A Framework for Multi-Service IP Network Planning

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Abstract

The planning of multi-service IP networks requires the consideration of many different and also diverse issues. Since Internet technology has been developed in a rather pragmatic way ("we believe in rough consensus and running code"), various approaches and concepts exist in most areas of networking, which are relevant for network planning (e.g., types of applications, routing schemes, Quality of Service mechanisms). In this paper, the key issues of the network planning process for multi-service IP networks are covered in a structured way. To provide a foundation for any network dimensioning procedure, we first introduce and categorize current IP Quality of Service mechanisms and identify their implications for network planning. Furthermore, a systematic approach for classification and modeling of Internet traffic is suggested and a universal link model together with appropriate dimensioning formulae is proposed. Finally, we go over different network planning scenarios and discuss relevant characteristics and possible solution approaches.

1 Introduction

The Internet Protocol (IP) with its related technologies has emerged as the most promising candidate for interconnecting different network technologies and providing a consistent view of the transport infrastructure. It is expected that many future communication networks will be IP-based, integrating diverse services such as voice, multimedia, and data, each with the appropriate quality. To enable such multi-service network architectures, various mechanisms and methodologies have been developed, which introduce the idea of Quality of Service (QoS) into the Internet and which promote efficient and proper use of available resources. Figure 1 depicts a typical architecture of a generalized, multi-service network scenario [1][2]. Due to scalability reasons the network is partitioned in areas or domains, which might be administrated autonomously. Functions like traffic control, resource control, or traffic engineering are coordinated by centralized entities, which are responsible for a single area. To guarantee network-wide (end-to-end) QoS to data flows, which traverse several areas, the affected control entities have to be able to communicate with each other in order to take appropriate measures.

In this paper we investigate the network planning process for multi-service IP networks under the premise of various QoS schemes, focusing on dimensioning issues for single control areas, which typically have a mesh or partial mesh structure. Assuming that the network topology and the locations of caches, application servers, media gateways, and peering points are given, the objective of network dimensioning is to determine link capacities combined with traffic routing, such that the total network cost is minimized and QoS and other constraints (like capacity upper bounds) are met. Since in the remainder of the paper we restrict our view to individual areas, we will use the expressions "area" and "network" interchangeably.

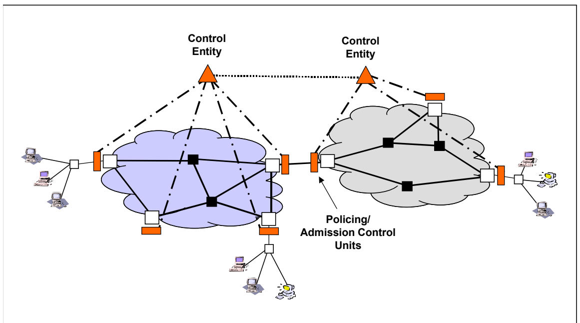


Fig. 1 Generalized Network Scenario

The paper is organized as follows: In order to derive a structured view of the network dimensioning process, we examine possible realizations of future QoS architectures in section 2 and discuss their significance for the network planner. In section 3 an approach for IP traffic classification and modeling is presented, providing the basis for our link dimensioning methodology introduced in section 4. In section 5 dimensioning issues for different network scenarios are discussed and possible solutions suggested. Section 6 concludes the paper.

Category	Mechanisms	Technologies	Implications
Traffic Control	packet classification + forwarding packet buffering, scheduling shaping	WFQ, WF2Q, WRR simple priority queuing	strict bandwidth partitioning traffic prioritization
Resource Control	flow/call admission control (CAC) class based policing at network edge	IntServ + RSVP DiffServ + Bandwidth Broker Resource Management	CAC → flow blocking Policing → fixed traffic bounds + service degradation
Traffic Engineering	optimized resource utilization routing optimization	OSPF, IS-IS, EIGRP MPLS multi-path technologies	destination/source-based routing single/multi path fixed/adaptive routing

Table 1 Categories of Internet QoS Mechanisms

2 Categorization of Internet QoS Mechanisms and Implications for Network Planning

Quality of Service mechanisms, which are currently developed and employed in the Internet, can roughly be divided into three main categories: traffic control, resource control, and traffic engineering. Table 1 gives an overview of these categories together with the implications for network planners.

2.1 Traffic Control

With traffic control we summarize all methodologies that directly impact the handling and forwarding of packets (scheduling, buffering) within hosts, routers or switches. It provides fundamental techniques to distinguish between several traffic streams (per flow or per class) and allows differentiated treatment of the corresponding packets, thus, establishing the foundation of a truly multi-service enabled network infrastructure. In order to do so, data packets need to be classified and assigned to a specific flow or class, which can be done either at the network edge (Differentiated Services DiffServ [3]) or at every individual router along the path (Integrated Services IntServ [4]). Typical scheduling strategies are prioritization where packets with higher priority are always sent out before lower-priority packets and bandwidth allocation where certain shares of the link capacity are virtually assigned to specific traffic flows or classes (WFQ, WRR, etc.). From a network planning perspective it is advisable to initially ignore the very details of the different traffic control schemes and only consider the two main implications:

1. Fixed bandwidth partitioning, i.e., predictable capacity assignment to individual flows or classes without detrimental interference, can be assumed. However, potential multiplexing gains in case of work-conserving systems are neglected.
2. Within an allocated bandwidth fraction, certain traffic streams can be treated preferentially.

These two concepts provide the basis for the universal link model, which is presented in section 4.

2.2 Resource Control

Resource control refers to techniques, which manage the access to available network resources at class, flow, or connection level and, thus, reduce or even avoid the possibility of service degradation resulting from traffic overload. Various such systems have been proposed and developed during recent years.

The IntServ concept for example suggests Call Admission Control (CAC) on a per-flow basis, where individual applications can make on-demand reservations along a path (e.g., using RSVP). This principle, however, requires every router on the way to support the reservation mechanism and to be able to handle a great number of concurrent active flows.

In order to reduce the complexity of the systems, DiffServ proposes a rather static resource control approach. Network operators establish only a few traffic classes, for which adequate bandwidth needs to be provided along the respective data paths through the network. Additionally, policing entities at the network edge control the amount of traffic, which is entering the network. This way, overload is avoided at the network edge, however, not necessarily on all links within the network. It should be noted that call admission control, as suggested by IntServ, works on a per-flow basis (a flow is either accepted or rejected), while policing is done within a traffic class on a per-packet basis (packets are dropped whenever the respective traffic exceeds a certain threshold).

Another interesting approach towards resource control is the combination of class-based bandwidth allocation and explicit flow reservation within such a class through overlay resource management entities [5]. So far, none of the proposed resource control systems are practically deployed. However, to be able to give hard QoS guarantees to selected applications with strict real-time requirements, resource management will be inevitable.

For the network planner, who again does not need to consider every facet, resource control basically comes in two notions: First, whenever a type of per-flow access control (CAC) scheme is realized, a blocking model is used to dimension the network. Second, traffic aggregates can be kept from exceeding pre-set bit rate limits through policing entities at the network edge, thus, giving upper bounds for the bandwidth requirements of such an aggregate within the network. However, when policing is used instead of CAC, an increasing number of active flows might lead to unwanted service degradation.

2.3 Traffic Engineering

Traffic engineering in the Internet denotes the comprehensive process of network performance optimization, which takes place during network operation [6]. Specifically, one core concept of traffic engineering is routing optimization. It can be based on conventional Internet routing protocols such as OSPF [7], IS-IS [8], or EIGRP [9] or on more advanced strategies such as MPLS [10]. In the first case, setting the link metrics in a smart way can achieve advantageous flow patterns [11][12], while the latter enables metric-independent, flexible source routing. In all cases, it is possible that traffic flows are either carried over single or over multiple paths between the source and the destination. Certainly, for the network design process the type of routing protocol plays an important role. Furthermore, it has to be known if traffic engineering is employed as a reactive process during network operation, thus, leading to a different routing whenever the network load changes. For a network planner, routing possibilities can range from “very limited and static” to “very flexible and dynamic”.

3 Classification and Modeling of IP Traffic

When planning multi-service IP networks, a rather pragmatic modeling approach is necessary. It is not practicable to consider every characteristic of each application, as this would make the planning process too complex. Besides, traffic uncertainties stemming from traffic statistics and forecasts are usually greater than inaccuracies due to negligence of certain application features. Thus, only a few traffic classes should be defined and the overall set of applications mapped upon them. The requirements and traffic behavior of these classes are then modeled at the flow level in order to be able to handle them for network dimensioning. Fig. 2 illustrates the mapping process by giving a few examples.

3.1 Classification of IP Traffic

As a first step, Internet applications are differentiated regarding their principle quality of service requirements and the corresponding type of traffic, which they generate. Here we distinguish between two fundamental traffic type notions:

1. elastic traffic, for which QoS correlates with the total time that it takes to transfer a bulk of data of a certain size, and
2. stream traffic, where QoS depends on the transmission characteristics of the individual packets.

Elastic traffic is generated by data-centric applications (e.g., Web, E-mail). In the Internet this type of traffic is normally carried by the TCP protocol, which adapts its transmission rate to the currently available bandwidth (i.e., the bottleneck link along a path determines the bit rate of the flow). A relevant QoS parameter for elastic traffic is the data throughput, which is obtained during transmission time. Stream traffic on the other side relates to time-sensitive applications such as IP telephony, network gaming, or video streaming. For these applications the corresponding packets have to be delivered in a more or less timely manner. Thus, appropriate QoS measures for stream traffic are packet delay, delay jitter, or packet loss. In cases where flow/call admission control (CAC) is performed, this set of parameters is complemented by the blocking probability.

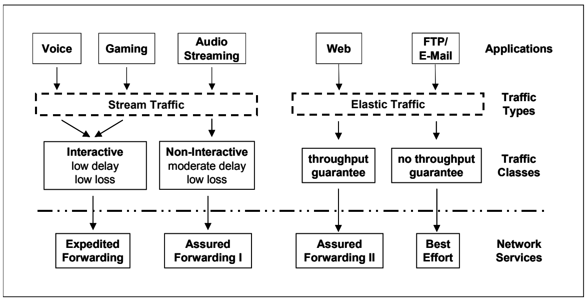


Fig. 2 Mapping Process

According to the respective QoS requirements, all applications have to be organized in traffic classes, possibly summarizing similar applications. In our example, voice and gaming traffic constitute one single traffic class since both applications demand low delay and also relatively low packet loss values. The mapping of traffic classes onto network service classes is technology dependent (e.g., DiffServ, as shown in the picture). At this point it might even turn out, that a chosen network technology cannot support a specific traffic class, which means that the corresponding application cannot be offered with the desired QoS.

3.2 Modeling IP Traffic

After having assigned all applications to traffic classes, suitable dimensioning models need to be derived. Modeling is done on the flow or connection level, since it hides details of the packet layer, which hardly can be estimated or predicted. In situations where packet-level characteristics have to be taken into account (such as packet delay or packet loss), transformations are performed in order to map the relevant parameters into respective counterparts of the flow layer.

Stream Traffic

Stream traffic flows are either specified through parameters "connection/flow arrival rate" and "mean holding time" or the value of the respective traffic volume in Erlang (which is the product of connection rate and holding time). Interarrival times and holding times are assumed to be exponentially distributed. The bit rate during a connection can vary over time (e.g., voice traffic with silence suppression or video traffic with variable bit rate encoding) and is characterized by parameters such as mean and maximum value. As QoS parameter at connection level the blocking probability is considered for cases where call admission control is performed. If CAC is not applied, we can define a so-called degradation probability, which denotes the expected fraction of time during which an individual flow does not receive the appropriate service quality (as may be specified in a Service Level Agreement).

Elastic Traffic

For elastic traffic we assume that each flow correlates with the transmission of a file. This way, elastic traffic can be characterized by the parameters "file arrival rate" (or flow arrival rate) and "mean file length", or by the product of these two values, which represents the average traffic volume. The service quality of elastic traffic transmission is usually specified through the average throughput value, which is observed during transfer phase.

Measurements of Internet traffic have shown that flow interarrival times as well as file lengths are sub-exponentially distributed (e.g., Weibull and Pareto, respectively) [13]. However, as these properties are quite difficult to deal with analytically, the flow arrival process is typically modeled as a Poisson process.

4 Universal Link Model and Link Dimensioning

Based on the QoS mechanisms introduced in section 2 and their implications for network planning, we now present a universal link model, which can be used for dimensioning purposes (see Figure 3). We assume that bandwidth partitioning together with policing is applied to split up the link capacity between elastic and stream traffic, and also between different traffic classes within one type of traffic. If desired, traffic prioritization can be used within each share of capacity. Furthermore, admission control might regulate all or just some of the stream traffic, but usually not elastic traffic. However, if this should become the case, it can be taken into account by introducing blocking probabilities for elastic traffic flows and modifying the respective dimensioning formula.

This link model allows us to consider the different traffic classes separately and determine their necessary capacity shares independently. To obtain the total capacity of each link, the individual bandwidth shares need to be summed up. Thus, our model considers worst-case load situations, while multiplexing gains are ignored (i.e., one traffic type uses the bandwidth shares of others whenever they are not fully utilized). Certainly, available QoS mechanisms permit further combinations, which might even achieve better utilization of network resources. However, taking into consideration every possible alternative would lead to complex link dimensioning formulae not suitable for network planning purposes.

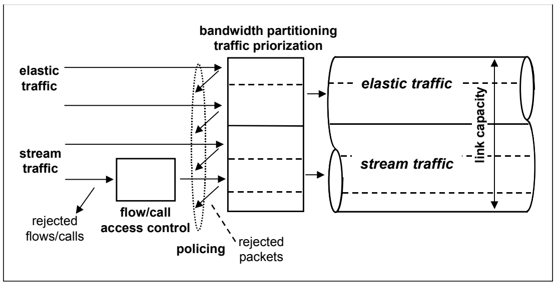


Fig. 3 Universal Link Model

4.1 Dimensioning for Stream Traffic

As mentioned earlier, stream traffic is characterized by the offered traffic value (Erlang value) at flow level as well as by characteristic bit rate parameters at packet level. In order to calculate the desired bandwidth, bit rate parameters have to be transformed into a single value – the effective bit rate. There exist several such formulae, their accuracy usually being application dependent. A quite general approach is Lindberger's formula [14][15], which expresses the effective bit rate as a function of the sources' mean and peak bit rates, the link capacity, and the packet loss probability. The formula is based on the rate envelope multiplexing principle (REM) and is valid for small buffers. Since stream traffic relates to time-sensitive applications, the constraint of small buffers does not represent a limitation of the formula. In order to meet the end-to-end delay budget for this type of traffic, the buffers within the routers along the path have to be kept small anyway. When calculating the effective bandwidth of an individual source, the packet loss probability is chosen small enough as not to impair the quality of the application, which is perceived by the user.

Based on the offered traffic value and the effective bandwidth of a single user, the necessary link capacity share can be derived. In cases where call admission control is performed, the bandwidth is computed by numerical inversion of the multi-service Erlang blocking formula [16][17] under consideration of a given blocking probability. If only policing is applied, the blocking probability is replaced by the degradation probability. This is the probability that the number of active flows exceeds a certain threshold, which causes service degradation for individual streams. Since the number of flows follows a Poisson distribution, the required capacity can again be computed numerically.

4.2 Dimensioning for Elastic Traffic

The dimensioning model for elastic traffic explicitly takes into account the dynamic behavior of TCP, which mostly is the origin of the traffic's "elastic" property: a TCP source tries to adapt its transmission rate to the minimum available bandwidth along the path in order to avoid overload situations. Assuming an ideal TCP feedback mechanism, a link that carries elastic traffic can be represented as a processor sharing (PS) system where all active flows share the available resources equally. Given the traffic model introduced in the preceding section, the capacity share, which it takes to carry a certain average traffic volume, can be determined by solving the sojourn time formula of the PS system for a desired per-flow throughput value. In cases where a single elastic flow is able to fully utilize the available bandwidth on its own (e.g., a server is directly connected to a link), the M/G/1 PS system is suitable [18]. Whenever individual flows are subject to bandwidth restrictions outside the observed system and, therefore, can never fully utilize the available bandwidth even in cases where no other flows are active (e.g., all flows have to go over modem connections), the M/G/R PS formula is applicable and needs to be solved numerically [19] [15][20]. A nice property of the processor sharing formula is that it does not require any knowledge about flow arrival rates and file sizes explicitly since it is based on the mean offered traffic volume. If several elastic traffic classes are differentiated through simple priority scheduling, the required bandwidth for all traffic classes can be calculated following the approaches in [21] or [22]. Also, formulae exist for scenarios where elastic traffic is subject to admission control [20].

5 Network Dimensioning Strategies

After having discussed fundamentals of network planning, we now formulate problem classes and discuss possible solution strategies for network-wide dimensioning. If not indicated otherwise, we consider all traffic classes independently from each other, following the approach outlined in section 4.

One criterion that greatly influences the network dimensioning process is the resource control scheme employed in the network. It determines in which way traffic is affected - either through blocking and policing or simply through suffering from overload situations - and, thus, influences the capacity assignment process. Furthermore, the points in the network at which resource control decisions actually take effect need to be considered. In a network wide context, we mainly distinguish between three types of resource control methodologies: CAC at each node, CAC at the network edge, and policing at the network edge. In the first case, each link along the path of a specific traffic demand has an effect on the overall acceptance probability of the corresponding flows ("multi-hop"). In the other two cases, only the load on the first hop determines whether or not a call is accepted or packets are dropped in a controlled manner ("single-hop"). Whenever CAC is performed, call-blocking probability becomes a relevant QoS measure (for stream traffic as well as for elastic traffic). If a certain upper bandwidth limit is enforced without CAC (i.e., pure policing is carried out), the probability of service degradation comes into play for stream traffic, while for elastic traffic it means that no absolute guarantee for a minimum throughput can be given. However, if a certain minimum is desirable, the probability that the number of concurrently active users exceeds a certain threshold can also be taken into account when dimensioning links. Table 2 gives an overview of the different dimensioning scenarios.

Let us first assume that a fixed routing pattern is given. This could be the case when the applied routing scheme depends only on fixed metrics and not on the optimization variables of the dimensioning problem, such as link capacities or link loads. Examples are networks, which run conventional routing protocols like OSPF or IS-IS and which have the routing metrics set either to 1 per hop or to some other fixed value (e.g., proportional to the physical link lengths). It is then possible to determine all end-to-end paths through the network by applying the appropriate routing algorithm (e.g., "shortest paths" for OSPF).

5.1 Dimensioning for Nominal Load

It is assumed that for every traffic class reasonable nominal traffic demand matrices have been found, which do not change over the considered time period

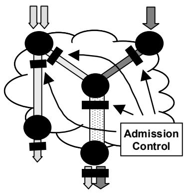
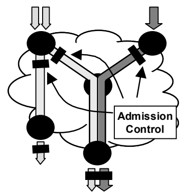
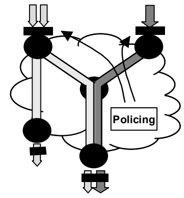
	Scenario I	Scenario II	Scenario III
Resource Control Scheme	Admission Control at each node	Admission Control at network edge	Policing at network edge
Network Scenario			
Path Representation	Multi-Hop	Single Hop	Single Hop
Streaming Traffic QoS	Call Blocking Probability Effective Bandwidth	Call Blocking Probability Effective Bandwidth	Degradation Probability Effective Bandwidth
Elastic Traffic QoS	(Flow Blocking Probability) (Average Throughput)	(Flow Blocking Probability) (Average Throughput)	Average Throughput

Table 2 General Dimensioning Scenarios

("single period"). Thus, based on the given routing we are able to deduce the traffic demand on each link. Taking these link demands, the capacity share for each traffic class can be derived. Depending on the dimensioning scenario described above, different procedures have to be performed.

<u>Stream traffic</u>

Scenario I is similar to circuit-switched networks such as PSTN or ATM. The dimensioning objective is to determine optimum link capacities such that the end-to-end blocking thresholds are fulfilled and the network cost is minimized. Since every link along a path influences the overall blocking probability, this requires the solution of a non-linear optimization problem known as the set of Erlang fixed-point equations. Mathematical programming methods or heuristics are available to perform this task [23].
A suitable approach for a situation with admission control only at the network edge (Scenario II) is to calculate the capacity share of each end-to-end traffic demand separately, just as it was done for a single link (by inverting the multi-service blocking formula for a given blocking QoS). Since this capacity share has to be available on every link along the path of a certain end-to-end demand, the actual bandwidth values of each link are determined by summing up all individual capacity shares. Being simpler than the previous method, more overall capacity is required due to not making explicit use of the bundling gain of different traffic streams on the same link.
Dimensioning for stream traffic under the premise of policing (Scenario III) is equivalent to the preceding scenario, only that the blocking probability is replaced by a degradation probability threshold, which should not be exceeded.

<u>Elastic traffic</u>

For elastic traffic only scenario III is relevant in practice. It can be shown by simulations, that the (network-wide) end-to-end QoS (average throughput per flow) is sufficiently met if each link is dimensioned independently for the required QoS. This relationship between link and network performance results from the operation of the TCP-protocol, which adapts the sender bit rate to the minimum available capacity faced on the path towards the destination [24][25][26]. Thus, desiring a certain average throughput QoS, the appropriate processor sharing formula can be solved for every link based on the total traffic demand traversing this link. The relevant traffic volumes can simply be obtained by summing up the individual traffic volume portions of all routes running over the specific link.
One tricky part about using the processor sharing formulae is to decide whether the elastic flows are subject to rate restrictions outside the network or not. If they are (for example when looking at dial-in traffic), a maximum bit rate value can be assumed, and the M/G/R PS formula has to be used. However, if one cannot be sure about any maximum bit rate restrictions other than what is enforced by the policer at the network edge, it is safer to take this policy-controlled bandwidth share as the peak rate and work either with M/G/1 PS or M/G/R PS, depending on which formula is applicable.

5.2 Robust Dimensioning

A network, which is dimensioned according to the nominal traffic load, fulfills the end-to-end QoS requirements as long as the traffic demands show no deviations. In practical cases, however, large fluctuations regarding traffic demand and traffic distribution may occur. Whereas excess traffic demand is assumed to be efficiently blocked at the network border by means of (class-specific) policing and/or admission control mechanisms, service degradation due to traffic shifts within the network can be prevented in following ways:

- Policing and admission control is applied at the network border for each end-to-end traffic relation. With this the nominal traffic values are enforced and (because of the assumption of a unique routing) congestion situations both on the network links as well at the egress points are prevented. This method however is not practical due to its inherent complexity, worse scalability (N^2 problem), and inflexibility: traffic relations with overload cannot make use of spare capacities, which stem from underloaded traffic relations.

- The network links are suitably overdimensioned. This can be achieved by applying a dimensioning method, which implicitly takes into account fluctuations with respect to the nominal traffic distribution. Possible realizations could be:
  - generation of multiple load patterns (traffic matrices) per traffic class and application of a multiple load period dimensioning algorithm.
  - "point-to-any" dimensioning: all network links are dimensioned for maximum traffic load (max flow problem). With this, all possible traffic patterns within the network are considered implicitly.

It should be noted that the amount of additional capacity strongly depends on the mechanisms, which influence the traffic flow distribution during network operation (tradeoff between complexity and capacity). Without the use of any load adaptation (traffic engineering) mechanisms, the capacity requirements are at maximum. On the other hand, a dimensioning method, which takes into account the reaction of the traffic engineering mechanisms (to compensate the load fluctuations), would be significantly more complex.

5.3 Dimensioning and Routing Optimization

Integration of routing optimization and dimensioning is required if capacity- or load-dependent routing metrics are used or if explicit routing (e.g. MPLS) is applied. Due to complexity reasons a joint solution within a single optimization step is only possible for networks of small size. A practical solution approach is to iteratively optimize the routing while keeping the link capacities fixed and vice versa. Similar procedures are commonly used for PSTN and ATM network planning [27][28].

6 Conclusion

In this paper, we discuss important issues of the network planning process for multi-service IP networks. Since a variety of services is offered in the Internet, and IP technologies are very diverse, it is essential to derive suitable abstractions and models for the individual steps of the planning procedure. The ideas and concepts presented in this work provide a first framework where we seek to develop a uniform view of the overall planning process. In order to do so, IP QoS mechanisms are categorized and a systematic approach for classification and modeling of Internet traffic is suggested. To facilitate the network dimensioning task, we introduce a universal link model and show how the appropriate dimensioning formulae can be applied for network dimensioning. Finally, some network planning scenarios are discussed.

Although the scenarios presented in this paper can be extended in many directions, we believe that our framework can serve as a good basis for the formulation of problem classes and the organization of further research in this area.

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