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Virtual Network Concept and Its Applications for Resource Management in ATM Based Networks *

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Abstract

In the paper we describe a framework for resource management and traffic control which is based on the virtual network concept. In this context the virtual networks are used as a tool for customization of networks management functions and for virtual separation of network resources. We identify three main categories of virtual network applications (service, user and management oriented virtual networks). We discuss generic and application oriented problems, which have to be solved to take full advantage of the proposed framework. We also study the relation between the virtual network concept and the virtual path concept in the context of bandwidth management. The study indicates that using virtual paths for bandwidth management involves some inherent contradictions.

Keywords

ATM networks, resource allocation, virtual networks, virtual paths.

1 INTRODUCTION

The integration of all services into one uniform transport layer is seen as a major advantage of the ATM standard. Nevertheless, this integration also creates several new problems. In particular a broad range of services, traffic characteristics, time scales and performance constraints, which are integrated into one transport system, causes the *resource management and traffic control* issues to become very complex and difficult. One can compare the situation to traffic control on a highway where the supersonic jet traffic is integrated with the personal car traffic. That is why, in many cases, the resource management and traffic control is trying to re-introduce some kind of separation in order to make the problem manageable. In this paper we argue that the virtual network concept can serve ideally for this purpose since it can provide a vehicle for two types of separation. The first is *separation of management functions* in order to allow customization to particular needs of some services and user groups. The second is *virtual separation of resources* in order to simplify the resource management functions and provide grade of service (GoS - connection layer performance metrics) guarantees for some services and user groups. The aim of this work is to propose a coherent framework for resource management and traffic control which takes full advantage of the virtual network concept.

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The notion of virtual networks is not new and was used in several papers (e.g. Mason (1987,1990), Walters (1992), Atkinson (1992), Dziong (1993,1994), Wernik (1993), Fotedax (1995), Dupuy (1995)) for particular applications such as virtual private networks or virtual networks associated with different qualities of service. In this paper we generalize the virtual network concept by showing that a common generic definition of virtual networks can be applied to all potential applications. There are five main objectives of this paper. First, to introduce a precise and coherent definition of the virtual network notion in order to avoid any vagueness and misinterpretations. Second, we identify the possible applications of the virtual network concept which would improve network management and utilization. The third objective is to specify the generic problems which are common to all virtual network applications. The fourth objective is to identify problems specific to particular applications. Finally we discuss what should be the relation between the virtual network concept and the virtual path concept defined by the standard bodies.

We start from the generic virtual network definition which is based on a virtual network link concept (Section 2). Then we discuss the potential applications of the virtual network (VN) concept which can be divided into three categories: service oriented VN, user oriented VN and management oriented VN (Section 3). The relation between virtual networks and virtual paths is described in Section 4. In particular we argue that the virtual path connections should not be used for bandwidth management purpose but rather for routing and switching simplification. The general architecture of the network bandwidth management system based on the virtual network concept as well as interaction of the virtual network with other traffic layers (cell, connection and physical network layers) are presented in Section 5. Finally in Section 6 we identify the generic and application oriented problems, which have to be solved to take full advantage of the proposed framework.

2 VN DEFINITION

A virtual network is defined by a set of network nodes and a set of virtual network links connecting the nodes. The virtual network is referred to by a virtual network identifier, VNI. The virtual network link (VNL) defines a path (consisting of one or more physical links) between two VN nodes and is referred to by a virtual network link identifier, VNLI. Examples of different VN topologies are given in Figure 1. Connections (VCCs or VPCs) associated with a particular VN can be established only on VNLs belonging to the VN.

Several virtual networks can co-exist in a physical network. They can constitute independent entities but in some cases a virtual network can be nested in another virtual network. In the latter case a VCC can belong to two or more virtual networks at the same time. In the example of Figure 1, VN3 can be nested in VN2. This means that the connections associated with VN3 belong also to VN2. At the same time there can be some connections associated with VN2 which do not belong to VN3 although they are carried on the same sequence of physical links as connections from VN3.

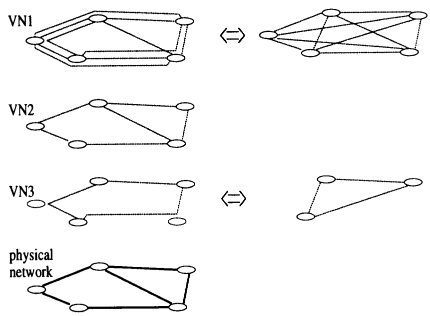

Figure 1 Examples of virtual network topology.

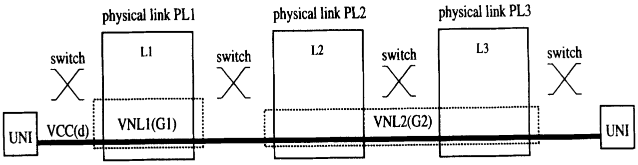

Figure 2 Allocation of resources to VN.

A set of resources can be allocated to the virtual network. In particular this set can include bandwidth and a set of resource management objects. It is important to emphasize that in this paper the notion of bandwidth is used in the sense of a qualified bandwidth. The qualified bandwidth includes the scheduling algorithm and buffer allocation and is characterized by quality if service (QoS - cell layer performance metrics) constraints for given traffic characteristics of connections using this bandwidth. In the following we concentrate on the application of the virtual network concept for bandwidth management purposes.

Figure 2 illustrates the logical bandwidth allocation to virtual network links along a particular VC connection which requires bandwidth d (denoted as VCC(d)). The connection is established on two VNLs: VNL1 and VNL2. Each of these VNLs is allocated a certain bandwidth (G1 and G2 respectively) from the physical link bandwidths, L1, L2, L3 (G1 from L1 and G2 from L2 and L3). The connection can be established if bandwidth d can be reserved on each of the VNLs.

3 POSSIBLE VN APPLICATIONS

In general the VN applications can be divided into three categories: service, user and management oriented.

Service oriented virtual networks are created to separate management functions specialized for different services (e.g. real-time vs data services) and/or to simplify the QoS management (each QoS class is served by a separate virtual network). Allocation of bandwidth to service oriented VNs aims at providing sufficient GoS and fairness for different services. Moreover, bandwidth allocation to QoS virtual networks can increase bandwidth utilization and simplify bandwidth allocation to connections as will be discussed in Section 6

User oriented virtual networks are created for some group of users who have specific requirements (e.g. guaranteed throughput, customized control algorithms, bandwidth management under the user control, increased security and reliability, "group" tariff, etc). The two most likely applications are private networks and multi-point connections. Note that in most cases the set of VN nodes will include only a subset of nodes to which the users are connected.

Management oriented virtual networks are created to facilitate some of the management functions (not associated with particular service or user group). The first application is connected with fault management and is called back-up virtual network. The bandwidth allocated to back-up VN should provide that in case of failure of network components (e.g. a link or node), all (or a given fraction of) connections affected by a failure can be restored in the back-up VN. The second application (henceforth referred to as CAC VN) is aimed at simplification of bandwidth reservation procedure during the connection setup. In particular, if all connections are routed via VNLs which connect directly origin and destination nodes, the connection admission procedure has to ask only the VNL bandwidth manager at the connection origin node for the required bandwidth (no need for bandwidth reservation in the transit nodes).

In the following we discuss interrelation between different types of VNs which is also illustrated in Figure 3:

- *Service oriented VN vs. management oriented VN:* In general, management oriented networks can divide bandwidth allocated to the backbone QoS VNL into several VNLs. Backbone QoS VN is defined as a VN where each VNL corresponds to one physical link.
  - The back-up networks are created for each QoS virtual network. It means that the bandwidth allocated to the backbone QoS VN is divided between primary QoS VN and back-up VN.

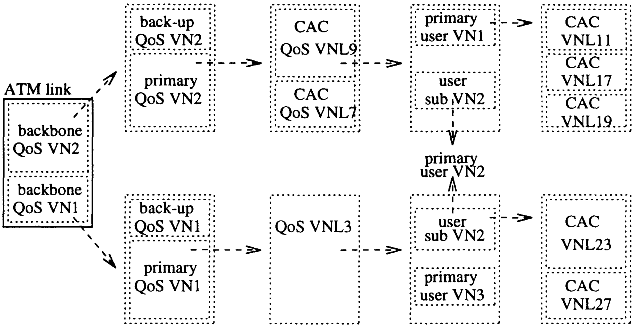

Figure 3 Interrelations between virtual networks.

- Application of CAC virtual network may cause the bandwidth allocated to the primary QoS VNL to be divided among several CAC VNLs (in general this case is not likely).

- *Service oriented VN vs. user oriented VN:* In general user oriented networks are nested in QoS virtual networks. In other words the user oriented VNLs are treated as connections within QoS VNLs. If a user oriented network requires different QoS connection classes it can be realized as:
  - one VN within the most stringent QoS virtual network.
  - a group of virtual subnetworks each of them nested in a corresponding QoS virtual network.
- *User oriented VN vs. management oriented VN:*
  - Since the user oriented VN is treated by its service oriented VN as a connection, there is no separate back-up network for user oriented VN.
  - Application of CAC virtual network may cause the bandwidth allocated to the primary user oriented VNL to be divided among several CAC VNLs

4 RELATION BETWEEN VNL AND VPC

There is a substantial literature on using virtual path connections for bandwidth management purposes by allocating bandwidth to a VPC. The main argument used by proponents of this approach is that the connection set-up is simplified since the first node of the VPC can reserve bandwidth for the new connection along the entire path. We argue that in general this approach has several drawbacks which significantly overweight the aforementioned advantage. To illustrate the problem we compare possible relations between VNL, VPC and routing paths (RP). To facilitate the comparison a network example is depicted in Fig.4. In this example we assume three QoS VNs. In the following we outline the main features of the three possible applications of VPC:

- *VPC=RP, bandwidth management by VNL:*
  - High bandwidth utilization (VNLs are optimized to provide this feature).
  - Simple bandwidth management on the virtual network layer (small number of variables).
  - Admission of a new VC connection does not require any changes in the routing tables of the transit nodes.
  - Admission of a new VC connection requires bandwidth reservation in the VNL's bandwidth managers located in the transit nodes of the path.
- *VPC=RP, bandwidth management by VPC:* - Low bandwidth utilization due to division of the link bandwidth into a large number of VPCs using the link (see Figure 4).
  - Complex bandwidth management (large number of interdependent variables).
  - Admission of a new VC connection does not require any changes in the routing tables of the transit nodes.

- Admission of a new VC connection does not require requires bandwidth reservation in the VNL's bandwidth managers located in the transit nodes of the path.

- *VPC=VNL, bandwidth management by VPC=VNL:*
  - High bandwidth utilization (VNLs are optimized to provide this feature).
  - Simple bandwidth management (small number of variables).
  - Admission of a new VC connection requires changes in the routing tables of the transient nodes between concatenated node-to-node VPCs (VC switches required).
  - Admission of a new VC connection requires bandwidth reservation in the VNL's bandwidth managers located in the transit nodes of the path.

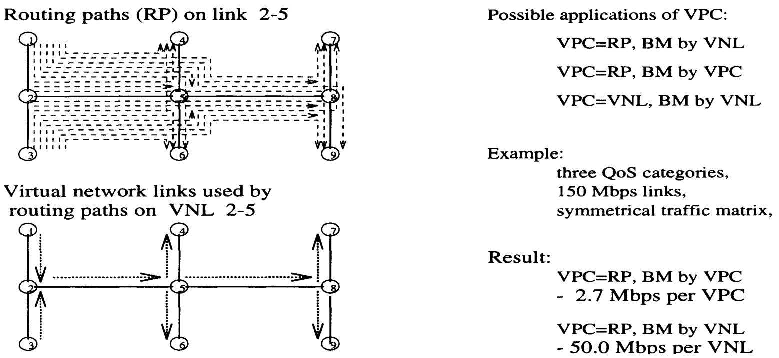

Figure 4 Analysis of possible VPC applications within the VN framework.

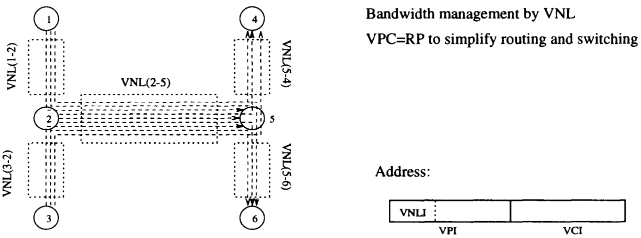

Figure 5 Decomposition of VN and VP functions.

The comparison of the main features shows that using VPCs for bandwidth management involves some contradictions. First, when used for call set-up simplification, the bandwidth utilization drops significantly due to the lack of statistical multiplexing between the VPCs on the connection level. Second, when used to optimize bandwidth utilization, the connection set-up becomes complex since the routing tables in the nodes between VPCs constituting the routing path have to be updated. To avoid these inherent contradictions we propose separation of bandwidth management function from VPC implementation. In this case the virtual paths should be used to simplify routing and switching (VPC=RP) only while the virtual networks should be used to optimize resource utilization. Observe that the processing and signaling cost of reserving bandwidth at VNL bandwidth managers for a new connection can become negligible if the resource management (RM) cells are used for this purpose on the pre-established routing paths (Dziong, 1995). This follows from the fact that the signaling traffic generated by ABT or ABR resource management cells will be significantly higher than the one generated by connection set-up RM cells. Other problems with application of VPC to bandwidth management are also indicated in (Dziong, 1991).

It should be noted that for particular network cost function assumptions and/or technical constraints, the optimization procedure can give VNL=VPC=RP for all VNLs.

Concerning implementation of the VNL identifier it can be defined by a part of VPI field with the highest weight as shown in Figure 4 (alternatively VNLI can be a general function of VPI or it may be unrelated directly to VPI).

5 BANDWIDTH MANAGEMENT ARCHITECTURE BASED ON VN CONCEPT.

The bandwidth management algorithms are distributed over three layers: connection layer, virtual network layer and physical layer. Interaction between these layers is discussed in Section 5.1. Besides distribution over different layers, these algorithms can be implemented in different locations and in different ways (e.g. centralized vs. distributed). These additional dimensions are illustrated in Figure 6 where a general architecture of the bandwidth management objects is presented. In the following the main functions of these objects are described:

- **Connection admission control and routing manager, CAC&RM**
  The main function of this object is to provide UNI-CAC objects with CAC and routing information which would facilitate establishment of the connections within the VN. In particular CAC&RM is responsible for evaluation of equivalent bandwidth functions used to map the connection's declared parameters into the bandwidth which should be reserved for the connections. Moreover CAC&RM should design a set of alternative paths for each OD pair (these paths can be implemented in the form of VPCs). Another important CAC&RM function is to provide the VN bandwidth manager with connection performance metrics which can be used to adapt the VN topology and bandwidth allocation. CAC&RM can be implemented in a centralized or distributed (over UNI-CAC and VNL-BM) fashion.
- **User-network interface connection admission control, UNI-CAC**
  The user-network interface CAC object is responsible for bandwidth allocation to connections originating at this interface. Based on the routing recommendation from CAC&RM, the UNI-CAC asks the bandwidth managers of VNLs constituting the chosen path to reserve bandwidth d required by the connection. If there is not enough bandwidth on this path, another path can be tried or the connection can be rejected.
- **Virtual network bandwidth manager, VN-BM**
  The main function of the VN-BM object is to update the VN topology and bandwidth allocation based on the performance measures from the connection layer. When there is a need to increase the bandwidth allocation, the VN-BM asks the network bandwidth manager to reserve this bandwidth. If there is not enough free bandwidth, the network bandwidth manager can realize only a part of the demand or reject the demand. The virtual network manager can be implemented in a centralized or distributed (over VNL-BM) fashion.
- **Virtual network link bandwidth manager, VNL-BM**
  The main function of the VNL-BM is link connection admission control. In particular VNL-BM decides whether a connection demand (VCC or VPC or another VNL) should be granted the required bandwidth. Several fixed or state dependent policies can be considered (e.g. complete sharing, coordinate convex, trunk reservation, dynamic trunk reservation, shadow price). Optionally, the VNL-BM can ask directly the link bandwidth managers to increase the bandwidth allocated to the VNL in the case of a high connection rejection rate.
- **Physical network bandwidth manager, PN-BM**
  There are two main functions of the network BM object. The first is to update the physical network topology and bandwidth allocation based on the performance measures from the VN layer. The second is to allocate bandwidth to virtual networks. The second function has to take into account fairness criteria when there is not enough resources to satisfy all VN demands.
- **Physical link bandwidth manager, PL-BM**
  The PL-BM can be seen as a part of the PN-BM. Its function is to control admission of new VNs and to update bandwidth allocation of the existing VNs. Several different policies can be applied.

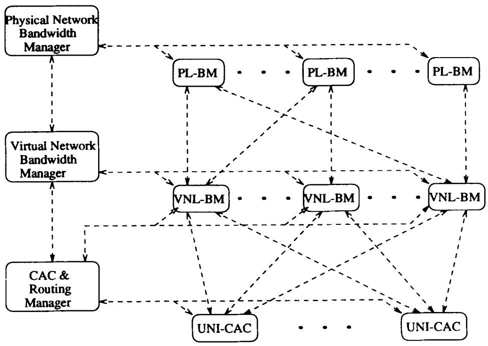

Figure 6 Bandwidth management architecture based on VN concept.

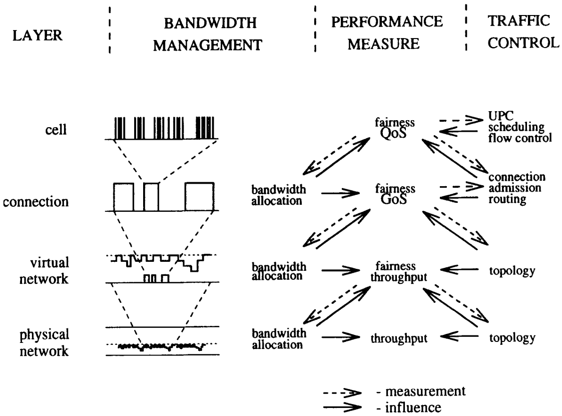

Figure 7 Interaction between layers.

5.1 Interaction between layers

The interaction between different layers is illustrated in Figure 7. The critical part of this interaction is measurement which allows one to adapt resource management algorithms to varying traffic conditions. In the following we specify the main measurement functions which are associated with the bandwidth management on the virtual network layer (directly or indirectly).

- *Cell layer measurements for connection layer:* The connection layer can use measurements on the cell layer to adapt bandwidth allocation to connections. This adaptation can have two objectives. The first aims at adapting bandwidth allocation to existing connections due to the source declaration errors and nonstationarity. The second objective is to adjust the bandwidth allocation function if some systematic allocation error is observed.
- *Connection layer measurements for virtual network and connection layers:* In general the values measured on the connection layer correspond to the GoS metrics (e.g. connection rejection rates) or to connection flow distribution in the virtual network. These values can be used by CAC and routing algorithms (connection layer) to improve bandwidth utilization and/or to provide fair access for all

users (according to fairness criteria). The virtual network layer can use the measured values to adapt the VN topology and bandwidth allocation.

- *Virtual network layer measurements for physical network layer:* The virtual network layer measurement metrics provide statistical information about the VN bandwidth allocation demands. The physical layer network uses these metrics to adapt the physical network topology and bandwidth allocation. These measurements can also serve to provide fair access to resources for all VNs (according to fairness criteria).

6 GENERIC AND APPLICATION ORIENTED PROBLEMS

We start by describing generic problems which are common to all basic applications of the virtual network concept. We identify three main generic problems associated with virtual network set up, virtual network update and back-up virtual network. Two main application oriented problems are described in Section 6.1 and Section 6.2.

The issue of virtual network set up is illustrated in Figure 8. The key element of the VN set-up procedure is an optimization procedure which designs the VN topology, allocation of bandwidth to VNLs and routing algorithm parameters. The optimization procedure is fed by the offered traffic matrix, GoS constraints, bandwidth cost functions, route set-up cost, bandwidth reservation cost during the set-up procedure and routing policy. Note that this formulation also includes design of CAC VN since the cost of bandwidth reservation and route set-up is taken into account. The result of the optimization procedure constitutes a VN demand for resource allocation which is considered by higher level bandwidth manager (physical network or virtual network in case of nested virtual networks). The demand can be accepted if there are enough free resources or rejected in case of resource shortage. In some cases of resource shortage the demand can be realized partially. In this case the optimization procedure can be applied one more time to take into account the resource limitations.

The issue of virtual network update is illustrated in Figure 9. The objective of the VN update is to correct the original VN set-up design and to adapt the VN design to the changes in traffic profiles. The structure of the VN update procedure is similar to the set-up procedure. The difference is that the algorithm is fed by measurements which are associated with offered traffic matrix, GoS metrics and bandwidth utilization metrics. This information is used to update the VN topology, allocation of bandwidth to VNLs and routing algorithm parameters. As in the case of VN set-up demand, the update demand can be accepted, rejected or realized partially.

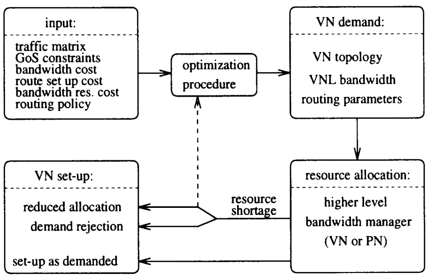

Figure 8 Virtual network set-up.

The back-up virtual networks are created to enable all (or a fraction) of the carried connections to be restored in case of failure of network components (e.g. a link of node). The restoration can be implemented on a link, fragment or path basis, as depicted in Figure 10, where fragment is a portion of the path. The path restoration seems to be most attractive in the ATM based networks. The design of the back-up VN has to provide the topology of the back-up virtual paths and bandwidth allocation to back-up VNLs. The backup virtual network usually has the same network topology as the physical network. Note that the

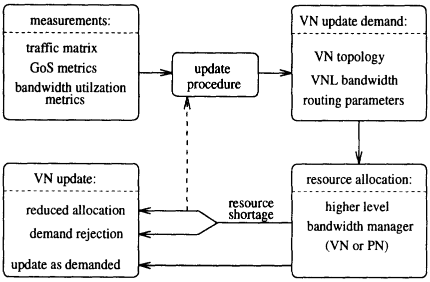

Figure 9 Virtual network update.

bandwidth allocated to the back-up VNL is not a sum of bandwidth required by all back-up VPs using this VNL since only a part of these VPs will be activated by failure of one link or node. That is why the back-up VN design is different from the design of the primary network. To illustrate this issue let us consider the case where two back-up VPs are asking the same back-up VNL bandwidth manager for equal bandwidth allocation increase. It may happen that the demand of one back-up VP is rejected while the other is accepted. To provide network reliability cost-effectively, an important objective of the back-up VN design is to minimize the bandwidth allocation to back-up VNLs while satisfying the restoration requirements.

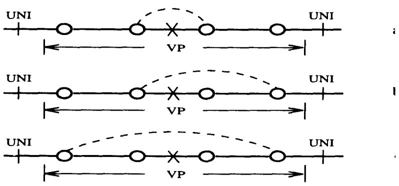

Figure 10 Link, fragment and path restorations.

6.1 Resource allocation in service oriented VN

A major application of service oriented virtual networks is to provide specialized treatment to different traffic classes. In particular (Classes A, B, C and D) as identified in the B-ISDN reference model, or (CBR, VBR, ABR, UBR) by ATM-Forum, as well as different QoS levels within those classes provide a natural classification for defining service oriented virtual networks. A fundamental question that arises is the manner in which these different virtual networks, which support different traffic and QoS classes, are managed as a function of the scheduling and flow control procedures at the cell level. In particular one should explore the bandwidth management options based on priority queuing as well as GPS-like scheduling (fair-queuing). While priority queuing is simpler to implement than "fair queuing" the later has certain advantages, among them flexibility, which is very desirable for a future-proof network.

Consider an example with two distinct QoS classes in the network. Each of these classes can be associated with the QoS virtual network. To provide high bandwidth utilization a buffer can be allocated to each of these virtual networks. Assume that the higher VN index, the more stringent the QoS requirements. The service priorities are implemented by a scheduler which can be realized as non-preemptive multi-priority system or a fair queuing system.

Three basic approaches to bandwidth allocation to virtual networks are presented in Figure 11. To illustrate the main features of these approaches, the figure includes the exact admissible region (continuous line) and linear admissible regions corresponding to each of the approaches (dotted lines). These admis-

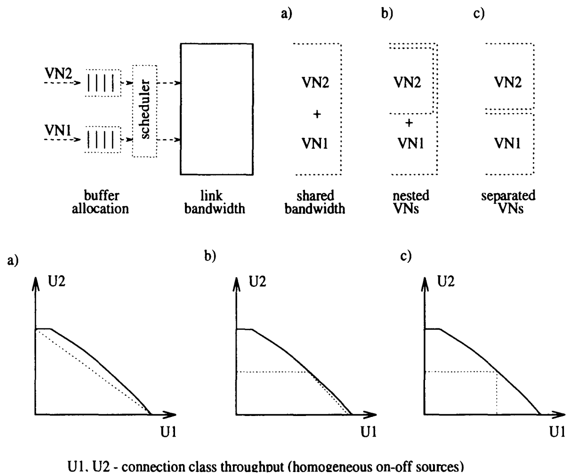

Figure 11 Resource allocation in service oriented VN.

sible regions are evaluated for a non-preemptive multi-priority system and statistical QoS constraints (Dziong, 1993). Nevertheless similar features can be expected for other scheduling algorithms and deterministic QoS constraints. In the following we indicate the main features of the three resource allocation schemes:

- All virtual networks share the same pool of link bandwidth Figure 11(a):
  - full statistical multiplexing between virtual networks (connection layer),
  - linear admissible regions are less efficient,
  - requires additional tools for GoS fairness between VNs.
- Nested virtual networks Figure 11(b) (the bandwidth allocated to a particular priority can be used by lower priority connections):
  - limited statistical multiplexing between virtual networks (connection layer),
  - linear admissible regions are efficient in the inclined region,
  - limited GoS fairness between VNs (tools to protect high priority traffic access against low priority traffic are required),
  - a scheme for fast bandwidth allocation to low priority VN is required for controllable traffic services (flow control problem).
- Each virtual network is allocated separate bandwidth Figure 11(c):
  - no statistical multiplexing between virtual networks (connection layer),
  - linear admissible regions are efficient only for the cases where the ratio of service traffic levels is similar to the one in the designed operating point,
  - GoS fairness between VNs is provided.

The choice of a particular resource allocation scheme depends on the services and the design objectives. In the following we identify the main problem categories which should be resolved to take advantage of the service oriented VNs:

- Evaluation of connection admissible regions as a function of bandwidth allocation to virtual networks and scheduling algorithm.
  - Statistical QoS guarantees (e.g. Dziong, 1993).
  - Deterministic QoS guarantees (fair queuing e.g. Noiseux, 1995).
- Fast bandwidth allocation to controllable traffic VNs (flow control).
  - Rate-based schemes.
  - Credit-based schemes.

- Providing GoS fairness for shared bandwidth and nested VN cases (fair CAC policies).
- Bandwidth allocation to virtual networks when demands exceed link capacity (fairness issue).

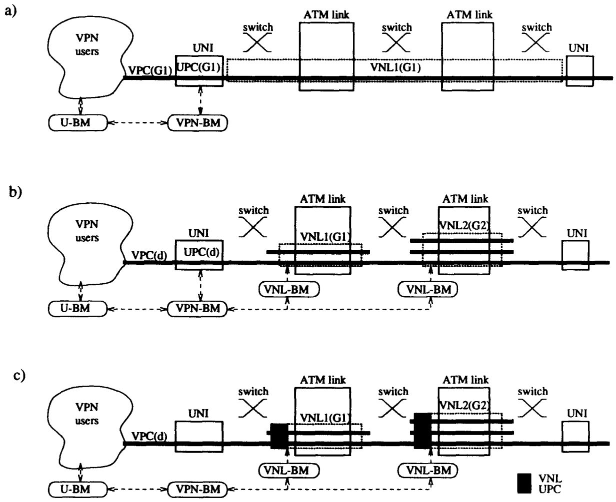

Figure 12 Bandwidth enforcement in virtual private networks.

6.2 Bandwidth enforcement in virtual private networks

In the case of service oriented VNs and user oriented VNs created for multi-point connections, the enforcement of bandwidth allocation to VCCs is under the network manager responsibility and is realized by UPC mechanism located at UNI. Thus the enforcement of bandwidth allocation to VNLs can be done logically by the connection admission procedure at VNL-BM.

Concerning virtual private networks, bandwidth allocation to VCCs and connection admission procedure can be under the user responsibility. In this case the virtual private network bandwidth manager has to provide enforcement of bandwidth allocation to VNLs independently of the user actions. Below we indicate three basic possibilities:

- Enforcement at UNI, VPC=RP=VNL, Figure 12(a):
  Here the virtual network links are realized as end-to-end VPC. Thus the bandwidth allocated to VNL can be enforced by a UPC algorithm applied to VPC at UNI.
- Enforcement at UNI, VPC=RP$\neq$VNL, Figure 12(b):
  This option requires that the user bandwidth manager (U-BM) asks the virtual network bandwidth manager for the bandwidth allocation to the end-to-end VPCs. This bandwidth allocation can be updated on a call-by-call basis and can take into account statistical multiplexing (cell layer) between the VPCs using the same VNL. For each update the VN-BM verifies whether the sum of bandwidth required by VPCs does not exceed the VNL capacities. If this condition is fulfilled the bandwidth required by VPC is enforced by a UPC algorithm at the UNI.
- Enforcement at switch output ports, VPC=RP$\neq$VNL, Figure 12(c).
  Bandwidth allocated to VNL is enforced by means of UPC mechanisms (e.g. fair queuing) installed in the VN node switch output port originating VNL.

7 CONCLUSIONS

In the paper we described a framework for resource management and traffic control which uses virtual networks as a tool for customization of network management functions and for virtual separation of network resources. The proposed generic definition of the virtual network is based on the virtual network link concept. We have shown that this definition fits many potential applications which can be divided into service, user and management oriented virtual network categories.

In the context of the virtual network application for bandwidth management there is an evident overlap with the concept of bandwidth allocation to virtual paths investigated in many publications. The presented study of the relation between the two concepts indicates that using virtual paths for bandwidth management involves some inherent contradictions. To avoid these drawbacks we propose separation of the bandwidth management function from VPC implementation. In this case the virtual paths are used to simplify routing and switching only.

In the last part of the paper we have identified generic and application oriented problems, which need to be solved to take full advantage of the proposed framework. These problems are currently under study.

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