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A Novel Adaptive Router Placement Scheme in Hybrid Wireless Optical Access Network

F. Mousavi Madani
Dept. of Computer Eng.Faculty
of Engineering Alzahra University
Tehran, Iran,
mosavif@alzahra.ac.ir

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***Abstract*— A typical wireless optical network takes advantage of passive optical network (PON) architecture in the back-end for last-mile broad-band connectivity combined with wireless mesh network at the front-end to provide high-quality cost-effective Internet access to end users. Wireless gateway routers collect upstream traffic from end-user devices within their transmission range and route them toward a nearby optical network unit (ONU) station and vice versa in the downstream direction. A major objectives of planning wireless optical networks is to place ONUs and wireless routers (WRs) in such a way to fully cover all end-users with minimum deployment cost while ensuring some quality metrics, such as delay or throughput. Computational complexity of mathematical formulations presented in previous works, restrains from scaling the network size and user population in accordance with the realistic circumstances. In this paper, we address this issue by introducing a novel adaptive segmentation scheme to offload the problem complexity without sacrificing the optimality of solution. Extensive numerical simulations verified the applicability of our approach to large-scale networks.**

Keywords-component; FiWi network, WOBAN, Router placement.

I. INTRODUCTION

The surge of emerging bandwidth-hungry user applications in recent years, has accelerated the need to design broad-band "last-mile" access network. Dominant networking applications tend to include media-rich services such as high-definition television (HDTV), video on demand (VoD), voice over IP (VoIP), multimedia conferencing, multiplayer online gaming, online content generation, and consumer-oriented cloud computing solutions. Today, passive optical network (PON) is widely adopted as a preferable access technology due to its excellent bandwidth capacity and robustness, which provides to end-users far higher bandwidths than DSL or CATV solutions. However, PON ceases to support "anywhere-anytime" access to Internet, and entails high deployment and maintenance costs. On the contrary, wireless access networks such as WiFi and WiMax can offer promising solution to flexibility and ease of deployment. However, scarce radio spectrum eventually limit their bandwidth capacity far less than PON. Consequently, the convergence of the wireless and optical access technologies, is likely to merge their innate benefits into hybrid wireless-optical broad-band access network (WOBAN) that can meet versatile performance requirements of future Internet services. A typical architecture of WOBAN comprises multi-segments of wireless mesh networks (WMNs) at front-end and PONs at the back-end. The wireless gateway at each segment is combined into optical network unit (ONU) that acts as the interface between wireless front-end and optical back-end. Users within the coverage area of a WMN are connected to the optical line terminal (OLT) via the WMN and the PON. In the upstream direction, OLT routes traffic multiplexed from ONUs across backbone infrastructure, while in the downstream direction, OLT broadcasts incoming traffic toward ONUs. Figure 1 shows typical architecture of a WOBAN.

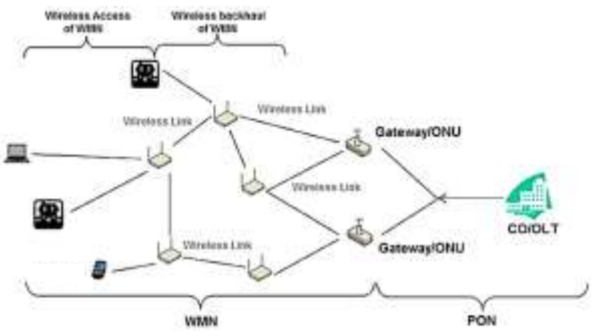


Fig. 1. An example arcitecture of a FiWi network

II. RELATED WORK

Authors of [1] proposed and implemented a WMN-SA system based on Simulation Annealing (SA) approach to deal with the node placement problem in WMNs. They considered 3 different realistic distributions of 48 and 96 mesh clients in a 32×32 and 64×64 grid sizes, and then deployed 16 and 32 mesh routers and applied SA, to maximize the number of covered mesh clients. Authors of [2] have studied the rechargeable router placement problem for a green mesh network. The problem was formulated as an optimization heuristic with the objective of minimizing the number of deployed routers, while ensuring QoS requirements on wireless coverage, traffic demand, energy efficiency and user fairness. They setup a simulation model based on a rectangular field with size of 160×120 (m^2) in which a number of mesh clients were uniformly distributed. The field was evenly partitioned into several grid cells of equal area, and the centers of the grid cells were candidate locations for placing routers. Due to the limitation posed by computation complexity, they considered a field with 3×4 grids. Various algorithms are proposed in the literature for ONU placements with the consideration of internet and p2p traffic [3-6]. All algorithms, divide the network into multiple non-overlapping regions. In random approach the ONUs are placed randomly in each region. In deterministic approach, the ONUs are placed in center points of each grid. Both approaches are not suitable for ONU placement because it does not provide proper connectivity in the network. In greedy approach, first, ONUs are placed in center points and according to minimum distance of ONU from the end users, primary ONUs are identified for all users. Authors of [7] proposed a cost-efficient algorithm for ONU placement that works in two stages. In first stage, they formed a set of WRs in a grid with their corresponding ONU. Then, they removed ONUs from empty grids. In the second stage, they further minimize the ONUs by removing those ONUs from the network whose all the wireless routers are in transmission range of other ONUs.

The rest of the paper is organized as follows. Section III presents a load-balanced ILP formulation for WR placement problem followed by the proposed grid segmentation and cell splitting algorithms. The performance of the proposed schemes are numerically evaluated in Section IV. Finally, Section V concludes the paper.

III. ROUTER PLACEMENT PROBLEM

Given a set of end users (x, y) coordinates scattered around a geographical area, their associated traffic loads, transmission range of wireless router, and maximum bandwidth (BW) of wireless link, the router placement problem seeks to deploy the optimum locations of wireless routers (WRs), among a set of preset potential locations, that provides full coverage with the least number of WRs. The optimization problem can formally be formulated as an integer linear programming (ILP) model.

A. Notations

N_{gr} : The square grid size for a given FiWi network. A wireless router can be placed at the center point of a grid cell.

m : The index of grid cell, $m \in \{1,2,3,\dots,N_{gr}\}$.

N_{eu} : Total number of end users in wireless front-end.

n : The index of the end user located within the grid, $n \in \{1,2,3,\dots,N_{eu}\}$.

g_m : The m^{th} numbered grid cell.

r_m : The WR located at the center point of grid cell g_m.

eu_n : The n^{th} numbered end user.

$l(eu_n)$: Traffic load of the end user eu_n.

$D_{m,n}$: Physical distance between end user eu_n and WR r_m.

CL : Constraint of WR load-balancing.

CLR : Maximum load carrying capacity of WR.

CD : Maximum distance between an end user and a WR (i.e. transmission range of WR).

B. Variables

δ_m : A binary variable, taking 1 if a WR is placed at the center point of grid cell m, 0 otherwise.

$\eta_{m,n}$: A binary variable, taking 1 if user eu_n is the subordinate user of WR r_m, 0 otherwise.

$l(r_m)$: Traffic load of WR r_m, which is equal to the total traffic load of its subordinate end users.

l_{max} : The maximum WR traffic load, $l_{max} = \max_m l(r_m)$.

l_{min} : The minimum WR traffic load, $l_{min} = \min_m l(r_m)$.

C. Objective Function

$$\text{Minimize } \sum_{m=1}^{N_{gr}} \delta_m \quad (1)$$

D. Constraints

$$l(r_m) = \sum_{n=1}^{N_{eu}} \eta_n^m l(eu_n) \le CLR, \quad \forall m \quad (2)$$

$$l_{max} - l_{min} \le CL \quad (3)$$

$$l_{max} = \max_{\forall m} l(r_m) \quad (4)$$

$$l_{min} = \min_{\forall m} l(r_m) \quad (5)$$

$$\sum_{m=1}^{N_{gr}} \eta_n^m \left(CD - D_{m,n}\right) \ge 0, \quad \forall n \quad (6)$$

$$N_{eu} \cdot \delta_m \ge \sum_{n=1}^{N_{eu}} \eta_n^m, \quad \forall m \quad (7)$$

$$\sum_{m=1}^{Ngr} \eta_n^m = 1, \quad \forall n \tag{8}$$

$$\eta_n^m, \delta_m \in \{0,1\}, \quad \forall m, n \tag{9}$$

The objective defined in Equation 1 is to minimize the number of required WRs. Equation 2 builds up traffic load of each WR by aggregating traffic loads of subordinate end users. Equation 3 uses the maximum and minimum WR load values provided by Equations 4 and 5, respectively, to force the limit CL of load-unbalancing. It should be noted here that although lower CL values are desirable from network design standpoint, too low CL may inhibit us from attaining full coverage rate, since there may be some outlier user with low traffic load that should be supported by a separate WR. Equation 6 states that a user can be supported by a WR if and only if it is located within the transmission radius of that WR. Equation 7 implicates a WR should be placed at a grid cell centre if it supports at least one user. Equation 8 declares that every user should be supported by exactly one WR, and finally Equation 9 defines $\eta_{m,n}$ and δ_m as binary variables.

Most of published works on WR placement consider a mesh of potential WR locations, stabilized at center points of square grid cells of equal size. When the model is going to be examined in the first attempt, the initial grid is simply set to a $N_{gr} = 1 \times 1$ large grid cell. If a valid solution cannot be found, grid size is incremented by one along each dimension. So the sequence of $N_{gr} = 2 \times 2, 3 \times 3, \dots, n \times n$ grid sizes are examined at each subsequent iteration, until a valid solution can be found finally. We distinguish this classic approach by the abbreviation CG-FCP-UCS to represent a contiguous-grid (CG) of elementary square cells with fixed-cell positions (FCP) and uniform cell sizes (UCS), where a potential WR may be placed at the center of an elementary grid cell. Obviously, the size of ILP model in classic approach grows with $O(n^2)$ where n is the number of grid cells in each row or column. Exponential expansion of the problem size makes this strategy soon become computationally intractable, thereby severely restricts its applicability to small-size geographical areas, typically in the order of several hundred square-meters. One may suggest scaling-down the problem by dividing a large FiWi network into small-size sub-grids and solve WR placement problem for each of them individually. This approach, however, leads to an over-provisioned WR placement around sub-grid borders, where the optimality gap tend to be exacerbated in densely populated regions. In the following subsections, four alternative strategies to enhance both the scalability and computational efficiency of the classic CG-FCP-UCS strategy are introduced. Each strategy tries, in a different manner, to prepare a minimal set of potential WR locations prior to launching the ILP engine, via a two phase discipline. Two different approaches are devised for each phase that evolve to four different strategies when combined together.

As a departure step, we note that the naïve assumption of uniform distribution of end users across FiWi network seems far from realistic situation in urban area, where plenty of vacant districts as well as highly condensed residential complexes are scattered around. So instead of solving for a large contiguous grid, the problem can be decomposed to several islands of grid fragments that can be solved separately without affecting the optimality of the solution.

Phase 1: Grid Segmentation

Let us first introduce how a segmented-grid with fixed-cell positions (SG-FCP) can be generated. We assume that, without loss of generality, the initial square area can be partitioned into a grid of *base cells* as shown in Figure 2. A base cell is defined as the largest square zone that can be fully covered by a WR placed at its center point. As depicted in Figure 3, for the cell width of $2CD$, some user may left out of the WR coverage, but the cell width set equal to $\sqrt{2}CD$ ensures that all users in the cell are covered by the central WR. Next, non-vacant base cells are marked and neighboring cells are grouped into one segment. Two adjacent cells are neighbor if they have one common side. Therefore, a segment includes a group of base cells, where each one has at least one common side with another member. Figure 4 illustrates how a segmented initial area into several islands of sub-areas may look like.

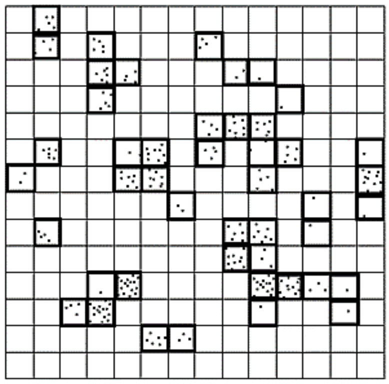


Fig. 2. A grid of base cells

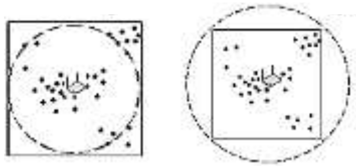


Fig. 3. Correct size of the base cell

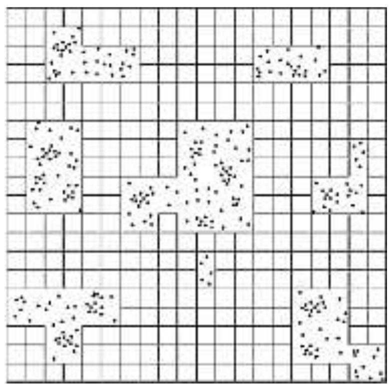


Fig. 4. Segmentation of a large area into smaller grid segments

The SG-FCP segmentation scheme, as the name implies, is constructed with a constellation of fixed position cells. It is very likely, however, that a group of end users concentrates near the border of two neighbouring cells can be fully covered by a WR placed at the centre of a merged rectangle, rather than by two separate WRs placed at the centres of neighbouring cells. So a grid-segmentation scheme with adaptive cell positions (SG-ACP) is proposed next to address this issue. The main steps of SG-ACP algorithm is schematically sketched in Figure 5. Hereinafter, we refer to square grid cell simply as "cell" and a merged combination of two neighbouring cells as "rectangle". Also, the term "sub-area" indicate either "cell" or "rectangle". Starting from the initial square area, set as the parent cell, it works by first checking if a single central WR can cover all end users in the parent cell. If so, it is added to the set of temporary candidate sub-areas (TempCandSubAreas()) and then goes on to phase 2. If not, it goes ahead by calling TrimCell() function, (see Figure 6) that splits the parent cell into four equal child cells, and trims the parent cell off the vacant cells. Figure 7 below shows two sample trimming of a parent cell.

The Next step calls SetTempCandSubAreas() function that takes child cells as input and constructs first, all possible merged rectangles. It examines all possible non-overlapping arrangements of sub-areas next, as shown for an example child cells of Figure 8, to recognize and enumerate the covered and uncovered sub-areas of each arrangement. The one arrangement which provides the largest covered sub-areas with the least number of covering WRs is selected (see Figure 9). Uncovered cells are put into the set of temporary parent cells (TempParentCells()) to be further split in the next round. Covered sub-areas and their associated tags are stored in TempCandSubAreas().

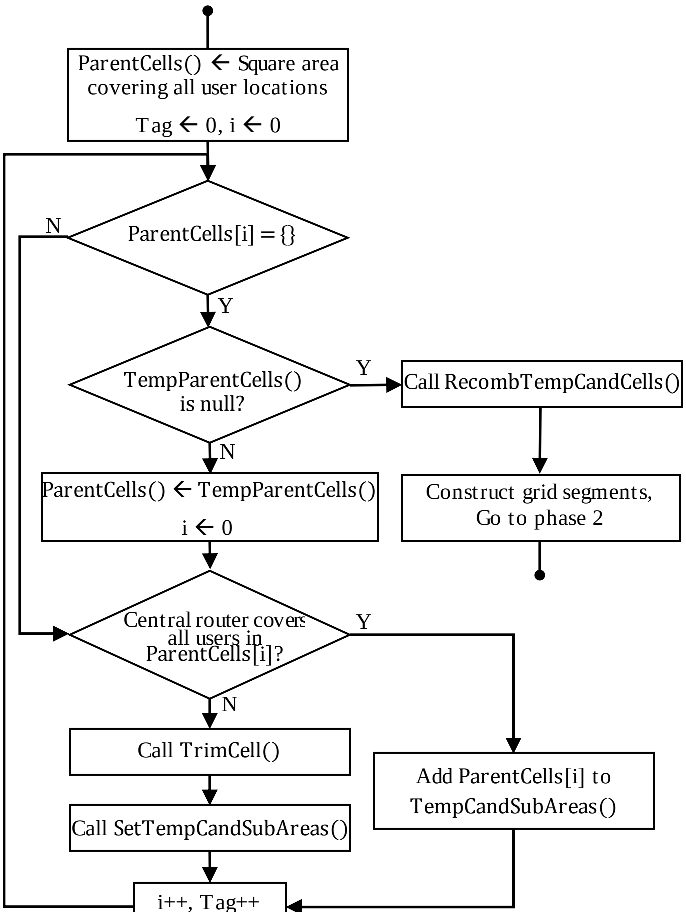


Fig. 5. Main steps of SG-ACP algorithm

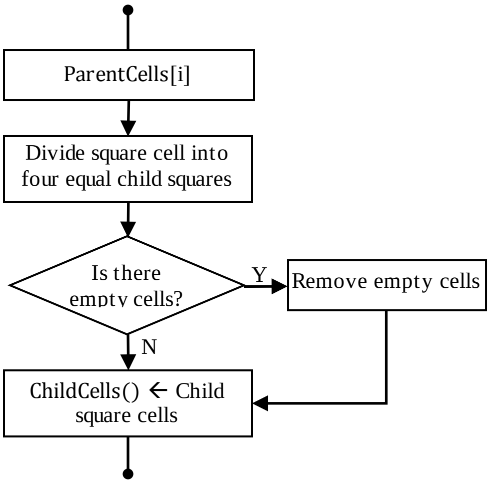


Fig. 6. Main steps of function TrimCell()

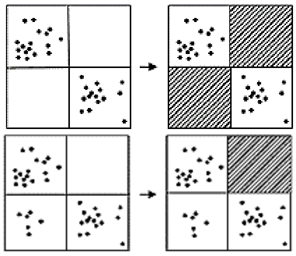


Fig. 7. Trimming a parentcell from empty cells

Since no other parent cell is left off at the end of first round, the second round now takes turns starting from a new set of parent cells (previously uncovered cells) and the process cycles until no uncovered sub-area remains. Though, at this stage, the layout of grid segments and the associated potential WR locations can be completely specified, further reduction in the number of WR locations would be attained if some pairs of child base cells belonging to different parent cells can be merged together into a covered rectangle. For this end, the function RecombTempCandCells() is invoked just before exiting phase one. In the first pass of inspecting temporary candidate sub-areas, all rectangular sub-areas are trimmed off to square base cells with their centres remain the same (see Figure 10). The second pass examines all base ells in TempCandSubAreas() one-by-one to explore the existence of a neighbouring base cell with different tag (i.e. belonging to two different parent cells). If so, and the coverage of the merged rectangle is also verified, then both cells are removed from TempCandSubAreas() and the new merged cell is added to CandBaseCells() (see Figures 11 and 12).

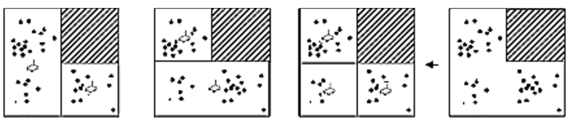


Fig. 8. Figuring out covered and uncovered sub-areas

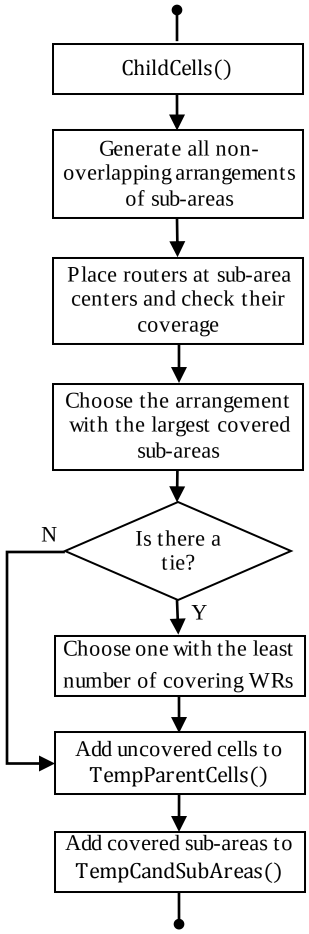


Fig. 9. Main steps of function SetTempCandSubAreas()

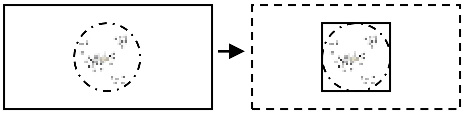


Fig. 10. Trimming off a rectangle into a base cell

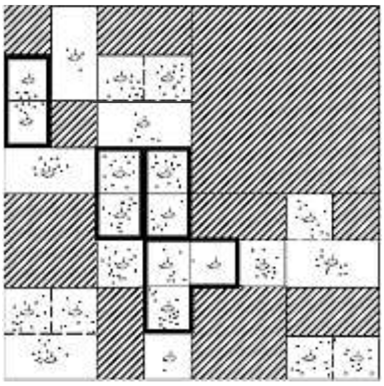


Fig. 11. Merging neighboring cells to explore new WR potential location

Having found the set of separate base cell locations, phase one is finalized by constructing the set of grid segments. A base cell in a grid segment should have side-by-side neighborship with at least one other element belonging to the same segment. The router placement problem is then solved separately for each grid segment, through an iterative execution of the ILP model. Each time a new set of potential WR locations provided in the second phase, are supplied until a valid optimal solution is eventually obtained. *Cell splitting* is known to be the most effective technique to proliferate the initial set of WR positions.

Phase 2: Cell Splitting

Upon failure of the first execution attempt, the rudimentary uniform cell splitting (UCS) scheme partitions every base cell into a mesh of 2 × 2 equal-size squares, with the problem of placing WR routers at their centroids is subsequently solved. If the second iteration fails too, the grid resolution is incremented by one (3 × 3) and the execution reiterated. This process cycles again up to the point a solution will be found. It is fairly simple to show that the size of ILP problem grows with $O(mn^2)$ where m is the initial number of base cells in the grid segment, and n denotes the cell grid resolution. With a moderate to large-size segment, the problem complexity may soon grow beyond the available computation capacity. Henceforth, the load-based cell splitting (LCS) scheme supplies a mesh of equidistance WRs in each base cell just enough to carry the traffic loads of end users within that cell. Let L represent total traffic load of users within the cell, CLR denotes the maximum load carrying capacity of WR, the initial number of potential router positions is given by $NR^0 = \lceil L/CLR \rceil$, whereby grid resolutions along horizontal and vertical directions can be derived, from $n_x^0 = \lceil \sqrt{NR^0} \rceil$ and $n_y^0 = \lceil NR^0/n_x^0 \rceil$, respectively. As an example, if $L = 240$, and $CLR = 50$, we get $NR^0 = 5$, which gives $n_x = 3$ and $n_y = 2$ that equals to a grid size of 2 × 3 (2 rows by 3 columns). If it didn't work, the grid size is incremented by one and set as the new value for NR. In mathematical notations, $NR^1 = n_x^0 n_y^0 + 1$, $n_x^1 = \lceil \sqrt{NR^1} \rceil$, and $n_y^1 = \lceil NR^1/n_x^1 \rceil$. For the example initial grid size, the second finer grid is computed by $NR^1 = 7$, and $n_x^1 = n_y^1 = 3$.

The combination of grid segmentation approaches with cell splitting methods will give rise to a set of four distinct solution strategies, SG-FCP-UCS, SG-FCP-LCS, SG-ACP-UCS, SC-ACP-LCS in short. Detailed performance evaluation of these strategies, with reference to the classic approach, is discussed in the next section.

IV. PERFORMANCE EVALUATION

In order to investigate and verify the performance of the proposed WR placement strategies, a custom-made simulator using IBM ILOG CPLEX 12.6 development environment was developed. The core of simulator is responsible for repeatedly generating a refreshed mesh of potential WR locations and feed them to the ILP engine.

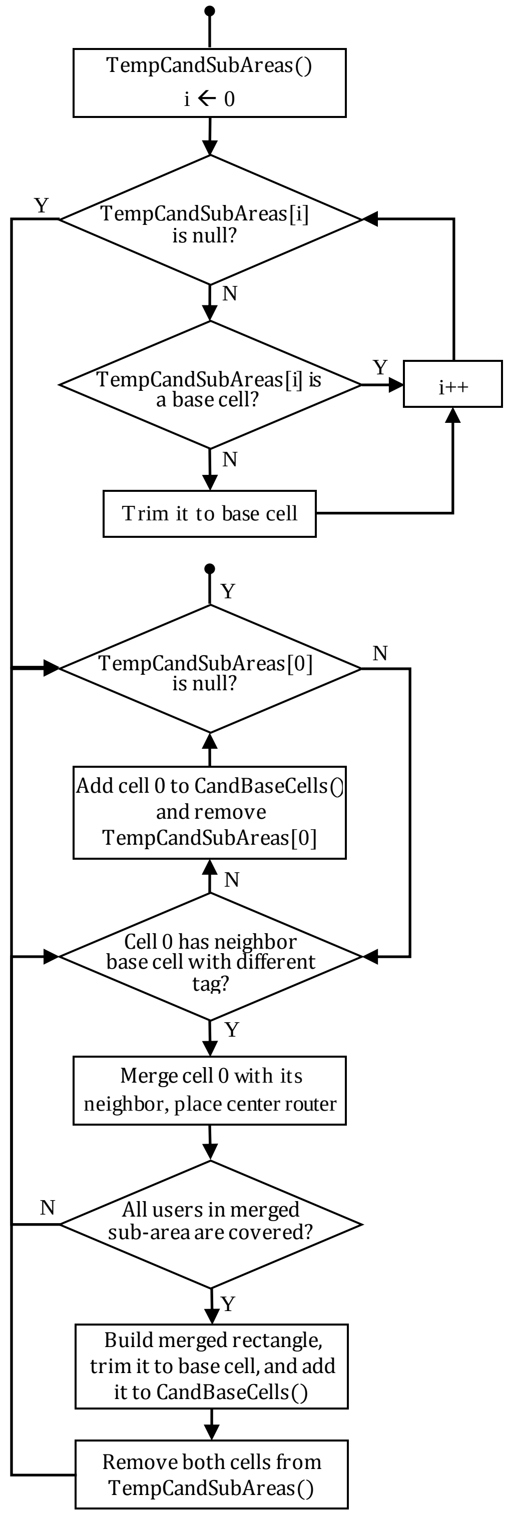


Fig. 12. Main steps of function RecombTempCandCells()

According to [1], transmission range of WR was set to 30 m, and the wireless bandwidth capacity to 50 Mbps. The span of FiWi network was picked from a preset multiples of base cell width $\sqrt{2} \times 30 = 42.426\ m$, arranged in a way to represent a variety of small, moderate, and large size networks. Accordingly, the population of end users was taken from a preset range, varied from 100 up to 10,000 inhabitants, and the traffic load of each user was randomly selected from a discrete array of 1 to 10 Mbps. In order to emulate uneven distribution and concentration of users across the breadth of network, a given number of local user clusters scattered around randomly, were generated. User geographical coordinates, in the surroundings of local centroids, were generated from Gaussian distributions with different variances, until their given random portions of partial user population are reached. Table I summarizes parameter settings of computer simulations. FiWi spans are varied from a range of 670, 1350 and 5430 meter, where for each area size, a corresponding range of preset values for user population, cluster size and radius can be selected.

TABLE 1.Simulation parameters

WR transmission range (m)	30
WR bandwidth capacity (Mbps)	50
Load balancing factor (Mbps)	30
Base cell width (m)	42.426
FiWi network area (m^2)	[670×670, 1350×1350, 5430×5430]
Network span multiplier	[16×16, 32×32, 128×128]
User populations	[(100, 250, 500), (400, 1000, 2000), (4000, 10000)]
Cluster number	[(4, 16), (16, 64), (128, 512)]
Cluster radius (m)	[(20, 40), (20, 40), (40, 60)]
User traffic load (Mbps)	[1, 2, 3, …, 10]

The result of numerical simulations of the fore-mentioned WR placement scenarios under different combinations of parameter settings are depicted in Tables II, III, and IV, for different FiWi spans, respectively. Bolded entries indicate the optimal number of WRs required to support a given number of user population averaged over different user distributions. The blank cell entries denote that a feasible solution could not be found by the ILP solver due to the lack of sufficient computing resources. Note that the classic scheme cannot scale at all with network size.

TABLE 2. Optimum number of WRs for FiWi span of 670 m

Simulation settings				Number of Wireless Routers				
Fiwi Span (m)	User Populatin	Cluster Number	Cluster Radious (m)	CG-FCP-UCS	SG-FCP-UCS	SG-FCP-LCS	SG-ACP-UCS	SG-ACP-LCS
670-100-4-20				12	12	12	12	12
670-100-4-40				32	31	29	26	27
670-100-16-20				32	35	35	26	26
670-100-16-40				36	40	40	31	31
670-100				**28**	**29.5**	**29**	**23.75**	**24**
670-250-4-20				29	29	29	29	29
670-250-4-40				31	31	35	32	36
670-250-16-20				49	45	47	42	43
670-250-16-40				54	57	67	65	66
670-250				**40.8**	**40.5**	**44.5**	**42**	**43.5**
670-500-4-20				55	55	56	55	56
670-500-4-40				57	57	70	57	70
670-500-16-20				-	66	67	69	69
670-500-16-40				74	83	89	83	85
670-500				**62**	**65.25**	**70.5**	**66**	**70**

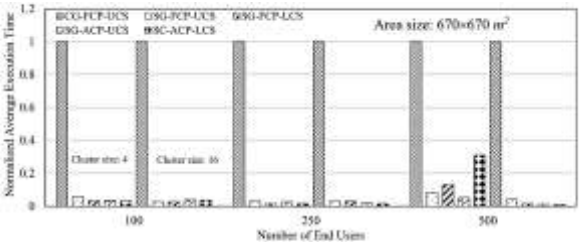
TABLE 3. Optimum number of WRs for FiWi span of 1350 m

Simulation settings				Number of Wireless Routers				
Span Width (m)	User Populatin	Cluster Number	Cluster Radious (m)	CG-FCP-UCS	SG-FCP-UCS	SG-FCP-LCS	SG-ACP-UCS	SG-ACP-LCS
1350-400-16-20				-	55	62	59	64
1350-400-16-40				-	74	88	75	82
1350-400-64-20				104	138	140	106	109
1350-400-64-40				147	169	171	143	145
1350-400				**105.5**	**109**	**115.3**	**95.8**	**100**
1350-1000-16-20				-	127	135	128	133
1350-1000-16-40				-	-	195	158	184
1350-1000-64-20				-	183	186	176	183
1350-1000-64-40				-	231	258	231	238
1350-1000				**-**	**180.3**	**193.5**	**173.3**	**184.5**
1350-2000-16-20				-	239	247	236	240
1350-2000-16-40				-	-	-	-	-
1350-2000-64-20				-	-	284	294	302
1350-2000-64-40				-	-	-	-	-
1350-2000				**-**	**-**	**265.5**	**265**	**271**

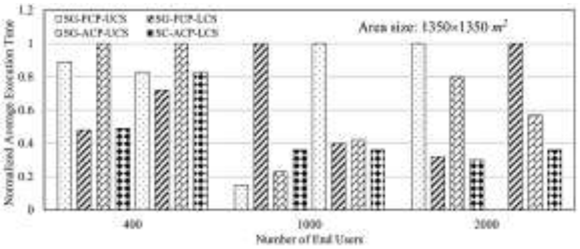
TABLE 4. Optimum number of WRs for FiWi span of 5430 m

Simulation settings				Number of Wireless Routers				
Span Width (m)	User Populatin	Cluster Number	Cluster Radious (m)	CG-FCP-UCS	SG-FCP-UCS	SG-FCP-LCS	SG-ACP-UCS	SG-ACP-LCS
5430-4000-128-40				-	818	945	831	910
5430-4000-128-60				-	1081	1174	1071	1117
5430-4000-512-40				-	1643	1644	1355	-
5430-4000-512-60				-	-	-	-	-
5430-4000				**-**	**1181**	**1254**	**1086**	**1013**
5430-10000-128-40				-	-	-	1593	1701
5430-10000-128-60				-	-	2198	1988	-
5430-10000-512-40				-	2621	2802	2521	2605
5430-10000-512-60				-	-	-	-	-
5430-10000				**-**	**-**	**2500**	**2034**	**2153**

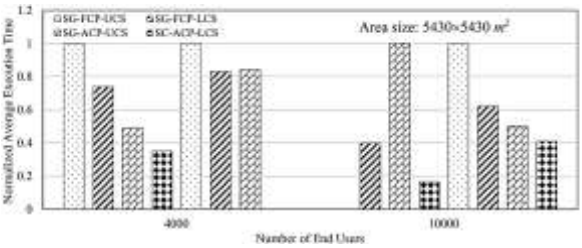
Among the four proposed strategies, however, SG-ACP-UCS has the highest success ratio (28 out of 32 test cases), while SG-FCP-UCS has the lowest success ratio (24 out of 32).Moreover, with respect to the number of WRs, SG-ACP-UCS outperforms all other strategies in almost all test cases. This can be attributed to an enhanced tracking of cluster centers in ACP algorithm and placing WRs as close to the users' concentration as possible. A minor superiority of UCS to LCS stems from the fact that higher grid resolution used in UCS contributes to the finer adjustment of WR positions, but with extended runtime period. Figure 13 (a) compares the average runtime of the proposed schemes with the classic CG-FCP-UCS scheme, for different user populations and number of clusters. Apparently, all proposed schemes are much more efficient than the classic one, while according to Figures 13 (b), (c), SG-ACP-LCS is the most efficient scheme among the others on the average.



(a)



(b)



(c)

Fig. 13. Comparison of execution times of different schemes for FiWi span (a) 670 m, (b) 1350 m, and (c) 5430 m.

V. CONCLUDING REMARKS

In this paper, we studied the problem of placing wireless routers in the FiWi front-end. So far, conventional algorithms decompose a given area into a large grid of fine square cells and solve the model for potential WRs at the center points. In order to overcome the poor performance and scalability issues of solving for the optimal WR locations in a large scale network comprising thousands of end users, we proposed novel adaptive grid segmentation and load-based cell splitting techniques and introduced a set of four efficient WR placement strategies. Simulation results demonstrated that our proposed schemes considerably outperforms the classic contiguous-grid fixed-cell approach.

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Fariborz Mousavi Madani was born in Shiraz, Iran, on August 23, 1962. He received the B.Sc. degree in electrical engineering from Shiraz University, Shiraz, Iran in 1987, and the M.S. degree in telecommunication engineering from Sharif University of Technology (SUT), Tehran, Iran in 1991. He received his Ph.D. degree in electrical engineering from University of Tokyo, Tokyo, Japan in 1999. He is currently working with the Department of Computer Engineering as a full-time Assistant Professor at Alzahra University. His research interests are in the areas of Optical Network Virtualization, Design and Optimization of Elastic Optical Networks and Next-Generation Passive Optical Networks, Fi-Wi networks