Heuristic-Based Cost-Efficient C-RAN Fronthaul Deployment Over TWDM-PON

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***Abstract*—In recent times, fiber-based time and wavelength division multiplexed passive optical networks (TWDM-PONs) are identified as the most cost-efficient transport network technology for Centralized Radio Access Network (C-RAN) fronthaul design. In this paper, we propose a heuristic-based two-phase optimized recursive clustering and cardinality re-organization algorithm (RCCRA) for cost-efficient C-RAN fronthaul design using TWDM-PON. In the first optimization phase, the proposed RCCRA scheme addresses the location-allocation problem of different ONUs/RRHs located at dispersed locations by forming clusters. In the second optimization phase, the algorithm re-organizes the cardinality of each formed clusters. RCCRA explores the optimal number and size of each ONU/RRH cluster, the most suitable location for placing passive devices, and the best fiber route from the BBU pool to the given ONUs/RRHs. We primarily focus on decreasing the total deployment cost by reducing the total length of deployed fibers and the number of required passive devices in the remote nodes.**

***Index Terms*—C-RAN fronthaul, TWDM-PON, Network optimization**

I. Introduction

In the current scenario, service providers are striving to overcome the challenge of being competent in offering networks that can efficiently provide gigabits of wireless connectivity. To support such a tremendous growth of data rate instigated in the mobile networks, mobile access network and the entire end-to-end network needs to be simultaneously redesigned in a cost-effective way. Centralized Radio Access Networks (C-RAN) is a new cloud-based paradigm already adopted by service providers in some LTE networks, and is acknowledged as one of the promising options for emerging 5G networks [1]. C-RAN reduces the deployment and operational cost (primarily due to power consumption) of the network by shifting the base-band units (BBU) from the cell sites to a centralized location called BBU pool, leaving behind remote radio heads (RRH) at the cell sites, which requires low energy [2]. In the C-RAN architecture, the data transmission between the BBU pool and RRHs is made through a transport network called the fronthaul.

In C-RAN, the centrally located BBU pool controls the radio signals originating from hundreds or even thousands of RRHs connected via the fronthaul network [3]. The common public radio interface (CPRI) protocol employed in the fronthaul requires strict latency and high traffic demands. Line rates due to the CPRI protocol depend on the aggregation type and multiple input multiple output (MIMO) configuration of the antennas. In the earlier case, every single RRH can transmit a CPRI flow coming from each antenna or an aggregated CPRI flow coming from distinct antennas [4]. The optical network is the most competent candidate for the fronthauling, and the convergence of mobile access networks with optical fronthaul will contribute to the low end-to-end latency, high capacity, total energy consumption, and the cheaper deployment costs of the network, and hence it needs to be strategically designed at the planning phase.

Fiber-based passive optical networks (PON) is recognized to be an excellent choice for fronthaul networks due to its low deployment and maintenance cost, although their transmission capacity still remains a limiting factor. To address this limitation, time and wavelength division multiplexed PON (TWDM- PON) is a promising PON technology that provides high bandwidth, more extended reach, and low end-to-end latency [5]. In TWDM-PON based fronthaul network, optical network units (ONUs) are placed near to RRHs to assign wavelengths, arrayed waveguide grating (AWG) and power splitter (PS) devices are placed at optical distribution network (ODN), and optical line terminals (OLTs) are installed at the central office (CO)/BBU pool. The optical signal is divided equally into multiple signals by PS, which depends on its splitting ratio (SR) while filtering a particular wavelength at individual output port is done by the AWG. Each output port of an AWG provides a dedicated wavelength to each connected PS enabling WDM access mode. On the other hand, the TDM access mode is enabled to the different ONUs/RRHs associated with a common PS as they share a common wavelength in the time domain.

The requisite level of network intelligence, capacity, scalability, and end-to-end latency supported by C-RAN essentially depend on the network technology and the fronthaul architecture in use. Hence, the fronthaul design has drawn considerable attention from both academia and industry. The authors in [6] examined the ability to employ different optical fronthaul and mid-haul architectures for 5G implementation. They mainly investigated the limitations present in the current systems and the potentialities of using various PONs for the fronthaul network design. In [7], the authors investigated the potential of fiber wireless (FiWi) enhanced LTE-A heterogeneous networks (HetNets) to deliver low latency and extremely reliable connectivity to end-users, which is an essential target in 5G network. The placement of the C-RAN network has been addressed by the authors in [8] to optimize the location of BBUs with wavelength assignment facility. It also allocates optimal routes to minimize fiber deployment length and the total number of BBU hotels. In [9], the authors proposed a heuristic approach to cost-optimally design backhaul networks for 4G small cells using TWDM-PON. However, regarding the 4G network, several critical aspects such as fronthaul network capacity, fiber deployments, BBU placement, the feasibility of using different optical technologies for fronthaul, etc., require to examine for cost-effective 5G deployment. The authors in [10] proposed the PON's application in C-RAN to reduce the number of handovers and improve the throughput with the help of executing virtualization at cell sites and BBU pools. Based on the existing LTE network's performance, various interface choices with different functional splits between BBU and RRH were investigated in [11]. These different interfaces were mainly investigated and compared in terms of bandwidth, the RRH's complexity, and the capability to support advanced wireless techniques. The authors in [12] propose an ILP based optimization model for designing cost-optimized two-stage TWDM/TDM-PON architecture. Based on the network node's locations, the method provides the number, type, splitting ratios of passive devices, and optimal place for passive device placement.

Despite these indispensable efforts, most of the investigations discussed above outline the C-RAN deployment challenges and suggested the related solutions. A few studies in the literature provide the actual mathematical or optimization model to address these challenges for deploying the C-RAN. In this paper, we propose to use TWDM-PON as a transport network for C-RAN fronthaul to minimize the deployment cost as much as possible. To do so, we suggest a heuristic-based two-phase optimized method called recursive clustering and cardinality re-organization algorithm (RCCRA). In the first optimization phase, the proposed RCCRA scheme addresses the location-allocation (L/A) problem of different ONUs/RRHs located at dispersed locations by forming clusters. In the second optimization phase, the proposed algorithm modify and re-organize the cardinality of each formed cluster. RCCRA explores the optimal number and size of each ONU/RRH cluster, the best suitable location of remote nodes (RNs) for placing passive devices (i.e., AWG and PS), and the best fiber route from the BBU pool to the given ONUs/RRHs. We primarily focus on decreasing the total deployment cost by reducing the total length of deployed fibers and the number of required passive devices in the RNs.

The remainder of the paper is arranged as follows. Section II introduces the C-RAN fronthaul architecture over TWDM-PON. In Section III, we discuss the RCCRA scheme. Section IV shows the simulation outcome and describes the performance of the proposed method. We conclude the paper in Section V.

II. C-RAN Fronthaul Interconnection Network

As shown in Fig. 1, in the proposed architecture, we use a point-to-multipoint TWDM-PON to connect all the cell sites with the BBU pool. The signaling and control messages exchanged through the X2 and S1 interfaces are assumed to be transmitted through the same fronthual network. Therefore, all the S1 and X2 signal processing are performed centrally at the BBU pool. We consider that each RRH of a cell site

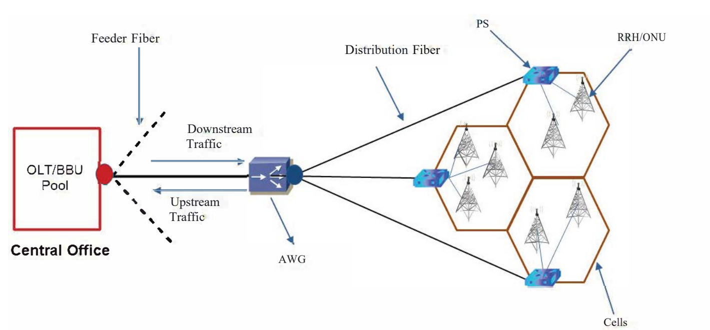

Fig. 1: C-RAN fronthaul architecture over TWDM-PON.

is be connected with a single ONU and the aggregated traffic of the RRH is transmitted through the distribution fiber. Each ONU is provided with a tunable laser that may be tuned to any available wavelength in the optical link for the transmission.

The topology shown in Fig. 1 has three stages of multiplexing. In the first multiplexing stage, the optical signal sent by different RRHs through the distribution fiber is multiplexed at AWG and move towards the BBU pool through a single feeder fiber. In the second multiplexing stage, PSs are used

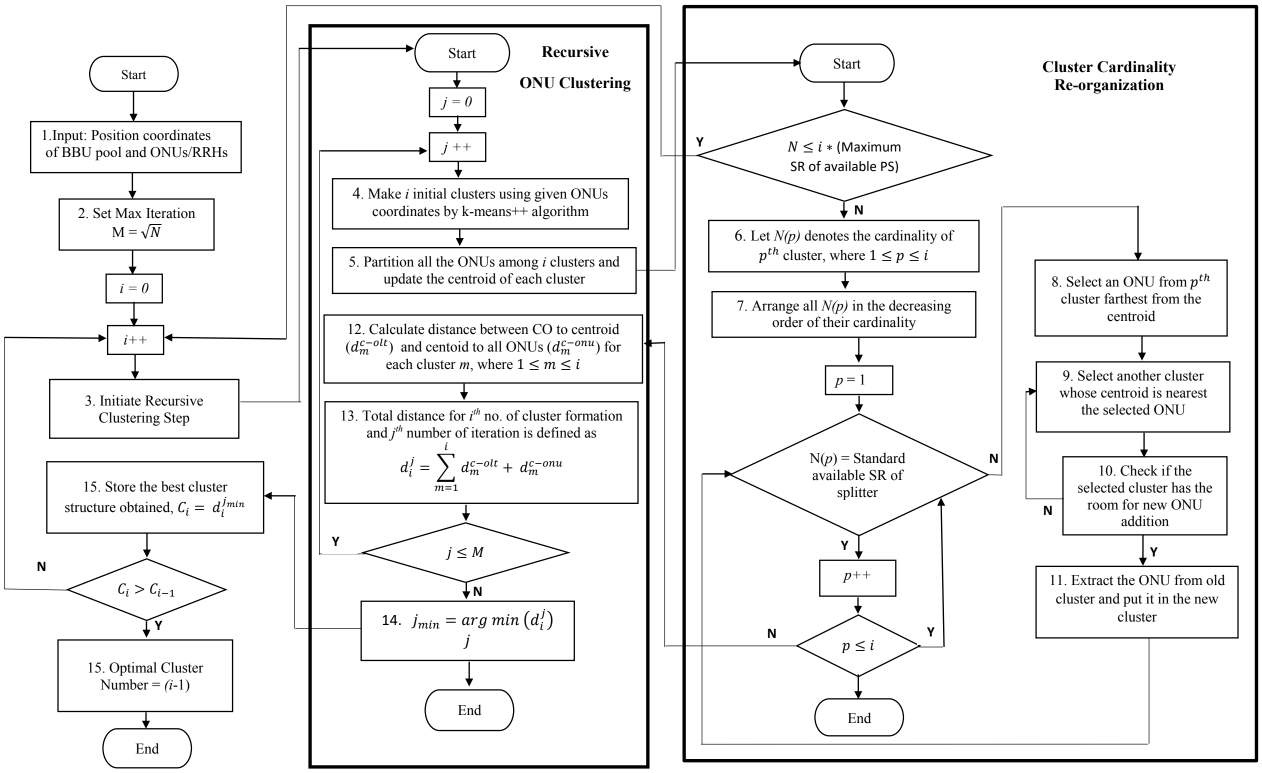

Fig. 2: Flowchart of RCCRA.

for multiplexing the traffic originating from different RRHs and transmitted through the distribution fiber. In the third multiplexing stage, at the BBU pool, various feeder fibers carrying the optical signal at a particular wavelength are multiplexed into a single line card (LC). The receiver node placed in the central office is provided with an OLT device that demultiplexes and switches the received traffic on individual wavelength to its related digital unit.

III. Problem Statement and Heuristic Algorithm

In this section, we discuss the optimization objective and present a heuristic algorithm for solving the problem.

A. Optimization Objective

For a system with dispersed locations of BBU pool and ONUs/RRHs placed at cell sites, we aim to design the C-RAN fronthaul architecture using TWDM-PON that offers a minimum deployment cost. The overall cost of deployment comprises the cost of OLT, AWG, PS and optical fiber cable, and labor cost for conduit trenching and laying fiber. The conduit trenching and laying fiber cost contributes the maximum in the overall cost of deployment. In our optimization model, we mainly focus on minimizing the total length of the deployed fibers. This study assumes a greenfield deployment, in which BBU pools needs to be constructed and fiber conduits and splitter cabinets are to be planned.

The solution of the stated optimization model provides the detail of the required number of first-stage and second-stage RNs for AWG and PS placement, respectively. The optimization model also provides the optimal location of the RNs for passive device placement and the complete association relation between the BBU pool, PS, AWGs, and ONUs/RRHS that guaranteed the minimum deployment cost.

B. Recursive Clustering and Cardinality Re-organization Algorithm (RCCRA)

Clustering is a procedure of grouping a given set of points (which corresponds to location of each ONU/RRH in our case) into many groups called clusters where each of the enclosed points are adjacent to each other. A traditional clustering method that has been widely used in earlier studies for solving the L/A problem is the *k*-means clustering algorithm, which is based on squared error measurement. However, the *k*-means algorithm has some notable theoretic deficiencies. First, the approximation obtained can be arbitrarily poor with reference to the objective function. This is due to the fact that different initial partitions result in different sets of final clusters each time. Second, it is hard to predict the optimal number of clusters that can provide the best design (i.e., the value of *k*). Third, in certain scenarios, a cluster may have plenty of ONUs exceeding the maximum available SR of a PS, resulting in the deployment of additional fiber from the BBU pool and installation of an extra PS.

RCCRA resolves the issues discussed above, whose flowchart is given in Fig. 2. In the figure, the first column executes an outer loop, which contains several steps. The middle column represents the recursive ONU clustering, and the third column is the cluster cardinality re-organization step. RCCRA is based on the *k*-means++ clustering algorithm that addresses the first issue by defining a better procedure to initialize the cluster centers before continuing with the conventional *k*-means optimization iterations. With the *k*-means++ initialization, the algorithm ensures to obtain the solution that is O(log *k*) competitive to the k-means solution. Recursive ONU clustering solves the issues of finding the optimal number of clusters that guarantees the best design (i.e., the optimal value of *k*). The cluster cardinality re-organization step addresses the problem of exceeding the number of ONUs in a group from the maximum available standard SR of the PS.

Fig. 3 illustrate the cardinality re-organization step. As an example, we consider a set of three clusters. The maximum available SR of each passive device is assumed to be 1:4. Fig. 3 (a) represents the initial cluster sets having the cardinality of C_2, C_1 and C_3 as 6, 3 and 2, respectively. For the given initial set of clusters, the network resources required will be two feeder fiber and two passive devices, each having SR of 1:4 and 1:2 for C_2, one feeder fiber and one 1:4 passive device for C_1, and one feeder fiber and one passive device of SR 1:2 for C_3. Now, we arrange the clusters in decreasing order of their cardinality, i.e., C_2, C_1, C_3. In the first cluster modification represented in Fig. 3 (b), we choose the farthest ONU from C_2 (i.e., ONU_{11}) for shifting to the most imminent cluster which is C_1 subjected to availability of space for the new addition. In the second cluster modification shown in Fig. 3 (c), ONU_3 is selected from cluster C_2 for moving to C_3, although C_1 is more closer to C_2 than C_3. It is due to the non-availability of further ONU addition in C_1. Centroids of both old and new clusters are updated after each adjustment. It may be noted that cardinalities of C_2 and C_1 matches the standard available SRs while the cardinality of C_3 remains unmatched, which is evident for the last cluster. The benefits of cardinality re-organization can be understood as the number of resources now required for final cluster sets will be one feeder fiber and one 1:4 passive for all the three cluster sets. So, the approximate cost saving includes the cost of one feeder fiber and one passive device. The step by step process of RCCRA is discussed as follows:

- Step 1: We input the coordinate information of the BBU pool and N number of ONUs/RRHs.
- Step 2: Each given set of clusters are generated M number of times, where $M = \sqrt{N}$.
- Step 3: Cluster formation is initialized, where for each number of i cluster, clusters are created M number of times. The optimal cluster that guarantees the global minima for each value of i lies between $1 \leq j \leq M$.
- Step 4,5: Using *k*-means++ algorithm, randomly generate i number of initial cluster centroids from the given ONUs locations and then partition them into i number of clusters, after that we update the individual cluster centroids. The sum of ONUs from each cluster formed should be less than or at least equal to N. If the condition is not fulfilled, increase the cluster number (i.e., $i = i+1$) otherwise move to the next step.
- Step 6,7: Find the number of ONUs (i.e., cardinality) of each cluster represented by $N(p)$, where $1 \leq p \leq i$ and arrange them in the decreasing order. If the cardinality of cluster p is equal to the standard available SR of the passive device then move to next cluster (i.e., $p = p+1$) otherwise move to step 8.
- Step 8: From the selected cluster whose cardinality needs to rearrange, separate the ONU having the maximum

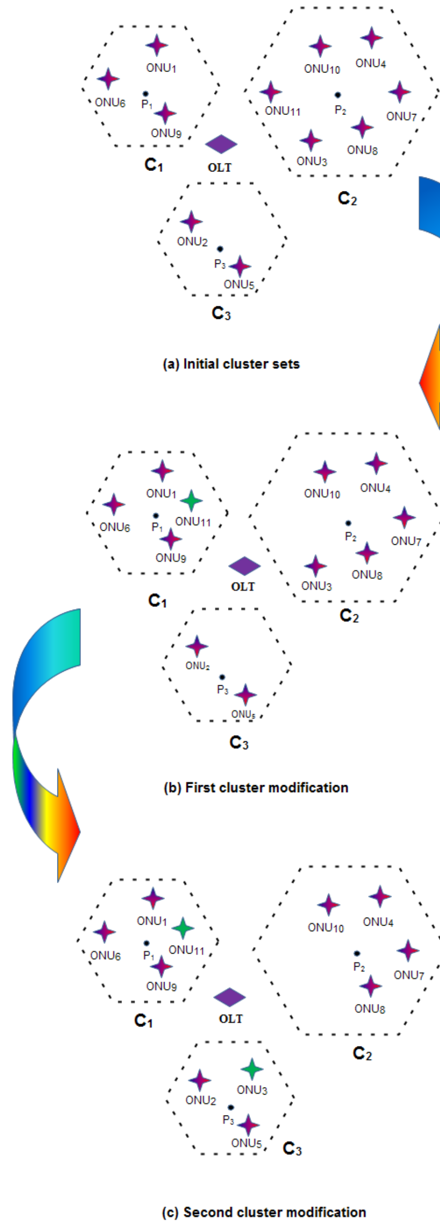

Fig. 3: Cluster cardinality re-organization illustration

distance from its respective centroid.

- Step 9: Find the cluster whose centroid is nearest from the ONU selected in step 8.
- Step 10,11: Check the feasibility of the new ONU addition in the selected cluster. If there is space, shift the ONU from old to new cluster otherwise move to step 9. Repeat the step 8-11 until cardinality of all clusters is checked and reorganized to standard available SR of the passive device.
- Step 12: For each cluster m obtained after cardinality reorganization step, calculate the distance of OLT to each cluster centroid (d_m^{c-olt}) and centroid to all ONUs in that cluster (d_m^{c-onu}) where $1 \leq m \leq i$.
- Step 13: Calculate the total sum of the distance from OLT to all the ONUs (d_i^j) for each j^{th} iteration. Repeat steps 4-13 till max iteration reached (i.e., $j \leq M$).
- Step 14: Find the value of j for which the total sum of the distance is minimum ($d_i^{j_{min}}$). For i number of cluster formation, we have obtained the best set of clusters that provide minimum distance from BBU pool to all the ONUs in j_{min} iteration.
- Step 15: Store the cluster detail for which we obtain $d_i^{j_{min}}$ in C_i.
- Repeat all the steps until $C_i > C_{i-1}$. The final cluster that gurantees the best set of clusters in terms of total distance is $(i-1)$.

The centroids of the ONU clusters produced following the RCCRA scheme are considered as the location of first-stage RNs for PS placement. Thus, we get single-stage RNs; however, for TWDM-PON, we require at least two cascaded stages of RNs. In TWDM-PON, we put PSs at the RN locations with direct connections to ONUs, and AWGs are positioned at second-stage RNs. We use the same RCCRA scheme to determine the second-stage RNs. However, rather than providing the ONU locations as inputs, we input the locations of first-stage RNs, which is achieved after solving RCCRA in the earlier steps as inputs. The proposed algorithm can also be used for the cases with more than two-stages of RNs by repeating the same process till the overall cost becomes higher on inserting one more stage of RNs.

Numerical Analysis

We assess the performance of the proposed RCCRA scheme for cost-efficient C-RAN fronthaul deployment through simulations. We consider three different test cases where we vary the number and location of ONUs/RRHs from 150 to 350 with a step size of 100 ONUs/RRHs. We also vary the maximum number of ONUs/RRHs that each OLT can support. We take a square deployment region having each side of 20km wherein the BBU pool is located at the center of the square. The locations of the ONUs/RRHs are randomly generated inside the square region. This study assumes that each OLT can support a maximum of 32 ONUs/RRHs. To ensure the average bandwidth per ONU/RRH, we also restrict the number of ONUs/RRHs supported per wavelength. We study three cases of ONUs/RRHs supported per wavelength, i.e., 4, 8, and 16, respectively, limiting the number of wavelengths employed per OLT to be 8, 4, and 2, resulting in the total number of ONUs/RRHs sustained per OLT to be 32. Thus, the average bandwidth available to each ONU/RRH differs; however, the maximum transmission capacity per PON remains fixed. We also assume that we have three different types of PSs with available SRs of 1:4, 1:8, and 1:16.

As the actual components cost are proprietary and hard to obtain, we take the following cost value for different components [13]: a) fiber cable cost per km = $4000; b) labor cost for conduit trenching and laying fiber per km = $16,000; c) each TWDM-PON OLT cost = $2500*$\sqrt{L}$, where L is the total number of wavelengths that each OLT can support; d) PS cost per port = $100; and e) AWG cost per port = $150. The revised component costs may simply be included in the simulation study when available. We use Matlab to execute the proposed RCCRA algorithm. The execution of the proposed algorithm is seen to be time-efficient, and for all the three test cases, the results are obtained within minutes.

Fig. 4 shows the total fronthauling cost of the proposed RCCRA scheme for different test cases. We also compare our method with two conventional clustering algorithms viz., *k*-means and BS clustering. The x-axis depicts the number of ONUs/RRHs, and the y axis represents the total deployment cost. As we expected, for all the value of ONUs/RRHs, the proposed RCCRA scheme performs much better in reducing the total C-RAN fronthaul deployment cost. For a given value of ONUs/RRHs, the total cost of deployment for the *k*-means algorithm is the highest, followed by BS clustering and RCCRA approaches.

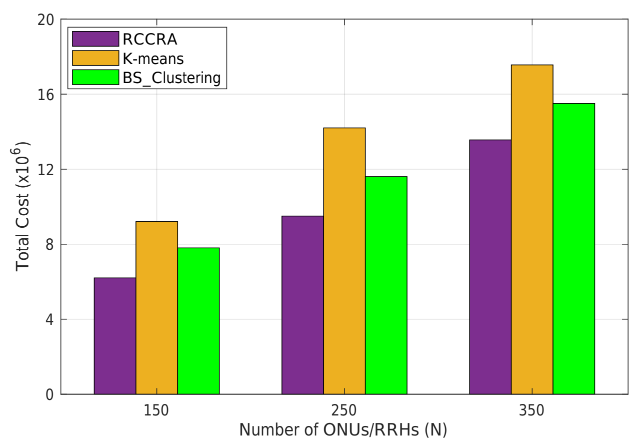

Fig. 4: Total C-RAN fronthaul deployment cost for different approaches.

In Fig. 5, we assess the effect of the number of ONUs/RRHs supported per OLT on the overall deployment cost of C-RAN fronthaul. It is clear from the figure that the overall cost declines with an increase in the number of ONUs/RRHs supported per OLT. This is because as the number of ONUs/RRHs supported per OLT increases, the sharing of feeder fibers by ONUs also increases, leading to a more cheaper deployment

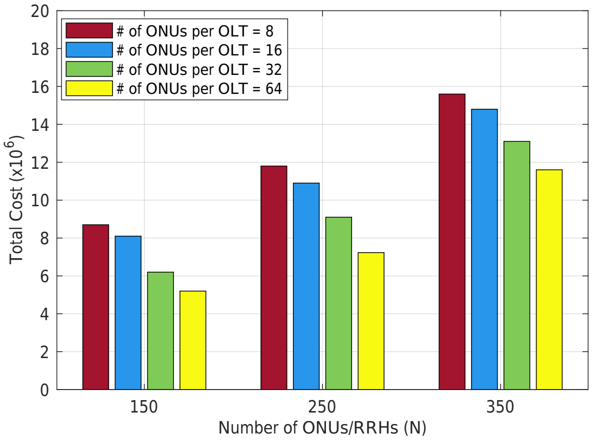

Fig. 5: Total cost versus number of ONUs/RRHs supported per OLT.

cost. However, the reduction in deployment cost is achieved on account of the lower average bandwidth provided to each ONU/RRH. Thus, we have to balance the required average bandwidth per ONU/RRH and the overall deployment cost in order to get an optimal design.

In Fig. 6, we evaluate the impact of the number of ONUs/RRHs per wavelength on the total cost of deployment. We observe that the total deployment cost reduces on increasing the number of ONUs/RRHs supported per wavelength. This is because as the number of ONUs/RRHs supported by each wavelength increases, the required number of passive devices (i.e., AWG, PSs) and OLT ports will reduce. Also, there will be more flexibility in connecting these ONUs/RRHs for a higher value of ONUs/RRHs supported per wavelength.

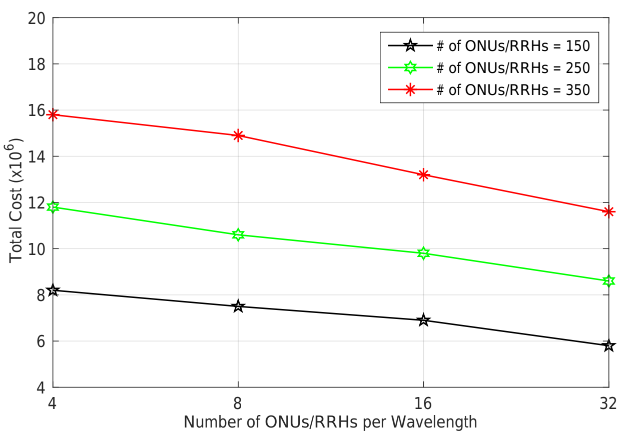

Fig. 6: Total cost versus number of ONUs/RRHs per wavelength.

Conclusion

In this paper, we propose to use TWDM-PON as a transport network for C-RAN fronthaul to minimize the deployment cost as much as possible. To do so, we suggest a heuristic-based two-phase optimized method called Recursive Clustering and Cardinality Re-organization Algorithm (RCCRA). RCCRA explores the optimal number and size of each ONU/RRH cluster, the best suitable location of remote nodes (RNs) for placing passive devices (i.e., AWG and PS), and the best fiber route from the BBU pool to the given ONUs/RRHs. We consider different test cases where we vary the number and location of ONUs/RRHs and the maximum number of ONUs/RRHs that a common OLT can support. Simulation results show that the proposed algorithm performs much better in reducing the overall deployment cost than the conventional clustering algorithm. We observe that the total cost declines with an increase in the number of ONUs/RRHs supported per OLT. We also observe that the total cost of deployment reduces on increasing the number of ONUs/RRHs supported per wavelength.

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References

[1] K. Chen and R. Duan, "C-RAN the road towards green RAN. White Paper," *China Mobile Research Institute, Tech. Rep*, 2011.
[2] J. Wu, Z. Zhang, Y. Hong, and Y. Wen, "Cloud radio access network (C-RAN): a primer," *IEEE Network*, vol. 29, no. 1, pp. 35–41, 2015.
[3] C. Ranaweera, E. Wong, A. Nirmalathas, C. Jayasundara, and C. Lim, "5G C-RAN with optical fronthaul: An analysis from a deployment perspective," *Journal of Lightwave Technology*, vol. 36, no. 11, pp. 2059–2068, 2017.
[4] A. De la Oliva, J. A. Hernandez, D. Larrabeiti, and A. Azcorra, "An overview of the CPRI specification and its application to C-RAN-based LTE scenarios," *IEEE Communications Magazine*, vol. 54, no. 2, pp. 152–159, 2016.
[5] H. S. Abbas and M. A. Gregory, "The next generation of passive optical networks: A review," *Journal of network and computer applications*, vol. 67, pp. 53–74, 2016.
[6] T. Pfeiffer, "Next generation mobile fronthaul and midhaul architectures," *Journal of Optical Communications and Networking*, vol. 7, no. 11, pp. B38–B45, 2015.
[7] H. Beyranvand, M. Lévesque, M. Maier, J. A. Salehi, C. Verikoukis, and D. Tipper, "Toward 5G: FiWi enhanced LTE-A HetNets with reliable low-latency fiber backhaul sharing and WiFi offloading," *IEEE/ACM Transactions on Networking*, vol. 25, no. 2, pp. 690–707, 2016.
[8] N. Carapellese, M. Tornatore, A. Pattavina, and S. Gosselin, "Bbu placement over a wdm aggregation network considering otn and overlay fronthaul transport," in *2015 European Conference on Optical Communication (ECOC)*. IEEE, 2015, pp. 1–3.
[9] C. Ranaweera, C. Lim, A. Nirmalathas, C. Jayasundara, and E. Wong, "Cost-optimal placement and backhauling of small-cell networks," *J. Lightwave Technol.*, vol. 33, no. 18, pp. 3850–3857, 2015.
[10] X. Wang, L. Wang, C. Cavdar, M. Tornatore, G. B. Figueiredo, H. S. Chung, H. H. Lee, S. Park, and B. Mukherjee, "Handover reduction in virtualized cloud radio access networks using TWDM-PON fronthaul," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 8, no. 12, pp. B124–B134, 2016.
[11] C. M. R. Institute, "Next generation fronthaul interface," *White Paper, 2015. [Online]. Available: http://labs. chinamobile.com/cran/.*
[12] M. S. Akhtar, P. Biswas, and A. Adhya, "An ILP-based CapEx and OpEx efficient multi-stage TDM/TWDM PON design methodology," *Optical Fiber Technol.*, vol. 46, pp. 205–214, 2018.
[13] H. Chen *et al.*, "Cost-Minimized Design for TWDM-PON-Based 5G Mobile Backhaul Networks," *IEEE/OSA J. Opt. Commun. Networking*, vol. 8, no. 11, pp. B1–B11, 2016.