# Analysis and Dimensioning of Switchless Networks for Single-Layer Optical Architecture

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***Abstract*—The "switchless" all-optical network is an alternative networking approach being developed in the framework of the ACTS project named SONATA, which aims to provide a future single layer, advanced transport architecture on a national scale. The single hop, shared access network employs time and wavelength agility (a WDMA/TDMA scheme), using fast tunable transmitters and receivers, to set up individual customer connections through a single wavelength router (suitably replicated for resilience). The dimensioning of this type of network is one of the main tasks for the design of networks serving a certain number of customers, connected together by means of passive optical networks (PON's). This paper reports an analytical model which allows the network dimensioning according to some relevant design parameters: the number of customers per PON, the number of PON's, the offered traffic per single user (either considering residential or business user), and the required system performance expressed in terms of blocking probability. Furthermore, relevant issues related to the dimensioning of switchless networks are discussed and some results achieved for relevant network scenarios are reported, to assess the feasibility of the system concept.**

***Index Terms*—High-density wavelength-division multiplexing (HDWDM) networks, network dimensioning, Poissonian traffic, switchless network, time and wavelength agility.**

## I. Introduction

THE "SWITCHLESS" network concept was born as a new networking approach with the twofold objectives of drastically simplifying the network structure and of avoiding the need for large and fast switching nodes [1], [2]. The new proposal consists of a single-layer network platform for end to end optical connections, able to serve a large number of terminals for both business and residential customers over a wide geographical area. This multiple access network is based on a single node providing passive routing functions and, optionally, actively controlled wavelength conversion (see [3]–[7]). A hybrid WDMA/TDMA scheme is used [1], [2]. A terminal is connected to the passive router by means of a set of wavelengths each of them carrying a time-division multiplexed (TDM) flow. A connection between two terminals is setup by selecting a time slot on the particular wavelength allowing the correct routing, through the passive node, between the two terminals. This mode of operation requires time and wavelength agile terminals, thus physical switching function is removed from the node and distributed at the terminals.

Although a centralized network control is required, we refer to this network structure as a "switchless" network. The network is "switchless" in the sense that neither electronic switches/cross connects (telephony, IP, ATM, SDH) [8], nor optical cross-connects [9] (except for the wavelength routing node) are required within the network; thus providing major network architecture simplifications and hardware reductions. The use of TDMA for time sharing of wavelength channels allows a very fine bandwidth handling and multipoint to multipoint connections to be supported without the need of multiple transmitters and receivers at the terminals, as in classical optical star structures [10].

The aim of the present work is to provide an analytical model which can be practically used for the dimensioning of switchless networks. Analysis is carried out under the assumption of telephone traffic only with the main scope of demonstrating the system capability and of investigating the main issues related to the system dimensioning, taking into considerations relevant cases of networks. In particular, Section II describes the switchless network structure; Section III reports the model we have developed for the dimensioning of the network, while Section IV shows the results of the analysis; finally Section V reports some general conclusions derived by the analysis of relevant cases.

## II. Network Structure

The switchless network has the target of performing the concentration/distribution, switching and routing functions within a single network layer by providing end to end optical connections between a large number of terminals over a large geographical area.

The structure of the switchless network is shown in Fig. 1. There are $N_p$ passive optical networks (PON's) which are interconnected by a passive wavelength router node (PWRN) [1]. $N_t$ fast tunable terminals are attached to each PON. A PWRN is essentially what is known in the literature as waveguide grating router, or wavelength grating router (WGR). In [11]–[13] design considerations and applications of this type of device are reported. The wavelengths in an access lines connecting each PON with the input port of the PWRN are arranged so that each wavelength allows a different PWRN output port, and consequently a different destination PON, to be reached. In this way, there is a direct connection between any pair of PON's, by means of a dedicated wavelength. Each wavelength channel supports a TDM stream flow. and a time slot in a particular wavelength can

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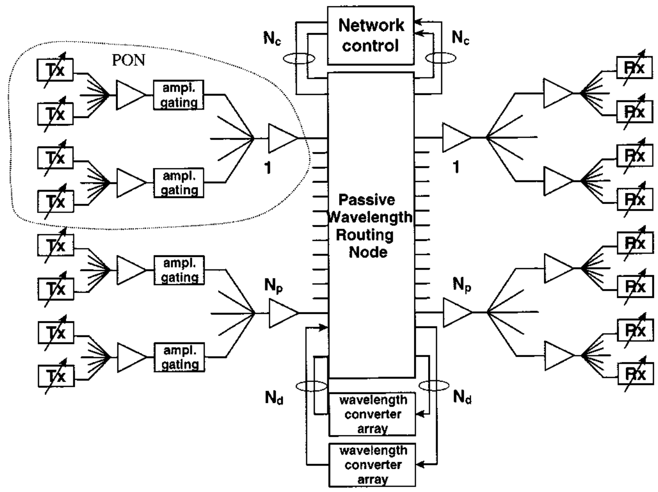


Fig. 1. Structure of the switchless network.

| | | $N_p$ output ports | | | | | | $N_d$ output ports | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| $N_p$ ports input | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | 2 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| | 3 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 |
| | 4 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 |
| | 5 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 |
| | 6 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 |
| $N_d$ input | 7 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 |
| | 8 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 |

Fig. 2. Example of conflict free allocation of wavelengths, for an $8 \times 8$ PWRN with $N_p = 6$ and $N_d = 2$.

be used by only one out of the terminals connected to the same router port. In this way, a user $A$ in PON $\Pi$ can communicate with a user $B$ in PON $\Theta$, through a time slot on the wavelength that links the PON's $\Pi$ and $\Theta$. Typical ranging techniques can be utilized to synchronize all the users.

A centralized network controller (see Fig. 1) has the task of assigning the slots to the users. A signaling protocol is used by the network controller to communicate with all the users, through dedicated channels (i.e., a wavelength channel is devoted to the communications among the controller and all the users belonging to a PON). $N_c$ ports of the PWRN are dedicated to the interconnection between the network terminals and the network controller.

Any pair of terminals wishing to communicate each other simply tunes, in the allocated time slots, its transmitter and its receiver to a known wavelength carrying multiplexed traffic through the PWRN.

In general, cascaded optical amplifiers are required, and in large-split "hyper PON's" a noise gating functional block (see [14] and [15]) has to be introduced after those amplifiers located before the last combiner in the upstream direction, for filtering out-band noise.

To achieve a higher degree of flexibility in the allocation of network capacity, a set of actively controlled wavelength converter arrays can be added in the optical node. The wavelength converter arrays are connected to a certain number $N_d$ of auxiliary ports (named "dummy ports") of a PWRN. In this way, a variable number of wavelengths, depending on the traffic requirements, can be dynamically allocated between a pair of terminal groups. So the total number of ports of the PWRN is: $N = N_p + N_d + N_c$.

To better understand the functionality of the wavelength conversion devices inserted in the node, it is worth making some clarifications. This additional capacity is utilized to support traffic that has overflowed from the wavelengths directly connecting the PON's. In fact, if the capacity of the wavelength directly supporting communications between a pair of PON is saturated, additional connections can be possibly supported by slots carried by the wavelengths connecting the PON's with the $N_d$ dummy ports. A call will be routed from a source PON toward the destination PON, via a proper wavelength conversion, by utilizing a free slot on a wavelength connecting the source PON with a dummy port, and the corresponding slot on the wavelength connecting that dummy port with the destination PON.

In summary, each incoming fiber connected to the PWRN carries $N$ wavelengths each dedicated to the transmission between the relevant input port and a specific output port. Conversely, each outgoing fiber carries $N$ wavelengths that come from different input ports. Each wavelength supports a TDM stream organized in frames of $T$ slots each.

Fig. 2 shows a conflict free allocation of eight wavelengths in a PWRN characterized by $N_p = 6$ and $N_d = 2$ $(N_c = 0)$. The $(i, j)$ entry of the matrix indicates the wavelength connecting the $i$th input port with the $j$th output port. For example, a connection between input 2 and output 5 can take place in three ways: i) via the direct wavelength #4; ii) via the cascade of the wavelengths #6 (connecting the input with the dummy port #7) and, after a conversion, the wavelength #7; and iii) via the cascade of the wavelengths #7 (connecting the input with the dummy port #8) and, after a conversion, the wavelength #6.

Fig. 3 shows an example of architecture of the wavelength conversion block.

As mentioned above, $N_d$ ports of the PWRN are dedicated for the connections with the $N_d$ wavelength converter arrays. A wavelength converter array is composed of a WDM demultiplexer and a set of $N_p$ (where $N_p$ equals the number of the PON's connected to the router) wavelength converters whose output wavelength is controlled by a tunable laser pump. The output signals are then combined in a passive optical combiner and postamplified, by a SOA or other device, to compensate for the combiner losses. The network controller controls the wavelength of the tunable lasers, on the basis of the network configuration requirements. It is to be noted that only $N_p$ lasers are needed since in a line accessing a conversion block only $N_p$ wavelengths will be utilized, one for each PON; so the tunable lasers must be capable to cover the whole available spectrum ($N_p$ wavelengths). It might be possible, by an optimal design of the network controller, to reduce the required tuning range of each laser with a slight degradation in the whole network performance. For example, it may be possible to shrink the tuning range of any laser in the array to a specific bandwidth.

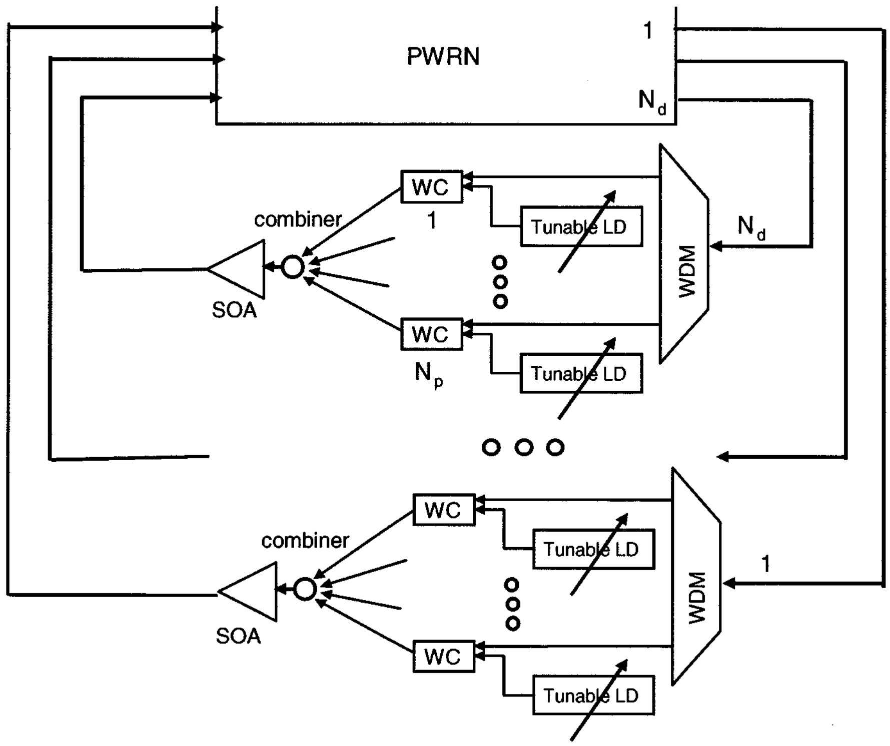


Fig. 3. Architecture of the wavelength conversion block.

An optimum solution for a “switchless” network depends on the size of the network. For instance, a small-scale network for few thousands of terminals could be realized using direct detection receivers with optical filters and simple amplified PON’s, while to cope with a national scale network (millions of customers), a complex solution, such as coherent detection and amplifier gating, should be adopted.

In the framework of the ACTS SONATA project, three relevant cases of networks were studied: small scale, medium scale, and large scale networks. For all the considered cases, a preliminary rough dimensioning was proposed, and the potentiality of the switchless network in all those cases were estimated (see [15]). For example, it was supposed that a small-scale network may support many thousands of customers with guaranteed minimum continuous rates of 20 Mb/s (i.e., regardless of traffic destinations). A consolidated node scale is capable of supporting hundreds of thousands of terminals, while a national scale network can be achieved by the use of amplifier gating in the upstream PON’s, to enable multiple stages of amplified splitters to be coupled into large “hyperPON’s” with around 50 000-way splits. This could provide guaranteed average customer rates of 5 Mb/s (regardless of traffic destinations), and maximum network throughput of 200 Tb/s (with uniform traffic distributions).

Details about the preliminary network dimensioning, which was carried out also considering transmission and technological constraints, are reported in [15].

## III. Modeling for the Network Dimensioning

To assess the feasibility of the switchless network concept, it is necessary to investigate how the network should be dimensioned in terms of available resources (number of wavelength conversion devices with respect to number of PWRN ports), considering relevant scenarios and realistic traffic demands.

As described in the previous section, the switchless network is constituted by a single central node and transmission employs a double multiplexing strategy; one in the time domain and one in the frequency (wavelength) domain. The network is organized so that for each PON-to-PON pair, there is a dedicated wavelength that contains $T$ time slots dedicated to that PON-to-PON connection. Moreover, each PON is connected via $N_d$ dedicated wavelengths, with $T$ time slots too, to the $N_d$ dummy ports of the PWRN and vice versa.

### A. Analytical Modeling

In this analysis, we assume that the network exclusively supports telephone traffic. This choice allows, on the one hand, the utilization of classical and analytically tractable traffic models (i.e., Poisson traffic) and, on the other hand, meaningful results to be reached highlighting the main system properties.

The model assumes that there are $N_p$ PON’s, with $n$ users for each PON, for a total number of users equal to $N_{tot} = n \cdot N_p$. We suppose to have uniform traffic distribution with respect to the input ports and to the output ports; i.e., the total traffic offered to the network is equally distributed between the $N_p$ input PON’s, and the total traffic offered by each input PON is equally distributed toward the $N_p$ output ports.

In order to investigate the network performance, an analytical model was developed, based on a classical approach widely used for analyzing circuit switched networks. In particular, the blocking probability is evaluated as a function of the network resources (number of PON’s, number of dummy ports/wavelength converter blocks) and network requests (number of users). The network dimensioning can be accomplished by evaluating which are the node parameters that guarantee a blocking probability less than a fixed value representing a quality parameter (e.g., $10^{-5}$).

As we are dealing just with telephone traffic, we suppose that the traffic offered by each PON is a Poisson distributed with mean value $A_o$. In addition to this, we suppose that the total traffic rejected by the wavelengths directly connecting a PON with all the others is offered to the wavelengths directed to the dummy ports. This assumption implies that a call is blocked if it cannot be accommodated neither on a slot of a direct wavelength connecting the source and destination PON's nor on a slot of the $N_d$ paths composed of two wavelengths: the first connecting the source PON with a dummy port, the second connecting the dummy port with the destination PON.

An exact computation of the blocking probability would require the solution of a $N_p$-dimensional Markov chain whose number of states would equal $T^{Np}$. Obviously, such a model becomes numerically too complex to be solved if the number of PON's and of time slots exceed few units.

In order to overcome this problem, we analyze a single traffic relation $(i, j)$ between the $i$th input PON and the $j$th output PON and evaluate the blocking probability associated with this relation taking into account the effect of the traffic associated to the other traffic relations. According to the uniform traffic hypothesis this probability also represents the blocking probability associated with the whole system.

Let us introduce the following notations:

- $A_0$ the average traffic intensity offered by an input PON toward a single output PON.
- $A_{0\text{tot}}$ the average traffic intensity offered to the network by all of the input PON's toward a single-output PON, i.e., $A_{0\text{tot}} = N_p A_0$.
- $A_{c1}$ the average traffic carried by a direct wavelength between an input and an output PON
- $A_{0R}$ the average traffic rejected by a direct wavelength between an input and an output PON and offered to the dummy ports.
- $A_P$ the average traffic rejected by all the other direct wavelengths and offered to the dummy ports, i.e., $A_P = (N_P - 1) \cdot A_{oR}$.
- $A_{c2}$ the average traffic carried by the dummy ports
- $A_R$ the average traffic rejected by the system.

The above defined traffic components are depicted in Fig. 4.

In order to analyze the model depicted in Fig. 4, we assume the following simplifying hypotheses:

The wavelengths connecting the source PON to the dummy ports are considered to be blocking free; this assumption allows the evaluation of the blocking probability due to the dummy ports as exclusively depending on the saturation of the slots of the wavelengths connecting the dummy ports with the destination PON's; that means that the dummy ports are considered as a common pool of $N_d T$ channels that can be accessed by all of the PON's.

Traffic refused by the direct wavelengths and offered to the dummy ports ($A_{0R}$ and $A_P$) is represented by means of only its first two moments (i.e., mean and variance); this assumptions allows the application of the equivalent random traffic (ERT) [16] method for the analysis of the blocking probability of the wavelengths outgoing from the dummy ports.

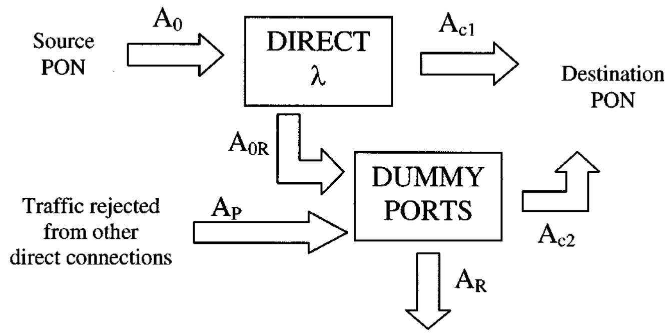


Fig. 4. Schematic of the traffic flows in a switchless network.

The approximate analysis is basically composed of three steps.

1) Evaluation of the loss probability $(\pi_1)$ experienced on the direct wavelengths that is the probability that a generic call from the $i$th input PON and the $j$th output PON will not be accommodated on the direct wavelength connecting them.
2) Evaluation of the traffic rejected by the dummy ports.
3) Calculation of the total loss probability $(\pi)$ that is the probability that a generic call will not be accommodated anyway.

As far as the step 1 is concerned, the direct wavelength connecting the source and the destination PON's can be considered as a group of $T$ servers loaded by a Poisson traffic of mean $A_0$; so the Erlang-B formula [16] can be applied to express the loss probability $(\pi_1)$. Hence

$$\pi_1 = B(A_0, T) = \frac{A_0^T/T!}{\sum_{j=0}^{T} A_0^j/j!}. \tag{1}$$

The mean and the variance of the traffic overflowing the direct wavelength, i.e., $A_{0R}$ and $\sigma_{0R}^2$, are given by [16]

$$A_{0R} = A_0 \pi_1 \tag{2}$$

$$\sigma_{0R}^2 = A_{0R}\left(1 - A_{0R} + \frac{A_0}{T + 1 - A_0 + A_{0R}}\right). \tag{3}$$

It is to be noted that, according to the uniform traffic assumptions, (2) and (3) characterize the first two moments of all of the traffics overflowing from the direct wavelengths. As these traffics are independent, the mean and the variance of the total traffic, directed to a specific PON, offered to the common pool of wavelength conversion blocks, corresponding to the dummy ports of the router, are given by

$$\begin{aligned} A_{0,\,\text{dummy}} &= A_{0R} + A_P = A_{0R} + (N_P - 1) \cdot A_{0R} \\ &= N_P \cdot A_{0R} \end{aligned} \tag{4}$$

$$\sigma_{0,\,\text{dummy}}^2 = \sigma_{0R}^2 + (N_P - 1) \cdot \sigma_{0R}^2 = N_P \cdot \sigma_{0R}^2. \tag{5}$$

This rejected traffic is then offered to the common pool of wavelength conversion blocks, corresponding to the dummy ports of the router, where there are $N_d T$ channels in which it can be accommodated.

It is known that the traffic given by (4) and (5) is peaked (i.e., $\sigma^2_{0,\,\text{dummy}}/A_{0,\,\text{dummy}} > 1$), so, according to the ERT method, it can be thought as the overflow traffic of a group of $N^*$ servers (called preamble system) loaded by a Poisson traffic of mean $A^*$. We can use the preamble system as the traffic generator for the system composed of $N_d$ wavelengths associated to the dummy ports. So, $A^*$ and $N^*$ can be evaluated by solving the following two equation system:

$$\begin{cases} A_{0,\,\text{dummy}} = A^* \cdot B(A^*, N^*) \\ V_{0,\,\text{dummy}} = A_{0,\,\text{dummy}} \left(1 - A_{0,\,\text{dummy}} + \dfrac{A^*}{N^* + 1 - A^* + A_{0,\,\text{dummy}}}\right). \end{cases} \tag{6}$$

Once $A^*$ and $N^*$ are known, the mean value of traffic overflowing the dummy port system is given by

$$A_R = A^* B\left[A^*, (N^* + N_d \cdot T)\right] \tag{7}$$

wherein $B(.,.)$ is the Erlang B formula [16].

Finally, the overall blocking probability presented by the system is

$$\pi = \frac{A_R}{A_{0\text{tot}}}. \tag{8}$$

### *B. The Upgraded Model: The Cascade Method*

The first method takes into consideration just one blocking case, as specified in the hypothesis A, that is just the conflicts on the wavelength connecting the dummy ports with the output PON's are considered. If we want to take into consideration both the conflicts at the input and the output of the recirculating lines, we must consider two different blocking possibilities. This means that we can consider a cascade of two gates in which the offered traffic can be rejected.

In this case the evaluation of the second choice loss probability $(\pi_2)$ is carried out as

$$\pi 2 = 1 - q_{\text{in}*} q_{\text{out}} \tag{9}$$

where

- $q_{\text{in}}$ is the probability that there is at least one slot for access a recirculating line, considering the traffic rejected by the direct connections;
- $q_{\text{out}}$ is the probability that there is at least one slot for exit the recirculating line, considering only the traffic that has passed the input block of the dummy ports.

Notice that even this model is not rigorously exact, since it does not take into account the coincidence of the time slots of the two blocks. In this sense, it is to be expected that the performance results provided by this approach are an underestimate of the actual one.

### *C. Test of the Analytical Models with the Simulation Model*

In order to compare the models described in the previous sections, and to test the reliability of the analytical models, we considered a relevant case of the switchless network and performed the dimensioning using the two reported models. Such results are compared with those arising by simulation. Analytical and simulation results are summarized in Fig. 5. Four curves are plotted, representing the blocking probability versus the number of dummy ports, using four models:

1) the analytical model which uses the ERT method described in Section III-A (A1);
2) the upgraded model which uses the cascaded method described in Section III-B (A2);
3) the actual simulation model;
4) the simulation model without the constraint concerning the coincidence between the time slot of the input and of the output of the wavelength conversion block (S2).

It can be noticed that the results provided by all the models are quite similar. The main point is that there is no difference between A2 and S2: this indicates that the cascade method is quite accurate. So, in the following of the paper we report results obtained using this method.

## IV. Results of Network Dimensioning

To investigate the system performance we consider three scenarios, corresponding to different sizes of the region served by the system; so, we have: a) *large region*, with $N_{\text{tot}}$(large) = 2 000 000 users; b) *medium region*, characterized by $N_{\text{tot}}$(medium) = 150 000 users; and c) *small region*, with $N_{\text{tot}}$(small) = 15 000 users.

Two user classes are considered: *business* and *residential*. The different traffic volumes they generate characterize these user classes. Here we assume that a single business user offers a traffic of $a_{obus}$ = 0.15 Erl while each residential user offers a traffic of $a_{ores}$ = 0.05 Erl. The average call holding time is supposed to be equal for the two user classes. Three user scenarios are analyzed: i) *full residential*, i.e., 100% of residential users; ii) *mixed*, in which residential and business users represent the 78 and the 22% of the total number of users, respectively; and iii) *full business*, i.e., 100% of business users. Finally, users, whichever category they belong to, are supposed to be uniformly distributed over the considered region.

Finally, $T = 1000$ is assumed as the maximum number of slots of the TDM flows dedicated to the telephone traffic on each wavelength of the lines accessing the PWRN. Summarizing, Table I shows the values of number of users and of the mean offered traffics in the three network scenarios.

The system dimensioning is accomplished by evaluating which are the values of the node parameters needed to guarantee a blocking probability less than a fixed value representing a quality parameter (e.g., $10^{-5}$). On the basis of the above mentioned assumptions, the system dimensioning consists in determining the best tradeoff between $N_p$, i.e., the number of PON's serving the region of interest, and $N_d$, i.e., the number of dummy ports needed by the PWRN to satisfy the blocking probability constraint.

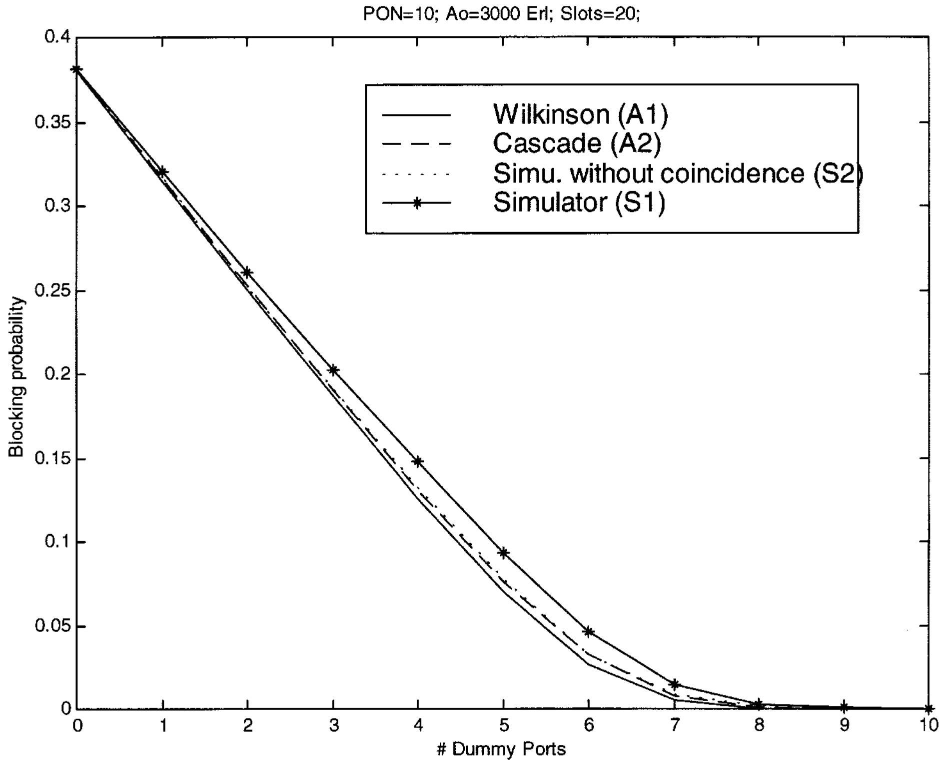


Fig. 5. Comparison among the different models. The blocking probability is reported versus the number of dummy ports, considering four different models.

TABLE I
NETWORK AND TRAFFIC SCENARIOS FOR THE SYSTEM DIMENSIONING

| Network scenarios | | Traffic scenarios | | |
|---|---|---|---|---|
| **Type** | **Number of users** | **Residentia** | **Mixed** | **Business** |
| Small region | 15000 | 750 Erl | 1080 Erl | 2250 Erl |
| Medium region | 150000 | 7500 Erl | 10800 Erl | 22500 Erl |
| Large region | 2000000 | 100000 Erl | 144000 Erl | 300000 Erl |

In order to make the comparison more meaningful among the various alternatives for system dimensioning, we have assumed that the PWRN port capacity $C_s(N_p)$ (expressed in slots) dedicated to the telephone traffic in $s$th scenario $s$ when $N_p$ is the number of PON's, is equal to the minimum between 1000 slots and the minimum value needed to ensure that the loss probability $(\pi_1)$ experienced on the direct wavelengths is less than 0.1. Fig. 6 shows the values of $C_s(N_p)$ in the considered system scenarios. It is to be emphasized that $\pi_1 = 0.1$, that is a typical value assumed for dimensioning telephone systems, is the loss probability of only the direct trunks (the wavelengths directly connecting the PON's), the final loss probability will be evaluated by taking into account the additional wavelengths of the dummy ports.

Let us start with the analysis of the results obtained relevant to the residential traffic scenario.

Although the graphs are not shown here, in case of the small and medium regions, three dummy ports are always sufficient to satisfy the $\pi < 10^{-5}$ constraint. The only exception is represented by the case with $N_d = 1$ in the medium region scenario in which seven dummy ports are needed. Much more resources are needed in case of large region scenario. Fig. 7 depicts, in this case, the blocking probability $(\pi)$ versus the number of dummy ports $(N_d)$.

From Fig. 7, it is clear that as the number of PON's $(N_p)$ increases the number of dummy ports decreases if a blocking probability of $10^{-5}$ has to be reached. However, such a decrease becomes more and more insensitive as the number of PON's increases. In addition to this, we can see that, for a given number of PON's, a certain number of dummy ports exists such that the addition of other ports leads to a rapid decrease of the blocking probability. This threshold effect is due to the Erlang formula whose characteristic presents a sharp knee, if the threshold value is crossed the blocking probability falls rapidly.

A parameter that can be chosen for representing the system cost is the total number of ports $(N_t)$ of the PWRN given by

$$N_t = N_p + N_d. \tag{10}$$

Fig. 8 depicts the behavior of $N_t$ versus the number of PON's $(N_d)$, in the three system scenarios. As it is evident, the curves

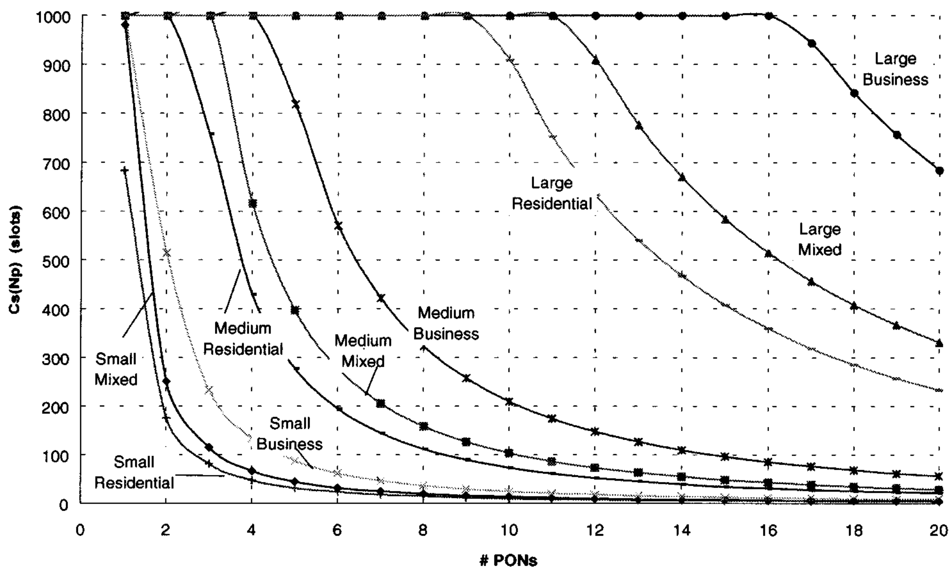


Fig. 6. Number of slots of the PWRN ports versus the number of PON's in the considered system scenarios (constraint: $\pi_1 < 10^{-1}$).

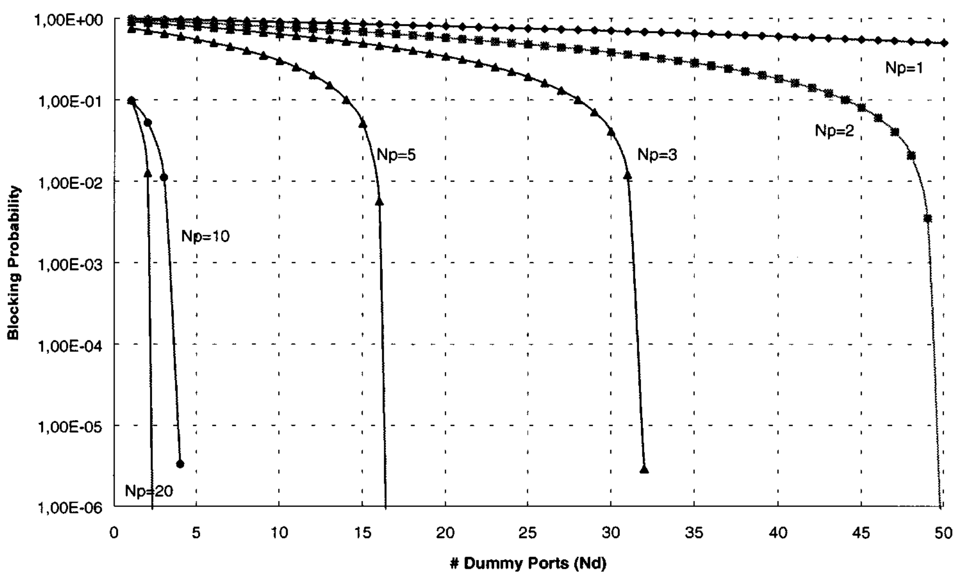


Fig. 7. Blocking probability $(\pi)$ versus number of dummy ports $(N_d)$ in case of large region and residential traffic scenario.

present two zones: i) for low values of $N_d$, the PWRN size decreases as $N_d$ increases and ii) for higher values of $N_d$, the PWRN size linearly increases as $N_d$ increases. The threshold between the two zones represents the optimum system configuration. In order to understand the real potentiality of the switchless network better we calculate the maximum number of users that can be served by the network, assuming a reasonable number of PON's. According to the previous positions, we assume that the blocking probability $(\pi)$ is lower than $10^{-5}$. In Fig. 9 the maximum number of users that can be supported by a PWRN as a function of $N_d$ with a constraint $\pi < 10^{-5}$ versus the number of dummy ports is shown. The curves have been determined considering that the capacity dedicated to the telephone traffic is equal to $T$ = 1000 slots per input/output fiber. The figure depicts three series of curves corresponding to 10, 30, and 50 PON's, respectively. Each series is composed of three curves relevant to residential, business, and mixed scenarios.

It is evident that the maximum number of users increases linearly with the number of dummy ports. The increase rate depends on both the user categories and on the number of PON's. It is worth underlining that the switchless network could support: i) about 10–20 million users if we consider 30 PON's and a PWRN with 20–30 dummy ports and ii) up to 100 million users if user population is divided in 50 PON's and a PWRN with 50 dummy ports is implemented. These data suggest as this kind of system could be used to serve an area comparable with a medium large country.

So far all the results have been obtained by assuming a uniformly distributed traffic. It is clear that in real practice, the traffic can be distributed in many different ways, and it is quite difficult to make a comprehensive analysis. However, a relevant case is represented by the asymmetry, which exists among intraregional traffic and extra-regional traffic. As a matter of fact, it has been observed that the total amount of traffic in a region

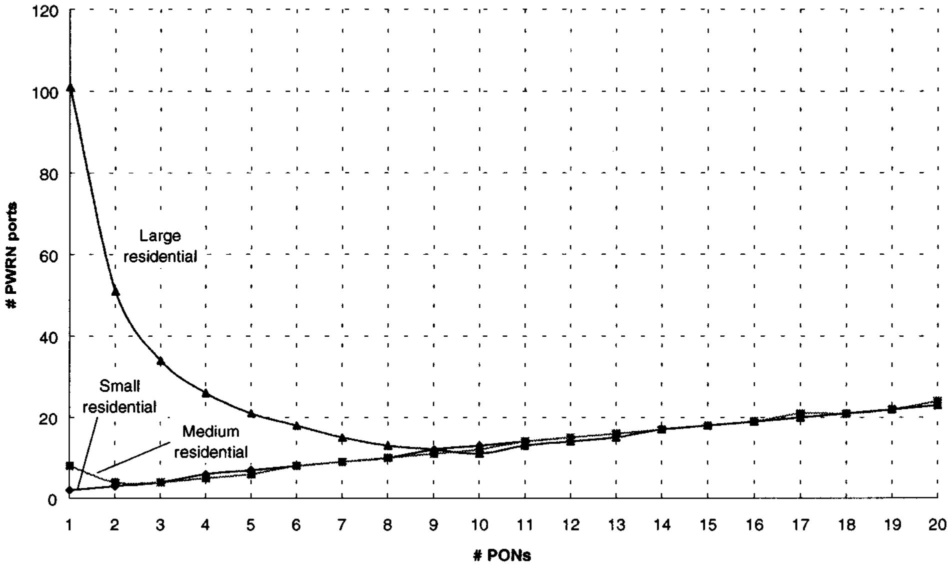


Fig. 8. Total number of PWRN ports $(N_t)$ versus number of PON's $(N_d)$, in case of mixed traffic scenario (constraint: $\pi < 10^{-5}$).

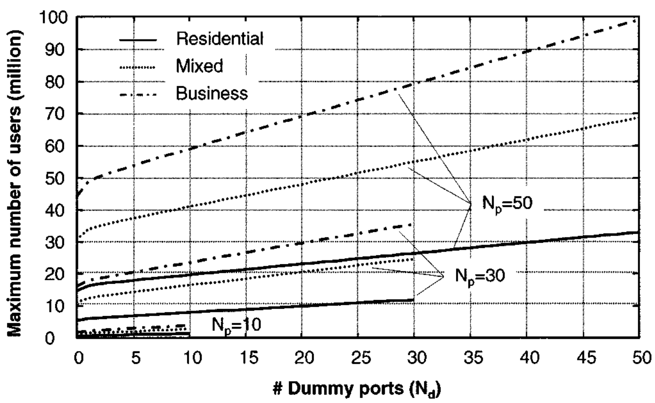


Fig. 9. Maximum number of users versus the number of dummy ports $(N_d)$ for $\pi < 10^{-5}$.

is about the 78%, while the remaining traffic (22%) is traffic toward outer regions [17]. In this condition, the network has to be dimensioned properly. In fact, Fig. 10 shows the blocking probability versus the number of dummy ports, in the large scale network scenario, assuming mixed (residential and business) traffic, in two cases corresponding to a dimensioning which does or does not take into account the traffic imbalance, respectively. It can be seen that the imbalance requires significantly more dummy ports than uniformly distributed traffic. This can be easily explained as follows. The bandwidth resources, in terms of wavelengths, which are dedicated to the PON-to-PON connections, are scarcely utilized when two PON's belong to different regions. At the same time, the connections required in the same region are large enough to saturate the wavelengths used for the direct PON-to-PON connections, and there is a strong need of the wavelengths posed as a common pool through the wavelength conversion blocks.

So far, we have assumed that an optical terminal is at disposal of any user, that is optical equipment with a tunable transmitter and a tunable receiver in each home. This corresponds to the classical fiber to the home (FTTH) approach. However, this solution could be highly costly. An interesting solution is to put the optical network unit (ONU) in a remote node, which serves a certain number of users. In this way, the different users share the costs. On the other hand, it is necessary to consider a drawback that could prevent the switchless network working properly: the block at the ONU that is caused when two or more users wish to communicate in the same time slot. Thus, there are some possibilities that, even if the network would not block a given connection, the ONU block it due to the time slot collision.

In fact, Fig. 11 shows the maximum number of users per ONU which can be set in order to avoid collisions, for different numbers of time slots, considering three different user scenarios, for an ONU blocking probability of $10^{-5}$.

The results show that the effect of blocking at the ONU does not pose significant limitations. The number of time slots, which are necessary to prevent blocking at the ONU, is much less than the number typically used in practical applications. This means that, even alternative access architectures, e.g., fiber to the curb, hybrid fiber coax, etc., can be supported by the switchless network.

## V. CONCLUSION

This paper reports an analytical model that allows system dimensioning of a switchless network to be accomplished, in the case of Poisson traffic. This model has been demonstrated to be in full agreement with a simulation model that we have developed. The number of customers in a PON, the number of PON's itself and the number of recirculating lines (i.e., the number of wavelength conversion blocks) are design parameters that the model can easily deal with.

As a result, the analysis reported here for some relevant cases showed that it is possible to assess the feasibility of the switchless network concept, since there are no constraints in realizing networks covering even large scale areas. Furthermore, it has been demonstrated that the proposed concept is not limited to the fiber to the home architecture, i.e., it is not necessary that

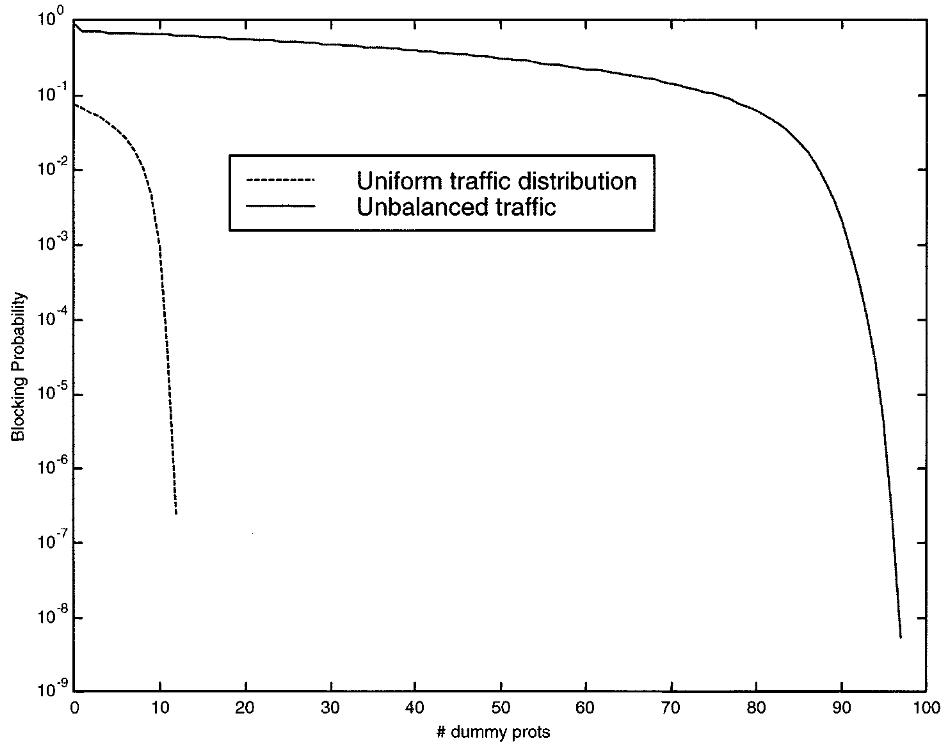


Fig. 10. Network dimensioning in the cases of uniformly distributed traffic and unbalanced traffic. The blocking probability is reported versus the number of dummy ports. The number of users is 20 000 000; the number of PON's is 100, and the number of time slots is 100.

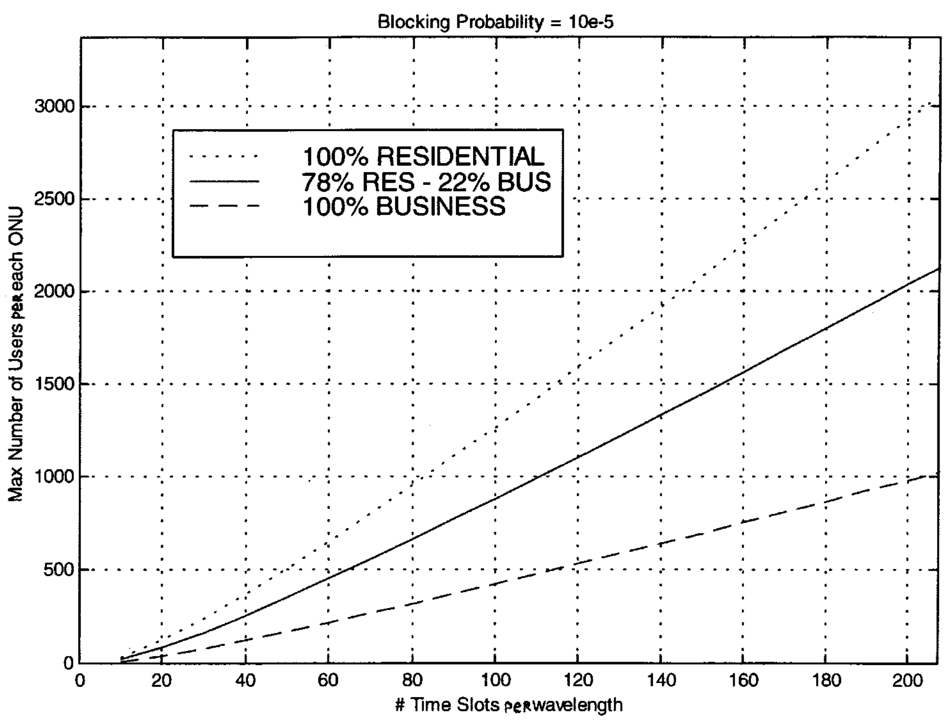


Fig. 11. Maximum number of users that can be handled by the same ONU, for having an access blocking probability at the ONU of $10^{-5}$, as a function of the number of time slots.

any user has the optical network unit (ONU), consisting of tunable optical transmitter and receiver operating in burst mode, at home. Even other access architecture can be supported, since they cause no significant limitations: this is quite important for reducing the costs of the access network itself.


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