Cost-efficient Mobile Backhaul Network Design over TWDM-PON

Md Shahbaz Akhtar*, Pramit Biswas†, Aneek Adhya‡ and Sudhan Majhi§
*†§Dept. of Electrical Engineering, Indian Institute of Technology Patna, India
‡G.S. Sanyal School of Telecommunications, Indian Institute of Technology Kharagpur, India
Email: {*shahbaz.pee16, †pramit.pee15, §smajhi}@iitp.ac.in, ‡aneek@gssst.iitkgp.ac.in

***Abstract*—In recent times, time and wavelength division multiplexed passive optical networks (TWDM-PONs) are recognized as promising transport network technology for mobile backhaul design. TWDM-PON is a multi-wavelength PON technology that offers high reliability, low maintenance cost, high capacity, and long transmission reach. In this paper, we propose a recursive clustering algorithm (RCA) to design cost-efficient TWDM-PON architecture for providing backhaul connectivity to the macro-cell base stations (BSs). Based on the geographical locations of BSs, RCA explores the optimal number of BS clusters, the size of each cluster, the most suitable location of remote nodes for passive device placement, and the best fiber route from operator's central office to the BS's locations. The primary objective is to reduce the total cost by minimizing the total length of deployed fibers. We also employ cable-conduit sharing, where the cable-conduits deployed for existing fiber links are utilized to place a new fiber link. We introduce two-stage cable-conduit sharing to maximize sharing of cable-conduits for last-mile fiber and distribution fiber so as to further tune down the cost. We compare the performance of our proposed RCA scheme with the existing benchmark studies, viz., BS clustering technique and random-cut sectoring approach. The simulation result confirms that our scheme substantially reduces the backhauling cost compared with the existing studies.**

***Index Terms*—Mobile backhaul, TWDM-PON, D-RAN, Cost-optimization**

I. Introduction

Bandwidth demand in access network has been rising by almost 50% per year due to continuous rise of extensive usage of data consuming multimedia applications, such as online HD games, ultra HDTV, video conferencing, peer-to-peer file sharing, cloud computing, etc. [1]. The upcoming fifth-generation (5G) mobile network is expected to offer a link rate of 1 Gb/s with mobility and 10 Gb/s without mobility, i.e., stationary access rate [2], [3]. Deploying a substantial number of macro-cell base stations (BSs) and small cells will facilitate network providers in adhering to the ever-growing traffic requirement [4], [5]. Small cells improve the coverage of the macro network, add targeted capacity, and support new services. At present scenario, network providers employ a distributed radio access network (D-RAN) to provide mobile connectivity to the end-users. In D-RAN, the baseband processing units (BBUs) are distributed over several independent BSs, and through these BSs, small cells are operated. Since the deployment of mobile backhaul network in D-RAN would entail huge investment, economical and efficient network planning would be essential for the optimal design.

Among different available transmission technologies for backhaul, fiber-based passive optical network (PON) is the most preferred choice due to its manifold advantages, which primarily include high reliability, low operational cost, huge bandwidth support, and long transmission reach [6]. Among different variations of PON technologies, the multi-wavelength PON technologies, such as time and wavelength division multiplexed PON (TWDM-PON) is considered to be the primary candidate for backhaul networks [7], [8]. As per the ITU-T G.989.3 specification, the maximum transmission bit rate per wavelength in TWDM-PON is 10 Gb/s and 2.5 Gb/s in the downstream and upstream direction respectively, which is expected to fulfill the required data rate by individual user equipment (UE) over the cellular network [9]. Thus, designing a cost-optimal TWDM-PON based transport network to carry BS traffic has brought extensive research interest [10].

Several recent studies investigate the cost-efficient deployment of different PON technologies for backhauling mobile BSs in D-RAN. Chen *et al.* propose a k-means based BS clustering algorithm to design cost-optimized TWDM-PON based mobile backhaul network [11]. The authors explore the optimal number of clusters for clustering mobile BSs located at different locations to reduce the length of deployed fibers. However, the proposed BS clustering algorithm only optimizes the length of last-mile fiber (LMF), not the feeder fiber (FF) or distribution fiber (DF). To reduce the cost further, single-stage cable-conduit sharing technique is also employed for maximizing the sharing of LMF's cable-conduits. In [12], the authors suggest a clustering method to group the users, and serve each group with a separate PON, and finally employ a genetic algorithm to explore the optimum fiber route. Jaumard *et al.* introduce an agglomerative hierarchical clustering method for partitioning optical network units (ONUs) placed at different geographical locations for multi-stage PONs. The author's objective is to find the most suitable sites for passive device placement that provides optimal fiber route from the central office (CO) to the ONUs. However, the proposed clustering scheme has high time complexity, and for a large dataset, determining the exact number of clusters by the dendrogram becomes difficult [13]. To configure the cost-optimal backhaul network using optical fibers for small cell deployment in the scenarios where earlier deployed fibers are sparsely located, an optimization model is recommended by Ranaweera *et al.* [14]. The authors in [15] propose a method to design a cost-

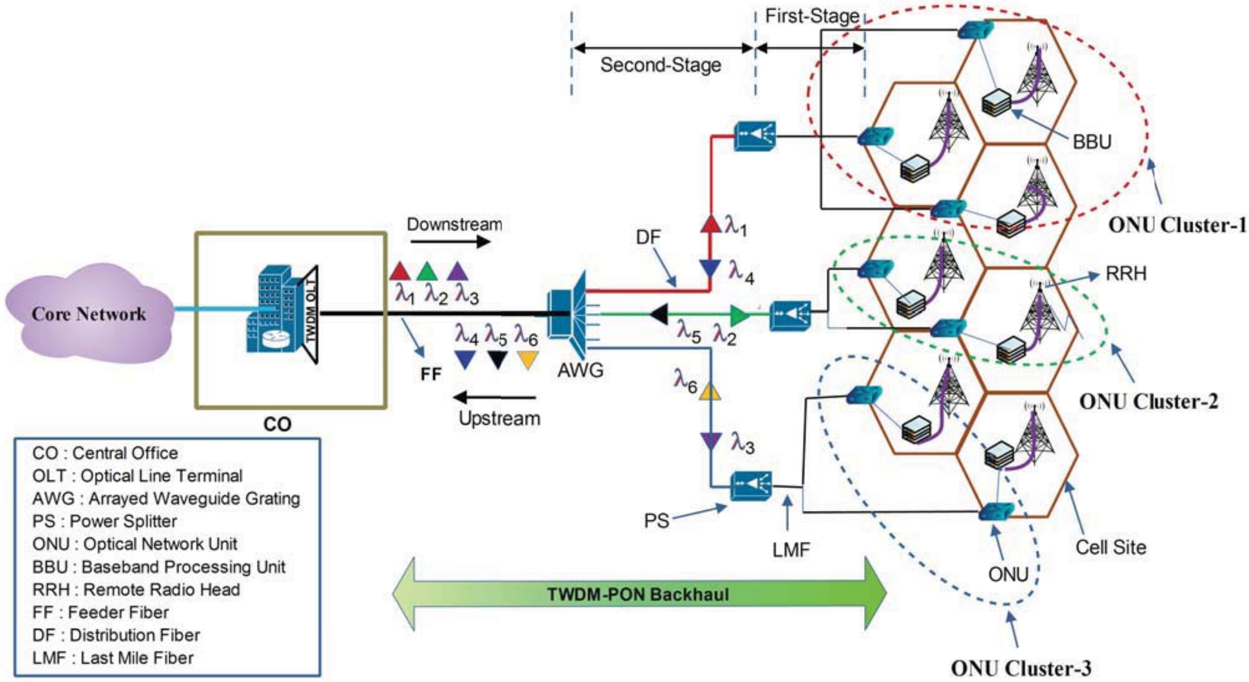


Fig. 1: D-RAN backhaul architecture over TWDM-PON.

optimized converged network by exploiting the benefits of both the optical networks and mobile/wireless networks. In this work, an integer linear programming (ILP) based optimization framework is proposed to backhaul wireless network with fiber targeting CapEx and OpEx reduction. In [16], the authors suggest an ILP based optimization model to design cost-optimized two-stage TWDM/TDM PON architecture. Depending on the geographical locations of network nodes, the model gives the number, type, splitting ratios, and optimal location for the placement of passive devices. Despite of all these research efforts, judicious network planning assisted with cable-conduit sharing in designing and deploying a cost-efficient mobile backhaul network using TWDM-PON is not adequately investigated.

In this study, we propose to employ TWDM-PON based transport network for providing mobile backhaul connectivity to macro-cell BSs in D-RAN. We propose a network planning algorithm, called recursive clustering algorithm (RCA) for cost-efficient backhaul network design over TWDM-PON. The suggested RCA scheme addresses the issue of location-allocation (L/A) problem of different ONUs located at macro-cell BS by making clusters. RCA explores the optimal number of BS/ONU clusters, the size of each cluster, the most suitable location of remote nodes (RNs) for passive device placement, and the best fiber route from operator's CO to the given BSs/ONUs. We mainly focus on reducing the total cost by minimizing the total length of deployed fibers. To further reduce the cost, which is significantly dominated by trenching and cable-conduit laying cost, we also suggest a two-stage cable-conduit sharing approach. The simulation result shows that the proposed method is useful in substantially decreasing the backhauling cost compared with benchmark studies, viz., BS clustering [11] and random-cut sectoring [17] techniques.

The rest of the paper is organized as follows. Section II includes network architecture of a point to multi-point TWDM-PON based mobile backhaul network. In Section III, we propose RCA and two-stage cable-conduit sharing for fiber deployment. Section IV presents the simulation result and outlines the performance of the proposed scheme. The paper is concluded in Section V.

II. Network Architecture

As shown in Fig. 1, we propose to employ a TWDM-PON based backhaul network for connecting the dispersed BSs to the operator's CO. The architecture comprises the CO equipped with TWDM optical line terminal (OLT), two different types of passive devices, i.e., arrayed waveguide grating (AWG) and power splitter (PS) installed at RNs, multiple ONUs and BSs located at different cell sites and deployed fibers in the optical distribution network. The AWGs placed at the second-stage RNs are connected to the TWDM OLT through FFs, and the multiple PSs placed at the first-stage RNs are connected to the AWGs through DFs. ONUs are connected to the PSs as leaf nodes through LMFs. Each ONU is connected with the BBU of a BS placed at the cell site to provide network access to the mobile terminals (i.e., UEs).

As an example, in Fig. 1, we show three wavelengths, viz., λ_1, λ_2 and λ_3 are used in the downstream direction, whereas three wavelengths, viz., λ_4, λ_5 and λ_6 are used in the upstream direction. AWG works as a wavelength multiplexer and demultiplexer. Each pair of wavelengths, e.g., (λ_1,λ_4), (λ_2,λ_5) and (λ_3,λ_6) is fed to an individual PS, which is then shared with multiple ONUs in the time domain. Mobile traffic of a BS is aggregated at its BBU, and transmitted through an ONU with the assigned wavelength. We consider that each ONU is provided with a tunable transceiver so that each ONU may be tuned to its assigned wavelengths for traffic transmission.

III. Problem Statement and Heuristic Algorithm

In this section, we describe the optimization problem and the proposed heuristic algorithm to solve the problem.

A. Optimization Objective

For a system with given locations of CO (i.e., OLT) and BSs/ONUs, we aim to explore the network architecture for mobile backhaul design employing the TWDM-PON and offering the least deployment cost. The total deployment cost includes the equipment cost of OLT, PS, AWG and fiber cable, and labor cost for trenching and laying of cable-conduits. Among all the cost components, the trenching and cable-conduit laying contribute the most in the total deployment cost. Thus, in our approach, we primarily focus on reducing the total length of laid fibers. Since the number and locations of dispersed BSs/ONUs that need to be connected are fixed, the cost of ONUs and BSs are not considered in this study. We consider that the cost of OLT increases with the increase in the number of wavelengths supported by it.

The solution of the proposed optimization model includes the required number of first-stage and second-stage RNs for PS and AWG placement respectively, the best location of the RNs and the complete interconnection links among the OLT, AWGs, PSs and BSs/ONUs that provide the least deployment cost.

B. Recursive Clustering Algorithm (RCA)

Clustering is the process of grouping a set of given points (elements) into multiple groups called clusters such that points contained in a group are adjacent to each other. In our study, the locations of the BSs/ONUs represents the given points. A well-known clustering approach widely used in previous studies to solve the L/A problems is the *k*-means clustering, which is based on the squared error measurement. However, the *k*-means clustering algorithm has certain limitations, such as i) different initial centroid selections result in different final clusters each time, and ii) hard to predict the optimal number of clusters that can provide the best design, i.e., the optimal value of *k*.

Recursive clustering algorithm (RCA) explores the optimal number of cluster (i.e., *k*) that can provide the best design for a given number and locations of ONUs. The flowchart of RCA is presented in Fig. 2. In the figure, the set of steps (outside the marked box) implements the outer loop, while the set of steps inside the marked box represents the recursive ONU clustering method. RCA is based on the *k*-means++ clustering

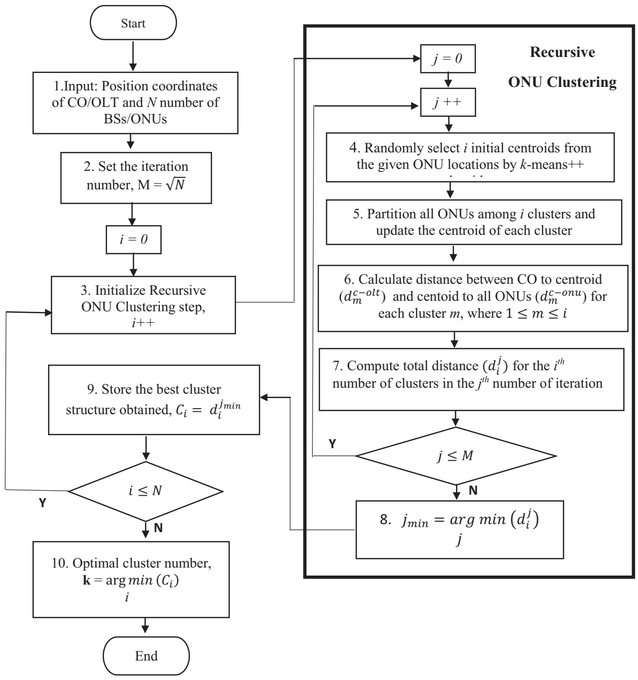


Fig. 2: Flowchart of RCA.

algorithm that defines an improved procedure to initialize the cluster centroids before moving with the standard *k*-means optimization iterations. Recursive ONU clustering addresses the issue of finding the optimal number of clusters and size of each cluster that provides the minimum distance from OLT to all the ONUs. The descriptions for main steps of RCA are as follows:

- Step 1: We provide as input the coordinates of CO/OLT and N number of BSs/ONUs.
- Step 2: We set the number of iterations equal to M, where $M = \sqrt{N}$.
- Step 3: Number of clusters is initialized to be i. It may be observed that i number of clusters are created for M number of times.
- Step 4: Using *k*-means++ clustering algorithm, randomly select i initial cluster centroids from the given ONUs.
- Step 5: Partition the ONUs into i clusters, after which update the individual cluster centroids.
- Step 6: For each cluster m, 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 7: Compute the total distance (d_i^j) for the i^{th} number of clusters in the j^{th} number of iteration, where
$$d_i^j = \sum_{m=1}^{i} \left(d_m^{c-olt} + d_m^{c-onu} \right).$$
Repeat steps 4-7 till the maximum number of iterations is reached (i.e., $j \leq M$).
- Step 8: Find the value of j for which the total distance is minimum ($d_i^{j_{min}}$). For i number of clusters, we obtain

the best set of clusters that offers the lowest total distance from OLT to all the ONUs in the j_{min}th iteration.

- Step 9: Store the cluster details and store $d_i^{j_{min}}$ in C_i.
- Step 10: Repeat steps 1-9 until $i \leq N$. The best number of clusters that guarantees the minimum distance from OLT to all ONUs is given as $k = \underbrace{\arg\min(C_i)}_{i}$.

The centroids of the BS/ONU clusters formed following the RCA scheme are treated as the location of first-stage RNs (to be used for PS placement). Thus, we obtain single-stage RNs; however, for TWDM-PON, we need at least two cascaded stages of RNs. Typically in TWDM-PON, we place PSs at the RN locations that have direct connections to BSs/ONUs, and AWGs are placed at second-stage RNs. We use the same scheme (i.e., RCA) to find the second-stage RNs. However, instead of the BS/ONU locations as inputs, we provide the locations of first-stage RNs, obtained after solving RCA in the previous step as inputs.

C. Two-stage Cable-Conduit Sharing

Typically, fibers are laid through cables followed by conduits. In RCA, a critical assumption is that each ONU is connected to a PS with an independent fiber link resulting in the creation of a dedicated cable-conduit. In cable-conduit sharing, the fiber deployment cost can be tuned down significantly by utilizing the existing cable-conduits, i.e., already deployed cable-conduits for previously considered fiber links are utilized to deploy a new fiber link. By doing this, the cost of trenching and laying conduits can be drastically reduced compared to providing fiber links through dedicated cable-conduits. In [17], the authors explore single-stage TDM-PON deployment using a minimum spanning tree (MST) based single-stage cable-conduit sharing where cable-conduit sharing is used only in the LMF. In this study, we propose two-stage cable-conduit sharing, wherein the first-stage, all the ONUs are connected with their associated first-stage RNs (i.e., PSs) directly using independent LMFs sharing the common cable-conduit wherever possible. In the second-stage cable-conduit sharing, all the PSs are connected with their associated second-stage RNs (i.e., AWGs) using independent DFs (if possible) sharing the common cable-conduit. We refer the first-stage cable-conduit sharing as LMF's cable-conduit sharing and second-stage cable-conduit sharing as DF's cable-conduit sharing.

Fig. 3 shows an example of the proposed two-stage cable-conduit sharing. In the figure, we show three different TWDM-PONs: TWDM-PON1 has no provision of cable-conduit sharing, and all the ONUs are connected with related PSs through independent LMFs requiring dedicated cable-conduit. In TWDM-PON2, only LMF's cable-conduit sharing is provisioned where it may be observed that two ONUs share the common cable-conduit of the third ONU, saving the labor cost of trenching and laying two dedicated conduits. TWDM-PON3 is provided with both DF's and LMF's cable-conduit sharing, where the connections to PSs from the AWG share a common cable-conduit.

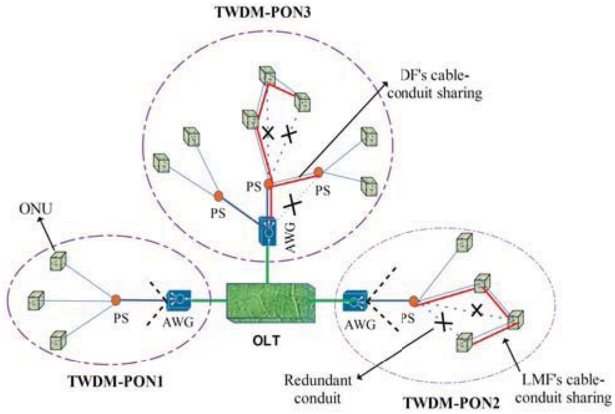


Fig. 3: Example of two-stage cable-conduit sharing.

The problem of cable-conduit sharing with limited deployment cost is solved as follows: for LMF's cable-conduit sharing, we consider each location of ONU and associated PS as the vertices, and apply the well-known MST algorithm [18]. The MST solution produces a spanning tree that joins all the vertices providing the minimum sum of link's lengths. After all the first-stage RNs and BSs/ONUs are checked for cable-conduit sharing possibilities, we move forward for second-stage cable-conduit sharing. In DF's cable-conduit sharing, for given PS locations connected with the associated second-stage RNs (i.e., AWGs), we again find a MST that connects all these vertices.

Numerical Analysis

The performance of the proposed RCA scheme to design TWDM-PON based mobile backhaul is evaluated through simulations considering different test cases. We consider the Manhattan street model [19] to generate the locations of the OLT/CO and BSs/ONUs. We use a square deployment region with a length of 20km for each side wherein the CO/OLT is placed at the center of the square. Multiple small square blocks with a length of 1km for each side are generated inside the square region with 20km side. The distance between two adjacent square blocks is 450 meters. The locations of the BSs/ONUs are selected randomly at the corner of the square blocks. We consider three test cases with different numbers of BSs/ONUs that vary from 100 to 500 with a step size of 200 BSs/ONUs. We consider that the locations of the existing BSs/ONUs are not altered when considering a new test case with a given step increase in the number of BSs/ONUs.

The exact cost of components are proprietary and difficult to obtain; we consider the following costs of different components [11]: a) fiber cable cost per km is \$4000; b) labor cost for trenching and cable-conduit laying per km is \$16,000; c) the cost of each TWDM-PON OLT port is estimated as \$2500*$\sqrt{w}$, where w is the number of wavelengths supported per OLT port; d) the cost of PS is \$100 per port; and e) the cost of AWG is \$150 per port. The modified component costs may easily be incorporated in the simulation study. We use Matlab to implement the proposed RCA algorithm. The execution of the algorithm is found to be time-efficient, and the solutions can be obtained within minutes for all three test cases.

We compare performance of our proposed clustering algorithm with the existing benchmark studies, viz., BS clustering technique [11] and the random-cut sectoring approach [17]. We use the following legends in Figs. 4-6 to represent different deployment techniques: 1) BS clustering technique is represented as "BS_Clustering" 2) Random cut sectoring approach is represented as "Random_Cut" 3) RCA without cable-conduit sharing is denoted as "RCA_Only" 4) RCA with first-stage cable-conduit sharing is denoted as "RCA_FS_CCS" and 5) RCA with two-stage cable-conduit sharing is denoted as "RCA_TS_CCS".

In Fig. 4, we show relative performance of the proposed RCA scheme with reference to two different approaches, viz., random-cut sectoring and BS clustering in terms of the total deployment cost. The number of BSs/ONUs for different test cases are represented along the x-axis, and the total deployment cost in units of USD is presented along the y-axis. For a given test case with random-cut sectoring method, we show the average costs taken over 12 different initial cuts. The proposed RCA approach performs considerably better in minimizing the total deployment cost of the backhaul network for all the test scenarios. For a given number of BSs/ONUs, deployment cost for the random-cut sectoring method is the largest, followed by that of BS clustering, and RCA approaches. We obtain cost savings primarily due to usage of single-stage TDM-PON architecture and non-optimal RN placement in [17], leading to its higher FF and DF lengths and related increase in fiber deployment cost and the proposed BS clustering algorithm in [11] only optimizes the length of last-mile fiber (LMF), not the feeder fiber (FF) or distribution fiber (DF). The relative differences in costs are also shown. Using the proposed method, the total cost is reduced by at least 45.67% compared with the random-cut sectoring method and 8.24% compared with the BS clustering approach.

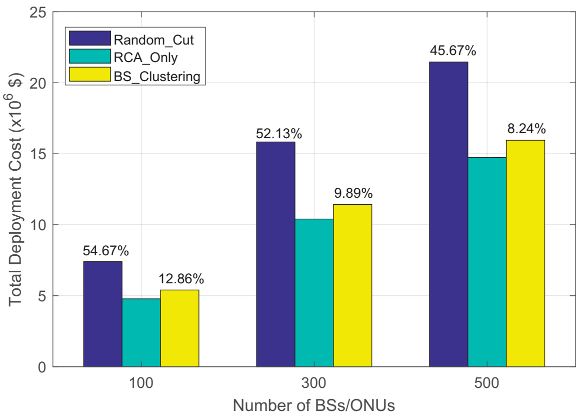


Fig. 4: Total deployment cost for different deployment techniques.

Fig. 5 shows the benefit of employing cable-conduit sharing on the total deployment cost. Since we try to maximize the sharing of existing cable-conduits, as excepted, we observe that the total cost is the highest for RCA_Only and the lowest for RCA_TS_CCS. The maximum cost saving is achieved with the first-stage cable-conduit sharing only (i.e., RCA_FS_CCS). This occurs since the maximum fraction of fiber length in the entire backhaul network is due to LMF only, and there exist more opportunities to exploit cable-conduit sharing due to close proximity of ONUs/BSs, and hence facilitating cable-conduit sharing in LMF provides the highest cost saving. Also, we observe that the total deployment cost is reduced marginally after employing cable-conduit sharing with DFs.

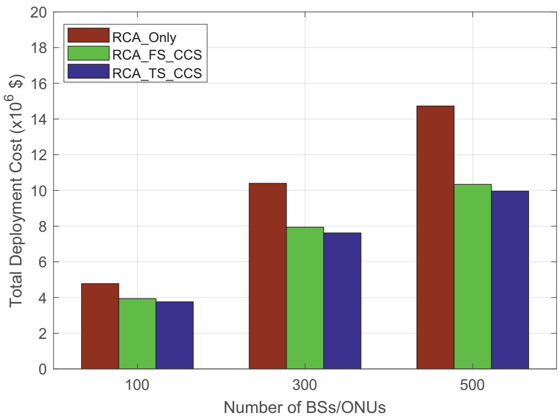


Fig. 5: Total deployment cost for different RCA-based deployment techniques.

As an example, for RCA_Only scheme with 300 number of BSs/ONUs, we show the percentage distribution of different component's cost, excluding the labor cost for trenching and laying cable-conduits in Fig. 6. It may be observed that LMF has the highest percentage of cost sharing, with 76% of the total component cost, followed by DF with 14% and FF with 7% of the total component cost. The collective cost due to OLT, PSs and AWGs devices contribute 3% of the total cost. Within this 3% share, the OLT cost sharing is 76%, followed by PS with cost sharing of 18% and AWG with cost sharing of 6%.

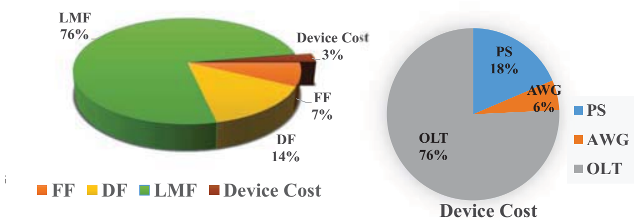
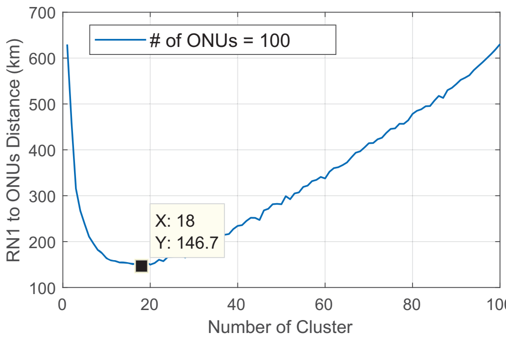
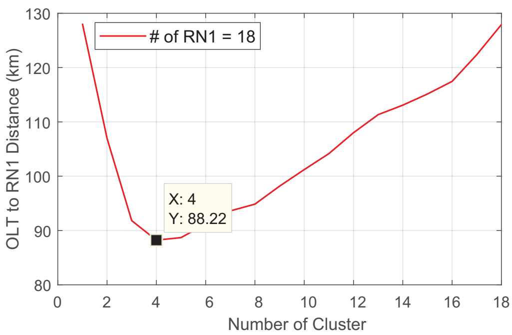


Fig. 6: Percentage distribution for different component's cost for RCA_Only scheme with 300 number of BSs/ONUs.

In Fig. 7, we show an example usage of RCA_Only scheme with 100 number of ONUs. Fig. 7(a) shows the first-stage clustering of 100 ONUs as input to the RCA scheme. We show results for different number of clusters with their related centroid locations selected as first-stage RNs (represented as RN1 in the figure). We observe that with 18 number of clusters, we obtain the minimum RN1 to ONU distances (considering all the clusters). The corresponding minimum distance is 146.7km. Fig. 7(b) shows the second-stage clustering of 18 first-stage RNs (obtained after first-stage clustering) as input to the RCA scheme. We observe that the number of clusters providing the minimum distance from OLT to the first-stage RNs is 4. The corresponding minimum distance is 88.22km. Hence, for 100 ONUs, the minimum number of first-stage and second-stage RNs are found to be 18 and 4, respectively.



(a) First-stage clustering



(b) Second-stage clustering

Fig. 7: Illustration of RCA_Only scheme with 100 ONUs.

Conclusion

In this study, we propose to employ TWDM-PON based transport network for providing mobile backhaul connectivity to macro-cell BSs. We suggest an efficient clustering algorithm called RCA to reduce the backhaul deployment cost by minimizing the total length of deployed fibers. As the labor cost due to trenching and laying cable-conduits significantly supersedes all other costs, the strategy of two-stage cable-conduit sharing is incorporated for maximizing the cable-conduit sharing. We observe that LMF cable-conduit sharing provides the highest cost savings while the DF cable-conduit sharing provides marginal cost savings. The percentage distribution of different component's costs, excluding the labor cost for trenching and laying cable-conduits is also presented. Among the different component's cost, LMF has the highest percentage of cost sharing, followed by DF and FF. Among the costs for OLT, PS and AWG devices, the OLT cost sharing is the maximum, followed by that of PS and AWG. The simulation result confirms that the proposed RCA scheme significantly reduces the total backhaul deployment cost by at least 45.67% compared with the random-cut sectoring method and 8.24% compared with the BS clustering approach.

Acknowledgment

Supported by Visvesvaraya PhD Scheme, MeitY, Govt. of India, MEITY-PHD-1190.

References

[1] J. Nielsen, "Nielsen's Law of Internet Bandwidth," *URL http://www.nngroup. com/articles/law-of-bandwidth*, 2010.

[2] A. Osseiran *et al.*, "Scenarios for 5G mobile and wireless communications: the vision of the METIS project," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 26–35, 2014.

[3] R. El Hattachi and J. Erfanian, "NGMN 5G, NGMN Alliance," *White Paper, February 2015*.

[4] U. Siddique, H. Tabassum, E. Hossain, and D. I. Kim, "Wireless backhauling of 5G small cells: challenges and solution approaches," *IEEE Wireless Commun.*, vol. 22, no. 5, pp. 22–31, 2015.

[5] N. Wang, E. Hossain, and V. K. Bhargava, "Backhauling 5G small cells: A radio resource management perspective," *IEEE Wireless Commun.*, vol. 22, no. 5, pp. 41–49, 2015.

[6] R. E. Wagner *et al.*, "Fiber-Based Broadband-Access Deployment in the United States," *J. Lightwave Technol.*, vol. 24, no. 12, pp. 4526–4540, 2006.

[7] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, and Y. Ma, "Time- and Wavelength-Division Multiplexed Passive Optical Network (TWDM-PON) for Next-Generation PON Stage 2 (NG-PON2)," *J. Lightwave Technol.*, vol. 31, no. 4, pp. 587–593, 2013.

[8] S. Bindhaiq *et al.*, "Recent development on time and wavelength-division multiplexed passive optical network (TWDM-PON) for next-generation passive optical network stage 2 (NG-PON2)," *Opt. Switching Networking*, vol. 15, pp. 53–66, 2015.

[9] D. Nesset, "NG-PON2 technology and standards," *J. Lightwave Technol.*, vol. 33, no. 5, pp. 1136–1143, 2015.

[10] N. Alliance, "Small cell backhaul requirements," *White Paper, June 2012*.

[11] 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.

[12] B. Lakic and M. Hajduczenia, "On optimized passive optical network (PON) deployment," in *Second International Conference on Access Networks & Workshops*. IEEE, pp. 1–8, 2007.

[13] B. Jaumard and R. Chowdhury, "An efficient optimization scheme for WDM/TDM PON network planning," *Computer Communications*, vol. 36, no. 14, pp. 1539–1551, 2013.

[14] 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.

[15] T. Orphanoudakis *et al.*, "Exploiting PONs for mobile backhaul," *IEEE Commun. Magazine*, vol. 51, no. 2, pp. S27–S34, 2013.

[16] 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.

[17] J. Li and G. Shen, "Cost minimization planning for greenfield passive optical networks," *IEEE/OSA J. Opt. Commun. Networking*, vol. 1, no. 1, pp. 17–29, 2009.

[18] D. Cieslik, *"Steiner minimal trees"*. Springer Science & Business Media, vol. 23.

[19] J. Gupta and A. Adhya, "Clustering-based multi-hop protection scheme for long-reach passive optical network against single shared-risk link group failure," *Photonic Network Communications*, vol. 32, no. 3, pp. 372–385, 2016.