Midhaul Transmission Using Edge Data Centers with Split PHY Processing and Wavelength Reassignment for 5G Wireless Networks

Jiakai Yu[1], Yao Li[2], Mariya Bhopalwala[1], Sandip Das[3], Marco Ruffini[3], Daniel C. Kilper[2]
[1]Department of Electrical and Computer Engineering, University of Arizona
[2]Optical Science College, University of Arizona
[3]CONNECT Research Centre, University of Dublin, Trinity College, Dublin, Ireland
{jiakaiyu, mariyab}@email.arizona.edu, {yaoli, dkilper}@optics.arizona.edu, dassa@tcd.ie, marco.ruffini@scss.tcd.ie

***Abstract*—Distributed processing of edge data centers in a metropolitan area is considered to reduce the large data traffic load due to Cloud Radio Access Network (C-RAN) fronthaul digitized radio-over-fiber protocols. A dynamic PHY split strategy is examined for high-capacity optical Dense Wavelength Division Multiplexing (DWDM) based C-RANs with limited edge data center resources. A network performance simulation model is developed based on a regional optical network in the New York metropolitan area to evaluate the dynamic midhaul approach. The use of a midhaul network improves the network performance by reducing traffic congestion and enhancing wavelength channel utilization. Simulation results show a 45% reduction in the required optical capacity in our proposed adaptive midhaul network compared to a traditional CPRI fronthaul network.**

Keywords*—*radio access networks, optical fiber networks; Functional PHY Split; Data Center; routing and wavelength assignment

I. Introduction

Wireless networks continue to face rapidly growing traffic demands while supporting an increasingly wide range of services and applications. Cellular radio access networks with baseband processing at every access point may not scale well for the high capacity and large numbers of small cells expected in 5G networks. Cloud radio access networks (C-RAN) have been proposed as a scalable solution by separating the radio components from the baseband unit (BBU), in order to gain the efficiencies of cloud computing for radio networks [1, 2]. Shared processing resources and commodity hardware used in the C-RAN architecture provide various benefits, such as low energy consumption, statistical multiplexing gain, and coordinated multi-point (CoMP) transmission/reception [3].

Optical networks can provide high capacity to satisfy the growing traffic needs in 5G networks. An effective method to facilitate 5G C-RAN architectures is the use of optical DWDM [4, 5]. However, the resulting fronthaul (FH) network in a C-RAN between the Remote Radio Heads (RRHs) and BBU pools requires high capacity in order to handle digitized radio signals. The raw I/Q waveform samples are bi-directionally transmitted over optical fiber by using bandwidth inefficient transmission protocols such as the Common Public Radio Interface (CPRI), which requires 2.5 Gbps optical bandwidth for a 150Mbps wireless transport rate with 2x2 MIMO and 20MHz carrier spectra in a small cell for downlink transmission [1]. In order to reduce FH optical transmission capacity requirements, functional split points in the baseband processing chain have been investigated with partial functionalities of BBUs placed into RRHs [6, 7]. This dual-site processing runs into trouble because it violates several main goals of C-RAN. Increasing use of distributed processing can increase cost and reduce the effectiveness of techniques such as CoMP [8]. Furthermore, optimal functional split points in FH might vary depending on different base station configurations, access network topology, network traffic load, and signal transmission routing, when Total Cost of Ownership (TCO) is considered.

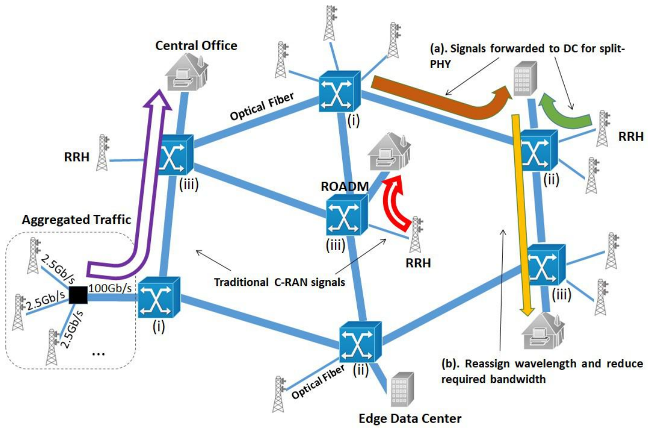


Fig. 1: Adaptive midhaul network architecture and strategy. Hollow arrow shows fronthaul-only C-RAN while solid arrow shows data center midhaul method. Different colors mean different wavelength channels. (i) pure access node with only RRHs; (ii) Data Center node with local data centers; (iii) BBU node with local BBU pool or Central Office.

Flexible centralization in C-RANs should not be limited to functional split processing between BBUs and RRHs. Adaptive PHY splits and processing job placement at multiple sites can also be considered, because a pre-designed architecture might be far from optimal, considering variable 5G application requirements over time and location [9]. Edge Data Centers (DCs) have been used in metropolitan areas for Ethernet switching services and are gaining attentions for telecom networks [10 - 12]. For example, Central Office Re-architected as a Datacenter (CORD) is a platform to bring data center economies to telecom networks using SDN, NFV, and other technologies [13]. These DCs can be utilized or more widely deployed to support midhaul networks, which provide partial PHY processing for signals enroute to their destination

978-3-903176-07-2c © 2018 IFIP

baseband processing location. Fig. 1 shows the use of midhaul links, taking advantage of edge data centers. Once certain data centers in DWDM-based C-RAN are implemented with PHY split processing and optical signal processing technologies, wireless signals are forwarded to these data centers, and split-PHY signals are transported over fiber between data centers and BBUs or Central Office. The midhaul connection shown in brown, green, and yellow arrows will not only be more efficient in transporting user data, but also allows for wavelength re-assignment and grooming of the optical signals. It is important to understand the impact of this approach on the optical network resources. In this work, we examine how midhaul links impact the optical network capacity requirement and wavelength blocking. We further consider adaptive PHY split processing in which different split points can be used for individual digitized radio signals.

The rest of the study is organized as follows. Section II introduces the DWDM based C-RAN architecture, PHY split technology, and edge datacenter development for 5G networks. In section III, we present the adaptive midhaul C-RAN approach. Section IV reports the simulation results of our framework compared with fronthaul-only C-RAN to validate the advantages of midhaul links in terms of overal optical network capacity. Section V concludes the paper.

II. BBU Functional Splits in C-RANs

A. DWDM based C-RAN Architecture

Fig. 1 illustrates an adaptive midhaul network in an optical DWDM based C-RAN architecture which we intend to examine. Each optical node is a reconfigurable optical add-drop multiplexer (ROADM) that serves as a hub for connecting various systems, such as RRHs, BBUs, and edge DCs via optical fibers. Depending on if there is a BBU pool (Central Office) or DCs connected with the ROADM, we classify these optical nodes into 3 categories: (i) wireless access point node, (ii) DC node, and (iii) BBU node. Wireless traffic requests can be sourced from any RRH in the optical nodes listed above, and traffic from the same source ROADM node and destination ROADM node are aggregated at the source ROADM node into a 100 Gb/s DWDM channel for transmission through the network. We assume that each optical link between ROADMs can support up to 40 high-capacity 100 Gb/s wavelength channels for upstream and downstream transmission.

In our reference C-RAN architecture, the light-path connection is set up directly between two ROADMs connecting the source RRH, and destination BBU pool respectively. In source ROADM, the fronthaul rates from all antennas of multiple sectors are aggregated into a single wavelength channel. Therefore, the final CPRI bit rate at source ROADM can be obtained from the equation [1]: $B_{CPRI} = 2 \times (16/15) \times S \times A \times f_S \times b_S \times LC$, where the 2 and 16/15 are IQ processing and overhead factors, respectively, and remaining factors are S number of sectors, A number of antennas per sector, f_s sample rate, b_s number of bits per sample, and LC line rate. Therefore, following equation [1], we obtain the aggregated CPRI rate of a cell with one mobile network operator, each coming with 3 sectors, 2x2 MIMO, and 20+20 MHz as 15 Gb/s. Functional Split in L1 Layer

Due to the large optical transmission capacity requirements of CPRI based fronthaul, functional splits in BBU-RRH digitized IQ data processing has been investigated such that some processing functions of the BBUs are moved to the RRHs. In order to support distributed MIMO and CoMP techniques, and also given the data rate reduction is not significant for split points higher than the L1 layer, current functional split processing architecture designs are focused on the MAC-PHY or PHY splits [6, 14]. Fig.2 (a) illustrates the general PHY split points of fronthaul. Although various methods are used to implement PHY splits, this analysis uses the capacity reduction factors corresponding to different splits shown in TABLE I, which were derived considering central small cell function virtualization with LTE HARQ approach [15].

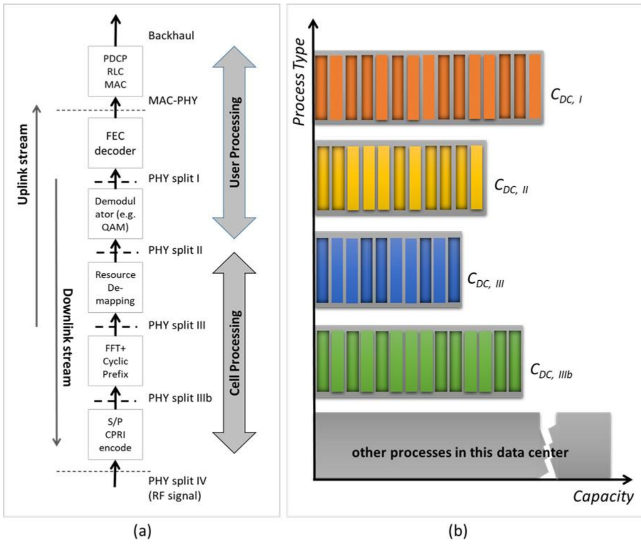


Fig. 2: Edge data center PHY split and processing capacity model. (a) Four PHY split steps. (b) DCs are randomly assigned processing capacity for each PHY split. Ocuppied resources are marked with shadow.

In a typical LTE processing chain, the radio frequency (RF) signals are received, and transformed to baseband. Then serial-to-parallel (S/P) conversion and CPRI encoding are applied. The cyclic prefix (CP) is removed and symbols are transformed to the frequency domain. Next, resource demapping is processed to disassemble sub-frames. Signal demodulator processing, such as Quadrature amplitude modulation (QAM) demodulation, is performed for each user. Finally, forwarded error correction (FEC) en-/de-coding is performed before sending the data to the higher layer functions and protocol processing, such as medium access control (MAC), radio link control protocol (RLC), and packet data convergence protocol (PDCP). The RRH-BBU processing split can be adopted after any of these processing components as mentioned above. Depending on the position of the split, the splits can be labelled accordingly as shown in the Fig. 2(a).

Various functional split options can be selected in a dual-site processing RAN framework to relieve the traffic load in fronthaul edge networks. However, decreasing the cost of fronthaul increases the cost of RRHs. This trade-off motivates the use of adaptive split PHY processing in edge data centers.

TABLE I. EFFECT OF SPLIT OPTIONS IN L1 LAYER [15]

Possible Split Levels	*Downlink bandwidth*	*Uplink bandwidth*
MAC - PHY	152 Mbps	49 Mbps
PHY split I: Soft Bit	173 Mbps	452 Mbps
PHY split II: Subframe data	933 Mbps	903 Mbps
PHY split III: Subframe	1075 Mbps	922 Mbps
PHY split IIIb: Subframe	1966 Mbps	1966 Mbps
PHY split IV: CPRI encoding	2457.6 Mbps	2457.6 Mbps

III. ADAPTIVE MIDHAUL C-RANS

A. Midhaul Networking

Generally, digitized baseband base station processing can be implemented in DCs. In a metropolitan area network, edge DCs with limited capacity or resources may conserve processing by partitioning split PHY processes. This strategy has the following benefits. First, these DCs are already widely deployed and can be easily implemented with PHY split processing functionality in a cost-efficient way. Secondly, they may have better processing performance than cost and power constrained RRHs. Thirdly, the PHY split point can be reconfigured and the resources can be tuned based on network or application requirements. Lastly, the wavelength of optical signals received by edge DCs can be dynamically reassigned. Those DCs implemented with PHY split processing act as temporary reconfigurable remote baseband processing or digital units, and work in coordination with the Central Office or BBU pools (which themselves may be implemented in a big data center). This midhaul strategy is a potential solution to the current trade-off problem between RRH placement expenditure and FH optical capacity requirements.

By deploying PHY split and wavelength reassignment in edge DCs, the DWDM based C-RAN architecture can be very flexible. The main features of this adaptive midhaul approach are as follows:

(1) All intra PHY split processing in RRHs is removed, only CPRI encoder remains
(2) Light-paths for RRH-BBU services can be multiple hops via DC nodes.
(3) Edge DCs have limited capacity to process various PHY split processing, and different functional split points require different capabilities and resource capacities.
(4) When a DC is the intermediate node along an RRH-BBU path, the wavelength channel can be reassigned.
(5) In a metropolitan area, the total length of fiber between source RRH and destination BBU pool should be less than 40km in order to meet ultra-low latency requirements [1].
(6) DCs can adapt processing resources for each PHY split function when other service resources are spare. The PHY split point is flexible for each signal, and it is dependent on current available resources in DCs.
(7) PHY split processing can still benefit from multiplexing gain when traffic is heavy.

We illustrate how edge data centers in this architecture work as follows. A RRH requests to set up a lightpath connection with a nearby Central Office or BBU pool to transmit the RF signal via CPRI. If there is a lightpath already set up from the aimed source to destination node, the signals are transmitted via an available channel or an occupied channel by grooming. Along the established light-path, any DC node can process PHY split with its available capacity. The preference of PHY split options for each DC node is from split I to split IIIb to best reduce the traffic data rate and save optical bandwidth. Every time the signal data rate is reduced in a DC node, signal is re-assigned and re-groomed into a new wavelength channel for transmission. If there is no available DC along the connection path, the original CPRI data rate is transmitted, and it acts like a traditional FH network connection in the C-RAN architecture. Fig.1 illustrates the edge datacenter midhaul strategy in DWDM based C-RANs.

B. Midhaul C-RAN based Routing and Wavelength Assignment

To evaluate this midhaul approach, a simulation model is needed. The key factor in this simulation model is to design an algorithm for routing and wavelength assignment (RWA) supporting split PHY processing and wavelength channel reallocation in DC nodes for RRH-BBU light-path connections.

We assume the final CPRI line rate per connection request from a RRH is aggregated by multiples of the 2.5 Gb/s basic CPRI rate signals. Besides, RF signals from different sectors can be groomed into a same channel. For example, a 3-sector cell with 2x2 MIMO, 20 MHz will occupy 3 channels, and each channel transmits a 7.5 Gb/s CPRI signal by using CPRI aggregated bit rate equation. In our work, we consider aggregated radio signals groomed into 100 Gb/s capacity optical channels. The simplified algorithm we designed is presented as below.

Algorithm: adaptive DC-PHY Split RWA Algorithm

Parameters:
network Graph *G,*
connection request $R_{s,d}$,
source node *s,*
destination node *d,*
allocated channel *chnl,*
occupied bandwidth *bw,*
routing path $rp_{s,d}$,
segmented routing path $srp_{s,d}$ (segmented points are DC nodes),
final connection path *CP,*
i-th DC node DC_i $(i = 1, 2, 3...)$,
available DC capacity for split $C_{i,j}$ $(j = I, II, III, IIIb)$,
resource exhausted by split $C_{PHY\text{-}k}$ $(k = I, II, III, IIIb)$

Input: network Graph *G,*
connection request $R(s, d)$

Output: connection path *CP*

for each connection request $R_{s,d}$ **do**
If $s{=}{=}d$ source equals destination **do**
  BBU node handles this local request
  return path results *CP* with NONE

```
    if s!=d not local request do
        find K candidate routing paths rp_{s,d} in G
        for each rp_{s,d} do
            for there is any DC_i in rp_{s,d} do
                routing path is segmented into srp_{s,d}
            if srp_{s,d} ==NONE, no DC node along rp_{s,d}, do
                assign an available chnl, bw (2.5 Gbps)
                if chnl or bw == NONE, no available resources
                    continue to next routing path rp_{s,d}
                else return CP with rp_{s,d}, bw and chnl
            else for each segment in srp_{s,d} do
                assign an available chnl per segment
                if chnl == NONE break to next path rp_{s,d}
                if the source node of the segment is DC_i do
                    find the traffic required split point
                    for k = from I to required split point do
                        if C_{i,k} > C_{PHY-k} do
                            C_{i,k} = C_{i,k} - C_{PHY-k}
                            bw is allocated based on processed split
                            break
                        else required bw does not change
                return CP with srp_{s,d}, a list of (bw, chnl)
    if no successful routing path rp_{s,d} is found do
        return CP with blocking, service fails
```

To better understand the performance of adaptive midhaul networks, we introduce two routing selection policies implemented in adaptive DC-PHY Split RWA: (1) Direct Link First (DLF) which searches the shortest candidate routing paths from source to destination, and (2) long multi-hop routing paths via DCs First (DCF) method that is greedy to find nearby DC nodes. If the direct path is chosen first, it means there is the least number of datacenters with PHY split processing along the traffic path, so that the C-RAN will consume the most capacity in the optical network. Otherwise, more DC resources are used to reduce the required capacity for the overall network.

C. Edge Data Center Model

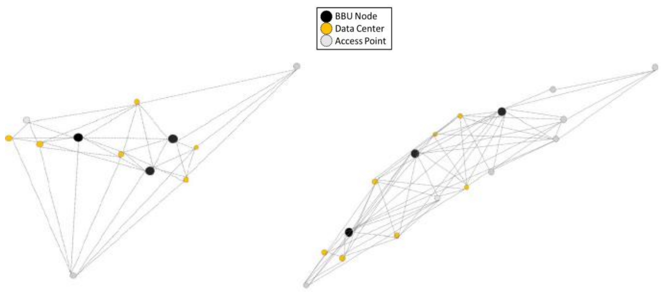
Our edge data center capacity model accounts for unique hardware processing capabilities and PHY split processing capacities. The model splits the PHY processing into four separate processing steps. The processing resources required for each step can be uniquely specified as well as the capacity within each data center for processing the corresponding steps. In this way, the model can account for pre-assigned resources for different processing steps and unique accelerated hardware for the steps. The model also allows for the steps to be grouped in different combinations or altogether for a uniform computing model. In practice, the specific resources for a given step in the PHY processing can be a complex function of the various hardware components or server configurations. By parameterizing the different processing steps, the impact of different processing constraints can be studied. This also enables the analysis of CoMP strategies utilizing different split points [16].

Our edge data center model is explained in Fig. 2. Fig. 2(a) illustrates PHY split processing steps deployed in data centers. And Fig. 2(b) shows the specific resources assigned to wireless signal PHY split processing in data centers. Different PHY split points need different processing equipment and capacity. This may relate to CPU performance and memory size. For example, PHY split point III and IIIb may use FPGA to finish processing, while computing split point I and II is using VMs deployed in performance servers [17], in order to meet the 5G latency requirement. In our simulation, each PHY split step is randomly assigned certain processing capacity for each PHY split step in a DC to mimic various data center conditions. When traffic is handled in this DC, it first determines if this traffic needs PHY split processing and what the split point is. Then accordingly, the appropriate split processing is applied when there is available capacity. And the handled traffic consumes its according PHY split capacity. For example, traffic processed only at PHY split point IIIb in a DC is forwarded into another DC for split point I. Then this new DC will only consume capacity C_{PHY-I}, C_{PHY-II}, and $C_{PHY-III}$ to complete the task, since the signal already consumes the capacity $C_{PHY-IIIb}$ in the previous DC.

IV. Simulation Results and Evaluations

A. Simulation Setup

The metropolitan network topologies were developed from commercial fiber networks deployed in New Jersey and Manhattan [www.zayo.com], shown in Fig. 3. The total 12 nodes are divided into 3 BBU nodes, 6 DC nodes and 3 wireless access nodes in the New Jersey topology, while 17 nodes are divided into 3 BBU nodes, 7 DC nodes, and 7 pure access points in the Manhattan topology. A discrete-event simulator is developed and 5000 Poisson traffic requests are generated with their source node and destination BBU node uniformly distributed in the topologies.



(a) New Jersey topology. (b) Manhattan topology.

Fig. 3: New Jersey and Manhattan radio access networks.

The selected DC nodes are randomly assigned with limited processing capacity for functional PHY split processing to simulate various sizes of data centers. The resulting CPRI data rate after the processing to a give split point are shown in TABLE I. For simplification, we only consider the downstream direction in our simulation.

Besides, the assigned limited capacity in edge DCs is scaled by a factor k (k = 0.5, 1.0 and 2.0). For example, certain capacity is randomly assigned to DCs for four PHY split processing in the beginning of the simulation. When scaling factor is 1.0, DC capability keeps same. When the factor becomes 0.5, PHY split points in this data center is assigned only for IIIb and III. And when the factor is 2.0, the data center can still process all PHY split point, and also have twice capacity for each split-PHY step than the factor set as 1.0.

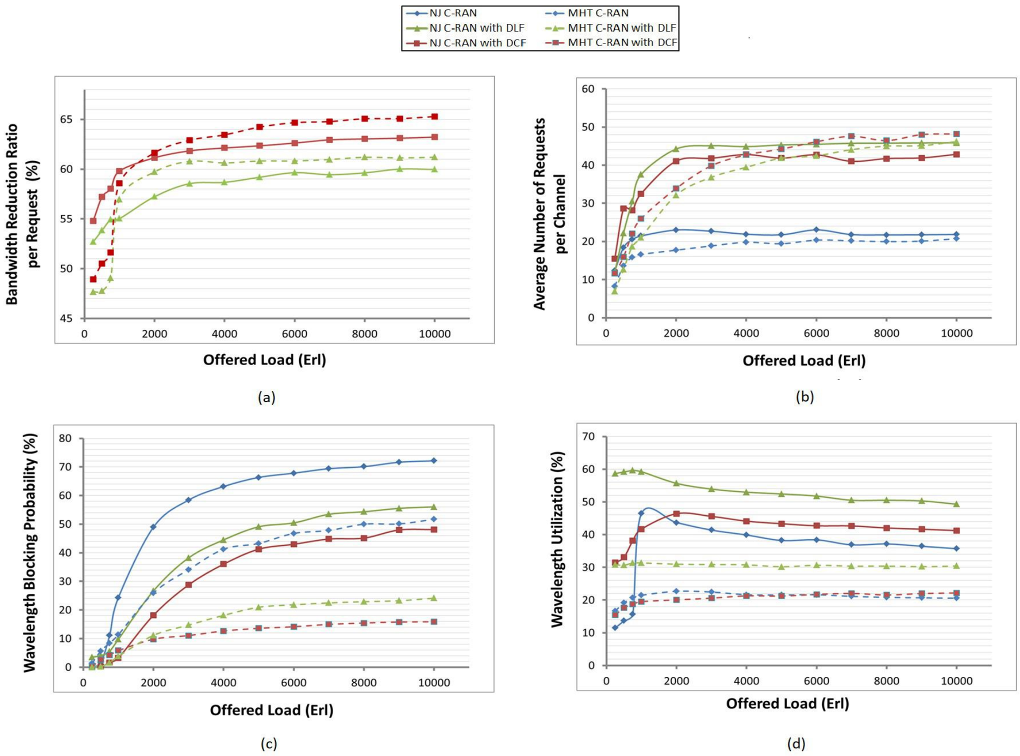


Fig. 4: New Jersey (NJ) topology simulation results of midhaul C-RAN with adaptive PHY split processing and wavelength reassignment in edge data centers compared with traditional C-RAN. Two routing policies implemented in adaptive DC-PHY split RWA are used: direct link first (DLF) for shortest path from source to destination, and long link via nearby data center first (DCF) algorithms.

B. Simulation Results

Fig. 4 shows our adaptive DC-PHY split midhaul networks simulation results compared with a pure fronthaul C-RAN. In Fig. 4(a), the average bandwidth reduction ratio per request is determined by calculating the average data rate per connection taken over all links in the network compared with the pure FH C-RAN case for the same set of demands. With assistance from PHY split processing in edge DCs, the average optical bandwidth used per request can be reduced more than 45% using midhaul networking. Also, the ratio keeps increasing as the traffic load increases. This result can be understood considering that for both networks there are more DC nodes than BBU nodes. This means a large portion of traffic is transported via the light-paths with DC nodes when the traffic load is heavy. Our midhaul network approach will use DC nodes to process traffic dynamically and flexibly as much as possible, by taking different PHY split points and discovering all available wavelengths for each request. When comparing DLF and DCF methods, we find the DCF method can have more effect on reducing bandwidth, due to its priority for using split PHY processing in DC nodes, while DLF provides a lower blocking rate by using shorter light-path.

Since the average data rate used per request becomes lower, the average number of processed connections per channel becomes higher, as illustrated in Fig. 4(b). Therefore, the utilization per wavelength channel is improved when compared with pure C-RAN. In midhaul networking, the average number of handled connections per channel can be at least twice that of a fronthaul C-RAN architecture in the both topologies.

As Fig. 4(c) shows, blocked connection requests in midhaul C-RAN are much less than traditional C-RAN. In midhaul networking, any DC node along the path can reduce the required data rate for each request, re-allocate the wavelength channel, and re-groom the signal into a working but bandwidth-spare light-path. This reduces the blocking rate due to the smaller wavelength management granularity of the networks. In this way, small path segments in midhaul C-RAN can be fully used for CPRI signal transmission.

Lastly, the results of wavelength utilization (total number of occupied wavelengths/number of all wavelengths) in our simulation model are shown in Fig. 4(d). The DCF method in C-RAN can provide significant improvement in channel utilization. Comparing C-RAN with midhaul C-RAN using the DLF method, there is a period between offered traffic load 1000 and 2000 Erlang in which C-RAN has higher utilization. This results from handling fewer requests per channel on average, as explained in Fig. 4(b). As the traffic load becomes high, more and more channels are used to set up light-path connections in midhaul networking, while fewer channels are available in C-RAN due to the high blocking rate. The link-level wavelength management on the segmented light-paths can keep midhaul C-RAN performing with better utilization at high traffic load.

To evaluate the impact of the processing resources of the edge datacenters, we linearly change the PHY split processing capacity of the DCs with a multiplicative factor, as Fig. 5 shows. With DC capacity scaling factor 2.0, DC nodes have twice the resources for PHY split processing. With scaling factor 0.5, the processing capacity in most edge DCs is too low to process higher PHY split points since we assume only large DCs have qualified equipment to process lower PHY split points. As a result, the transmitted bandwidth of the CPRI signal is close to the unprocessed data rate. So the blocking ratio remains as high as pure FH C-RAN.

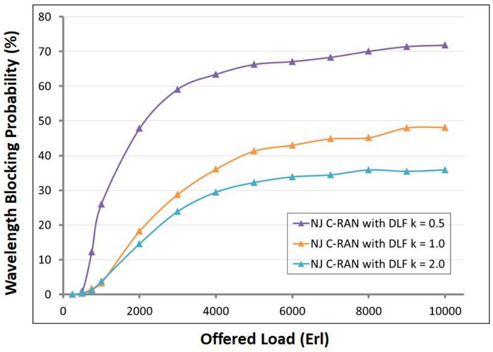


Fig. 5: Evaluating the effect of DC processing capacity by scaling the total capacity with a factor *k*. The result is based on adaptive DC-PHY split RWA with DLF policy in New Jersey topology.

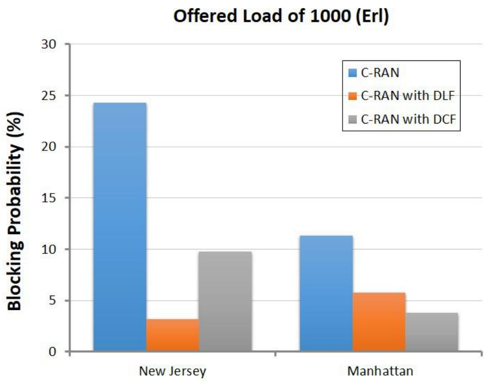


Fig. 6: Blocking probability of two policies in two network topologies when offered load is 1000 Erlang.

Simulations using the Manhattan topology show similar results except that the DLF method has a higher blocking rate than the DCF method when offered traffic is low, while this result is opposite in the New Jersey topology case, shown in Fig. 6. In the New Jersey networks, access points are widely spread, while access points with low connectivity degree are centralized in the northeast in Manhattan areas. When traffic is sourced from these access points in the Manhattan network, it is difficult to offer sufficient resources to handle these signals in edge DCs, when using the DCF method. Additionally, long multi-hop paths would cause severe traffic congestion, since there are insufficient resources for channel re-allocation in nearby DC nodes.

V. CONCLUSION

This paper examines the network efficiency gains through using midhaul networks in DWDM based C-RANs. PHY processing is adaptively split based on available edge data center processing resources in metropolitan areas. Midhaul networks are shown to reduce the CPRI optical bandwidth by deploying functional PHY split processing in edge datacenters. At the same time, functionality of dynamic wavelength reassignment deployed in edge data centers can improve optical network performance, such as blocking ratio and channel utilization, due to segment-scale granularity management of the C-RAN architecture. Besides, midhaul networks provide reconfigurable and cost-efficient performance, since functionalities and resources in edge data centers can be tuned to fit the network topology and traffic load pattern.

ACKNOWLEDGEMENTS

This work was supported by Science Foundation Ireland (SFI) 15/US-C2C/I3132 and 13/RC/2077, and the NSF Center for Integrated Access Networks (CIAN) EEC-0812072.

REFERENCES

[1] Pfeiffer, Thomas. "Next generation mobile fronthaul and midhaul architectures." *Journal of Optical Communications and Networking*, vol. 7, no. 11, pp. B38-B45, 2015.
[2] Jun, Wu, et al. "Cloud radio access network (C-RAN): a primer." *IEEE Network*, vol. 29, no. 1, pp. 35-41, 2015.
[3] Rost, Peter, et al. "Cloud technologies for flexible 5G radio access networks." *IEEE Communications Magazine*, vol. 52, no. 5, pp. 68-76, 2014.
[4] Fiorani, Matteo, et al. "Challenges for 5G transport networks." *IEEE International Conference on Advanced Networks and Telecommunication Systems (ANTS)*, pp. 1-6, 2014.
[5] Skubic, Björn, et al. "The role of DWDM for 5G transport." *European Conference on Optical Communication (ECOC)*, pp. 1-3, 2014.
[6] Dötsch, Uwe, et al. "Quantitative analysis of split base station processing and determination of advantageous architectures for LTE." *Bell Labs Technical Journal*, vol. 18, no.1, pp. 105-128, 2013.
[7] Checko, Aleksandra, et al. "Evaluating C-RAN fronthaul functional splits in terms of network level energy and cost savings." *Journal of Communications and Networks*, vol. 18, no. 2, pp. 162-172, 2016.
[8] Miyamoto, Kenji, et al. "Performance evaluation of Ethernet-based mobile fronthaul and wireless CoMP in split-PHY processing." *Journal of Optical Communications and Networking*, vol. 9, no. 1, pp. A46-A54, 2017.
[9] Xinbo, Wang, et al. "Centralize or distribute? A techno-economic study to design a low-cost cloud radio access network." *IEEE International Conference on Communications (ICC)*, pp. 1-7, 2017.
[10] Bhaumik, Sourjya, et al. "CloudIQ: A framework for processing base stations in a data center." *Proceedings of the 18th annual international conference on Mobile computing and networking*. pp. 125-136, 2012.
[11] Wubben, Dirk, et al. "Benefits and impact of cloud computing on 5G signal processing: Flexible centralization through cloud-RAN." *IEEE signal processing magazine*, vol. 31, no. 6, pp. 35-44, 2014.
[12] Al-Fares, Mohammad, Alexander Loukissas, and Amin Vahdat. "A scalable, commodity data center network architecture." *ACM SIGCOMM Computer Communication Review*. vol. 38, no. 4, pp. 63-74, 2008.
[13] Peterson, Larry, et al. "Central office re-architected as a data center." *IEEE Communications Magazine*, vol. 54, no. 10, pp. 96-101, 2016.
[14] Miyamoto, Kenji, et al. "Split-PHY processing architecture to realize base station coordination and transmission bandwidth reduction in mobile fronthaul." *Optical Fiber Communications Conference and Exhibition (OFC)*, pp. 1-3, 2015.
[15] "Small Cell Virtualization: Functional Splits and Use Cases", Small Cell Forum whitepaper, rel. 7, Jan. 2016.
[16] Shibata, Naotaka, et al. "System level performance of uplink transmission in split-PHY processing architecture with joint reception for future radio access." *IEEE 26th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, pp. 1375-1379, 2015.
[17] Amos, Doug, Austin Lesea, and René Richter. FPGA-based prototyping methodology manual: Best practices in design-for-prototyping, 2011.