Optimization of the use of Radio Resource of Radio-Over-Fiber Access Networks

Pedro Henrique Gomes and Nelson L. S. da Fonseca
Institute of Computing
State University of Campinas
Campinas, Brazil
psilva@lrc.ic.unicamp.br, nfonseca@ic.unicamp.br

Omar C. Branquinho
Pontifical Catholic University of Campinas
Campinas, Brazil
branquinho@puc-campinas.edu.br

Abstract—In this paper, we introduce a radio resource optimization model for Radio-over-Fiber (RoF) access networks. We propose an integer programming model to minimize the network cost while providing service to all mobile users. The proposed architecture arranges cells in a multi-layer fashion, with cells in each layer providing different coverage radius. The optimization algorithm performs dynamic cell splitting to improve network capacity in congested areas and cell merging in areas with low demand to save resources. The computational demand of the proposed model increases proportionally to the number of layers of RAUs in the infrastructure. Results indicate that two layers of RAUs give the best trade-off between network cost reduction and computational demand.


I. INTRODUCTION

The Radio-over-Fiber (RoF) technology integrates radio and optic fiber technologies capitalizing on the best of these technologies for the design of efficient access networks. In RoF networks, the optical part provides reliable and high-capacity transmissions, while the wireless part allows mobility at low cost. In these networks, radio-frequency (RF) signals are carried in optic fibers. These networks involve one or more Base Station Controllers (BSCs) and several Remote Antenna Units (RAUs) attached to a fiber backhaul. Most all RF components are centralized at the BSCs and RAUs are responsible only for the electro-optic conversion of RF signals. All radio resources, called Base Stations (BSs), are located at the BSCs and these resources can be dynamically distributed along the network allowing different (“overlay”) configurations which can provide better coverage at reduced costs under dynamic demands [1].

Beyond-3G network infrastructures are supposed to provide cost-effective, ubiquitous, high-data rate solutions for large number of mobile users. These requirements, however, are not always uniformly demanded along the network. Traditional cellular networks are based on static resource allocation (system-centric) management. Resources such as channels, multiplexing codes, sub-carriers and time slots, are allocated first to the Base Stations, considering the network cost and the overall quality of service, and then assigned to users, in a divide-and-conquer approach. Static system-centric resource allocation is not efficient, especially in dynamic, mobile and bandwidth-consuming networks, since users’ demands can be geographically concentrated in certain regions of the network [2]. Recently, a user-centric top-down approach has been proposed for resource allocation in mobile wireless network [3], allowing allocation upon demand. Differently from the traditional approach, user-centric radio resource management first allocates resources based on users’ requirements and then it searches for the best Base Station to provide connectivity.

This paper introduces a solution based on integer programming formulation for the user-centric resource allocation problem. The network considered consists of several Remote Antenna Units connected by optical links to a Base Station Controller at which there are limited number of radio equipments (Base Stations). The solution of the problem is to find an optimal distribution of radio resources to the RAUs so that a minimum number of BSs are used, decreasing operational costs and deploying energy-efficient wireless networks.

This paper is organized as follows. Section II presents the related works. Section III introduces the proposed architecture. Section IV introduces the integer programming formulation of the problem. Section V illustrates the use of the proposed method. Finally, Section VI concludes the paper.

II. RELATED WORKS

Radio Resource Management (RRM) techniques have been extensively used in cellular networks planning and, currently, they are also used in the deployment of wireless networks such as Wi-Fi and WiMAX. In this technique, a central problem is the positioning of Base Stations for optimal use of radio resources. Solutions for this traditional problem are usually based on static methods and can lead to resource waste in dynamic networks such as mobile environments. Novel RRM techniques have been proposed for mobile networks such as user-centric solutions [4], so that the dynamic clustering of users can be accounted for. Next, some recent works on RRM in wireless networks are briefly surveyed.

In [5], dynamic channel allocation, dynamic transmission power control and load balancing solutions are proposed for Wi-Fi networks based on centralized network agents. In [6] and [7], the Base Station placement problem is studied; while
in [6] the feasibility of the problem solution based on Nelder-Mead method is investigated, in [7], detailed modeling of the problem as well as a solution via simulated annealing are presented. In [3], the authors argue that current system-centric RRM uses a divide-and-conquer approach, showing that it can be potentially inefficient for mobile networks.

In [8] and [9], the RAU positioning problem in hybrid Wireless-Optical networks is addressed. A greedy algorithm for solving this problem is proposed in [9], and compared to random and deterministic approaches. Based on a set of pre-established positions the algorithm tries to minimize the euclidean distance between RAUs and users. In [8], a solution based on simulated annealing is proposed; results show significant cost reduction. All these solutions, however, provide last-mile access for fixed users and are not appropriate to mobile users since in these networks the clustering of users is dynamic.

The solution proposed in this paper deals with mobility and yet minimizes the number of radios employed. This work shows an example of user-centric RRM algorithm focused on solving mobile network resource allocation, which was not yet considered in previous works.

III. PROPOSED ARCHITECTURE

Given that the distance between antennas and users is a limiting factor for spectrum-efficiency and, consequently, for achieving high data rates, a good deployment of wireless networks should consider a large number of cells and co-located wireless systems, leading to efficient spectrum reuse and reliability. Co-located systems can employ different types of technologies or even a single technology with different set-up parameters (such as cell radius, number of channels, type of antenna). One example of such infrastructure is shown in figure 1. It consists of 2 BSCs with several BSs, each BS connected to a few RAUs spread over the network area. The BSs employ different technologies, such as Wi-Fi, WiMAX, GSM and HSPA and can deploy different types of access networks, with diverse coverage area, capacity and cost. In figure 1, RAUs 2, 3 and 7 deploy micro-cells based on WiMAX technology with large capacity and medium coverage, RAU 6 deploys a pico-cell based on Wi-Fi with medium capacity and small coverage, while RAU 5 deploys a HSPA-based macro-cell with small capacity and large coverage. The type of technology and position of cells are dynamically chosen among the available infrastructure according to users demand. RAUs 1 and 4, for instance, remain disassociated since network load is low at their locations.

Another way of obtaining a flexible architecture is through the employment of a single wireless technology and use of cellular techniques, such as cell splitting and merging. Cell splitting consists of diving large cells into a number of small cells and, consequently, increasing the network capacity in congested areas. Increasing the number of cells, however, increases the number of BSs and, as a consequence, the network cost. A typical solution is to implement cells with different sizes, adopting small cells only where they are necessary. Static deployment of cells with different sizes, however, can still lead to waste of resources in mobile networks, since congested areas can “move”. Consequently, a dynamic process of cell splitting and merging is required to address the demands of mobile users.

In the proposed architecture, RAUs are organized in a multi-layer structure in a way that each layer has a different cell radius, as illustrated in Figure 2. RAUs can be activated or deactivated so that a topology can be dynamically set to satisfy the demand at minimum cost. The splitting process can form a cluster of \( n \) smaller cells in layer \( N \) from cells at layer \( N - 1 \), and the merging process results on the opposite. If a RAU at a higher layer is active, all RAUs located in its coverage at a lower level should be deactivated, which saves energy and avoids channel overlapping, facilitating frequency reuse.
IV. PROPOSED OPTIMIZATION MODEL

The proposed optimization model aims at deploying small-couverture cells in congested areas and large-radius cells in low-density areas, so that network cost can be minimized. It associates network resources (centralized at the BSCs) to the RAUs to dynamically configure the network topology in order to cope with users’ mobility. We assume that there is a sufficiently large number of RAUs installed and these can be dynamically “turned on” or “turned off”, creating new cells or splitting them when needed and merging them when they are not needed. The network consists of a single wireless technology and cell splitting/merging is performed in a multi-layer fashion.

The BSCs are represented by the set $ \mathcal{C} = \{C_1, C_2, ..., C_p\}$. The BSs are represented by set $ \mathcal{B} = \{B_1, B_2, ..., B_n\}$ and their main characteristic is the capacity $c_i$. The capacity of the BSs can be expressed by the maximum number of channels, the maximum throughput or maximum number of users, depending on the BS technology. The RAUs are represented by the set $ \mathcal{R} = \{R_1, R_2, ..., R_m\}$. Their main characteristics are the geographical location $(X_{R_i}, Y_{R_i})$ and the coverage radius $r_i$. The Mobile Stations (MSs) are represented by the set $ \mathcal{M} = \{M_1, M_2, ..., M_n\}$ and their main characteristics are the geographical location $(X_{M_i}, Y_{M_i})$ and demand $d_i$. This last parameter can correspond to the number of required channels or the minimum throughput required by all the flows of $M_i$.

The solution of the problem determines: the BSCs that should operate; the BSs that should be activated in the operating BSCs; the RAUs associated to the active BSs; and the MSs which should be served by the associated RAUs.

The problem is formulated as an integer programming (IP) model. The objective of the problem is to minimize the number of BSs for reducing the network cost while serving all MSs. The formulation of the problem is shown next:

$$ \text{Minimize} \sum \sum \sum x_{i,j,k}$$

subject to:

1. $x_{i,j,k} \in \{0,1\}$ for all $i \in \mathcal{R}, j \in \mathcal{B}, k \in \mathcal{C}$ (C1)
2. $y_{i,j} \in \{0,1\}$ for all $i \in \mathcal{M}, j \in \mathcal{R}$ (C2)
3. $x_{i,j,k} \leq a_{i,k}$ for all $i \in \mathcal{R}, j \in \mathcal{B}, k \in \mathcal{C}$ (C3)
4. $x_{i,j,k} \leq b_{i,k}$ for all $i \in \mathcal{R}, j \in \mathcal{B}, k \in \mathcal{C}$ (C4)
5. \( \sum \sum \sum x_{i,j,k} \leq 1 \) for all $i \in \mathcal{R}$ (C5)
6. \( \sum \sum x_{i,j,k} \leq 1 \) for all $j \in \mathcal{B}$ (C6)
7. $y_{i,j} = 1$ for all $i \in \mathcal{M}$ (C7)
8. \( \sum \sum \sum x_{i,j,k} \geq y_{i,j} \) for all $j \in \mathcal{R}$ (C8)
9. $\sum \sum y_{i,j} \leq r_j$ for all $i \in \mathcal{M}, j \in \mathcal{R}$ (C9)
10. \( \sum y_{i,j} d_i \leq \sum \sum \sum x_{i,j,k} \sum_{i \in \mathcal{R}} \sum_{j \in \mathcal{B}} \sum_{k \in \mathcal{C}} x_{i,j,k} \) for all $j \in \mathcal{R}$ (C10)

The objective function minimizes the number of BSs used, which is the main cost of the network.

Constraints C1 and C2 express the values of the decision variables: the RAUs associated to a certain BS and the mobile users covered by such association. Constraint C3 states that a RAU can be associated only to a BS in a certain BSC if there is a fiber link connecting the RAU to the BSC. Constraint C4 establishes that a RAU can only be associated to a BS in a certain BSC if the BS is located at that BSC. Constraints C5 and C6 provide a one-to-one association between the RAUs and the BSs, which means that only one RAU can be associated to any BS and only one BS can be associated to a specific RAU. Constraint C7 guarantees that all MSs are served by exactly one RAU. Constraint C8 ensures that only RAUs associated to a BS can serve users. Constraint C9 enforces that RAUs can only serve users in their coverage area. Constraint C10 limits the aggregated demand to be less or equal the BS’s capacity. Finally, constraint C11 prevents that RAUs from two different layers to be used in a certain cluster.

V. NUMERICAL EVALUATION

To assess the effectiveness of the proposed approach, different scenarios were evaluated. Results from the evaluation are discussed next.

A. Scenarios used in the evaluation

The optimization model was implemented using the C programming language and the optimization library FICO Xpress 7.0 [10], which implements LP-based Branch and Bound for solving integer linear programming problems. All experiments were executed in a workstation with Intel Core 2...
infrastructure.

Figure 3 illustrates the BSs, each BS with capacity of 30 users. All the 64 BSs can operate simultaneously to cover a certain area. In the worst case, the network will operate with 64 BSs, which happens if all RAUs from the lowest layer are active. Therefore, the network infrastructure consists of 1 BSC, 85 RAUs and 64 BSs, each BS with capacity of 30 users. All the 64 BSs can be associated to any of the 85 RAUs. Figure 3 illustrates the infrastructure.

To evaluate real mobile network we employed the well-known Random Way-point and the Random Trip Model. The streets used for Random Trip Model represent a real snapshot of the city of Houston in Texas/USA, near West University (http://www.cs.rice.edu/~amsaha/Research/MobilityModel/). For both models the average speed was set to 5m/s and the delta speed value was 2m/s; the pause time and the pause time delta were 20s and 50s, respectively.

All experiments lasted 1000s, during which the optimization algorithm was executed every 100s. The number of users varied up to 1000 users. For each experiment with different number of users at least 10 samples were taken to compute the desired statistics and intervals with 95% confidence were derived. In all the experiments, four different network infrastructures were considered: infrastructure 1 involved only the lowest layer of RAUs (64 RAUs); infrastructure 2 consisted of the lowest 2 layers (64 + 16 RAUs); infrastructure 3 was composed by 3 layers (64 + 16 + 4 RAUs); and infrastructure 4 involved all 4 layers (64 + 16 + 4 + 1 RAUs). By considering these four infrastructures it is possible to evaluate the benefits of structuring the RAUs in a hierarchical fashion. By activating a RAU at a higher layer, RAUs at a lower layer should be deactivated. Therefore, the higher the layer is, the lower is the network cost. Infrastructures involving a higher number of layers have more flexibility to reduce the network cost, but the optimization problem demands more computational effort.

B. Numerical results

Figure 4 shows the network cost considering the Random Trip mobility model. It can be noticed that the number of required BSs by infrastructure 1 with just one layer of RAUs presents the highest network cost, demanding a much higher number of active BS. For a number of MS lower than 100, while infrastructure 1 with a single layer of RAUs demands from 30 to 40 active BS, infrastructure 3 and infrastructure 4 demand only 5 BSs. Up to 400 MSs, the difference in BS demand between infrastructure 1 and the others was constant and on average of 35 BSs. For a number of users lower than 400, cells are merged and BSs at higher layers are active and a large number of BSs at lower layers are deactivated.

In the experiments, we set a bound of 90s to the execution time of the algorithm. Such limit leads to solutions to infrastructure 4 far from the optimum one since the computational demand to solve the problem with 4 layers is much greater than the complexity required to solve problems with less layers. Moreover, it can be seen that there is very small differences on the results given by infrastructure 2 and infrastructure 3. In summary, it is not worthwhile to have a number of layers larger than 3 given the computational demands. Moreover, two layers is good enough to reduce network costs.

Figure 5 shows the average number of MSs per RAU. In infrastructure 1 (with only 1 layer) the number of MSs per RAU increases linearly and it is considerably lower than in the other three infrastructures. However, the mean number of MSs per RAU given by the other infrastructures is still quite reasonable to maintain acceptable congestion levels and quality of transmission. Configurations with 2 and 3 layers produce similar mean numbers of MSs per RAU.

Figure 6 shows the execution time of the optimization program. The time taken to produce solutions for a flat

![Fig. 3. Radio-over-Fiber infrastructure used in the evaluation](http://www.cs.rice.edu/~amsaha/Research/MobilityModel/)

![Fig. 4. Number of used BSs as a function of the number of MSs](http://www.cs.rice.edu/~amsaha/Research/MobilityModel/)
Fig. 5. Number of MSs per RAU as a function of the number of MSs in the network

Fig. 6. Execution time of the optimization model

Fig. 7. A comparison of network cost (number of Base Stations) given by the Random Way-Point and Random Trip models

infrastructure (with one layer) is not significant at all which is an advantage when there are strict time constraints for the solution. The execution time increases with the number of levels of the RAU hierarchy. The execution time can be six times and twice longer, for infrastructures with 4 layers and 3 layers, respectively, when compared to the time required for infrastructure with 2 layers. Overall, it can be concluded that infrastructure 2 presents the best trade-off between cost, computational demand and quality of transmission.

Figure 7 compares the number of BSs required by the two mobility models when considering infrastructure 2. Results are quite similar until 500 MSs. After that, the Random Way-Point demands a small number of additional BSs. The execution time and mean number of MSs per cell were quite similar regardless of the mobility model adopted.

VI. CONCLUSION

In this paper, we explored a user-centric centralized resource optimization model for mobile users, which consists of a dynamic cell splitting/merging process executed in a multi-layer infrastructures of several RAUs spread over the coverage area. The proposed optimization model indicated attractive cost reduction when multi-layer infrastructures are used. The computational demand to obtain a solution for such infrastructure, however, increase with the number of layers. Considering both improvement and computational complexity, we can conclude that infrastructure with two 2 layers presents the best trade-off between performance and computational complexity. Results derived in this paper can be used for planning and management of mobile networks with RoF centralized architecture.

REFERENCES