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Topology optimization for hybrid optical/wireless access networks

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ABSTRACT

Hybrid Wireless–Optical Broadband Access Networks (WOBANs) are gauging momentum as flexible, bandwidth-effective, and cost-effective solutions for providing connectivity to residential users in metropolitan areas. In this work, we address the issue of designing the topology of deployed WOBANs. Namely, we consider the case where the coverage of a Ethernet-based Passive Optical Network (EPON) is extended by an additional wireless segment which features multi-hop wireless links operated either according to the IEEE 802.11 standard, or to the IEEE 802.16 one. We propose a mathematical programming model which optimizes the overall WOBAN topology in terms of deployment cost, while accounting for the specific traffic requirements of the residential users, and the specific features of the technological components. The potentials of the proposed model are showcased by deriving and commenting numerical results obtained when planning realistic WOBAN scenarios.

1. Introduction

The issue of providing effective access solutions to residential users is attracting increasing attention from different actors like service providers, commonalities, and academia. Indeed, in the last ten years, the quality of experience requested by residential users has incredibly increased (think of the quadruple play services), thus challenging the architectures of the deployed metropolitan access networks. To this extent, even if most of current access networks are mainly based on copper, optical technology is gauging momentum as an effective way to bring bandwidth to the final users. Among optical network architectures, Passive Optical Networks (PONs) are currently being deployed in many metropolitan environment, due to their favorable features in terms of offered bandwidth, robustness and maintainability.

On the other side, in many cases it is not possible or cost effective for the operator to reach every single residential user with the fiber, and consequently some type of connectivity extension must be provided through other communication technologies. In this scenario, the recent progresses in the field of wireless technologies have boosted the adoption of wireless access networks to reach the final residential users with cost effective, flexible and ubiquitous network deployments. As a consequence, it is straightforward to envision the use of Hybrid Wireless–Optical Broadband Access Networks (WOBANs) for "covering" metropolitan-scale areas, having desirable features in terms of provided bandwidth, deployment and maintenance costs.

To fully unleash the potentials of WOBAN architectures, several technical challenges have to be addressed and resolved, including the QoS management across the wireless/optical boundary [1,2], the routing in the hybrid architecture [3] and the overall network management. Several testbeds have been recently developed to evaluate proposed algorithms and protocols [4–6]. Moreover, effective methods are needed to plan and optimize the WOBAN topology for two main reasons: first, the topology itself may have a huge impact on the overall "quality" of the network (both on the end user's side, quality of service, and on the operator's side, deployment cost); second, network

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deployments can involve hundreds of devices (optical and wireless), thus manual tuning is very unpractical and automatic topology planning and optimization tools are required.

In this work, we address the issue of designing the topology of a WOBAN composed by a Ethernet-based Passive Optical Networks (EPONs), which can be extended through a Wireless Mesh Network (WMN) operated by IEEE 802.11 and/or IEEE 802.16 standards. In details, we develop a complete mathematical programming model for the automatic planning of the entire WOBAN topology with the objective of minimizing the overall deployment costs, while accounting for the specific traffic requirements of the residential users, and the specific features of the technological components.

The main contributions of this work are:

- A complete optimization framework for planning and dimensioning WOBANs. Solved to the optimality, it selects the best network devices to be installed, their positions and the configuration of the entire network.
- The inclusion of a multi-hop network paradigm in the wireless domain.
- The possibility of selecting between IEEE 802.11 and IEEE 802.16 devices for the wireless domain. The outcome shows which is the best technology to deploy in each part of the network according to technical characteristics, traffic distribution and device costs.

To the best of our knowledge, this is the first work on WOBAN planning accounting for multi-hop wireless extensions to the optical segment, further considering the choice between different wireless technologies with different features and constraints (IEEE 802.11 vs. IEEE 802.16).

The remainder of the paper is structured as follows: Section 2 overviews the related work in the field, Section 3 overviews the main building blocks of the reference WOBAN architecture, and provides the problem statement. In Section 4, we introduce the optimization model for WOBAN planning and comment on the corresponding formulation. Section 5 reports on the performance evaluation carried out to assess the quality and the utility of the proposed optimization model. Finally, concluding remarks are given in Section 6.

2. Related works

Previous work on Hybrid Optical/Wireless Access Networks can be categorized into three main areas: contributions on the general architecture of hybrid optical/wireless networks, contributions on protocol-oriented aspects of routing and channel assignment, and contributions on hybrid network planning and optimization.

Referring to the first class, architecture papers aims at analyzing the challenges to be faced when deploying such hybrid networks, deriving general guidelines on the best type of enabling technologies and the specific solutions to be implemented across the border between the optical and wireless domains to bind them together. References [2,7,8,5] share this approach.

On protocol-oriented issues of WOBAN, a good deal of work has been carried out to design optimized routing solutions for the wireless segment of WOBANs. As an example, Refs. [9,5,3,10] propose enhanced routing algorithms/protocols accounting for wireless links' quality, delay and capacity issues in a single-channel scenario, whereas other recent studies address scenarios where multiple channels and radios are available in the wireless segment [11,12]. These latter works aim at developing models and algorithms to evenly distribute the traffic load among channels and exploit available resources by spatial and channel re-use.

In general, the literature on network planning and optimization includes many pieces of work focusing on the optimization of single building blocks of WOBANs like Passive Optical Networks [13–15], IEEE 802.11 Wireless Mesh Networks [16] and IEEE 802.16 multi-hop networks [17–20]. The common approach is to resort to Integer Linear Programming (ILP) and/or Mixed-Integer Linear Programming (MILP) to model the optimization problem, further proposing heuristic algorithms, often leveraging the traditional results on cellular coverage optimization.

Despite the presence of many contributions dealing with the optimization of each WOBAN's technological building block, only fewer papers have appeared dealing with the joint wireless/optical optimization. Within this field, Sarkar et al. [21] propose a set of heuristic algorithms to optimize the location of multiple Optical Network Units (ONUs) in a WOBAN, followed by a combined heuristic that includes the placement of wireless access points as well. Access points are co-located to ONUs and are further characterized by hexagonal coverage cells; the optimization considers inter-cell interference constraints, similarly to 3G cellular networks. The same authors present in [22] a MILP model to optimize ONUs and Access Points placement subject to coverage and capacity constraints. The objective is the minimization of the installation costs (device and trenching costs) and the formulation is solved applying a Lagrangian relaxation method. The same problem is addressed in [23] including also the channel assignment for the deployed access points. A Lagrangian relaxation is designed to compute a lower bound on the installation costs, which is used in a second step to design a heuristic algorithm for the planning and channel assignment problem. Different to our approach, the aforementioned contributions consider a single-hop hot-spot-like coverage model for the wireless domain, whereas our framework also allows the possibility of having multiple wireless hops in the wireless domain of the WOBAN. Moreover, our optimization approach also allows to choose/optimize the type of technology used in the wireless domain, whereas a single and given technology is used in the three previous references.

The same one-hop wireless extension assumption is considered in [24], where the problem of network planning and dimensioning under EPON-WiMAX integration is faced. The proposed Mixed-Integer Nonlinear Mathematical Programming formulation is solved via problem decomposition and linearization techniques. The formulation provides the optimal placement of ONU-cabled WiMAX devices that minimizes installation costs. In addition, the considered architecture allows cooperative communication among base stations in such a way that users can benefit from the cooperative diversity.

Integer Linear Programming (ILP) is used in [25], which focuses on the design of the wireless segment. Namely, starting from a given single-radio wireless network instance, the work defines the optimum assignment of a given number of additional radio interfaces to the bottleneck nodes in the wireless distribution system. The objective is to improve the global throughput-delay ratio of the entire set of data connections. This work shares with our the possibility of having multi-hop wireless networks in the wireless realm of WOBANs, but, different to our approach, it focuses only on the optimization of the wireless domain neglecting the optical domain.

Finally, the recent work in [26] focuses on the design of the optical domain, and proposes a MILP model with the purpose to maximize the WOBANs survivability, by setting up pre-determined protection paths among ONUs.

3. Background and problem statement

The problem addressed in this paper is the planning of a WOBAN considering both optical and wireless realms, where the former consists of a EPON and the latter can be managed via IEEE 802.11 or IEEE 802.16 devices. Given a traffic demand distributed over a deployment area, we want to design the whole backbone infrastructure delegated to collect traffic. The backbone consists of a metropolitan Central Office (CO) from where optical fibers depart in order to feed wireless access points, both IEEE 802.11 and IEEE 802.16. Users can either transmit directly to these access points or associate to wireless relaying devices that form a wireless multi-hop extension network connected to the access points. In order to do that, we jointly optimize the position of wireless devices and optical terminations, as well as traffic routing within the backbone. Moreover, the optimization process can select the best wireless technology to cope with the characteristics of the specific scenarios according to device features and costs. The overall objective is minimizing installation costs while providing bandwidth guarantees to the residential users.

Finally, we analyze the scenario where connectivity can be provided by multiple COs. In this case, network design must select among possible sites the number and the position of ones to use to build up the optimal WOBAN.

3.1. Technology overview

In the following paragraphs we glance through the main details of the involved technologies in order to understand the assumptions and the choices made in the problem formulation of the next section.

3.2. EPONs [27]

EPONs, standardized by IEEE 802.3ah, are all-Passive Optical Networks composed of two types of devices: Optical Line Terminals (OLT) and Optical Network Units (ONUs). ONUs are user devices and connect to the single OLT, located at the CO, through a point-to-multipoint topology; the covered distance can reach 15–30 km, while the split-ratio varies from 32 to 64 ONUs for each OLT. Optical fibers coming from ONUs are coupled before reaching the OLT in such a way that the downstream flow (from OLT to ONUs) sees a broadcast channel received by all ONUs. On the other side, upstream transmissions (from ONUs to OLT) must share the common channel, and its capacity. EPONs use a TDMA scheme controlled by the OLT, which processes ONU bandwidth requests and accordingly grants per-ONU transmission slots.

3.3. WiFi-based Wireless Mesh Networks [28]

Wireless Mesh Networks (WMNs) are composed of fixed and mobile nodes interconnected through multi-hop wireless links. WMN devices are hierarchically organized in terms of networking functionalities and hardware capabilities. WMN devices are of three types: *Mesh Routers* (MRs), *Mesh Gateways* (MGs) and *Mesh Clients* (MCs). The functionality of both the MRs and the MGs is twofold: they act as classical access points towards the MCs, whereas they have the capability to set up a *Wireless Distribution System* (WDS) by connecting to other MRs or MGs through point-to-point wireless links. To further improve the flexibility of mesh networking, a mesh router is usually equipped with multiple wireless interfaces with the same or different wireless access technologies. Furthermore, the MGs are provided of gateway/bridge functionalities that permit the integration of WMNs with existing wireless and wired networks. MCs are users terminals connected to the network through MGs or MRs.

The availability of multiple wireless interfaces allows to use orthogonal channels for the access traffic from MCs and the WDS traffic among MRs and MGs. This permits to share the channel capacity only among MCs associated to the MR(MG). Furthermore, multiple interfaces can be used to reduce, or even eliminate, the interference among WDS flows thanks to a proper channel assignment. MRs and MGs are often fixed and electrically powered devices, this enables the use of advanced physical layer solutions within the WDS, such as directional antennas or sophisticated coding/modulation schemes. As a consequence, these wireless links can cover longer distance, be more reliable and better re-use the wireless medium due to a limited interference effect.

3.4. WiMax networks [29]

IEEE 802.16 standards regulate WiMAX networks in static or mobile scenarios with point-to-multipoint or mesh topologies. The typical scenario consists of a wired access point, called *Base Station* (BS), that provides wireless connectivity to covered *Subscriber Stations* (SSs). In order to provide link level QoS, a TDMA scheme is used. SSs negotiate their QoS requests with the BS, which assigns frame slots according to an internal scheduling policy. TDMA frames are divided into two sub-frames: the downlink (DL) sub-frame and the uplink (UL) sub-frame. The BS uses a variable part of the DL sub-frame to transmit data to the different SSs as well as to communicate SSs the frame structure and their transmission opportunities in the UL sub-frame. The UL sub-frame contains data transmission slots from SSs to the BS and SS bandwidth requests (new or upgraded).

The recent IEEE 802.16j standard introduces a new network topology to improve flexibility and coverage of WiMAX networks. It considers a new type of devices, called *Relay Stations* (RSs), connected to the BS with a tree topology. RSs manage traffic of SSs far from the BS and act as relays for it. The TDMA frame changes to include the new devices while keeping compatibility with the traditional ones. In detail, a multi-hop (MH) sub-frame is introduced within the UL sub-frame originated at the BS. During MH sub-frame, the BS does not manage traffic, it passes the control to the RS, which builds up itself an entire TDMA frame, as shown in Fig. 1. For the BS, RSs appear to be regular SSs, DL sub-frame contains packets for both SSs directly associated to the BS and connected RSs. In the UL sub-frame, instead, there are three type of slots: slots reserved to the transmission of SSs associated to the BS, slots reserved to RSs to transmit their traffic to the BS, and slots for MH sub-frame. During MH sub-frame, the RS exchanges data with its SSs, which are 2-hop away from the BS. If the BS is equipped with more that one RS, several MH sub-frames must be scheduled in the BS frame. Even though the scheme could be iteratively repeated when RSs are provided with a further level of RSs, only one RS level is usually considered ([17,20,19]). Indeed, due to the MH sub-frame encapsulation, the total channel capacity must be shared among access links from SSs and backbone links among BS and RSs; this leads to a RS resources wastage when RS trees become deep.

4. Problem formulation

We consider a deployment area where traffic source points, named test points, are placed. Each test point can represent a single residential user or a centroid of a discrete/continuous traffic distribution according to the desired planning scenario. The set of test points is denoted by $\mathscr{P}$. Similarly, IEEE 802.11 devices (MRs) and IEEE 802.16 devices (RSs) can be installed in discrete sets of candidate sites $\mathscr{S}_{11}$ and $\mathscr{S}_{16}$, respectively. Due to wiring issues, ONUs can be placed only in a limited number of locations identified by set $\mathscr{S}_{ONU}$. We assume, with no loss of generality, that a site where the wiring for an ONU is available can also host either a IEEE 802.11 or IEEE 802.16 device, that is, $\mathscr{S}_{ONU} \subseteq \mathscr{S}_{11} \cap \mathscr{S}_{16}$. Therefore, wireless devices equipped with a wired interface (MGs and BSs) can be activated only within the set $\mathscr{S}_{ONU}$, while only-wireless devices (WRs and RSs) can be installed in every site of the proper set $\mathscr{S}_{11}$ or $\mathscr{S}_{16}$.

Propagation conditions, antenna patterns, and device parameters define the set of wireless links that can be used. We condense all the physical layer details in four families of sets, where each set contains links that can be activated. In detail, we denote the ordered set $\mathscr{A}_i^{11}$ as the set of candidate sites in $\mathscr{S}_{11}$ that can be reached from test point $i \in \mathscr{P}$ using IEEE 802.11 technology. Sites in $\mathscr{A}_i^{11}$ are ordered according to non-decreasing distance from i. Similarly, we define $\mathscr{A}_i^{16}$ when using IEEE 802.16. In addition, we use sets $\mathscr{B}_j^{11}$ to express available links from site $j \in \mathscr{S}_{11}$ to other sites in $\mathscr{S}_{11}$ using IEEE 802.11 connections. Set $\mathscr{B}_j^{16}$ is defined for IEEE 802.16 in the same fashion.

The entire set of names and symbols for sets, variables and parameters is summarized in Table 1. The decision variables we must consider are:

Association variables

$$x_{ij}^{11} = \begin{cases} 1 & \text{test point } i \in \mathscr{P} \text{ connects to site } j \in \mathscr{S}_{11} \\ & \text{with IEEE 802.11 technology} \\ 0 & \text{otherwise} \end{cases}$$

$$x_{ij}^{16} = \begin{cases} 1 & \text{test point } i \in \mathscr{P} \text{ connects to site } j \in \mathscr{S}_{16} \\ & \text{with IEEE 802.16 technology} \\ 0 & \text{otherwise} \end{cases}$$

Wireless device variables

$$y_j^{11} = \begin{cases} 1 & \text{a MR is installed in site } j \in \mathscr{S}_{11} \\ 0 & \text{otherwise} \end{cases}$$

$$y_j^{16} = \begin{cases} 1 & \text{a RS is installed in site } j \in \mathscr{S}_{16} \\ 0 & \text{otherwise} \end{cases}$$

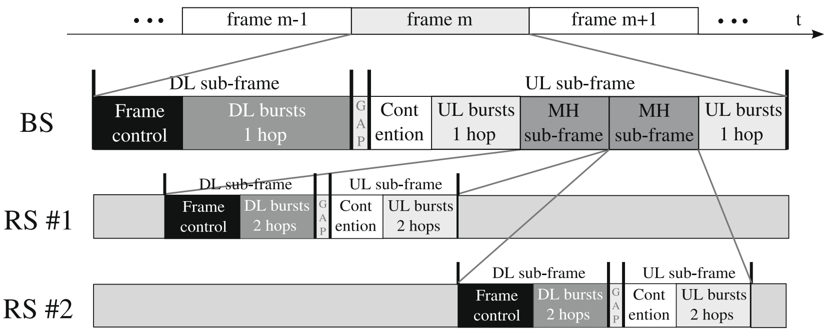


Fig. 1. 802.16j framing example.

Table 1
Notations used throughout the paper.

Names	
MG	IEEE 802.11 Mesh Gateway
MR	IEEE 802.11 Mesh Router
BS	IEEE 802.16 Base station
RS	IEEE 802.16 Relay Station
OLT	EPON Optical Line Terminal
ONU	EPON Optical Network Unit
Sets	
$\mathscr{P}$	Test points
$\mathscr{S}_{11}(\mathscr{S}_{16})$	Candidate sites for IEEE 802.11 (IEEE 802.16) devices
$\mathscr{S}_{OLT}$	Candidate sites for OLTs
$\mathscr{S}_{ONU}$	Candidate sites for ONUs
$\mathscr{A}_i^{11}(\mathscr{A}_i^{16})$	Candidate sites in $\mathscr{S}_{11}(\mathscr{S}_{16})$ reachable from test point i
$\mathscr{B}_i^{11}(\mathscr{B}_i^{16})$	Candidate sites in $\mathscr{S}_{11}(\mathscr{S}_{16})$ reachable from candidate site $j \in \mathscr{S}_{11}(j \in \mathscr{S}_{16})$
Variables	
$f_{ij}^{11}(f_{ij}^{16})$	Flow amount from IEEE 802.11 (IEEE 802.16) device i to device j
f_j^O	Flow amount from ONU j to the EPON
f_{jk}^O	Flow amount from ONU j to OLT k trough the EPON
o_k	OLT installation
r_{lj}^{16}	Association between RS l and BS j
$x_{ij}^{11}(x_{ij}^{16})$	Association between test point i and candidate site $j \in \mathscr{S}_{11}(j \in \mathscr{S}_{16})$
$y_j^{11}(y_j^{16})$	MR(RS) installation in candidate site $j \in \mathscr{S}_{11}(j \in \mathscr{S}_{16})$
$z_j^{11}(z_j^{16})$	MG(BS) installation in candidate site $j \in \mathscr{S}_{ONU}$
$z_{jk}^{11}(z_{jk}^{16})$	MG(BS) installation in candidate site $j \in \mathscr{S}_{ONU}$ connected to OLT k
Parameters	
C^{MR}	Mesh Router cost
C^{RS}	Relay Station cost
C^{MG}	Upgrade cost from MR to MG
C^{BS}	Upgrade cost from RS to BS
C^{OLT}	Optical Line Terminal cost
C_j^{ONU}	Optical Network Unit cost at site j (device + trenching)
D_i	Bandwidth request of test point i
F_{OUT}	Maximum number of ONUs associated to a OLT
N_I	Number of wireless interfaces at each WR/MG
$T^{11}(T_{16})$	Maximum transmission rate over IEEE 802.11(IEEE 802.16) channels
T^{EPON}	EPON capacity

Gateway device variables

$$z_j^{11} = \begin{cases} 1 & \text{a MG is installed in site } j \in \mathscr{S}_{ONU} \\ 0 & \text{otherwise} \end{cases}$$

$$z_j^{16} = \begin{cases} 1 & \text{a BS is installed in site } j \in \mathscr{S}_{ONU} \\ 0 & \text{otherwise} \end{cases}$$

IEEE 802.16 RS variables

$$r_{lj}^{16} = \begin{cases} 1 & \text{RS } l \in \mathscr{S}_{16} \text{ is associated to BS } j \in \mathscr{S}_{ONU} \\ 0 & \text{otherwise} \end{cases}$$

In addition, we need to introduce non-negative flow variables; variables $f_{jl}^{11}(f_{jl}^{16})$ store the flow amount in the backbone from MR $j \in \mathscr{S}_{11}$(RS $j \in \mathscr{S}_{16}$) to MR $l \in \mathscr{S}_{11}$(BS $l \in \mathscr{S}_{ONU}$). Variables f_j^O record the traffic from the wireless interface of device $j \in \mathscr{S}_{ONU}$ that is forwarded to the EPON through the ONU interface. These flow variables define the backbone topology indicating which links must be set up as well as flows routing.

The remainder of the section shows and explains the Mixed-Integer Linear Programming (MILP) model that describes the WOBAN planning problem. For the sake of clarity, we divide the formulation in groups of constraints dealing with common aspects.

The objective function

$$\max \sum_{j\in\mathscr{S}_{11}} \left(C^{MR}y_j^{11}\right) + \sum_{j\in\mathscr{S}_{16}} \left(C^{RS}y_j^{16}\right) + \sum_{j\in\mathscr{S}_{ONU}} \left(\left(C^{MG}+C_j^{ONU}\right)z_j^{11} + \left(C^{BS}+C_j^{ONU}\right)z_j^{16}\right) \tag{1}$$

Eq. (1) adds installation costs for each device. C^{MR} and C^{RS} refer to MR and RS costs, while C^{MG} and C^{BS} are the costs to upgrade a MR to a MG and a RS to a BS, respectively. Actually, the activation of a MG(BS) in site $j \in \mathscr{S}_{ONU}$ is expressed by having both $y_j^{11}(y_j^{16}) = 1$ and $z_j^{11}(z_j^{16}) = 1$. Finally, C_j^{ONU} includes the cost of an ONU device and the trenching cost to lay down the optical fiber from the OLT to the site $j \in \mathscr{S}_{ONU}$. The objective function aims at minimizing such installation costs subject to:

Access traffic constraints

$$\sum_{j\in\mathscr{S}_{11}} x_{ij}^{11} + \sum_{j\in\mathscr{S}_{16}} x_{ij}^{16} = 1 \qquad \forall i \in \mathscr{P} \tag{2}$$

$$x_{ij}^{11} \leqslant \begin{cases} y_j^{11} & j \in \mathscr{A}_i^{11} \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in \mathscr{P},\ j \in \mathscr{S}_{11} \tag{3}$$

$$x_{ij}^{16} \leqslant \begin{cases} y_j^{16} & j \in \mathscr{A}_i^{16} \\ 0 & \text{otherwise} \end{cases} \qquad \forall i \in \mathscr{P},\ j \in \mathscr{S}_{16}$$

$$y_j^{11} + \sum_{\substack{h\in\mathscr{A}_i^{11}: \\ \omega(h)>\omega(j)}} x_{ij}^{11} \leqslant 1 \qquad \forall i \in \mathscr{P},\ j \in \mathscr{S}_{11} \tag{4}$$

$$y_j^{16} + \sum_{\substack{h\in\mathscr{A}_i^{16}: \\ \omega(h)>\omega(j)}} x_{ij}^{16} \leqslant 1 \qquad \forall i \in \mathscr{P}, j \in \mathscr{S}_{16}$$

Constraints (2) force each test point to transmit its data using either IEEE 802.11 or IEEE 802.16 technology. Constraints (3) and (4) are repeated both for variables related to IEEE 802.11 devices and IEEE 802.16, in each case the proper sets and variables must be used. Constraints (3) assure that a test point can associate only to a site with an active device. Constraints expressed by (4) force the assignment of a test point to the best site in which a MR(RS) or MG(BS) is installed according to proper sorting criteria (such as the received signal strength). Function $\omega(j)$ returns the site j's position within the ordered sets $\mathscr{A}_i^{11}$ or $\mathscr{A}_i^{16}$.

Backbone traffic constraints

$$f_{lj}^{11} + f_{jl}^{11} \leqslant \begin{cases} T^{11} y_l^{11} & j \in \mathscr{B}_l^{11} \\ 0 & \text{otherwise} \end{cases} \qquad \forall (l,j) \in \mathscr{S}_{11} \times \mathscr{S}_{11} \tag{5}$$

$$f_{lj}^{16} + f_{jl}^{16} \leqslant \begin{cases} T^{16} y_l^{16} & j \in \mathscr{B}_l^{16} \\ 0 & \text{otherwise} \end{cases} \qquad \forall (l,j) \in \mathscr{S}_{16} \times \mathscr{S}_{16}$$

$$f_{lj}^{11} + f_{jl}^{11} \leqslant \begin{cases} T^{11} y_j^{11} & j \in \mathscr{B}_l^{11} \\ 0 & \text{otherwise} \end{cases} \qquad \forall (l,j) \in \mathscr{S}_{11} \times \mathscr{S}_{11} \tag{6}$$

$$f_{lj}^{16} + f_{jl}^{16} \leqslant \begin{cases} T^{16} y_j^{16} & j \in \mathscr{B}_l^{16} \\ 0 & \text{otherwise} \end{cases} \qquad \forall (l,j) \in \mathscr{S}_{16} \times \mathscr{S}_{16}$$

$$f_{lj}^{16} \leqslant \begin{cases} T^{16} r_{lj}^{16} & l \in \mathscr{S}_{16} \setminus \mathscr{S}_{ONU}, j \in \mathscr{S}_{ONU} \\ 0 & \text{otherwise} \end{cases} \qquad \forall (l,j) \in \mathscr{S}_{16} \times \mathscr{S}_{16} \tag{7}$$

$$\sum_{j\in\mathscr{S}_{ONU}} r_{jl}^{16} \leqslant 1 \qquad \forall l \in \mathscr{S}_{16} \tag{8}$$

$$\sum_{i\in\mathscr{P}} D_i x_{ij}^{11} + \sum_{l\in\mathscr{S}_{11}} \left(f_{lj}^{11} - f_{jl}^{11}\right) = 0 \qquad \forall j \in \mathscr{S}_{11} \setminus \mathscr{S}_{ONU} \tag{9}$$

$$\sum_{i\in\mathscr{P}} D_i x_{ij}^{16} - \sum_{l\in\mathscr{S}_{ONU}} f_{jl}^{16} = 0 \qquad \forall j \in \mathscr{S}_{16} \setminus \mathscr{S}_{ONU} \tag{10}$$

$$\sum_{i\in\mathscr{P}} D_i \left(x_{ij}^{11} + x_{ij}^{16}\right) + \sum_{l\in\mathscr{S}_{11}} \left(f_{lj}^{11} - f_{jl}^{11}\right) + \sum_{l\in\mathscr{S}_{16}} (f_{lj}^{16}) - f_j^{O} = 0 \qquad \forall j \in \mathscr{S}_{ONU} \tag{11}$$

Constraints (5) and (6), repeated for both IEEE 802.11 and IEEE 802.16, assure that a wireless backbone link is active only if both transmitter and receiver are installed. T^{11} and T^{16} are the maximum transmission rates over IEEE 802.11 and IEEE 802.16 channels, respectively. Given the star topology of considered IEEE 802.16 networks, additional constraints (7) and (8) force a RS to transmit its traffic only toward the BS it is associated to. Constraints (9)–(11) are flow balance constraints for the three types of candidate sites, actually defining routing paths within the wireless backbone. The value of D_i is the bandwidth request of test point $i \in \mathscr{P}$.

Capacity constraints

$$\sum_{i\in\mathscr{P}} D_i x_{ij}^{11} \leqslant T^{11} y_j^{11} \qquad j \in \mathscr{S}_{11} \tag{12}$$

$$\sum_{i\in\mathscr{P}} D_i x_{ij}^{16} \leqslant T^{16} y_j^{16} \qquad j \in \mathscr{S}_{16}$$

$$\sum_{l\in\mathscr{S}_{11}} \left(f_{jl}^{11} + f_{lj}^{11}\right) \leqslant N_I T^{11} \qquad j \in \mathscr{S}_{11} \tag{13}$$

$$\sum_{l\in\mathscr{S}_{16}} 2 f_{lj}^{16} + \sum_{i\in\mathscr{P}} D_i x_{ij}^{16} \leqslant M \cdot T^{16} - (M-1) T^{16} z_j^{16} \qquad \forall j \in \mathscr{S}_{ONU} \tag{14}$$

Constraints (12) limit the total access traffic of test points associated to each installed wireless device (both IEEE 802.11 and IEEE 802.16) according to the capacity of its access technology, given by T^{11} or T^{16}. This constraint formulation assumes that interference among traffic generated by test points associated to different access devices of the wireless distribution system can be neglected. We believe that this approximation is reasonable, since wireless interfaces can be tuned to different channels according to an optimization strategy, which reduces the interference effects. This is further supported by the number of available orthogonal channels (up to 13 [30]) in IEEE 802.11 and the high number of sub-carriers and symbols considered for OFDM/OFDMA techniques in IEEE 802.16 [31]. Once the WOBAN has been planned, a channel assignment algorithm for WLAN [32] can be used to configure the access interfaces of WRs and MGs, and, similarly, interference mitigation techniques can be applied to configure BSs and RSs [33,34]. Finally, in those scenarios where only a single common channel can be assigned to all the access interfaces, interference effects can be taken into account replacing constraints (12) with:

$$\sum_{\substack{i\in\mathscr{P}: \\ j\in\mathscr{A}_i^{11}}} d_i \leqslant T^{11} + M_j^{11}(1 - y_j^{11}) \qquad j \in \mathscr{S}_{11}$$

$$\sum_{\substack{i\in\mathscr{P}: \\ j\in\mathscr{A}_i^{16}}} d_i \leqslant T^{16} + M_j^{16}(1 - y_j^{16}) \qquad j \in \mathscr{S}_{16}$$

where $M_j^{11}(M_j^{16})$ is the smallest constant that is large enough to ensure that the inequality is always satisfied when $y_j^{11}(y_j^{16}) = 0$ (regardless of the other variable values).

Constraints (13) define the maximum flow crossing a IEEE 802.11 device. Since multiple channels and radios are available, inter-flow and intra-flow interference can be mitigated by a proper channel assignment. Therefore, with a good approximation [16], we can state that the total traffic flow going through a device cannot exceed the total bandwidth provided by the number of interfaces, N_I, it is equipped with. Finally, constraints (14) reflect the common channel capacity sharing among access transmissions and backbone links in IEEE 802.16 due to the RS frame encapsulation scheme.

Wireless–optical border constraints

$$f_j^O \leqslant N_I T^{11} z_j^{11} + T^{16} z_j^{16} \qquad j \in \mathscr{S}_{ONU} \tag{15}$$

$$z_j^{11} \leqslant y_j^{11} \qquad \forall j \in \mathscr{S}_{ONU} \tag{16}$$

$$z_j^{16} \leqslant y_j^{16} \qquad \forall j \in \mathscr{S}_{ONU}$$

$$y_j^{11} + y_j^{16} \leqslant 1 \qquad j \in \mathscr{S}_{ONU} \tag{17}$$

Constraints (15) force a gateway device to be installed in site j in order to forward flow f_j^O to the optical realm. The gateway device consists of either a MG or a BS, as stated by constraints (16) and (17).

4.1. Multiple OLTs

The formulation proposed in the previous section can be extended to the general scenario where the number of OLTs and their positions are unknown and must be determined by the WOBAN design, in addition to the aspects of the previous section.

We extended the single-OLT model defining a set of candidate sites for OLTs, denoted as $\mathscr{S}_{OLT}$, and a set of binary variables o_k, $k \in \mathscr{S}_{OLT}$, indicating whether or not an OLT is installed at site k. Furthermore, the old variables expressing the installation of gateway devices (MGs and BSs), z_j^{11} and z_j^{16}, need to be changed in z_{jk}^{11} and z_{jk}^{16}, $j \in \mathscr{S}_{ONU}$, $k \in \mathscr{S}_{OLT}$, in order to indicate with the value 1 that the device j is installed and connected to OLT k. The same change applies to f_j^O variables as well, which become variables f_{jk}^O.

Objective function (1) changes into

$$\begin{aligned}\max \sum_{j \in \mathscr{S}_{11}} \left(C^{MR} y_j^{11}\right) + \sum_{j \in \mathscr{S}_{16}} \left(C^{RS} y_j^{16}\right) \\ + \sum_{\substack{j \in \mathscr{S}_{ONU},\\ k \in \mathscr{S}_{OLT}}} \left(\left(C^{MG} + C_j^{ONU}\right) z_{jk}^{11} + \left(C^{BS} + C_j^{ONU}\right) z_{jk}^{16}\right) \\ + \sum_{k \in \mathscr{S}_{OLT}} C^{OLT} o_k\end{aligned} \tag{18}$$

while constraints (2)–(17) must be modified replacing old variables $z_j^{11}(z_j^{16})$ with $\sum_{k \in \mathscr{S}_{OLT}} z_{jk}^{11} \left(\sum_{k \in \mathscr{S}_{OLT}} z_{jk}^{16}\right)$ and old variables f_j^O with $\sum_{k \in \mathscr{S}_{OLT}} f_{jk}^O$ wherever they appear and the following constraints must be added:

$$z_{jk}^{11} + z_{jk}^{16} \leqslant o_k \qquad \forall j \in \mathscr{S}_{ONU}, k \in \mathscr{S}_{OLT} \tag{19}$$

$$\sum_{k \in \mathscr{S}_{OLT}} \left(z_{jk}^{11} + z_{jk}^{16}\right) \leqslant 1 \qquad \forall j \in \mathscr{S}_{ONU} \tag{20}$$

$$\sum_{j \in \mathscr{S}_{ONU}} \left(z_{jk}^{11} + z_{jk}^{16}\right) \leqslant F_{OUT} o_k \qquad \forall k \in \mathscr{S}_{OLT} \tag{21}$$

$$\sum_{j \in \mathscr{S}_{ONU}} f_{jk}^O \leqslant T^{EPON} o_k \qquad \forall k \in \mathscr{S}_{OLT} \tag{22}$$

Objective function (18) includes the cost of installed OLTs, denoted as C^{OLT}. Constraints (19) assure that gateway devices connect only to installed OLTs via optical fibers, while constraints (20) force every installed gateway device to connect to a single OLT. Constraints (21) and (22) refer to the EPON topology: constraints (21) limit the number of ONUs that can join the EPON rooted at each OLT to be smaller than F_{OUT}, constraints (22) force the traffic through the EPON to not exceed its capacity T^{EPON}.

5. Numerical results

We analyzed solutions obtained by solving to optimality the proposed formulations. This allows us to highlight the effects on the solutions when some important design parameters change, as we show in Section 5.1, or when more OLT site locations are available, as reported in Section 5.2. Then, we give some commented snapshots of planned networks for a couple of interesting scenarios under different traffic conditions in Section 5.3.

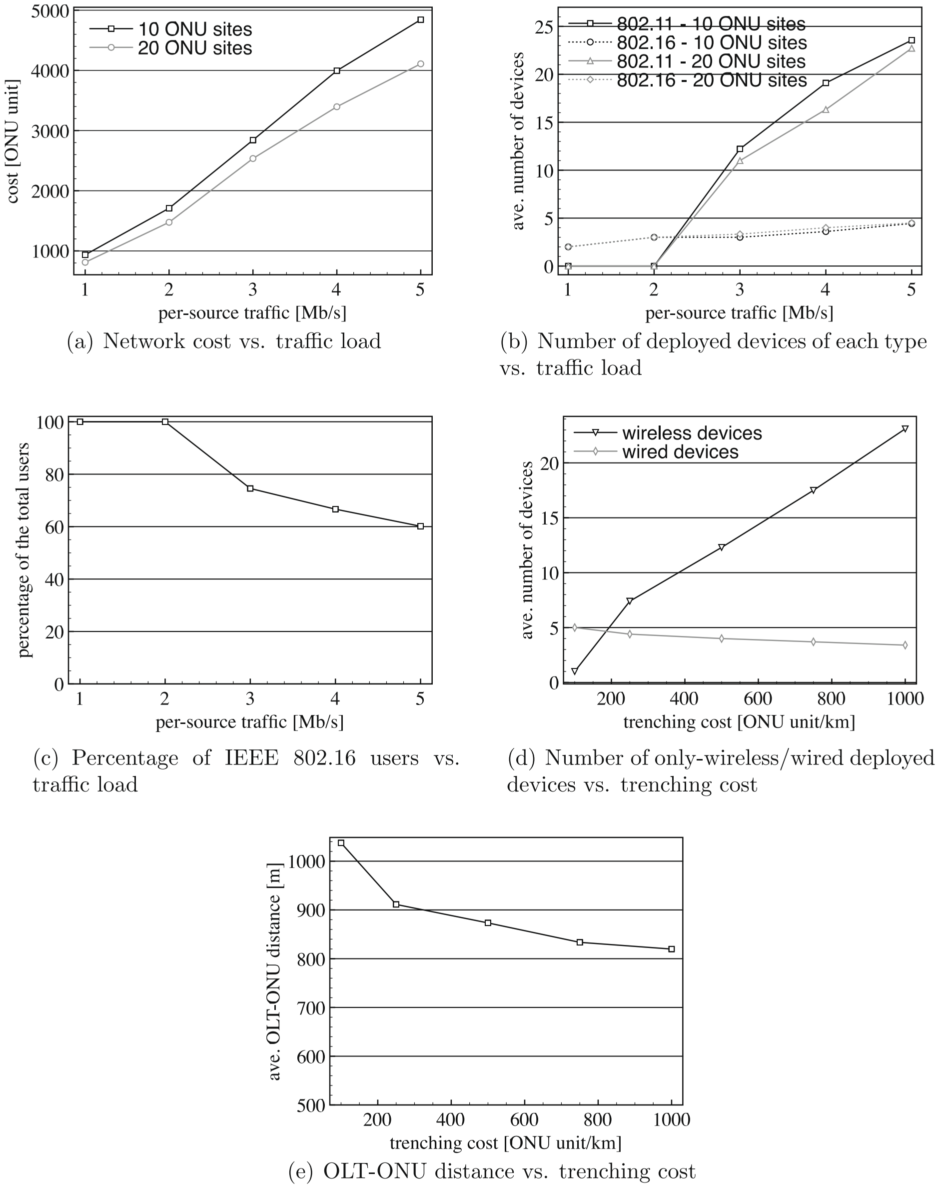
Instances are solved running the state-of-the-art solver CPLEX 11.0 [35] on 3 GHz machines powered by Linux. Where not differently stated, parameters used in the model are the following. Raw bandwidth values are set to 54 Mb/s for IEEE 802.11 and 75 Mb/s for IEEE 802.16. MRs have been equipped with $N_I = 3$ radio interfaces. Communication ranges are 3 km for links with IEEE 802.16 technology, 500 m for backbone links with IEEE 802.11 technology, and 250 m for IEEE 802.11 access links (user-MR/MG). Device costs normalized to the cost of a ONU are defined as follows [21]: MR cost, C_{MR}, is set to 60 ONU units and RS cost, C_{RS}, to 100 ONU units, while the corresponding gateway device costs are $C_{GW} = 100$ for MGs and $C_{BS} = 150$ for BSs due to their higher complexity and computational power. Trenching costs to deploy a ONU are 500 ONU units/km, depending on the distance between the ONU and its OLT.

5.1. Evaluating design parameters

The reference scenario is a 3 km square area are where 100 test points have been randomly deployed, the OLT is assumed to be in the center of the square. Each point of the following plots is averaged on 10 instances.

Fig. 2a shows installation costs as the traffic demand per each test point increases. As expected, costs increase due to the higher number of devices deployed to sustain the higher load. It is more interesting to compare costs when the same scenario (same traffic requirements) is planned with the number of possible ONU locations (cardinality of $\mathscr{S}_{ONU}$) changing from 10 to 20: deployment costs are lower when more ONU locations are available. Since in this case the solution space is larger, there are better choices to install ONUs and associated gateway devices, thus, the solver selects ONUs closer to the OLT. Furthermore, note that the gap between the two plots increases when the traffic load is higher. In this condition having better ONU candidate sites provides a larger cost margin.

In Fig. 2b the average number of IEEE 802.11 and IEEE 802.16 installed devices is shown under different traffic conditions. Note that, after an initial phase with light load where no IEEE 802.11 device is installed, the number of this type of devices rapidly increases when the traffic increases. Thanks to their lower cost and higher wireless meshing flexibility, IEEE 802.11 devices are preferred when the traffic density to be served increases. The same trend is confirmed by Fig. 2c, where the average percentage in all scenarios of the total users exchanging data using IEEE 802.16 devices is shown.



(a) Network cost vs. traffic load

(b) Number of deployed devices of each type vs. traffic load

(c) Percentage of IEEE 802.16 users vs. traffic load

(d) Number of only-wireless/wired deployed devices vs. trenching cost

(e) OLT-ONU distance vs. trenching cost

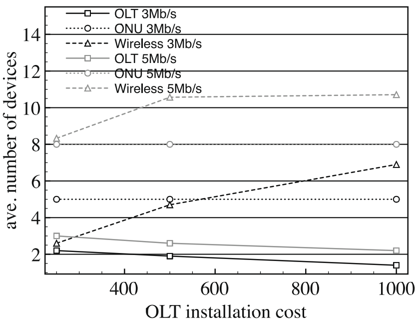
Fig. 2. Evaluation of design parameter effects on the solution.

Finally, it is worth analyzing the impact of the fiber trenching cost on the planned WOBAN. Fig. 2d reports the number of installed network devices versus the fiber trenching cost. Notably, as the trenching cost increases the number of gateway devices (total number of MGs and BSs) decreases due to higher costs. On the other side, the number of only-wireless devices (MRs and RSs) significantly increases. Fig. 2e gives a different perspective of the very same issue by reporting average distance from ONUs to the OLT which decreases when trenching costs are higher. The last two commented figures demonstrate that when trenching costs are considerable, it is preferable to deploy few gateways, close to the OLT, and cover the area with wireless multi-hop networks.

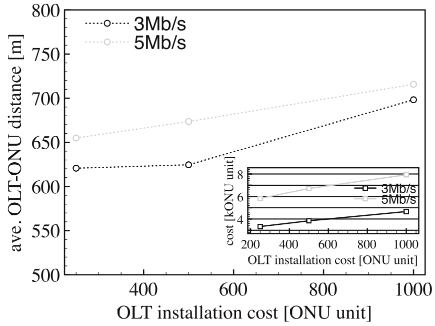
5.2. Considering multiple OLTs

It is interesting to analyze the case where multiple OLTs can be used in the optical segment. To this extent, we randomly identify a set of 5 candidate sites ($\mathscr{S}_{OLT}$) where an OLT can be placed. Each OLT is the root of an EPON with a traffic capacity T^{EPON} of 1 Gb/s that can include up to $F_{OUT} = 32$ ONU stations.

Fig. 3a shows the number of OLTs, gateway devices, and only-wireless devices for three different OLT installation costs, C^{OLT}, and two traffic demands. Note that the number of deployed gateway devices is constant. Roughly speaking, it mainly depends on the total test point demand to be sent to the wired domain, which does not change when the OLT

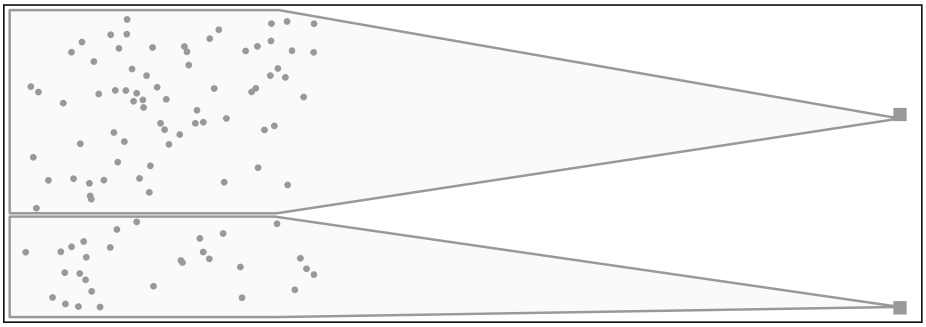


(a) Deployed devices vs. OLT installation cost

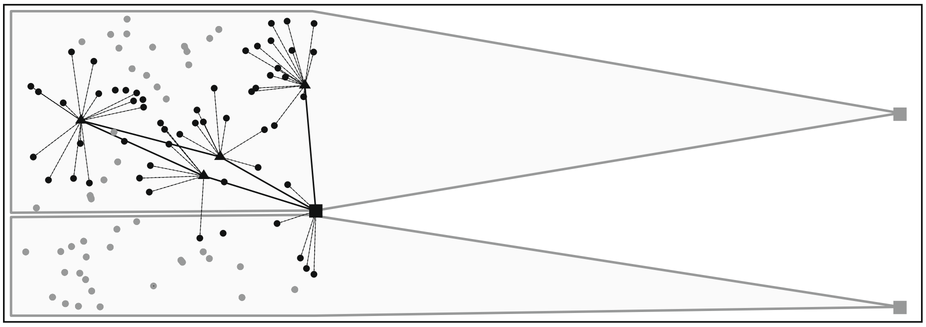


(b) Ave. OLT-ONU distance and network cost vs. OLT installation cost

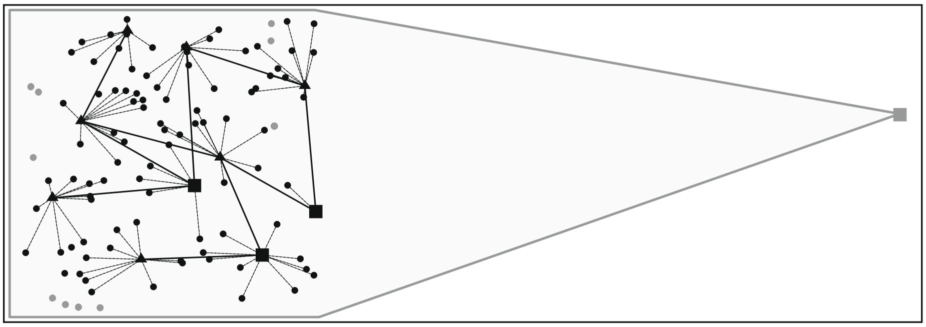
Fig. 3. Multiple-OLT formulation results.



(a) Per-source traffic demand 1Mb/s



(b) Per-source traffic demand 3Mb/s



(c) Per-source traffic demand 5Mb/s

Fig. 4. First deployment example.

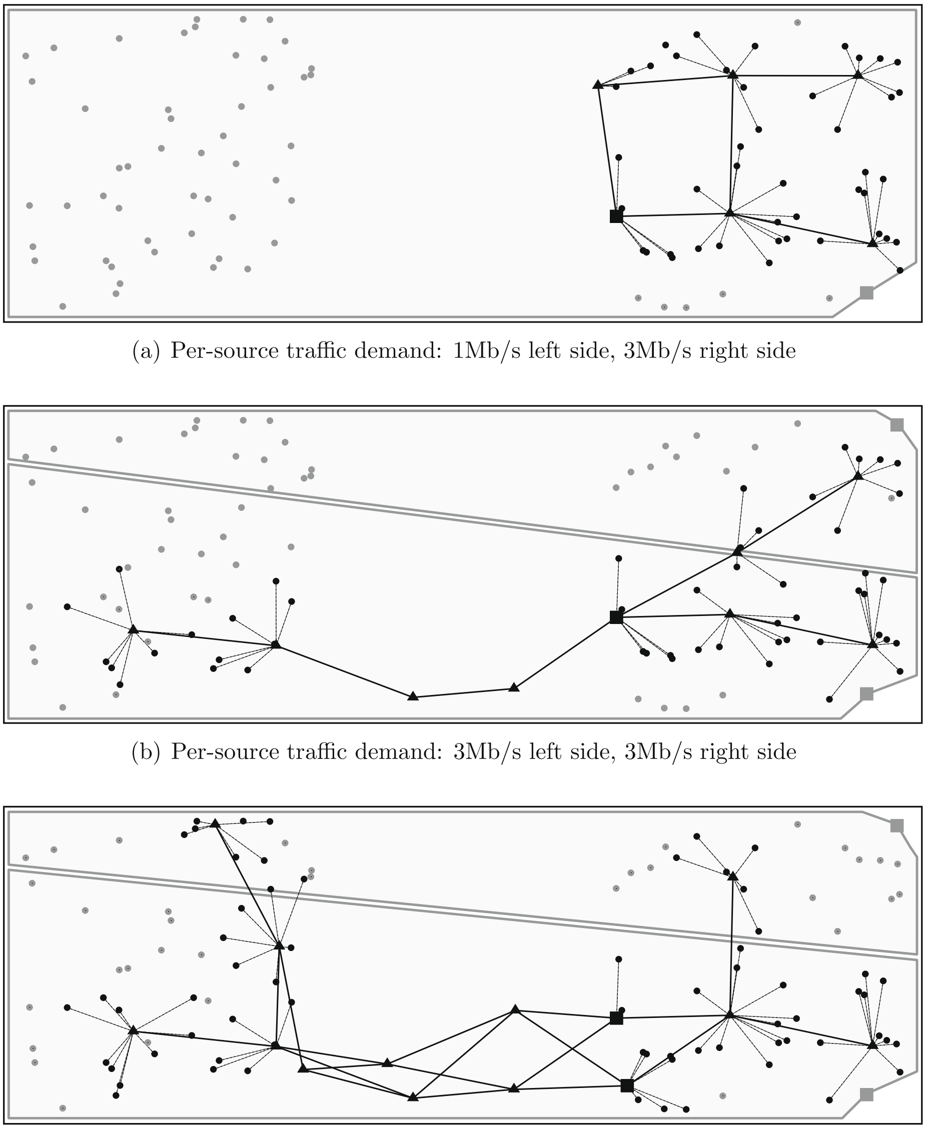
installation cost varies. As installation costs increase, the number of deployed OLTs reduces, therefore, isolated groups of test points are reached preferably using MRs or RSs. Indeed, the number of such devices increases when OLT installation costs rise. Moreover, when the traffic demand grows, the trend is similar, but shifted to higher numbers of deployed devices.

Fig. 3b reports the average distance from an ONU to its associated OLT, as the OLT installation cost increases. The more expensive is installing an OLT, the lower is the number of such deployed devices. Installing few OLTs leads to larger distances to be covered with optical fibers, hence higher trenching expenditures. Therefore, even though fewer OLTs are installed, their augmented cost and the higher trenching expenditure lead to more expensive WOBANs, as shown for our reference scenario in Fig. 3b.

5.3. Deployment examples

We evaluate two scenarios created by horizontally putting side by side three of the 1 km $\times$ 1 km squares mentioned in Section 5.1. Each of the squares is randomly populated with 20 IEEE 802.11 sites (in $\mathscr{S}_{11}$), 5 IEEE 802.16 sites (in $\mathscr{S}_{16}$), while $\mathscr{S}_{ONU}$ is composed of 5 sites both in the left-most and in the right-most squares. The OLT is placed in the middle point of the right side of the right-most square.

The two scenarios differ for the test point distribution. The first scenario has 100 points randomly placed in the left-most square and no one in the others. This is the case when the users to be served are far from the OLT and the project designer must select between installing ONUs close to the OLT and serve users through long wireless



(a) Per-source traffic demand: 1Mb/s left side, 3Mb/s right side

(b) Per-source traffic demand: 3Mb/s left side, 3Mb/s right side

(c) Per-source traffic demand: 5Mb/s left side, 3Mb/s right side

Fig. 5. Second deployment example.

connections, or facing high trenching cost to install ONUs close to the users and then locally collect the traffic. Fig. 4a–c shows the optimum network planning for three traffic conditions. In each figure, test points using IEEE 802.11 technology are represented by black dots, MRs by black triangles, and MGs by black squares. Solid black lines indicate wireless backbone links using IEEE 802.11 standard, while dashed black lines show which MR/MG IEEE 802.11 test points are associated to. Grey squares represent IEEE 802.16 BSs and shadowed areas indicate their coverage areas. Grey dots in such areas are test points using IEEE 802.16 associated to the BS. Note that, when the traffic is low, far test points are preferably covered with IEEE 802.16 BSs served by ONUs installed close to the OLT. As the traffic increases, we need flexible networks able to sustain higher capacities. As a consequence, far test points are served installing ONUs that, although far from the OLT, enable structured wireless mesh networks with IEEE 802.11 devices. The share of the users that use IEEE 802.16 technologies decreases.

In the second scenario the 100 test points are split, 50 in the left-most square and 50 in the right-most. In this case we want to evaluate how the planned network reacts to different traffic distributions within the area to be served. Namely, we evaluated the case where the area close to the OLT has a medium traffic load while the area far away has a light load (Fig. 5a), a high load (Fig. 5c), or both have a comparable load (Fig. 5b). As we can see from the relative figures, when the farthest area has a light load it is served with IEEE 802.16 devices while the closer is covered with IEEE 802.11 wireless mesh networks. As the farthest area's traffic demand increases, a IEEE 802.11-based "bridge" between the two areas begins to appear, and its width is larger and larger as the traffic to be carried increases.

6. Conclusion and future work

In this work, we have addressed the issue of designing the topology of hybrid optical/wireless access networks, which are increasingly deployed to provide residential coverage to metropolitan areas. Mathematical programming formulations have been proposed to automatically plan the topology of hybrid network architectures based on Ethernet-Passive Optical Networks (EPONs) and Wireless Mesh Networks (WMNs) operated according to the IEEE 802.11 and IEEE 802.16 standards. The proposed formulation aims at minimizing the overall network deployment costs, while accounting for the specific service requirements (users' traffic) and the particular characteristics of the different communication technologies, in terms of link capacity, available topologies and deployment costs.

We have finally tested the proposed formulation by solving it to optimality in different realistic scenarios of hybrid networks. The numerical results derived in such analysis showcase the capability of the proposed approach to planning consistent and effective hybrid networks.

Our ongoing work is devoted to the study of methods to extend the automatic planning to very-large scale networks. In particular, we are currently investigating the use of relaxation-based techniques to obtain quality initial solutions to be consequently fed into metaheuristics exploiting the problem structure emerging from the behavior of the solutions shown in Section 5.

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