Effects of Optical Network Unit Placement Schemes for Multi-Channel Hybrid Wireless-Optical Broadband-Access Networks

Amitangshu Pal and Asis Nasipuri
Electrical & Computer Engineering, The University of North Carolina at Charlotte, Charlotte, NC 28223-0001
E-mail:{apal,anasipur}@uncc.edu

***Abstract-* Wireless-optical broadband-access networks (WOBAN) present a promising solution for meeting the growing customer demands in access networks. In this paper, we address the optimal placement of optical network units (ONUs) in a WOBAN to improve its performance and reduce the fiber cost. We propose a solution for ONU placement that employs a clustering technique to distribute the ONUs across the network, for a given distribution of wireless mesh routers. We also explore the effect of routing and channel assignment on top of the ONU placement schemes. Performance evaluations from simulations are presented.**

***Keywords:* Optical networks, Wireless mesh networks, Optical network unit, Clustering algorithm.**

I. Introduction

The wireless-optical broadband-access network (WOBAN) is a novel hybrid access network paradigm that consists of a high-capacity optical backhaul along with a highly flexible wireless front-end to provide high bandwidth network connectivity to mobile users in a cost effective manner. In a WOBAN, optical fibers are extended as far as possible from the telecom central office (CO), allowing the end users to access the network using a wireless front end. The WOBAN architecture has lower deployment costs because of reduced fiber costs in comparison to traditional passive optical networks.

In a WOBAN, the ONUs modulate the upstream data that are received from the wireless mesh routers to optical signals and transmit them to the optical line terminal (OLT). In the downstream direction, the optical signal is demodulated into wireless and transmitted to the mesh routers. Due to the broadcast nature of the wireless transmission, the network throughput of an WOBAN in the upstream direction is limited by wireless interference. Wireless interference can be minimized by selecting appropriate quality aware routing [1], [2], [3], [4] as well as effective channel assignment schemes [5]. Besides channel selection and routing, the placement of ONUs [6], [7], [8] in the network plays an important role in determining the performance of the network. In practice, the placements of wireless access points and routers are dictated by the need, as determined by the density and usage patterns of users in different regions of a deployment area. Here, we consider the problem of optimizing the placement of ONUs to serve a fixed set of mesh routers to minimize a performance cost metric. To achieve this, we propose a *cluster-based* scheme for ONU placement where ONUs are the cluster-heads and performance cost depends on the average distance between the mesh routers and their corresponding ONUs. Extensive simulations are conducted to evaluate the performance of the proposed clustering scheme in comparison with uniform-random ONU placement.

A key aspect of designing a WOBAN includes fiber deployment from OLT to the ONUs to form the optical backend. The planning for fiber deployment depends on the *passive optical networks* (PON) architecture, which can be based on a tree or ring topology. We also compare schemes for laying out fiber for tree and ring PON topologies and evaluate their cost comparison.

II. WOBAN Architecture and the Motivation Behind WOBAN

At the front end, a WOBAN consists of a multi-hop multi-radio wireless mesh network, while at the back end an optical access network provides connection to the Internet. At the back end the dominant technology is the passive optical network (PON) having OLTs located at the CO and optical network units (ONUs) that are connected to the wireless gateways routers. The PON interior elements are basically passive combiners, couplers and splitters. Since no active elements exist between the OLTs and the ONUs, PONs are considered as robust networks because of it's cost-effectiveness and power efficiency.

In the wireless infrastructure, standard WiFi and WiMAX technology can be used for wireless mesh networks. The subscribers, i.e. the end-users (also known as mesh clients) send packets to their neighborhood mesh routers. The mesh routers inject packets to the wireless mesh of the WOBAN. The mesh routers can reach any of the gateways/ONUs through multi-hop routing. Thus in upstream direction (mesh routers to ONUs), the routing is basically anycast and in the downstream direction (ONUs to mesh routers), the routing is unicast as traffic is sent from an ONU to a particular mesh router only. The gateways/ONUs can be strategically placed over a geographic region to better serve the wireless users. The WOBAN architecture is depicted in Fig 1.

The advantages of WOBAN can be summarized as follows:

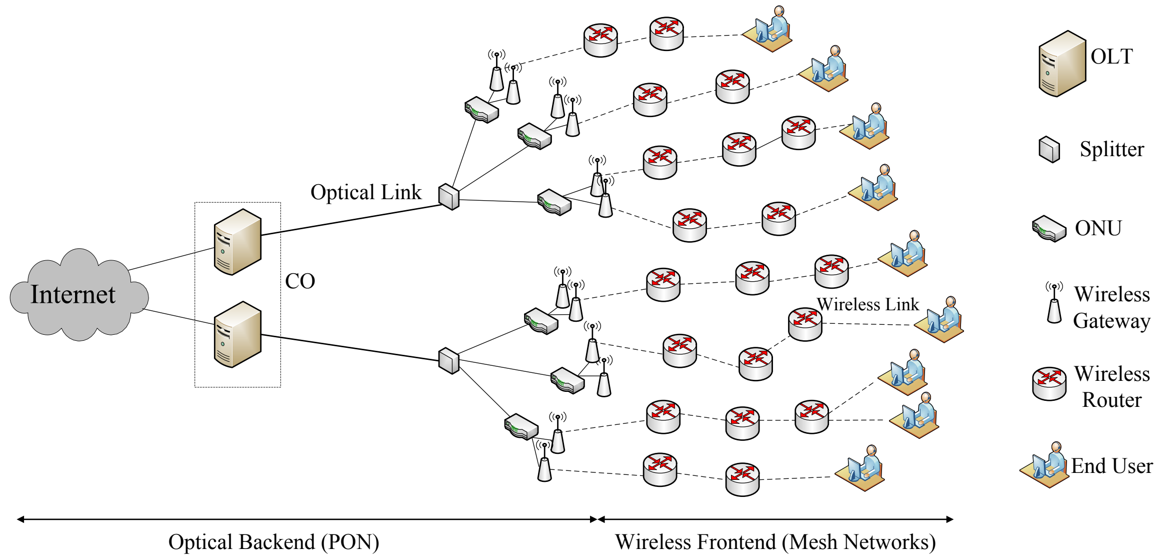

Fig. 1. Architecture of a *WOBAN*.

- A WOBAN can be very cost effective in comparison to PONs, since a WOBAN does not require fibers to be penetrated to all subscriber's homes, premises, or offices.
- The wireless mesh architecture provides a more flexible wireless access to the users compared to optical access networks. This is particularly important in highly populated areas as well as in rugged environments where it is difficult to deploy optical fibers and equipments.
- The self-healing nature of the wireless front end makes a WOBAN more robust and fault tolerant than traditional a PON. In traditional PON, a broken fiber link between the splitter and an ONU or between the splitter and the OLT makes some or all of the ONUs disconnected from OLT. In WOBAN, the traffic disrupted by any failure on a fiber link can still be forwarded through the wireless mesh routers using multi-hop routing to other ONUs and then to the OLT.
- WOBAN enjoys the advantages of anycast routing. If one gateway is congested, a wireless router can route it's traffic through other gateways. This reduces load and congestion on one gateway and gives WOBAN a better load-balancing capability.
- WOBAN has much higher bandwidth capacity compared to the low capacity wireless networks, which reduces the traffic congestion, packet loss rate as well as end-to-end packet delay.

However, maximizing the performance of a WOBAN involves several issues that includes design of efficient routing protocols for the mesh routers to communicate with the ONUs, ONU/gateway selection for anycast routing, channel assignment in multi-channel multi-radio WOBAN as well as optimum ONU placement across the network area. In this paper, we mainly focus on ONU placement problem in an WOBAN under an assumed distribution of the mesh routers. Developing a proper ONU placement scheme is important as it is hard to move the ONUs and connected fibers after deployment. While planning for a network setup, the network architects need to know the peak demands of the customers in a geographic area. A typical example is an academic campus, where office buildings, living areas and lobby areas will be crowded by users for getting Internet access. The ONU placement scheme needs to be developed based on the peak demands and the known distribution of corresponding mesh routers to meet the demands.

III. ONU Placement Scheme

Our objective is to place the ONUs in a geographic area (such as in a college campus or in a residential area) with the assumption that the location of the wireless mesh routers $(MR_1, MR_2, ..., MR_V)$ are known. Let us assume that the locations of the ONUs are given by (X_i, Y_i), $i \in (1, 2, ..., U)$, and the locations of all the routers are given by (x_j, y_j), $j \in (1, 2, ..., V)$. We develop a clustering scheme for ONU placement which is described as follows.

The ONU placement problem is to divide the network into U clusters and place the ONUs in the centroid of the cluster routers so that the distance between each ONU and its corresponding routers is minimized. This problem is basically same as *minimum sum-of-squares clustering (MSSC) problem*. The MSSC problem is to partition a given set of n entities into k clusters in order to minimize the sum of squared distances from the entities to the centroid of their clusters. A mathematical programming formulation of MSSC is as follows:

$$Minimize \sum_{i=1}^{V} \sum_{j=1}^{U} w_{ij} \{(X_i - x_j)^2 + (Y_i - y_j)^2\} \quad (1)$$

subject to

$$\sum_{j=1}^{U} w_{ij} = 1 (1 \leq i \leq V) \quad (2)$$

$$w_{ij} = 0 \text{ or } 1 \ (1 \leq i \leq V) \ (1 \leq j \leq U) \quad (3)$$

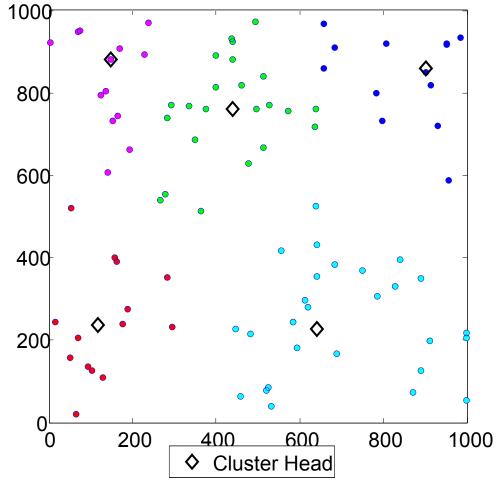

Fig. 2. The placement of ONUs in a random distribution of mesh routers.

where w_{ij} is a binary variable which is 1 if ONU_i is assigned to cluster j and 0 otherwise. The MSSC problem is shown to be a *NP-hard* problem in [9]. A number of approximation algorithms for MSSC are reported in [10]. Here, we propose a heuristic to solve this problem.

Proposed clustering scheme for ONU Placement: In this section we discuss our propose clustering scheme for ONU placement. First, we need to find how many ONUs are required to satisfy the demands of all users. If the peak demand of the whole network is D and each ONU can serve a demand of d then the number of ONU required is $U = \frac{D}{d}$. Now, we propose a greedy algorithm to place these U ONUs. We describe this with the help of Fig. 2. In Fig. 2, there are $V = 100$ routers and $U = 5$ ONUs. Our idea of choosing ONU locations is mainly based on *k-means clustering* technique. At first, an initial set of U locations are generate randomly, these points are denoted by $m_1^{(1)}, m_2^{(1)}, ..., m_U^{(1)}$ (the superscripts (1) corresponds to initial position). The algorithm consists of two steps:

- *Assignment phase:* In this phase, the routers are assigned to their closest ONUs, i.e. an ONU and its corresponding routers are in one cluster (this is basically partition the routers according to the *Voronoi diagram* generated by the ONUs. Mathematically, if a router V_j (the position of V_j is denoted by vector x_j) is in cluster $S_i^{(t)}$ in the t-th iteration then

$$S_i^{(t)} = \{x_j : \|x_j - m_i^{(t)}\| \leq \|x_j - m_{i^*}^{(t)}\| \quad \forall i^* = 1, 2, ..., U\} \tag{4}$$

- *Update phase:* In this stage, the new ONU position of cluster i are calculated by taking the mean of all the router-positions, i.e.

$$m_i^{(t+1)} = \frac{1}{|S_i^{(t)}|} \sum_{x_j \in S_i^{(t)}} x_j \tag{5}$$

The *Assignment* and *Update* phase is repeated until the solution converged, i.e. the coordinates of the ONUs no longer change.

The algorithm is repeated a large number of times with different random ONU positions and the best solution is taken at last. A pseudocode is shown in Algorithm 1.

Algorithm 1 ONU placement scheme

1: INPUT : ONU=set of ONUs; MR=set of mesh routers; (x_j, y_j)=position of the j-th mesh router
2: OUTPUT : the placement of the ONUs
3: Generate U ONU locations randomly
4: **while** Solution does not converge **do**
5: Assign the routers to the nearest ONU // Assignment phase
6: Put ONUs at the mean of all router-positions // Update phase
7: **end while**
8: Repeat step 3-7 for a large number of time and take the best solution

Fiber deployment from OLT to the ONUs: After the positions of the ONUs are identified, the OLT and the ONUs need to be connected using optical fiber. Depending on the network planning, in the optical backend the OLT and the ONUs can be connected using a tree topology or a ring topology. In case of a tree topology, a *minimum spanning tree* is constructed to connect the OLT and the ONUs. The reason behind using the minimum spanning tree is to minimize the length of the fiber needed, thus the cost of deployment is also minimized. In case of a ring architecture, the laying out of fiber with minimum length can be modeled as a *travelling salesman problem (TSP)*. TSP can be defined as follows: given a list of cities and the distances between each pair of cities, we need to find the shortest possible route that visits each city exactly once and returns to the origin city. TSP is typical NP-hard problem. In our case the position of the OLT and the ONUs can be thought as the cities and the shortest possible route gives the minimum fiber needed.

IV. Performance Study

In this section we compare the performance of our ONU placement scheme along with the random placement scheme using *network simulator–2 (ns2)* [11] simulator with IEEE 802.11 MAC, with substantial modifications in the physical and the MAC layers, to model the cumulative interference calculations and also include the physical carrier sensing based on cumulative received power at the transmitter. The *DataCapture* is also modeled in our modified *ns-2* version. Next we extend *ns-2* to support multiple channels and multiple radios as described in [12]. We also compare the effects of these ONU placement schemes on minimum hop-count routing in the upstream direction of the WOBAN. The effects and benefits of using multiple channels are also explored. The amount of total fiber required for designing the PON backend is also calculated. We consider two different network topologies based on the distribution of mesh routers. In the first case, we distribute the mesh routers uniformly in an area of 1000×1000 square meters as shown in Fig. 3. In the second case, we simulate our ONU placement, routing and channel assignment scheme where the distribution of the mesh routers is non-uniform. This is modeled by considering a bivariate Gaussian distribution of routers that are centered at four specific locations in the region, as depicted in Fig. 8. The

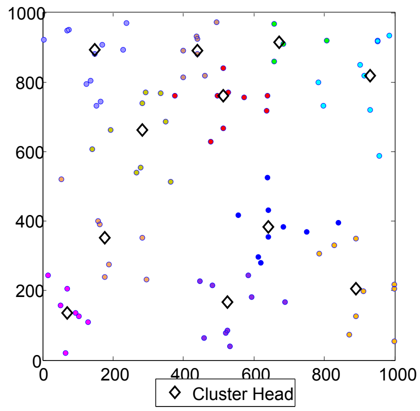

Fig. 3. The placement of eleven ONUs with cluster-heads where mesh routers are uniformly distributed.

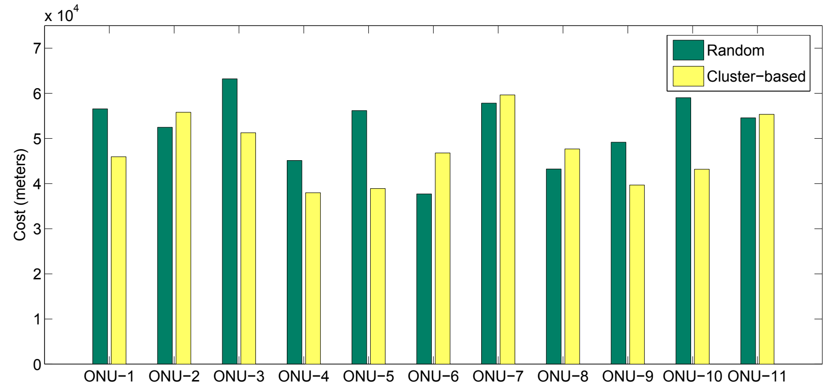

Fig. 4. Costs of different ONUs for random placement and clustering-based schemes where mesh routers are uniformly distributed.

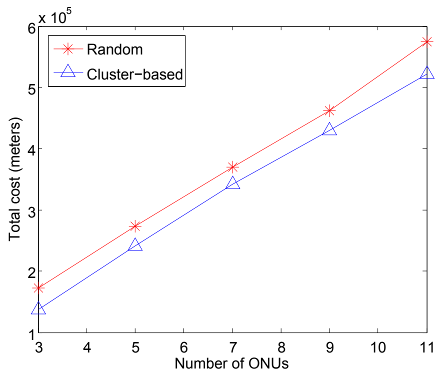

Fig. 5. Comparison of overall cost for random placement and clustering-based schemes for uniform distribution of mesh routers.

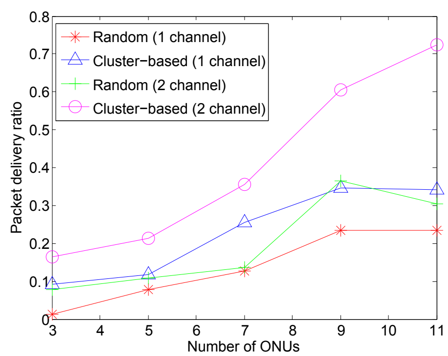

Fig. 6. Comparison of delivery ratio with different number of ONUs for random placement and clustering-based schemes for uniform distribution of mesh routers.

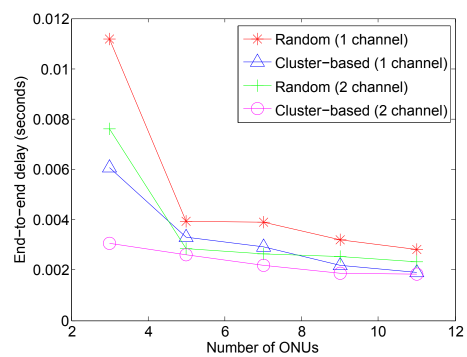

Fig. 7. Comparison of end-to-end delay with different number of ONUs for random placement and clustering-based schemes for uniform distribution of mesh routers.

transmission power is assumed to be 20 dBm for all cases. All the mesh routes generate traffic at a rate of 15 KBps which are carried to the ONUs using multi-hop communications based on shortest hop-count routes. Each flow runs UDP and is alive for 140 seconds. The parameters used in the simulations are listed in Table I.

TABLE I
SIMULATION ENVIRONMENT

Parameter	Values	Parameter	Values
Max queue length	200	Data packets size	1000 bytes
Propagation Model	Two Ray Ground	Traffic Generation	Exponential
Antenna gain	0 dB	Transmit power	20 dBm
Noise floor	-101 dBm	SINRDatacapture	10 dB
Bandwidth	6 Mbps	PowerMonitor Thresh	-86.77 dBm
Modulation scheme	BPSK	Traffic Generation	Exponential

Performance evaluation on uniformly distributed mesh routers: Fig. 3 shows the placement of eleven ONUs in a geographic area comprising of uniformly distributed mesh routers. Fig. 4 shows the costs of the ONUs in case of random (uniformly) ONU placement scheme and clustering scheme. The cost of the ONU$_i$ is defined as follows:

$$C_{ONU_i} = \sum_{j=1}^{V} \sqrt{(X_i - x_j)^2 + (Y_i - y_j)^2} \qquad (6)$$

From Fig. 4, we can observe that the clustering scheme improves the cost of most of the ONUs, compared to random placement scheme. Fig. 5 shows the variation of overall cost with the number of ONUs for both random placement and clustering schemes. It is observed that the clustering scheme generates a significantly lower cost in comparison to the random placement scheme.

We also compare the effects of ONU placement on routing when multiple orthogonal channels are used. Here we consider routing in upstream direction, i.e. from the mesh router to any one of the ONUs (anycast routing). We consider minimum hop-count based routing. The minimum hop-count routes are calculated from each mesh router to all the ONUs. Then the ONU with the minimum hop is chosen as the best ONU for that mesh router as well as the corresponding route. We use Dijkstra's shortest path algorithm for deciding the minimum hop-count path. After the routes are decided, the channels are assigned to the links as follows. The links are sorted in the

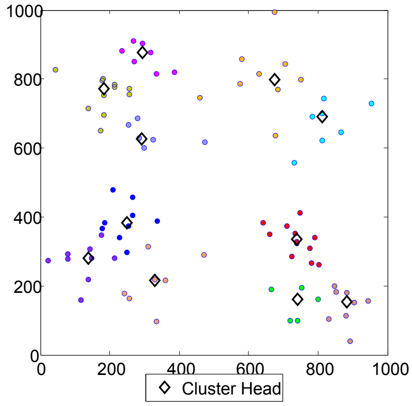

Fig. 8. The placement of eleven ONUs with cluster-heads where mesh routers are non-uniformly distributed.

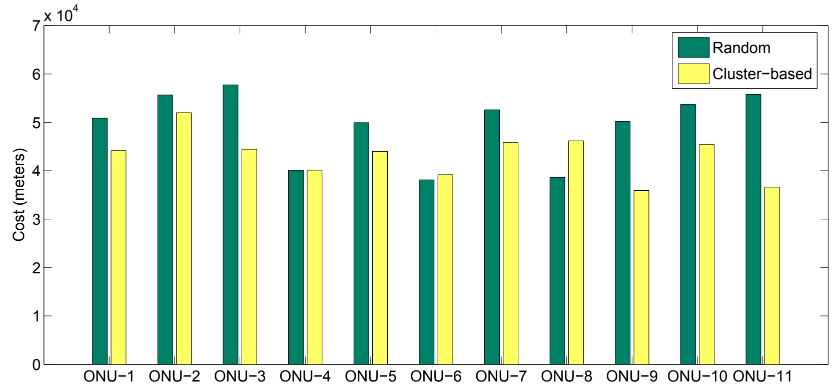

Fig. 9. Costs of different ONUs for random placement and clustering-based schemes where mesh routers are non-uniformly distributed.

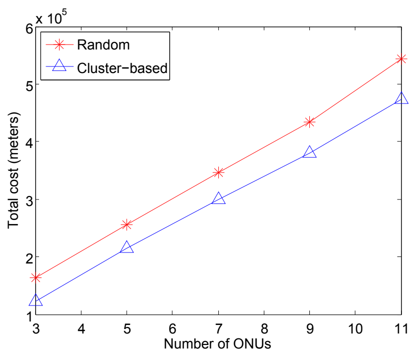

Fig. 10. Comparison of overall cost for random placement and clustering-based schemes for non-uniform distribution of mesh routers.

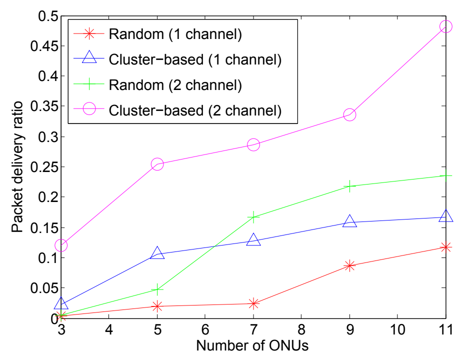

Fig. 11. Comparison of delivery ratio with different number of ONUs for random placement and clustering-based schemes for non-uniform distribution of mesh routers.

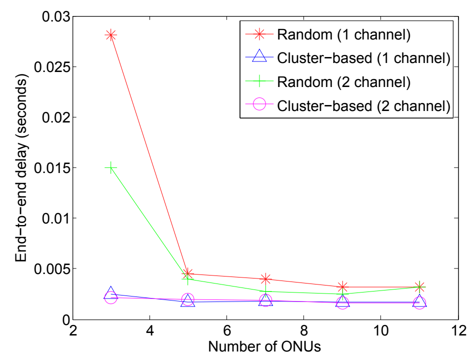

Fig. 12. Comparison of end-to-end delay with different number of ONUs for random placement and clustering-based schemes for non-uniform distribution of mesh routers.

decreasing order of their interfering load. Then channels are assigned to the links one-by-one as the least used channel in their interfering neighborhood. In case of a tie, a random channel is chosen among the channels that make the tie.

Fig. 6 shows the variation of packet delivery ratio with the number of ONUs. From this figure we can observe that the delivery ratio increases with the increase in number of ONUs. This is because the increase in ONUs results in reduced route length as well as traffic load on each link, which results in better route quality as well as delivery ratio. Fig. 7 shows variation of end-to-end delay with the number of ONUs. We can observe that the delay decreases with the increase in ONUs due to reduced route length and less channel access delay due to less traffic load on each link. We can also observe that the clustering scheme performs better compared to the random ONU placement scheme, which shows the effectiveness of our proposed scheme. Also we can observe that the delivery ratio is improved in case of two channels because of reduced interference due to the presence of multiple channels, whereas the reduction in delay is mainly due to reduction in channel access delay from using multiple channels in neighbouring transmitting nodes.

Performance evaluation on non-uniformly distributed mesh routers: Now we consider the case of ONU placement on a more realistic scenario, where the mesh routers are non-uniformly distributed as shown in Fig. 8. Fig. 9 and Fig. 10 show the improvement of cost in case of clustering scheme compared to the random placement scheme. The performance of packet delivery ratio and end-to-end delay are shown in Fig. 11 and Fig. 12, respectively. Comparing Fig. 6- 7 and Fig. 11- 12, we observe that the delivery ratio as well as the end-to-end delay experience higher improvements under uniform distributions of routers in comparison to the non-uniform case. This is because, in case of non-uniform distribution, the mesh routers are confined in few areas. This makes those areas more congested which results in more interference and access delay, which in turn reduces delivery ratio and increases the end-to-end packet delay. On the other hand in case of uniform distribution of mesh routers, the traffic is uniformly distributed, which results in improved delivery ratio and end-to-end delay.

Comparison of total required fiber for tree and ring topology at the optical backend: Depending on how the OLT and the ONUs are connected using optical fiber, the required fiber length will be different as well as the total deployment cost. Fig. 13- 14 show the network topology for uniform and non-uniform distribution of mesh routers respectively, where the minimum spanning tree is constructed joining the OLT and the ONUs to ensure the minimum fiber cost. The position of

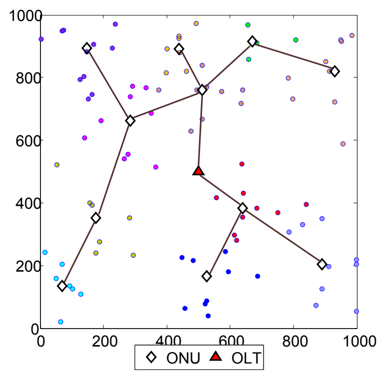

Fig. 13. Fiber layout using minimum spanning tree for uniform distribution of mesh routers.

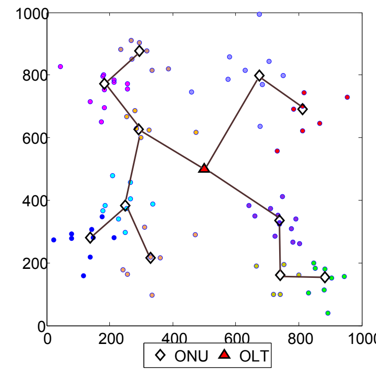

Fig. 14. Fiber layout using minimum spanning tree for non-uniform distribution of mesh routers.

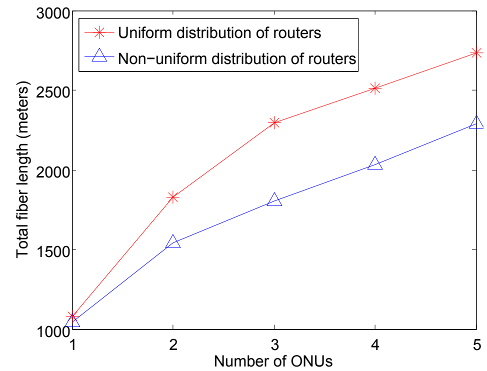

Fig. 15. Comparison of total fiber length required for tree PON architecture for uniform and non-uniform distribution of mesh routers.

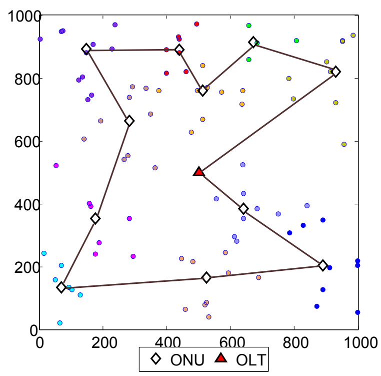

Fig. 16. Fiber layout by solving the travelling salesman problem for uniform distribution of mesh routers.

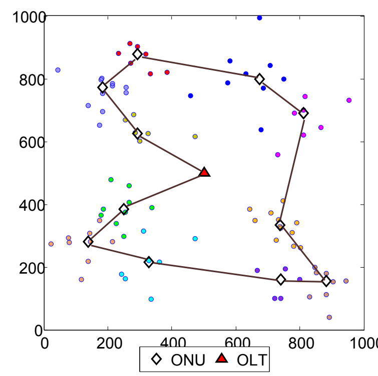

Fig. 17. Fiber layout by solving the travelling salesman problem for non-uniform distribution of mesh routers.

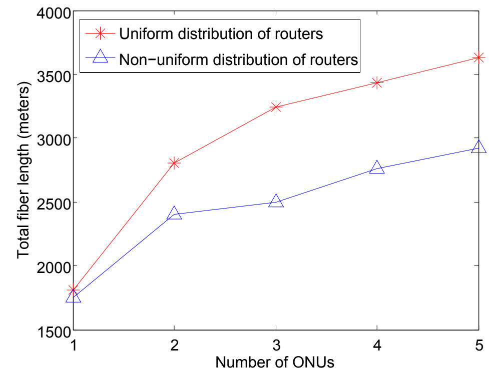

Fig. 18. Comparison of total fiber length required for ring PON architecture for uniform and non-uniform distribution of mesh routers.

the OLT is assumed to be (500, 500). Fig. 16- 17 depict of case of a ring topology where the fiber layout is done by solving the travelling salesman problem. For solving the TSP, we derive all the possible *Hamiltonian cycles* of the graph constructed by OLT and the ONUs and then choose the shortest cycle to minimize the fiber deployment cost. Fig. 15 and Fig. 18 show the total fiber required for both tree and ring topology with different distribution of mesh routers. These figures clearly show the amount of extra fiber required for the ring topology compared to the tree PON architecture.

V. Conclusion

In this paper, we study the ONU placement problem in WOBAN which aims to minimize some cost function. We propose a clustering technique to solve the problem of ONU placement and compare its benefits compared to the random ONU placement scheme in improving the network quality. We also studied the effects of number of ONUs as well as well as the effects of routing and multiple channels on the overall network packet delivery ratio and end-to-end packet delay. We also explain different PON architectures and their corresponding fiber layout schemes along with their deployment cost comparison.

References

[1] A. Pal, S. Adimadhyam, and A. Nasipuri, "QoSBR: A quality based routing protocol for wireless mesh networks," in *ICDCN*, 2010, pp. 497–508.

[2] A. Pal and A. Nasipuri, "A quality aware anycast routing protocol for wireless mesh networks," in *IEEE SoutheastCon*, 2010, pp. 451–454.

[3] A. Pal and A. Nasipuri, "A quality based routing protocol for wireless mesh networks," *Pervasive and Mobile Computing*, vol. 7, no. 5, pp. 611–626, 2011.

[4] A. Pal and A. Nasipuri, "GSQAR: A quality aware anycast routing protocol for wireless mesh networks," in *IEEE GLOBECOM*, 2010.

[5] A. Pal and A. Nasipuri, "JRCA: A joint routing and channel assignment scheme for wireless mesh networks," in *IEEE IPCCC*, 2011.

[6] S. Sarkar, B. Mukherjee, and S. Dixit, "Optimum placement of multiple optical network units (ONUs) in optical-wireless hybrid access networks," in *Optical Fiber Communications*, 2006.

[7] S. Sarkar, B. Mukherjee, and S. Dixit, "Towards global optimization of multiple ONUs placement in hybrid optical-wireless broadband access networks," in *COIN, Jeju, Korea*, 2006.

[8] S. Sarkar et. al, "A mixed integer programming model for optimum placement of base stations and optical network units in a hybrid wireless-optical broadband access network (WOBAN)," in *Wireless Communications and Networking Conference, Hong Kong*, 2007.

[9] D. Aloise, A. Deshpande, P. Hansen, and P. Popat, "NP-hardness of euclidean sum-of-squares clustering," *Mach. Learn.*, vol. 75, pp. 245–248, May 2009.

[10] P. Hansen and D. Aloise, "A survey on exact methods for minimum sum-of-squares clustering," `http://www.math.iit.edu/Buck65files/msscStLouis.pdf`.

[11] "The netwrok simulator ns-2," `http://www.isi.edu/nsnam/ns/`.

[12] "Multi-channel multi-interface simulation in ns2," `http://www.cse.msu.edu/ wangbo1/ns2/nshowto8.html`.