suitability of a fronthaul technology to satisfy the unprecedented demands of future 5G wireless network in a cost-effective manner, different architecture and technologies need to be equitably compared in terms of all major requirements of 5G fronthaul network such as bandwidth requirements, delay budgets, deployment costs, complexity of radio remote head (RRH), and the ability to support advanced wireless functions. Therefore, in this paper, we equitably compare a multiple fronthaul architectures that can be used for 5G networks. In particular, we first analyze the stringent requirements of the 5G fronthaul network. Then, we investigate the applicability of three fronthaul technologies (PLS, ARoF, and CPRI) for the C-RAN architecture. We provide comparative analyses of these technologies by elaborating on their ability to fulfill 5G latency and capacity requirements, the complexity of RRH, and also to support advanced wireless features such as cooperative communication. To provide a well-balanced comparison of these fronthaul technologies, we also comparatively analyze the deployment costs of these architectures by developing an optimization framework to plan 5G C-RAN. Our analyses provide insights into how a future-proof fronthaul network can be modeled for 5G C-RAN.**

***Index Terms*—Optical fronthaul; 5G; CRAN.**

I. Introduction

The continuous growth in mobile access and machine-centric applications has caused demands that exceed the capabilities of current mobile technologies. These next generation mobile and Internet of things (IoT) applications will require ubiquitous, quality-of-service (QoS) guaranteed, high capacity, and continuous access to the Internet. As a solution to this supply-demand battle, development of the fifth generation (5G) mobile technology is currently underway to enable fully connected and mobile society by year 2020 [1], [2]. To cope with the exponentially growing traffic demand that is predicted to increase eight fold over the next few years [3], deployment of small cells is considered as one of the prominent features of 5G [4]. Introduction of small-cells into 5G will create an enormous requirement in the transport network to carry huge amounts of data with a minimal delay requirement from thousands of cells. As a result, the evolution of radio access networks need to be complemented by the evolution of transport networks in order to realize the benchmarks of 5G. In particular, to support low latency, high capacity, cost-effective, and greener communication, the entire end-to-end network should be overhauled. As the first step of this evolution, the concept of centralized control of radio signals is introduced into 5G network which is known as the Centralized/Cloud Radio Access Network (C-RAN) architecture [5].

5G C-RAN is composed of a Base-Band Unit (BBU) pool and Remote Radio Heads (RRHs). The centrally located BBU pool is connected to hundreds or thousands of RRHs via the fronthaul network. A major advantage of C-RAN architecture is its ability to establish significantly lower costs, greener communication, and capability of supporting advanced wireless technologies such as coordination multi-point due to the centralized processing of the radio signal. However, as in any other new network technology, the 5G C-RAN architecture also has its challenges. In particular, development of a reliable fronthaul network with required capacity and delay for a large number of cells in a cost and energy efficient manner is one of the major challenges [6]. Amongst many wired and wireless technologies, the optical network is considered to be the best candidate for the 5G fronthaul networks due to its inherited capabilities of low latency and high capacity. Nevertheless, the convergence of optical fronthaul with radio networks should be carefully designed, as it is one of the prominent factors that will contribute to end-to-end latency, capacity, and the cost of the C-RAN

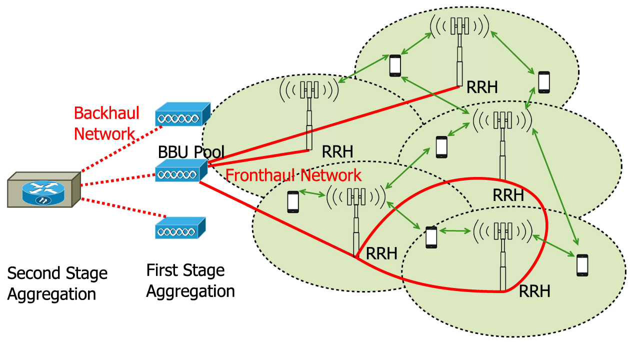

Fig. 1. Centralized Radio Access Network (C-RAN).

network. Therefore, in this paper, we first analyze the requirements of 5G fronthaul networks. We then investigate the applicability of three optical fronthaul technologies for the C-RAN architecture. We provide detailed analyses of these architectures by elaborating on their ability to fulfill 5G latency limits and capacity requirements, to support advanced wireless technologies, and also the deployment costs. Furthermore, to investigate the cost-effectiveness of these architectures, we comparatively analyze the total deployment costs of these architectures by using an optimization framework to plan the networks.

II. Design Challenges in 5G C-RAN Network

A 5G C-RAN architecture consists of three major components which are illustrated in Fig. 1. RRHs that are deployed closer to the end users are connected to the centrally controlled BBU pool over the fronthaul network. Then, the BBU pools that are deployed in different geographical locations are connected through backhaul to the next level aggregation. The C-RAN architecture has been proven to be efficient in reducing CAPEX/OPEX, power consumption and duration of construction cycle [5], [7].

In C-RAN, the transport network affects the capacity, latency, and level of intelligence of the network. Therefore, development of architectures, technologies, interfaces, and networks for 5G fronthaul has gained significant attention from both academia and industry in last few years. Different optical fronthaul and midhaul architectures were discussed by the authors in [9]. The authors also discussed the limitations in the current systems and the possibility of using a variety of wavelength division multiplexing (WDM) passive optical network (PON) as the fronthaul network. Moreover, in [8], the authors proposed a concept to use photonics-aided cooperative multipoint (CoMP) transmissions for mm-wave small-cell where the fronthaul architecture is proposed based on the radio over fiber (RoF) infrastructure.

In addition, optimal deployment of C-RAN network has also been addressed in the literature. In [10], the authors investigated how BBUs can be optimally placed over a WDM aggregation network. They formulated an optimization framework to place the BBUs, assign wavelengths, and allocate routes such that the total number of BBU hotels and fiber used are minimized. Moreover, they extended their framework to include the latency requirement of the network in [11].

Furthermore, in order to support capacity and latency requirements of fronthaul, a concept of using different RRH and BBU interfaces was introduced by a group of service providers in [7]. This proposal was called next generation fronthaul interface. A range of interface options that have different splits between RRH and BBU functional blocks was evaluated under the condition of current LTE networks [6]. These different interfaces were analyzed and compared in term of bandwidth, ability to support advanced wireless technique, and complexity of RRH [6], [12].

However, to identify the suitability of these fronthaul technologies to satisfy the unprecedented demands of future 5G wireless network in a cost-effective manner, different architecture and technologies need to be equitably compared in terms of all major requirements of 5G fronthaul network such as bandwidth requirements, delay budgets, deployment costs, complexity of RRH, and the ability to support advanced wireless functions. Therefore, a fair comparison of these architectures/ technologies warrant further investigations. As a result, in this paper, after analyzing the requirements of the 5G fronthaul network, we investigate the applicability of different optical fronthaul technologies for C-RAN in terms of delay, bandwidth, advance wireless function capabilities, the complexity of RRH, and the deployment cost. Our analyses will provide insight into how a future proof fronthaul network can be modeled for 5G C-RAN.

III. Requirements of 5G C-RAN

In the current C-RAN architecture that is designed for Long Term Evolution-Advanced (LTE-A) network, the fronthaul network uses common public radio interface (CPRI) [13] over fiber links for the data transmission between the RRH and BBU. A CPRI link transmits IQ data of the baseband signals. However, the transmission of IQ samples requires a larger bandwidth. For example, a current LTE base station which supports 150 Mbps of downlink bandwidth in the access network requires more than 2 Gbps of optical bandwidth to send its IQ samples over the CPRI interface. Therefore, it is important to analyze the feasibility of using CPRI in 5G C-RAN.

A. Capacity

The 5G fronthaul network has a huge capacity requirement to support targeted data rates and latency for the end user applications. In 5G, one of the major

TABLE I
PARAMETERS FOR CPRI BANDWIDTH CALCULATION

Parameters	Current LTE	5G requirement
N_s	3	3
N_a	1	8
S_f	30	30
S_{bw}	30.72 (for 20 MZ)	30.72*5 (for 100MZ)
B_e	16/15	16/15
L_c	10/8	10/8

evolutions is to use massive MIMO techniques for the radio to increase the bandwidth. This, in turn, increases the bandwidth requirement of the fronthaul networks. The required bandwidth of a CPRI link depends on the radio access technology in use, and it can be calculated using Eq. 1.

$$B_{CPRI} = N_s * N_a * S_f * S_{bw} * B_e * L_c \tag{1}$$

where, N_s is the number of sectors per RRH, N_a is the number of antennas correspond to antenna configuration, S_f is the sampling frequency, S_{bw} is the sampling bit-width for I/Q samples, B_e is the ratio considered for the controlling overhead (a basic frame consists of 16 words and one used for controlling purposes), and L_c is the factor that accounts for the capacity increase due to 8B/10B encoding used. Table I lists the typical values that can be used for these parameters in LTE and 5G networks.

Next, we evaluate the bandwidth requirement of a CPRI-based 5G fronthaul network by using the values listed in Table I. To transport the wireless data to achieve the targeted data rate of 1 Gbps with 8X8 MIMO antennas from 3 sectors, 147.5 Gbps of optical fiber link is required for a CPRI-based fronthaul network. One of the major drawbacks of using current CPRI for fronthaul technology is that for a given network configuration, the bandwidth requirement is fixed and independent from the real traffic load. For example, even RRHs do not have user traffic all the time, an optical link that has a constant bandwidth of 48.3 Gbps (for RRH that has only one sector) needs to be dedicated for each RRH. The capacity requirement of CPRI links can be reduced using compression techniques [14]. However, despite these techniques can reduce the capacity requirement up to 50%, still a significant capacity is still required by the CPRI links. Moreover, optical networks such as passive optical network (PON) would not be the most suitable option due to bandwidth sharing, since CPRI needs dedicated bandwidth irrespective of the traffic load. Therefore, it is necessary to investigate and modify fronthaul technologies that require less capacity.

B. Latency

In addition to the capacity requirement, there is a stringent requirement for the latency in the 5G fronthaul network. In particular, some of the applications that will run on the 5G network are high delay sensitive. For example, applications such as Tactile Internet will require a tolerant margin of 1 ms for end-to-end communication [17]. In order to achieve such a low latency, not only the fronthaul technology but also the fronthaul architecture should also be taken into consideration in designing 5G C-RAN. Since radio signals are processed at the BBU, the fronthaul network needs to transport the signals within the required time frame to be processed at the BBU without any losses. Currently, the maximum allowable delay for HARQ in LTE is 4ms, there is a 3ms upper limit for the round trip latency between the BBU and RRH which includes processing time at each equipment and prorogation delays of both uplink and downlink [18].

The 5G network has an even more stringent delay budget for fronthaul. For example the BBU round trip processing delay and RF processing delay can be as large as 2 ms. Therefore, with a safe margin the fronthaul network delay can only increase by a few hundreds of microseconds including the propagation delay, round trip CPRI processing delay, and the other fronthaul equipment processing delays. This in turn sets a constraint on the maximum span of each fiber-based fronthaul architecture. In particular, if the CPRI processing delay is to be less than 100 μs, then the CPRI-based fronthaul architecture, RRH can be placed within 20 kms from a BBU considering the 5 μs/km light propagation delay. Therefore, it is clear that the targeted performance can not be achieved if the fronthaul network delay is increased beyond few hundred microseconds. Hence, irrespective of the functional splits between BBU and RRH, all type of fronthaul networks will have a similar or more stringent latency requirement compared to CPRI links.

IV. NEXT-GENERATION FRONTHAUL TECHNOLOGIES AND ARCHITECTURES FOR 5G

When using CPRI-based traditional C-RAN architecture, the 5G C-RAN will require a high capacity optical fiber fronthaul network. This will limit the possible cost savings of the C-RAN architecture. Therefore, new technologies, concepts, and architectures will be required to realize cost-effective and energy-efficient deployment of C-RAN in 5G network. To this end, in this section, we analyze C-RAN architectures which use two different fronthaul networks with different functional splits between RRH and BBU as oppose to the CPRI architecture.

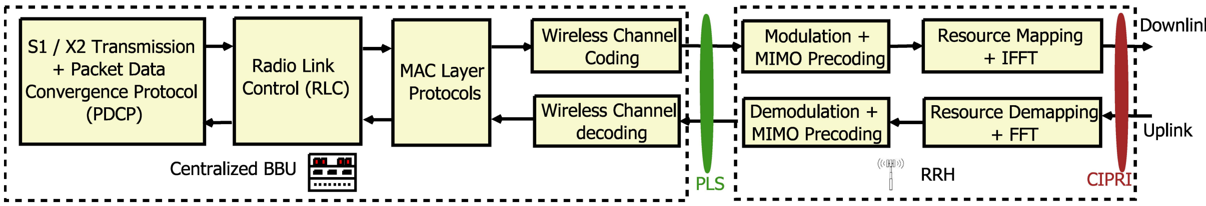

Fig. 2. Functional Split in CRAN Architecture.

A. Physical Layer Split (PLS) Architecture

The functional split between the BBU and RRH of the architecture in consideration is shown in Fig. 2. As shown in 2, all of RLC and MAC layer protocols, and some of the physical layer functions are implemented in the centralized BBU. However, physical layer functions below the wireless channel coding such as modulation, Fast Fourier Transformation (FFT) and resource mapping are moved to the RRH. Since the physical layer functions are split among the BBU and RRH, we called this architecture Physical Layer Split (PLS) architecture. The differences of functional splits between PLS and CPRI are shown in Fig. 2. The main advantage of the PLS architecture over CPRI is its low fronthaul bandwidth requirement. Since the modulation, demodulation and resource mapping are now embedded into RRH, the PLS architecture significantly reduces the requirements of fronthaul transmission bandwidth and resources, which will contribute towards the low cost fronthaul deployment. Moreover, since the wireless coding functions and MAC layer functions are centralized in the BBU, this architecture can also facilitate advance wireless cooperations technologies. However, in comparison to CPRI architecture, if the functions implemented in the RRH need an upgrade, software and related equipment need to be accordingly upgraded in the RRH. Nevertheless, implementation of network function virtualization (NVF) paradigm can be used to overcome the difficulty of upgrading the software installed in RRHs.

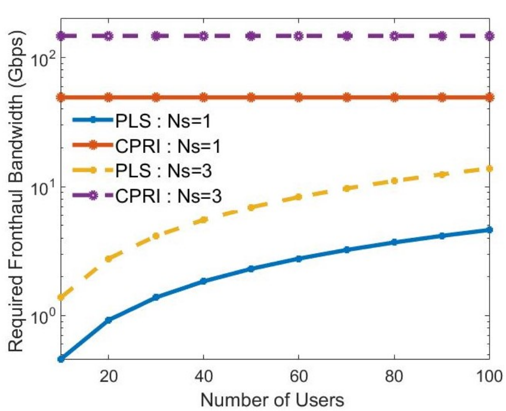

Fig. 3. Fronthaul bandwidth comparison

Next, we evaluate the fronthaul bandwidth requirement of the PLS architecture and compare it with the requirement of CPRI. The maximum downlink bandwidth requirement for PLS architecture can be calculated as follows,

$$B_{PLS} = M * N_{sy} * N_{sc} * N_{rb} * N_{mimo} * N_s \setminus TTI \quad (2)$$

where TTI is the transmission time interval which is the duration of radio signal transmission, M is the highest modulation order of the radio signal, N_{sy} is the number of symbol within a TTI, N_{sc} is the number of subcarriers in a resource block, N_{rb} is the number of resource blocks, and N_{mimo} is the number of MIMO streams. For 5G network implementation, TTI, M, N_{sy}, N_{sc}, N_{rb}, and N_{mimo} are chosen as 1ms, 8 corresponds to 64 QAM, 12, 12, 500, and 8, respectively. These values are chosen to accord with 100 MHz wireless bandwidth. Considering the total number of RBs of 500 and according to the above data, the maximum bandwidth required for fronthaul in the PLS architecture can be calculated as 4.6 Gbps. In order to clearly understand the fronthaul bandwidth requirements, we plot the fronthaul bandwidth requirements of PLS and CPRI as a function of the number of users in Fig. 3. Here we assume each user will be allocated 5 RBs per TTI. It is clear from Fig. 3, that CPRI always requires more than the ten times of the bandwidth of PLS. Moreover, as expected, B_{PLS} increases with the number of users while B_{CPRI} remains same.

In term of the latency requirement of PLS architecture, there is an additional processing delay at the RRH compared to the CPRI based fronthaul network due to symbol level processing implemented in RRH. However, the processing delay that adds from the additional functions in RRH architecture is less than few microseconds. This is because the modulation functions along with RF processing delay and propagation delay should be less than the cyclic prefix of OFDM symbol which is less than 5 μs [19].

B. Analogue Radio-over-Fiber architecture

Radio over Fiber (RoF) is a well-known technology which integrates the advantages of both fiber and wireless networks and used to distribute wireless signal over fiber in applications such as distributed antenna

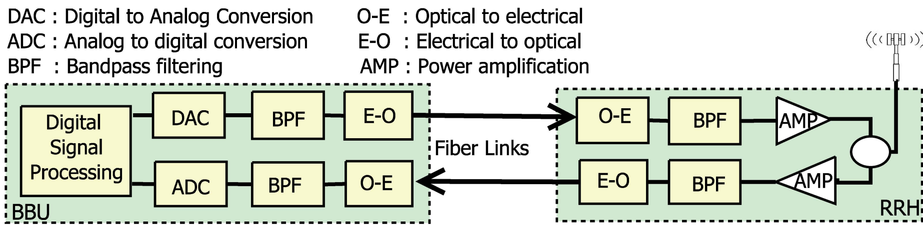

Fig. 4. Analog RoF for 5G fronthauling

system [20], [21]. In analog RoF (ARoF), RRH comprises simple functions such as electrical to optical conversion whilst the BBU resides in a centralized location carries most of the signal processing functions including modulation, coding, and multiplexing. However, impairments in the analog signal transmissions such as noise and distortion caused by nonlinearities of the components limit the performance of the ARoF system. In particular, the dynamic range of the link decreases with the transmission distance. Nevertheless, new technologies are discovered to mitigate nonlinearity issue in a cost-effective manner and also few telco-economic analysis favors the deployment of ARoF as a fronthaul/ backhaul technology as it is a cost-effective solution compared to digital-RoF systems such as CPRI and OBSAI [22].

In ARoF, the bandwidth required for the fiber network depends on the wireless bandwidth in use and hence a typical 10 Gbps fiber transceiver can be used for the network deployment. Therefore, ARoF can be considered as a suitable candidate for the fronthaul network. In addition, lower power consumption and usage of mm-wave frequency bands for the 5G access network give an added benefits for employing ARoF in the fronthaul network. For the illustrative purposes, a simple ARoF system is shown in Fig. 4. However, depending on the wireless frequency band in use, ARoF can use direct wireless signal or an intermediate frequency to modulate light before the transmission through the fiber. Since the 5G fronthaul network would be in the vicinity of few kilometers where the BBU can be collocated in the existing central office locations, ARoF is a viable option for 5G fronthaul network. In term of the delay, RRH will be more delay efficient compared to the CPRI-based traditional C-RAN architecture as RRH comprises of simplest functions and this can provide added flexibility to adapt advanced wireless domain functions as all the wireless signals are processed centrally at the BBU.

C. Deployment Cost Analysis

It is clear from the above discussion that 5G requires more robust fronthaul such as the PLS architecture which can cater high bandwidth and lower delay budget, and facilitate advanced wireless network functions. However, providing a proper fronthaul network in a cost-effective manner has become a challenge [23].Therefore, we also comparatively analyze the deployment costs of C-RAN when it uses CPRI-based, PLS and ARoF as a fronthaul network. In particular, we formulate an optimization framework to plan a cost optimal C-RAN. The objective function of the framework is as follows:

$$\min\ (\eta_r+\eta_{ri})\sum_{i\in\mathbf{V}}x_i+(\eta_t+\eta_{fb})\sum_{i\in\mathbf{V}}\sum_{j\in\mathbf{V}}c_{i,j}d_{i,j}+ \\ \eta_{fs}\sum_{i\in\mathbf{V}}\sum_{j\in\mathbf{V}}y_{i,j}d_{i,j}+\eta_e\sum_{i\in\mathbf{V}}x_i+(\eta_b+\eta_{bi})\sum_{i\in\mathbf{V}}z_i \quad (3)$$

where the objective is to minimize the total deployment cost arising from the CRAN deployment. The total cost consists of the cost of BBU placement, fronthaul cost, and cost of deploying RRHs. In particular, the first cost component (summation) in (3) represents the equipment and installation costs arising from RRHs. The second cost component represents the deployment of new fiber routes and fiber bundles. The third summation captures the total cost associated with fiber preparation while fourth cost component captures the total costs of fiber connections at the central office for using existing fiber facility. Final cost component accounts for the total cost of BBUs and their installation. In addition, our optimization framework also consists of a set of constraints to guarantee other network requirements such as population coverage, the maximum number of BBUs in one central office location, and the maximum distance that a RRH can be deployed from its BBU. The detailed description of the optimal network planning framework and evaluations will be presented in our forthcoming paper.

Here we only present the comparative cost analysis of the optimal deployment under different population coverages and the results are shown in Fig. 5. The contributions of frontahul, RRH, and BBU for the total deployment cost is shown in Fig. 5 and the cost values are normalized with respect to the total deployment cost of CPRI-based C-RAN under 90% population coverage requirement. In this analysis, we assume that CPRI uses a 1/2 compression technique without additional cost for the compression and hence require only 40 Gbps transceivers instead of 100 Gbps

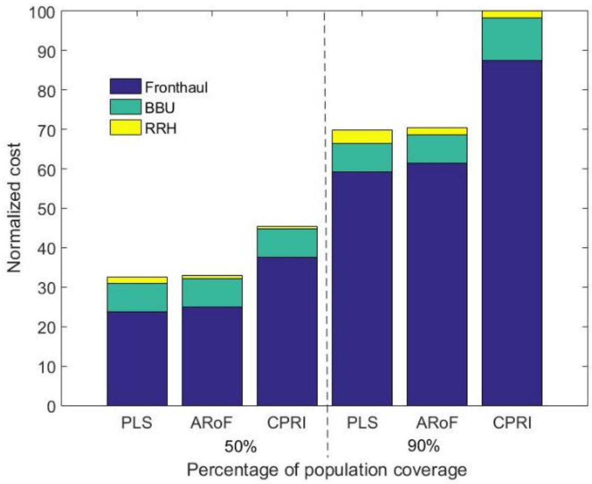

Fig. 5. Cost Comparison

transceivers. On the other hand, the PLS and ARoF architectures uses 10 Gbps transceivers. Moreover, the wireless carrier frequency that is considered for the deployment is less than 5 GHz. The cost values which are used for evaluation are taken from various studies and vendors [21], [24]. With the cost values in consideration, it is clear from Fig. 5, that the highest cost contributor for all considered deployment scenarios is the fronthaul network. This is mainly because of the cost arising from the deployment of fiber and high capacity transceivers. We can also observe that even though we have carried out a favorable analysis for CPRI, for all considered deployment scenarios, PLS architecture has the lowest deployment cost. The ARoF architecture has a slightly higher cost compared to PLS. The additional cost in CPRI arises from the cost of high capacity transceiver architecture. In particular, when the required population coverage is 90%, the PLS architecture shows 40% reduction in the deployment compared to the CPRI. It is evident from these results that architectures such as PLS and ARoF not only satisfy the primary requirements of 5G but also reduces the deployment cost compared to the traditional C-RAN architecture when it is used for 5G.

V. Summary

In this paper, we investigated the approaches that can be used to realize a low-latency, bandwidth-efficient, and cost-effective fronthaul network for 5G CRAN. In particular, we investigated the applicability of different optical fronthaul technologies for C-RAN and analyzed their ability to fulfill requirements of delay, bandwidth, and cost-effectiveness of 5G C-RAN. The comparative analyses of CPRI, PLS, and ARoF based fronthaul networks showed that cost-effective fronthaul for 5G could be achieved using PLS and ARoF architectures. Overall, our analyses carried throughout the paper provide insight into how a future proof fronthaul network can be realized for 5G C-RAN.

References

[1] F. Boccardi *et al*, "Five disruptive technology directions for 5G," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 74-80, 2014.

[2] Next Generation Mobile Networks Alliance, "NGMN 5G White Paper," *White Paper*, 2015. Available: https://www.ngmn.org

[3] Cisco, "Cisco VNI: Global Mobile Data Traffic Forecast Update, 20152020," *online*, 2012. Available: http://www.cisco.com/

[4] A. Ghosh *et al*, "Heterogeneous cellular networks: From theory to practice," *Communications Magazine, IEEE*, vol. 50, no. 6, pp. 54-64, 2012.

[5] China Mobile Research Institute, "C-RAN: The Road Towards Green RAN," *White Paper*, 2013. Available: http://labs.chinamobile.com/cran/

[6] China Mobile Research Institute *et al*, "Next Generation Fronthaul Interface," *White Paper*, 2015. Available: http://labs.chinamobile.com/cran/

[7] Next Generation Mobile Networks Alliance, NGMN, "Further study on critical CRAN technologies," *White Paper*, 2015. Available: https://www.ngmn.org

[8] L. Cheng *et al*, "Adaptive Photonics-Aided Coordinated Multipoint Transmissions for Next-Generation Mobile Fronthaul,," *Journal of Lightwave Tech.*, vol. 32, no. 10, pp. 1907-1914, 2014.

[9] T. Pfeiffer, "Next Generation Mobile Fronthaul and Midhaul Architectures [Invited],," *Journal of Optical Communication and Networking*, vol. 7, no. 11, pp. B38-B45, 2015.

[10] N. Carapellese *et al*, "BBU placement over a WDM aggregation network considering OTN and overlay fronthaul transport,," *European Conf. on Optical Com. (ECOC)*, pp. 1-3, 2015.

[11] F. Musumeci *et al*, "Optimal BBU Placement for 5G C-RAN Deployment Over WDM Aggregation Networks,," *Journal of Lightwave Technology*, vol. 34, no. 8, pp. 1963-1970, 2016.

[12] K. Miyamoto *et al*, "Analysis of mobile fronthaul bandwidth and wireless transmission performance in split-PHY processing architecture,," *Optical Express*, vol. 24, no. 2, pp. 1261-1268, 2016.

[13] Common Public Radio Interface, CPRI, http://www.cpri.info/

[14] G. Bin *et al*, "LTE/LTEA Signal Compression on the CPRI Interface," *Bell Labs Technical Journal*, vol.18, no.2, pp.117-133, 2013.

[15] C. Ranaweera *et al*, "Next generation optical-wireless converged network architectures,", *IEEE Network*, vol. 26, no. 2, pp. 22-27, 2012.

[16] P. Chanclou *et al*, "Optical fiber solution for mobile fronthaul to achieve cloud radio access network", *Future Network and Mobile Summit (FutureNetworkSummit)*, pp. 1-11, 2013.

[17] E. Wong, I. Dias, and L. Ruan. "Predictive Resource Allocation for Tactile Internet Capable Passive Optical LANs." Journal of Lightwave Technology, 2017.

[18] 3GPP TS-36.213 (Physical layer procedures). [Online]. Available: http:// www.3gpp.org

[19] J. Armstrong, "OFDM for Optical Communications," *Journal of Lightwave Technology*, vol. 27, no. 3, pp. 189-204, Feb.1, 2009.

[20] C. Lim *et al*, "Fiber-Wireless Networks and Subsystem Technologies", *Journal of Lightwave Tech.*, vol. 28, pp. 390-405, 2010.

[21] D. Wake *et al*, ", "Radio Over Fiber Link Design for Next Generation Wireless Systems,", *Journal of Lightwave Technology*, vol. 28, no. 16, pp. 2456-2464, 2010.

[22] A. Haddad and M. Gagnaire, "Radio-over-Fiber (RoF) for mobile backhauling: A technical and economic comparison between analog and digitized RoF," *International Conference on Optical Network Design and Modeling*, pp. 132-137, 2014.

[23] S. Chia, M. Gasparroni, and P. Brick, "The next challenge for cellular networks: backhaul," *Microwave Magazine, IEEE*, vol. 10, no. 5, pp. 54-66, 2009.

[24] C. Ranaweera *et al*, "Design and optimization of fiber optic small-cell backhaul based on an existing fiber-to-the-node residential access network," *Communications Magazine*, IEEE , vol.51, no.9, pp.62-69, 2013.