Passive Optical Network Design Optimization for Wireless Backhauling

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ABSTRACT

The increasing popularity of converged media services is promoting the deployment of a range of broadband networking technologies aiming at serving the increased bandwidth as well as service portability and user mobility demands. To optimally address the above requirements hybrid access network architectures coupling the benefits of optical (high capacity, robustness) and mobile/wireless networks (extended reach and mobility) are quite promising. In this paper we present the basic steps for converged network design and planning and evaluate algorithms for wireless backhaul optimization based on a PON architecture. Network optimization addresses the capacity requirements per access segment and optical backhaul segment, the physical layer limitations (e.g. power budget) and overall cost (in terms of CAPEX including number of nodes, active ports, civil engineering works etc. and OPEX mainly including real estate and power consumption) by means of both heuristic algorithms and stochastic optimization techniques.

Keywords: Passive Optical Networks, wireless backhaul networks, stochastic optimization, network planning.

1. INTRODUCTION

The fast growing popularity for (both fixed and mobile) data services featuring distributed content storage, converged media and high data rates is exceeding the capabilities of existing broadband access networks. The existing and new services/applications that are becoming available to the end users are currently supported by wireline access technologies such as relatively limited capacity cable modems, and ADSL or high capacity FTTx/VDSL as well as wireless technologies such as HSDPA, WiFi and WiMax. Wireline (optical) networks can provide high bandwidth but face limitations in terms of the trade-off between limited reach and high cost, when extended penetration is attempted (especially in case of p2p active networks). Next generation wireless access should support a large number of users per cell, large bandwidth (e.g. 100 Mbit/s for clients moving at high speeds and 1 Gbit/s for stationary clients), smooth handoff across heterogeneous networks and high quality of service. Therefore, mobile network operators have been looking for network topologies/technologies to increase the network capacity either on the air interface with the end use but also in the backhauling. In order to achieve the required data rate, cells have to be small, which leads to an increase of their number. Additionally backbone connectivity is a limitation due to the increased cost of leasing when moving to higher data rates.

At present, mobile operators mostly use point-to-point wireless to backhaul to the central office but that is not going to be possible anymore with 4G. FTTx (Fiber to the “x”-point) is the most “future proof” technology because it can handle the new bandwidth-intensive applications. Fiber is increasingly used by providers to cope with high-bandwidth online applications for businesses and consumers, but serving a large number of cells with point to point links is extremely inefficient. Due to the above considerations Passive Optical Networks (PONs) become very attractive as a backhaul solution for a new hybrid wireless/optical access network architecture ([1], [2]). While international standards evolve to enable interoperability between heterogeneous networks there is still a need for cross layer optimization in order to develop a converged network infrastructure enabling resource optimization and flexible service provisioning. In this paper we present the basic steps for backhaul network planning and evaluate algorithms for network optimization based on a PON architecture. Network optimization addresses the capacity requirements in each access segment and the physical layer limitations (e.g. power budget) and results in network node assignment reducing the overall cost (in terms of CAPEX including number of nodes, active ports, civil engineering works etc. and OPEX mainly including real estate and power consumption) by means of both heuristic algorithms and stochastic optimization techniques. In the following section we discuss the details of our approach and formulate an optimization problem regarding a PON-based backhaul design. We present the algorithms used to get near-optimal results and in Section 3 we evaluate their performance through a number of scenarios. Finally Section 4 concludes our paper.

2. DESIGN METHODOLOGY

The expected benefits of (co)designing a hybrid wireless-optical broadband access architecture as mentioned above is that network operators can achieve optimal planning of access and backhaul segments as well as flexible resource provisioning providing increased capacity per user at a lower CAPEX/OPEX (compared to competitive solutions). The initial steps towards designing such a converged infrastructure should follow the analysis of service and capacity requirements (mainly in terms of their spatial and temporal distribution) as they are derived by service providers. Legacy wireless network planning methodologies considered only the expected demand and spectrum availability on the wireless segment in order to result in the optimal allocation of cells and the position and interconnection of wireless Base Stations (BSs). While in a green-field deployment a pure co-design approach with tight integration could be envisaged allowing simultaneous optimization of both the wireless and the optical backhaul segments (e.g. as proposed in [3]) in this paper we focus on a more realistic approach taking into account only evolutionary scenarios, where the positions of the BSs (i.e. gateways to the backhaul network) are fixed and known a-priori. Moreover, a tighter wireless/optical converged network design assumes that the control plane mechanisms allowing optimal routing between wireless and backhaul segments for optimal load balancing are in place, an assumption that limits interoperability especially in the case of mobile 3G and 4G networks (whereas WiMAX has been studied in [1]- [3]). Therefore we do not consider these possibilities and only focus on backhaul optimization in this study.

Clearly the optimization problem needs to address the spatial distribution of network terminations and respective capacity demand, the physical layer limitations and overall cost as described above. The problem therefore can be broadly defined as follows: given a number of optical network termination points at known positions in a 2-dimensional space (Fig. 1a), with a known expected demand (which will be then used to establish corresponding Service Level Agreements – SLAs), distributed around the position of a Central Office (CO), find the optimal interconnection scheme that will minimize overall network cost. Since PONs inherently reduce cost due to the sharing of available infrastructure and resources, we assume that the corresponding Optical Networking Units (ONUs) will be installed at the termination points and will be interconnected to a number of Optical Network Line termination units (OLTs), which will in turn reside at the premises of the operator at the CO, implementing the tree-shaped topology of PONs. Due to the capacity and power budget limitations of a PON, in general more than one OLTs will be required resulting in a star topology of multiple PONs with a common root point as shown in Fig. 1b. While most approaches in the literature (e.g. [4], [5]) attempt to maximize the split ratio reducing the number of required OLTs and overall fiber path requirements, in this work, under the context of wireless backhauling described above the additional limitation of the minimum required capacity (to serve the minimum expected capacity per network termination) is introduced. Furthermore the same limitation is met in a mixed service provisioning scenario where network operators offer service bundles to mobile/wireless network operators as well as other enterprise or residential users over the same PON infrastructure. Finally in the context of mobile services an additional requirement arises that will be called hereafter as "capacity migration" and is graphically depicted in Fig. 1a. This is the phenomenon where the dynamic spatial redistribution of users causes temporal variations at the capacity demand at different network segments. Therefore, while handovers are well studied and handled by wireless technologies the effect of dynamic transitions of users between BS/ONUs as well as between PONs/OLTs should also be taken into account during network design and planning.

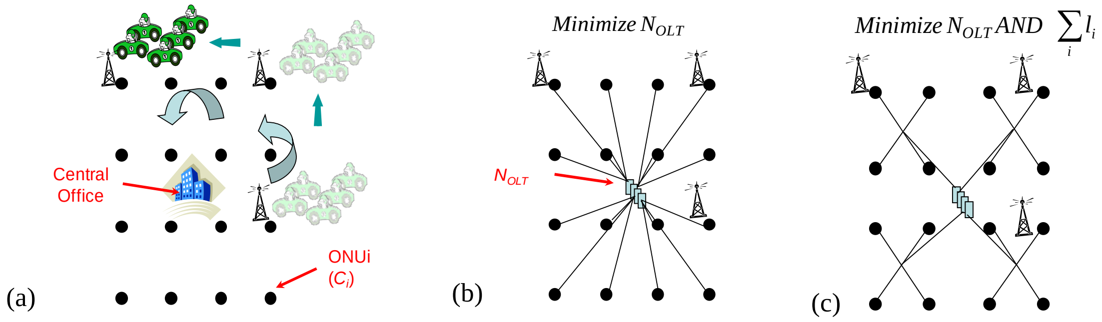

Figure 1 (a) spatial distribution of fixed and mobile terminals(and potentially temporal distribution of capacity demand), (b) potential PON backhaul design serving capacity demand, (c) potential PON backhaul design optimizing total fiber path length

The above optimization problem can be briefly expressed for the PON backhaul design as follows (assuming ideal couplers with 3dB loss per passive split and only one centralized splitting point):

$$\text{Minimize } F \text{ subject to} \quad 1)\ P_{MAX} - 3 \cdot \log_2 N_{ONU} - \alpha \cdot l_{max} \geq P_{MIN} \quad \text{and} \quad 2)\ \sum_{i=1}^{N_{ONU}} C_i \leq C_{MAX}$$

where

F is the total cost clearly related to the number of PON segments (active elements including discrete wavelength transmission either in spatially distributed segments through stacked OLTs or WDM multiplexing) as well as total link distances affecting related fiber deployment costs and equipment costs and capacity distribution between PON segments

a the attenuation of fiber in db per km

l_{max} the maximum fiber path for reaching an ONU located at the maximum distance from the splitting point (km)

P_{MIN} the power threshold as defined by the ONU sensitivity (dB)
P_{MAX} the power at the output of the OLT (dB)
C_i the projected bandwidth requirements of ONU i
C_{MAX} the maximum shared capacity of a PON segment serving N_{ONU} ONUs in total

2.1 Cost minimization algorithms

The above representation simplifies the problem formulation assuming that there is a centralized splitting point either located at the CO (i.e. without any optimization of fiber paths – Fig. 1b e.g. assuming legacy/dark fiber infrastructure) or at the geometric center of the ONU positions assigned to each PON segment/OLT (Figure 1c) reducing overall fiber paths. Obviously further fiber routing algorithms could apply ([3], [5]) further decreasing the overall fiber cost (at the cost of increased complexity). However, the above problem remains NP-hard even in its most simplified versions [6] and due to space limitations we only present in this work results under the above simplifying assumptions and employing stochastic optimization techniques.
As discussed above the backhaul design optimization aims at the minimization of active nodes (OLTs) to serve the capacity demand, minimization of fiber installation as well as even distribution of spare capacity (headroom) to accommodate traffic fluctuations (capacity migration) due to user mobility with the following cost function:

$$F = K_1 \cdot \sum_{i=1}^{N_{OLT}} \{1 - e^{-S_i}\} + K_2 \cdot Var(C_{S_i}) + K_3 \cdot \sum_{i=1}^{N_{OLT}} \left\{ l_{s,i} + \sum_{j=1}^{N_i} l_{j,i} \right\})$$

where S_i and Var(C_{Si}) represent the split ratio (to be maximized) and variance of the distribution of spare capacity among segments and ONUs (to be minimized) and $l_{s,i}$ and $l_{j,i}$ represent the distance of the splitter location from the OLT and distance of each ONU j from the splitter of each PON segment *i* (to be minimized).
Simulated annealing is a global optimization technique that was proposed by Metropolis [6] and is considered a good choice for a wide variety of problems. It attempts to minimise a cost function C by doing a random change in the initial configuration and then accepting the change if the difference $\Delta = C_1 - C_0$ of the new cost C_1 and the old cost C_0 is negative, or with probability $p = e^{-\Delta/T}$ when Δ is positive, where T is called the "temperature", and is progressively reduced. This way the probability of accepting a new configuration that increases the cost function is reduced as the optimization progresses, while smaller increases are always more likely to be accepted than larger ones. When only negative differences are accepted we have a local optimization technique called "hill climbing". In the following section we present the results for different scenarios (in terms of numbers of ONUs and the distribution of their distances and capacity demand). We benchmark the results of the simulated annealing (SA) against three "hill climbing" variations, namely HC where both the spare capacity variance term K_2=0 and fiber path term K_3=0 (a simplified version ignoring capacity distribution and length factors), HC-C where $K_3 \neq 0$ (without length optimization)and HC-CL where $K_2 \neq 0$ and $K_3 \neq 0$.

3. PERFORMANCE EVALUATION

Obviously the basic factors affecting the performance of a cost optimization technique in the above context include the size of the network under optimization (number and geographical distribution of termination points/ONUs) and the distribution of the capacity demands (number of ONUs with heavy or low demand). Similarly, performance metrics that are of interest for the assessment of the optimization methodology include the actual resulting cost in terms of the required number of PON segments/OLTs, distribution of spare capacity among segments and overall fiber infrastructure. Therefore in Fig. 2 below we present the respective results for a number of scenarios with the number of termination points/ONUs ranging from tens to thousands (100, 250, 600, 1000 and 2000), distributed in a geographical area of several kilometres around the CO. The position of the ONUs in each scenario is selected randomly following a uniform distribution within a square of 20x20 Km around the center. The capacity demand is assumed to correspond to a random mix of residential/low demand users and enterprise/high capacity users including BSs. Low demand users correspond in average to 70% of the total number of ONUs with a projected capacity demand of 20Mb/s and BSs (30% in average) are assumed to have an order of magnitude higher capacity demand i.e. 200Mb/s.
In Fig. 2 below we present the best results we obtained in each case regarding the above metrics of interest i.e. total number of PON segments/OLTs Fig. 2(a), (c), distribution of spare capacity (i.e. headroom to serve capacity migration) per segment/OLT Fig. 2(b) and total (across all segments) fiber path length Fig. 2(d). We also present for comparison the ideal minimum value of segment/OLTs to serve the capacity demand not taking into account physical layer limitations (i.e. a case that may not be feasible; thus there are no corresponding actual fiber path lengths) and also express the normalized figure of the number of OLTs over this ideal minimum value in Fig. 2(c). In the ideal case also optimal bandwidth distribution is assumed (even distribution among OLTs).
As we can observe from Fig. 2 higher optimization in terms of numbers of OLTs (8-15%) and variation of headroom per OLT can be achieved especially for large numbers of ONUs with simulated annealing at the cost of longer run time. Since optimization is expected to be implemented at design phase the real-time response of

the optimization algorithm is not considered critical. If the latter is not the case simpler stochastic optimization approaches like HC can provide near-optimal solutions in terms of the final number of OLTs, while a slightly more complicated algorithm like HC-CL can significantly improve the total length of fiber paths and spare capacity variance for a slightly larger OLT number with no discernible penalty over HC-C. Obviously there is a trade-off between the minimization of active nodes (OLTs) and fiber path lengths since denser topologies (fewer OLTs) impose higher restrictions in fiber paths and positioning of splitting points.

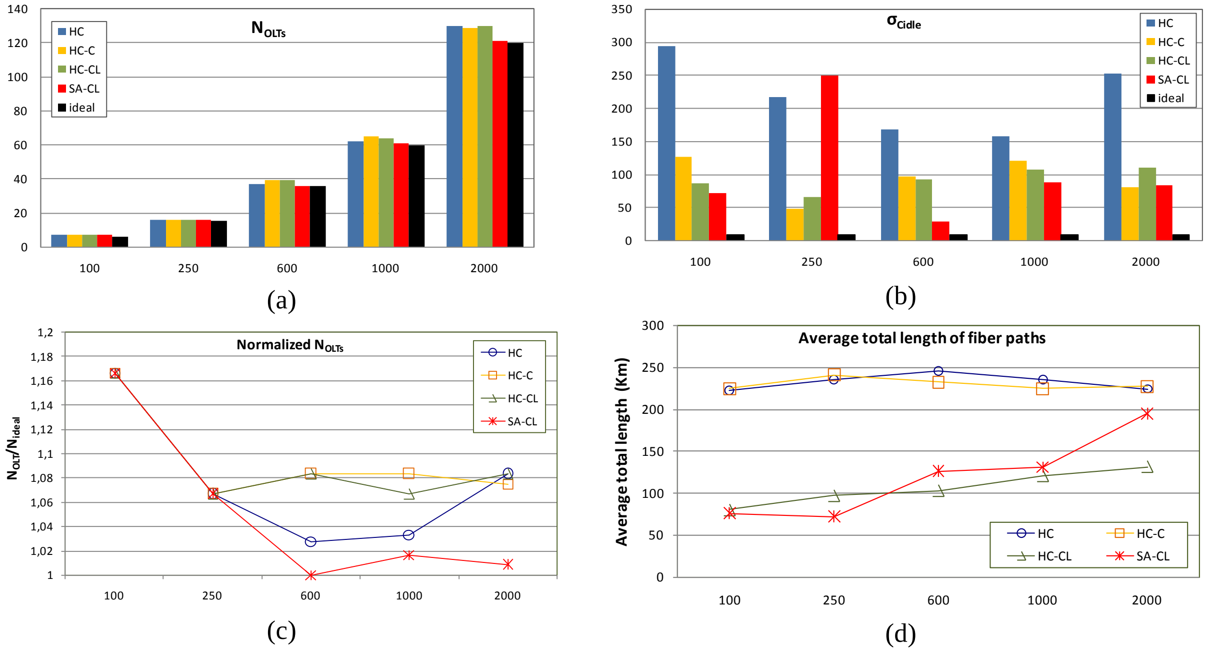

Figure 2 (a) number of PON segments/OLTs per scenario (b) std. deviation (σ) of spare capacity per segment/OLT, (c) normalized figure of OLTs over the ideal minimum (d) average total length of fiber paths

4. CONCLUSIONS

We have presented a new approach on network optimization aimed at the design of wireless backhaul networks exploiting the benefits of PONs. The results show that legacy approaches for cost optimization may not result in optimal backhaul designs if we do not take into account the capacity/QoS requirements of enterprise users (including mobile operators) and possible effects of capacity migration. As a most efficient approach to deal with the resulting complex optimization problem we proposed a stochastic optimization technique following the simulated annealing approach and computed near optimal solutions for a range of scenarios balancing the overall requirements in installed infrastructure and the distribution of resources supporting user and service mobility.

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