

Design of optical content distribution networks for video on demand services

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Abstract This paper presents the design of optical content distribution networks for video on demand (VoD) services. The proposed Ethernet-based WDM network architecture is decentralized and consists of independent regional ring networks with locally deployed video servers. Based on an Integer Linear Programming (ILP) model, a network design tool, minimizing the total installation cost for optical network equipment on the metro and the Hybrid Fiber Coax (HFC) access network, has been developed. Unicast as well as broadcast VoD services are taken into account. The influence of different parameters in our traffic and content models on the network design is studied.

Keywords Network design · Gigabit Ethernet · WDM · Video on demand

Introduction

Nowadays video on demand (VoD) is emerging as one of the most promising interactive services. Until recently however, no successful VoD services have been observed in Europe, due to high deployment costs. Higher numbers of consumers with broadband connectivity and more competitive technologies now enable operators to bring high-quality multimedia applications to the customer's home.

The introduction of Gigabit Ethernet (GbE) transport over WDM networks offers high bandwidth streaming opportunities for VoD services. When designing the transport network

that supports these services, it is important to decide where to place the video servers, the WDM equipment, and the switches on the network. The installation cost on the access network, like for QAM devices on a Hybrid Fiber Coax (HFC) network, also has to be taken into account.

One of the most important VoD services is interactive VoD (iVoD), also called real VoD. Customers can select any available movie or program at any time on their TV screen and pause, fast forward, or fast rewind as they please. This approach is different from near VoD (nVoD), where movies only start at specific times and no interaction from the customer can be supported. Where nVoD can be broadcast to the users, the more user-friendly iVoD service requires bandwidth-intensive unicast streaming.

The successful introduction of Content Delivery Networks (CDNs) for the delivery of this kind of high-quality multimedia content has proven that a decentralized approach is most efficient. Deploying smaller, local servers appears to be more favorable than using a single server architecture, once the number of subscribers is sufficiently high [1]. Significant savings in the transport network compensate the installation and maintenance costs for extra servers. Introducing local servers also reduces latency and improves the overall quality-of-service. In this paper, we therefore introduce video servers at regional (metro) ring networks, thus offloading the national (core) backbone. A possible network architecture is shown in Fig. 1.

The transport network (core and metro) is based on optical fiber and has high transport capacity. The access network can be based on old copper twisted pair technology, with limited capacity. Asynchronous Digital Subscriber Line (ADSL) technology is sufficient for one VoD stream per household, so no access upgrade is required (only when multiple broadband services would be offered) [1]. In cable networks, extra QAM devices have to be installed on the HFC access networks to

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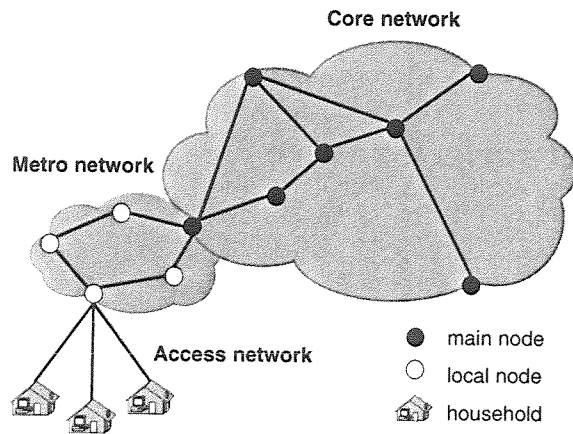


Fig. 1 General network architecture (the transport network is divided into a core network and local metro networks)

support additional RF channels for the VoD services. The network dimensioning for VoD services considered in this paper will consequently focus on the metro and access network. Since no upgrade on DSL access networks is necessary, an HFC access network architecture will be studied.

In our model, the optimal number of servers and their positioning in the local metro networks is determined. Each of the local nodes in Fig. 1 is a candidate node for placing a video server. The installation of additional switches and WDM network equipment in these local nodes will be investigated as well.

In discovering the most optimal design, issues like viewing behavior, grooming strategies, statistical multiplexing, and Erlang modeling are brought into play.

The rest of this paper is organized as follows. First some issues on the traffic model are discussed. Afterwards we present a basic Integer Linear Programming (ILP) model for the design of the metro network for iVoD services only. A linear network model is built and the necessary GbE and WDM restrictions are integrated in it. Finally, a network design tool, based on heuristics derived from the ILP model, is introduced. Simulations with this tool allow us to study different VoD services and the influence of network and user parameters.

Traffic model

Daily user behavior for video on demand is shown in Fig. 2a, characterized by peak values between 8 and 9 pm. The weekly VoD behavior shows that Saturday is the most popular day (Fig. 2b).

Combining both figures learns that about 5% of all weekly download requests are made during peak hour on Saturday night [2].

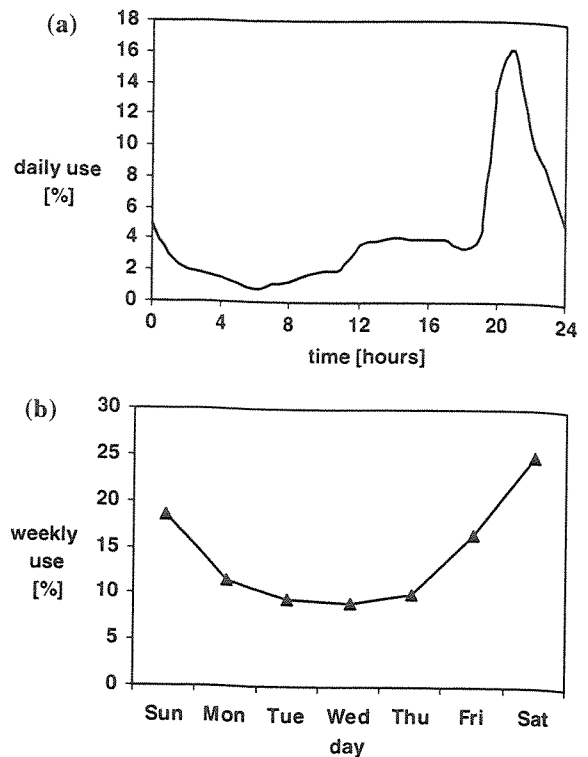


Fig. 2 Viewing behavior for video on demand: daily (a) and weekly (b) (peak traffic occurs on Saturdays, between 8 and 9 pm)

Currently about 1.5–3 movies are watched per month, per subscriber. In our model, we assume that 5% of all VoD subscribers watch a video simultaneously during peak hour. The network should therefore be designed to cope with this peak traffic.

In a typical HFC access network architecture, users are grouped together at an optical node (on a coax trunk), while multiple nodes are combined at one head end (on a fiber network). About thousand users (“homes passed”, HP) per node and several tens of nodes per head end are average numbers. Dedicated QAM RF channels for the video traffic on the HFC network have to be present. These channels account for an additional installation cost for QAM devices at the head ends. To determine the exact number of extra RF channels, a traffic model similar to the Erlang model for telephony has been studied.

Erlang model

In the Erlang model for telephony, the traffic intensity is defined as the average number of calls simultaneously in progress during a particular period of time. It is measured in units of Erlang. The assumptions for the traffic model for telephony are also valid for VoD services:

1. pure-chance (Poissonian) traffic: the arrivals of user requests are independent.
2. statistical equilibrium: statistics do not change during peak hour.

The traffic intensity per optical node can easily be calculated. Of all 1000 HP at one node, only a fraction will be VoD subscribers. When eventually one third of all users become VoD subscribers and 5% of them watch a movie at peak hours simultaneously, about 17 simultaneous video sessions will be present on average. A linear approximation of the Erlang lost-call formula, determining the number of required video slots N , when 99% of all requests have to be served successfully, is

$$N = 6 + A/0.85, \quad A < 75, \quad (1)$$

where A is the traffic intensity in Erlang. This means that according to Erlang's model 26 video channels have to be available, for an average number of 17 simultaneous requests. Depending on the QAM modulation techniques used, about 38 (64-QAM) to 51 Mb/s (256-QAM) is available per RF channel. This way 10–13 MPEG-2 streams at 3.8 Mb/s can be carried. In case of 64-QAM modulation, Erlang's model asks for 3 RF channels per node. Therefore, QAM devices with on average 150 RF channels should be installed additionally on every head end (with 50 optical nodes) for iVoD services. We assume that QAM devices with one GbE input ports and a fixed number of RF output ports are available.

On the metro network, traffic from different nodes can be aggregated at the head end, so that a statistical multiplexing gain can be achieved [3]. While the necessary capacity at the node level is more than 50% higher than the average value (26 video channels needed for an average value of 17 simultaneous streams), the aggregated capacity is only 8% higher at the head end level (903 channels needed for an average of 833 requests, for 50 nodes). The reason for this is that, for large values (where the Erlang model can be approximated by the normal distribution), the variance follows a square-root dependency, while the average traffic volume grows linearly [4].

Content popularity

The popularity of the content is modeled by a Zipf-like distribution. In such a distribution the request rate for the i -th most popular file is proportional to $i^{-\beta}$, with β generally about 0.7, according to [5] and our own measurements on several popular P2P file sharing applications [6]. Figure 3 shows the cumulative request rate for different values of the Zipf parameter. When β is 0.7 and 200 files are available, half of the requests are made for the 33 most popular files.

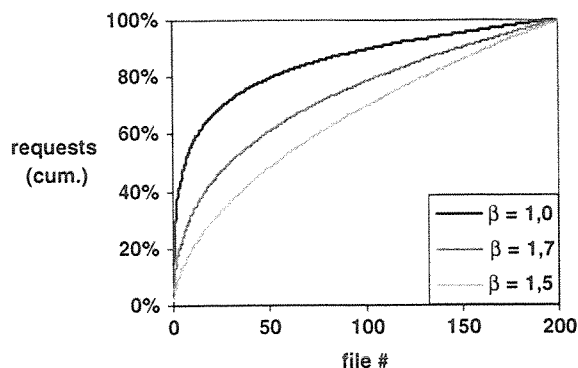


Fig. 3 Zipf-like file popularity (videos are ranked according to popularity)

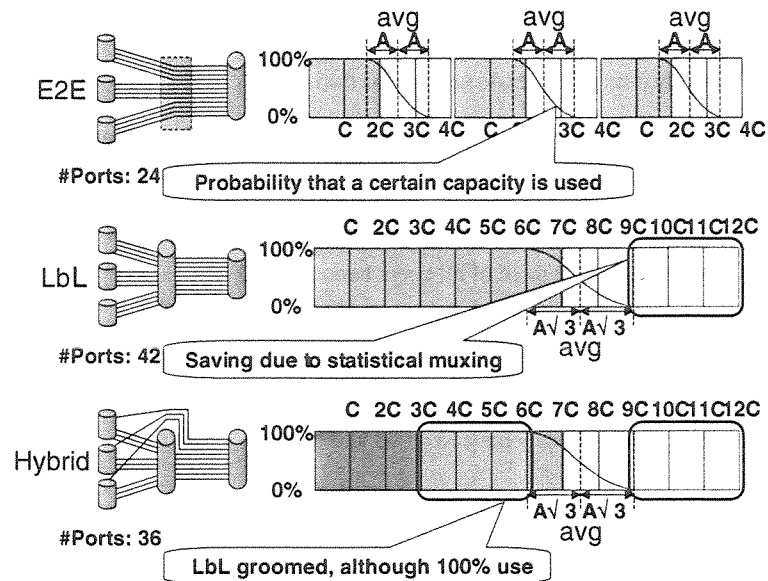
Traffic grooming

Another key issue in network design is to groom the traffic in such a way that a good compromise between capacity efficiency and node cost can be achieved. Two extreme strategies exist: end-to-end (E2E) and link-by-link (LbL) grooming. In E2E grooming, a dedicated logical link is used for each traffic demand, while in LbL grooming, each network node terminates all logical links entering that node.

In the Erlang model, we have indicated the variable nature of the aggregated video traffic. Therefore, we will use E2E grooming only for all completely filled GbE links. The GbE links that are not always completely filled, due to the traffic variability, are combined and sent LbL (i.e., through the switches). This strategy is called hybrid grooming [3].

An example is given in Fig. 4. The demands from the left nodes (e.g., the head ends) to the right node (e.g., the server) require on average 2.5 circuits (e.g., GbE signals), but only a capacity of $2.5C - A$ is (almost) always needed, while up to $2.5C + A$ is sporadically required. We assume that in 99% of all cases, the actual demand is in the interval $[2.5C - A, 2.5C + A]$. In case of E2E traffic, $3 \cdot 4 = 12$ circuits are cross-connected in the middle node. In the LbL grooming case, only $7.5C + \sqrt{3}A = 9$ circuits are needed (if $A \leq 1.5/\sqrt{3}$), but 18 extra GbE ports are required in the middle node. In the hybrid strategy, the completely filled circuits are cross-connected, while the partially filled circuits are sent link-by-link. This way six GbE ports are saved in the middle node. Note that cross-connecting a second circuit per demand would probably also make sense, since these circuits are also nearly completely filled. This requires an additional circuit between the middle and the right node, but it saves six GbE ports in the middle node. The optimal case will then depend on the costs of GbE ports in the middle node (e.g., switch ports) compared to GbE ports in the right node (e.g., server ports).

Fig. 4 Different grooming strategies (the hybrid strategy combines the benefits of end-to-end and link-by-link grooming)



ILP model

To determine the optimal placement of video servers, switches, and WDM equipment on the local nodes of each metro network in Fig. 1, an ILP model for this dimensioning problem has been formulated. This model will describe the iVoD traffic on the metro network only.

In an ILP model, the network and the traffic on it must be described by linear equations with integer coefficients. First some assumptions about the different network technologies are given. Afterwards the objective function and the network restrictions for the actual ILP formulation are presented. Finally, a standard network configuration will be simulated and examined.

Network model

The modeling of the Ethernet over WDM technology is done in a multi-layer structure. Every network link consists of a number of fibers, each with a fixed number of wavelengths on it. On these wavelengths, GbE signals carrying the video streams can be transported. We assumed a CWDM technology, for the benefits of reduced hardware costs and low power dissipation on these short-haul metro networks. In our simulations eight wavelengths per fiber are supported. Each of these wavelengths can carry two GbE signals. The top layer is responsible for the transport of the individual streams (e.g., 300 MPEG-2 streams per GbE signal).

Each of the layers has its own equipment, with different equations describing them. We assume that the servers and the switches have GbE ports. Different CWDM network elements are used for multiplexing: mux1 combines the wavelengths on one fiber (WDM layer), mux2 combines the GbE signals in one wavelength (GbE layer).

Before the ILP formulation is given, extra server and destination nodes are added to the network and the links are split up into GbE layer signals (Fig. 5).

Each of the links at the bottom side in Fig. 5 can now transport one GbE signal. GbE signals coming from the server are either sent to switch ports (“switch nodes”) or not (“non-switch nodes”) and further on to the client nodes. The value of n_{max} depends on the number of fibers, wavelengths and GbE signals per link. In our simulations (one fiber with eight wavelengths, each with two GbE signals) n_{max} is 16.

ILP formulation

The objective function and the restrictions for the ILP formulation of the problem are given in this section. First the necessary symbols are introduced.

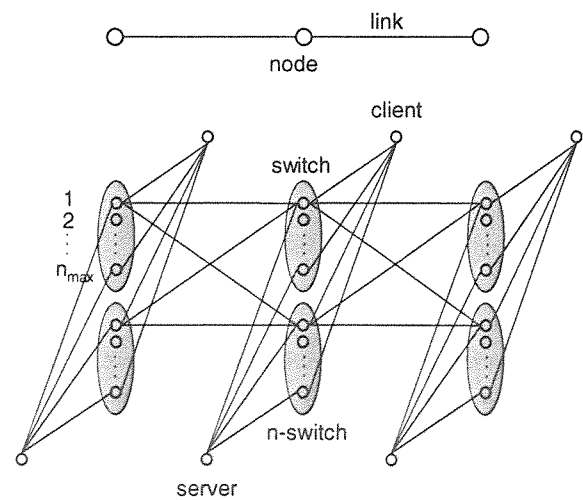


Fig. 5 The network links (top) are split up into GbE level links (bottom). Each network node (top) is split up into a server node, a client node, switch nodes and non-switch nodes accordingly (bottom)

Table 1 Symbols for the ILP formulation

Input parameters	Solution
v_d , number of streams for destination d	p_s , number of ports used at server s
i_s , installation cost for server s	m_{1n} , number of mux1 used at node n
c_s , cost for a server port	m_{2n} , number of mux2 used at node n
c_{m1} , cost for a mux1	g_n , number of switch ports used at node n
c_{m2} , cost for a mux2	
c_x , cost for a switch port	

(1) *Symbols.* The network nodes $n \in N$ are now split up in server nodes $s_n \in S$, destination nodes $d_n \in D$, switch nodes $x_n^1 \in X^1$ and non-switch nodes $x_n^0 \in X^0$.

Each GbE link $e \in E$ carries v_e simultaneous video streams, of which $v_{e,d}$ are for destination node d . If v_e is larger than zero, the link e is in use: $b_e = 1$ (else $b_e = 0$).

If a server s_n has to be placed in node n , $b_s = 1$ (else $b_s = 0$). The input parameters and the variables describing the final solution are explained in Table 1.

I_n contains all incoming links of node n , O_n all outgoing links.

(2) *Objective function.* The objective function that has to be minimized represents the installation cost of all network elements. It is given by

$$\min \left(\sum_{s \in S} (i_s b_s + c_s p_s) + \sum_{n \in N} (c_x g_n + c_{m1} m_{1n} + c_{m2} m_{2n}) \right) \quad (2)$$

Equation (2) consists of two parts. The first part determines the installation costs and the costs for the GbE ports at the servers. The second part gives the costs of the WDM equipment and the GbE ports at the switches.

(3) *Restrictions.* While minimizing Eq. (2), several restrictions have to be taken into account. These constraints, explained below, describe the traffic flow, the GbE and WDM technology limitations and network equipment.

(a) *Capacity restrictions.* The maximum number of streams per GbE link and the maximum number of server ports are given by (e.g., $v_{\max} = 300$):

$$\sum_{d \in D} v_{e,d} \leq v_{\max} b_e, \quad \forall e \in E \quad (3)$$

$$\sum_{e \in O_s} b_e \leq s_{\max} b_s, \quad \forall s \in S. \quad (4)$$

The binary variables b_e and b_s are now automatically forced to 1 if traffic is present on link e or out of server s respectively.

(b) *In/out restrictions.* In/out restrictions make sure that the streams reach their destination through the network. Equation (5) takes care of server nodes, Eqs. (6)–(8)

describe the behavior of switch nodes, Eqs. (9)–(11) are used for non-switch nodes and Eqs. (12)–(13) for destination nodes.

$$\sum_{s \in S} \sum_{e \in O_s} v_{e,d} = v_d, \quad \forall d \in D \quad (5)$$

$$\sum_{x \in X_n^1} \sum_{e \in I_x} v_{e,d} = \sum_{x \in X_n^1} \sum_{e \in O_x} v_{e,d}, \quad \forall d \in D, \quad \forall n \in N \quad (6)$$

$$\sum_{e \in I_x} \sum_{d \in D} v_{e,d} \leq v_{\max}, \quad \forall x \in X_n^1, \quad \forall n \in N \quad (7)$$

$$\sum_{e \in O_x} \sum_{d \in D} v_{e,d} \leq v_{\max}, \quad \forall x \in X_n^1, \quad \forall n \in N \quad (8)$$

$$\sum_{e \in I_x} v_{e,d} = \sum_{e \in O_x} v_{e,d}, \quad \forall d \in D, \quad \forall x \in X_n^0, \quad \forall n \in N \quad (9)$$

$$\sum_{e \in I_x} b_e \leq 1, \quad \forall x \in X_n^0, \quad \forall n \in N \quad (10)$$

$$\sum_{e \in O_x} b_e = \sum_{e \in I_x} b_e, \quad \forall x \in X_n^0, \quad \forall n \in N \quad (11)$$

$$\sum_{e \in I_d} v_{e,d} = v_d, \quad \forall d \in D \quad (12)$$

$$\sum_{e \in I_d} v_{e,d'} = 0, \quad \forall d \in D, \quad \forall d' \neq d. \quad (13)$$

Equation (5) states that every destination node has to be served from (any of) the potential servers. In Eq. (6) it is made sure that all incoming traffic in the switch nodes has to leave on the outgoing links of one of the switch nodes. Per switch node, the total amount of in- and outgoing video streams has to be limited by v_{\max} through Eqs. (7) and (8). Similar restrictions can be found at the non-switch nodes, but the incoming traffic on a non-switch node has to leave on the outgoing links of the same non-switch node, because of Eqs. (9), (10) and (11). Equation (12) ensures that every destination node receives the requested streams on its incoming links (and no other traffic: Eq. (13)).

(c) *Equipment restrictions.* The equations for the WDM equipment are described below. The parameters n_1 and

n_2 indicate the maximum number of wavelengths per fiber (e.g., 8) and the maximum number of GbE signals per wavelength (e.g., 2) respectively.

$$\sum_{x \in X_n^l} \sum_{e \in L_x} b_e + \sum_{x \in X_n^0} \sum_{e \in L'_x} b_e \leq n_2 m_{2n}^l, \quad \forall n \in N \quad (14)$$

$$\sum_{x \in X_n^l} \sum_{e \in R_x} b_e + \sum_{x \in X_n^0} \sum_{e \in R'_x} b_e \leq n_2 m_{2n}^r, \quad \forall n \in N \quad (15)$$

$$\sum_{x \in X_n} \sum_{e \in L_x} b_e \leq n_1 n_2 m_{1n}^l, \quad \forall n \in N \quad (16)$$

$$\sum_{x \in X_n} \sum_{e \in R_x} b_e \leq n_1 n_2 m_{1n}^r, \quad \forall n \in N. \quad (17)$$

Equations (14) and (15) determine the number of GbE layer multiplexers (mux2) at both sides of node n . The total number of GbE signals that have to be (de-)multiplexed in this layer can be found by counting all signals going through the switch nodes (L_x) and all signals passing through non-switch nodes, coming from the server or going to the destination node (L'_x). GbE signals that are just passing through the node (end-to-end signals) remain in the WDM layer. Since all signals have to be counted for WDM layer multiplexing, Eqs. (16) and (17) are more straightforward.

- (d) *Type restrictions.* The types of the different variables are described in Eqs. (18).

$$v_{e,d} \text{ integer}, \quad \forall e \in E, \quad \forall d \in D \quad (18)$$

$$b_e, b_s \text{ binary}, \quad \forall e \in e, \quad \forall s \in S \quad (18')$$

$$m_{1n}^l, m_{1n}^r, f_n^l, f_n^r \text{ integer}, \quad \forall n \in V. \quad (18'')$$

- (e) *Solution.* The number of server ports, switch ports, and WDM elements for each of the network nodes are given by the following equations:

$$\sum_{e \in O_s} b_e = p_s, \quad \forall s \in S \quad (19)$$

Table 2 Input parameters

Equipment cost		Number of HP	
Installation server	25 u	head end A	100 k
1 server port	25 u	head end B	45 k
1 switch port	1 u	head end C	20 k
1 mux1	4 u	head end D	55 k
1 mux2	2 u	head end E	15 k
		head end F	65 k

$$\sum_{x \in X_n^l} \left(\sum_{e \in L_x} b_e + \sum_{e \in R_x} b_e \right) = g_n, \quad \forall n \in N \quad (20)$$

$$m_{2n}^l + m_{2n}^r = m_{2n}, \quad \forall n \in N \quad (21)$$

$$m_{1n}^l + m_{1n}^r = m_{1n}, \quad \forall n \in N. \quad (22)$$

Equation (19) determines the number of server ports by counting the occupied outgoing GbE links of each server. Equation (20) gives the switch port count. The number of multiplexers for the WDM and GbE layers is shown in Eqs. (21) and (22).

Simulations

Simulations based on this ILP model were performed on a metro ring network with six head ends and an average user population. Before the results are studied, the input parameters are given.

(1) *Input parameters.* As indicated before, the available movies are MPEG-2 coded, so that 300 videos can be transported in one GbE signal. Two GbE signals are combined in one wavelength and eight CWDM wavelengths are multiplexed in one fiber. Possible equipment costs (in base units u) and number of HP on the head ends are summarized in Table 2.

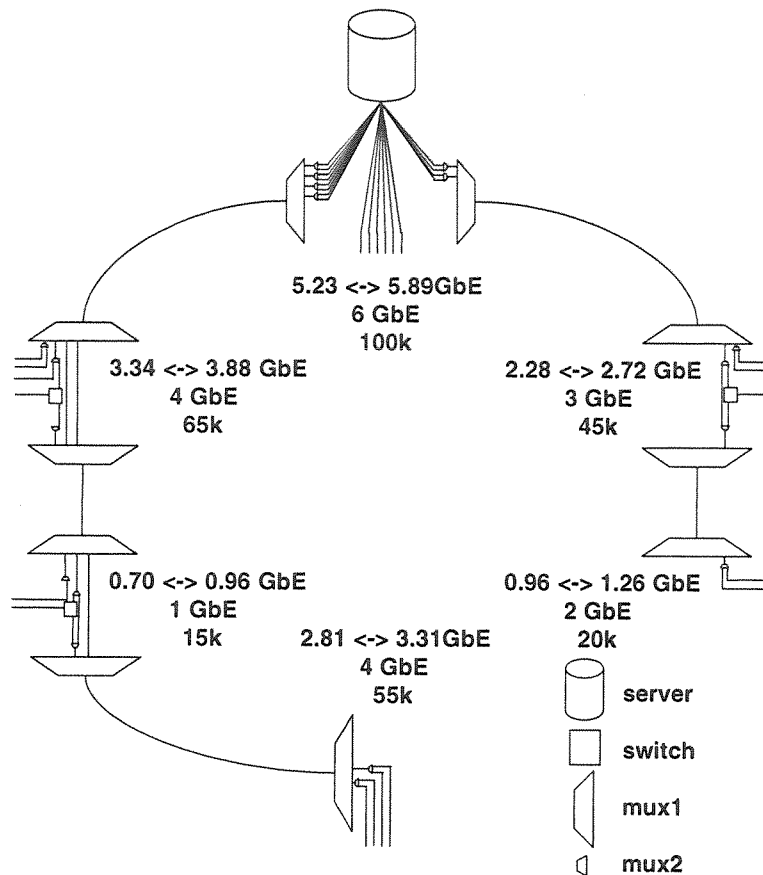
(2) *Results.* The design for the ring network with the above-mentioned parameters is shown in Fig. 6. At each of the head ends, the amount of expected traffic in GbE signals (99% interval), the maximum number of GbE signals and the number of HP are given. The upper border of the 99% interval is used as the input parameter for the ILP model (v_d in Eq. (5)).

We notice that all GbE signals that are completely filled with video streams are sent end-to-end (E2E), while not completely filled GbE signals are combined at the server and split at several switches at the head ends (LbL). This corresponds to the hybrid grooming strategy proposed in our traffic model.

In this case, only one video server is installed on the network, in the head end with most users. In three head ends, a 3-port switch for link-by-link traffic has to be installed. The total cost on the metro network for this design is 560 u (25 u server installation cost, 450 u server port cost, 9 u switch port cost and 76 u CWDM equipment cost) to offer iVoD services to 100 k subscribers (33% of all 300 k HP). An additional cost for QAM devices with three RF channels per node on the HFC network, or 900 RF channels in total, also has to be taken into account. The cost for one RF channel can be estimated at about 0.5 u , so the total cost for the access network part is 450 u .

The total installation cost is therefore 1010 u , about 0.01 u per subscriber.

Fig. 6 ILP solution for a ring network with 6 head ends (installation of servers, switches and WDM equipment)



Network design tool

Since this network design problem is an NP-complete problem, calculation times for the ILP model are increasing exponentially for larger networks or growing user demands. Besides that, no (straightforward) linear equations can be introduced to include regeneration of optical signals in this model. Furthermore, the ILP model does not take statistical multiplexing on the metro network itself into account. As input parameters for the demand per head end, the upper border of the 99% interval is used and the aggregated traffic for multiple head ends is determined as the sum of those values. According to our Erlang model however, the variance for the aggregated traffic (and thus the upper border of the 99% interval) is relatively smaller than for the individual demands.

Therefore, a network design tool, based on a simplified version of the ILP model, has been developed. The main focus of the heuristic for this tool is on minimizing the major costs: number of server ports and number of RF channels. The only differences with the exact ILP solution can be found in the placement of the CWDM equipment. As a result, the heuristic is maximum 1% less optimal than the ILP solution (if only iVoD is considered), as the simulations show (see below).

Other VoD services than iVoD will also be discussed, as well as their impact on the installation cost on the access network.

Calculation times are never longer than several minutes for the simulations presented in this paper, while the ILP model sometimes needed more than a day.

Heuristic

The tool makes use of an exhaustive strategy to find the optimal design of the network. All possible combinations of server placements and choices for VoD services are calculated. For each of these combinations the optimal installation of CWDM equipment and switch ports is determined, as described below. Of all possible configurations, the cheapest one is chosen as the final design.

First we describe how traffic for the different VoD services is handled.

- (1) *Unicast*. A first part of the algorithm describes how it deals with unicast traffic, like iVoD. Totally filled GbE signals are sent end-to-end (E2E) from the server to the head ends. For the partially filled GbE signals, sent link-by-link, a similar approach as in the ILP model is used. From the simulations of the ILP model, we learned that

for similar input parameters as described in Table 2, the number of switch ports needed per head end is either 0 (no GbE signals switched), 3 (one GbE signal switched), 4 or 5 (two GbE signals switched), never more. Therefore, the strategy shown in Fig. 7 is used.

The partially filled GbE signals at the head ends are combined at the server in groups of one or two GbE signals. At the right side of Fig. 7, one GbE signal is sufficient ($0.2 + 0.7 = 0.9$), while two GbE signals are sent link-by-link at the left side ($0.6 + 0.5 + 0.8 = 1.9$), together with one end-to-end signal (0.8 GbE). This way four server ports are enough to handle the LbL traffic.

When the route of all GbE signals is determined, the necessary CWDM equipment is added accordingly. This equipment now also includes elements for regeneration of the optical signals (e.g. every 80 km), at a cost of about 2 u per wavelength.

- (2) *Broadcast*. Unicast services, like iVoD, are much more user-friendly than broadcast services, since video streams can be paused, forwarded or rewinded at any time. iVoD streams are sent on different unicast RF channels to all nodes. Broadcast traffic (nVoD) however requires much less bandwidth on the transport network, since all user requests during a certain period are served at once after a fixed “stagger time” (e.g., 15 min). This way only six

copies of each nVoD video of 90 min are present on the network at any given moment, probably much less than the number of simultaneous requests for that video (see also Fig. 9). A problem here is that broadcast channels have to be available at the HFC network. RF channels carrying nVoD traffic can then be split at the head ends and sent over broadcast channels to all nodes connected to that head end, as shown in Fig. 8.

Other solutions, like virtual VoD (vVoD, a VoD solution similar to Switched Broadcast [7]), try to combine the benefits from both worlds. The videos are still broadcast on the WDM network, but with a shorter stagger time (e.g., 5 min, this means 18 copies of each 90' video), and only the locally requested videos are streamed on the access network, so that no broadcast channels have to be available. This however requires intelligent routing at the head ends.

In the design tool broadcast traffic is integrated by dedicating a certain number of GbE signals on the metro network to broadcast traffic (nVoD or vVoD). The optimal number is again found through an exhaustive strategy.

Wavelength adapters (WLA) are used to drop-and-continue one or two broadcast GbE signals at the head ends. The cost for one WLA can be estimated at 1 u.

Fig. 7 Strategy for link-by-link iVoD traffic (the partial GbE signals at each head end are given)

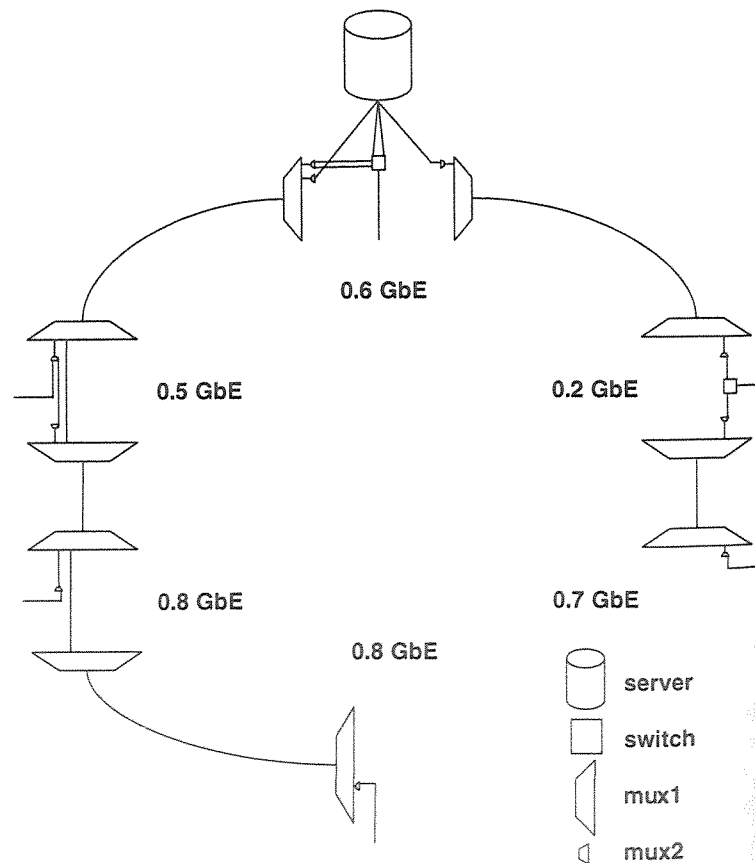
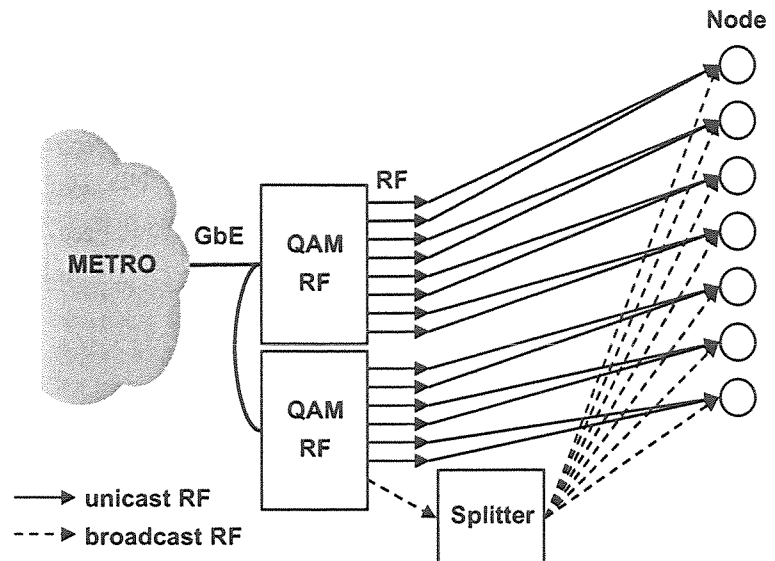


Fig. 8 Difference between unicast and broadcast traffic on the HFC access network



- (3) *Personal Video Recorder*. When VoD customers have a personal video recorder (PVR) at their set-top box (STB) at home, part of its hard disk could be used by the content provider to store popular videos before they are requested. This way a significant amount of network traffic can be avoided during peak hours.
- (4) *Combination of VoD services*. When different VoD services are available, a choice has to be made for each video to determine which service has to be used:

- (1) The most popular videos should be pushed to the STBs (if a PVR service is available) at the subscriber's home, so that traffic for these videos can be avoided.
- (2) The next most popular videos should be sent as nVoD videos, if any broadcast channels are available at the HFC network. NVoD causes the least traffic on the metro network (only six simultaneous streams per video) and at the HFC network (broadcast RF channels can be split at the QAM devices at no extra cost to all optical nodes at one head end).
- (3) For the rest of the videos, the choice between vVoD and iVoD depends on the load on the metro network, since both services have an almost equal load on the HFC network. Videos that are requested more than 18 times (for a stagger time of 5 min) on the total ring network are sent using vVoD, the rest using iVoD. This is also demonstrated in Fig. 9 for a total of 5000 simultaneous requests (present on an average network with 300 k HP).

Under these circumstances, the videos in the top 74 that are not yet stored on the PVRs or sent using nVoD, should be transported by the vVoD service (if available).

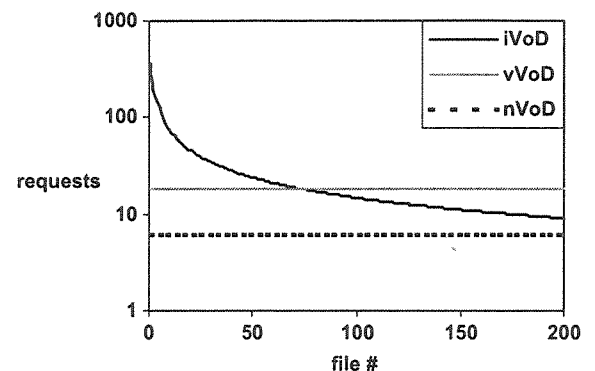


Fig. 9 Choice between iVoD and vVoD for video files (the videos are ranked according to popularity)

Simulations

First the network design for a standard configuration, with the same input parameters as given in Table 2, is determined and compared to the one shown in Fig. 6. This design will be the starting configuration to compare the other results to.

- (1) *Standard configuration*. In this configuration only iVoD services for the 200 available MPEG-2 videos are offered. Our network tool then gives exactly the same results as shown in Fig. 6. The total cost is again calculated as 1010u. Note that the actual cost for CWDM equipment will be a bit higher, due to costs for the CWDM shelves, client plugins, etc. that are not included in this model. The main cost however is still caused by the server ports and the RF devices, as Fig. 10 indicates.

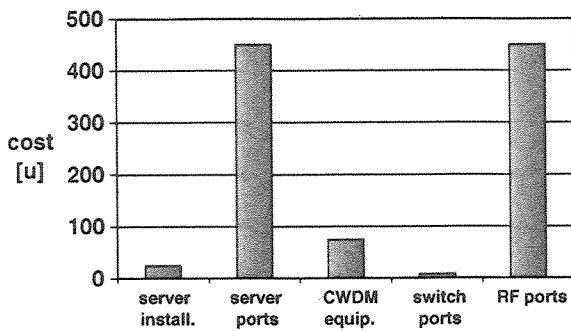


Fig. 10 Total installation costs for the standard configuration (server ports and RF ports generate the major costs)

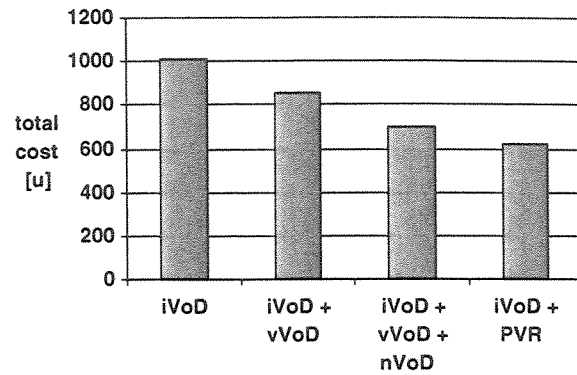


Fig. 11 Total installation costs for different VoD services (iVoD, nVoD, vVoD, PVR)

(2) *Server installation costs.* When the server installation costs are set to less than 8 u, a server is placed in every head end of the ring network. In this case, no costs for switches or CWDM equipment is required, since all traffic is sent directly from the local server to the QAM devices. The total number of server ports has now increased to 20 (instead of 18), because of the loss in statistical multiplexing. For higher values than 8 u, only one server is installed.

(3) *Broadcast VoD services.* The introduction of vVoD decreases the total cost to 853 u (15% gain). Now the 33 most popular videos are sent with vVoD and the rest with iVoD. NVoD can only be used if broadcast channels are available on the HFC network. Even then offering nVoD is not always profitable, since it increases the number of required RF channels on the devices. Only if six or more broadcast channels are present, introducing nVoD becomes beneficial, because the number of unicast RF channels per node decreases (from 3 to 2 in case of six broadcast channels). The total number of RF channels per average head end is then 106 (50 · 2 unicast + 6 broadcast) instead of 150 (50 · 3 unicast + 0 broadcast).

In that case the 10 most popular videos are transmitted using nVoD, 46 with vVoD and the other 144 videos with iVoD. The total cost is than 698 u (30% gain). The different situations are compared in Fig. 11.

(4) *PVR service.* If all subscribers have a PVR (100% penetration) and hard disks are 100 GB in size (about 37 MPEG-2 videos, representing 52% of all traffic), a gain of almost 40% can be obtained (total installation cost: 625 u), compared to the standard configuration (see also Fig. 11).

(5) *Video codec.* In case MPEG-4 video streams are used, the total cost is reduced by almost 60% to 428 u. This is because 800 streams can be carried in one GbE signal (instead of 300) and 30 in one RF channel (instead of 10). MPEG-4 streams have a bandwidth of 1.5 Mb/s, while 3.8 Mb/s has to be reserved for an MPEG-2 video.

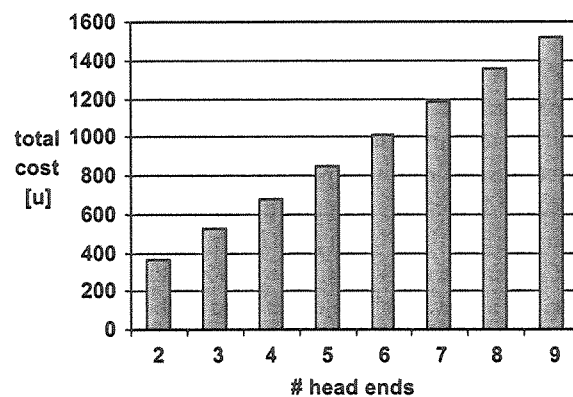


Fig. 12 Total installation costs for different network sizes (the installation cost per subscriber remains constant)

(6) *Network size.* Changing the network size to nine head ends (50000 HP per head end on average) still does not increase the number of servers. The total cost is higher (1,523 u).

A smaller network (three head ends) also only requires one server (total cost 534 u). The installation cost per subscriber remains about 0.01 u (Fig. 12).

(7) *Video popularity distribution.* When we change the video popularity, no differences occur when only iVoD is available. In case of broadcast services, a gain can be achieved when the most popular videos become even more popular, because the amount of network traffic for those broadcast videos remains the same anyway. When we set the Zipf parameter to 1.0 instead of 0.7, half of the requests are made for the top ten videos instead of the top 33. This causes a decrease of 10% in the total installation cost (628 u instead of 698 u).

Conclusions

A decentralized network design for VoD services on Ethernet-based WDM networks has been presented in this paper. By dividing the network into regional subnetworks with a ring topology, the transport network can be offloaded. The installation of a single local server per metro network appears to be sufficient in most cases.

Introducing PVR or broadcast VoD services besides interactive VoD can further decrease the installation costs. The gain in deployment costs might have to be evaluated against other economical perspectives, like feasibility and user-friendliness. The influence of other parameters, like video codec, content popularity and equipment costs, also appear to have an important influence on the network design.

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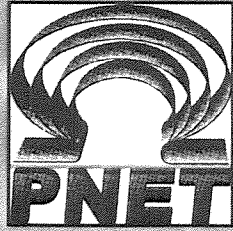
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