

A Dynamic Resource Allocation and  
Measurement-Based Call Admission Control  
Algorithm for Integrated Services Networks

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# A Dynamic Resource Allocation and Measurement-Based Call Admission Control Algorithm for Integrated Services Networks

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## ABSTRACT

The future network must be able to provide QoS to deliver multimedia traffic. Utilizing network resource efficiently will reduce the operation cost and benefit every user. In order to achieve these two goals, accurate traffic modeling, estimation, and prediction is the solution to the problem.

The existing solution for traffic modeling is not satisfactory. Modern network traffic is more chaotic than we expect. Many applications and aggregate traffic on backbone network exhibit long range dependence. Traditional traffic models can not predict the network performance precisely and usually underestimate the required bandwidth.

For a traffic model to be useful, it must be able to achieve two goals – predicting the queueing performance with a finite buffer space and evaluating the behavior of aggregated homogeneous traffic. Solutions exist for simple traffic models, for example, on-off process. However, simple traffic models fail to model the statistics and dynamics for many applications. Complex traffic models are able to accurately model the traffic sources. However, the queueing performance and the behavior of aggregate traffic for complex traffic models are still under studying.

To provide QoS, we need to prevent the network from overload. Call admission control and traffic policing mechanism must be enforced on connections without network-dependent flow control. Call admission control should be established on neither average bandwidth allocation nor peak bandwidth allocation, but effective bandwidth allocation. Accurately evaluating the effective bandwidth for a single source or aggregate traffic is the core of call admission control. Effective bandwidth is a function of traffic characteristics, QoS requirements, and the buffer size assigned. Once call admission control policy is established, the capacity planning of network resource is based on minimizing the call blocking probability for all services.

In our work, we have clearly defined a bandwidth management framework for integrated services networks. The G/D/1/K queue is examined and a clear definition of effective bandwidth is given. We propose an LBC matrix to characterize the traffic with the exact bandwidth required to deliver the QoS. Based on LBC matrix, we propose a

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dynamic resource allocation and call admission control scheme, which performs on-line, measured traffic to evaluate current load on network.

**Keywords:** Traffic characteristics; Multiplexing gain; G/D/1/K queue; Quality of service; Resource allocation; Call admission control.

## 1 INTRODUCTION

Computer network is not only a media for delivering text documents over the world nowadays, but also a media to support multimedia application in the future. As network bandwidth is further broadened, heterogeneous multimedia applications, for example, voice and video, can be integrated on broadband networks. Different applications have different *Quality-of-Service* (QoS) requirements. They can be either loss-sensitive or delay-sensitive. Computer network of the future must be able to provide different QoS to different classes of traffic. Computer networks that are able to provide QoS for various multimedia applications are called *Integrated Services Networks* (ISN).

*Asynchronous Transfer Mode* (ATM) networks [1] are the promising broadband networks to provide integrated services. The traffic is divided into cells of 53-byte to be delivered over the network. Another candidate for integrated services networks is the *Integrated Services Packet Networks* (ISPN). In packet-switched networks, the information is delivered in packets of variable size. Now *Internet Engineering Task Force* (IETF) is working on designing protocols that provide real-time multimedia services on the Internet.

Clark et. al. [3] proposed an ISPN architecture that supports two distinct kinds of real-time services: guaranteed service and predicted services. Guaranteed service is the traditional form of real time services discussed in most of the literature and involves pre-computed worst-case delay bounds. Predicted services uses the measured performance of the network in computing delay bounds.

There are two QoS requirements to be met for multimedia applications. One is the loss bound, and the other is the delay bound. In our analysis, we assume that the delay bound to be met is deterministic. In a deterministic service system like ATM networks, we realize that the worst-case delay experienced in a node for a specific connection can be constrained by the buffer size for the connection if the buffer is dedicated to it, or by the buffer size for all connections if they are multiplexed in a statistical way. The deterministic delay bound is defined as follows.

$$\text{Maximum Delay} = \frac{\text{Maximum Buffer Size}}{\text{Channel Rate}} < \sigma \quad (1)$$

where  $\sigma$  is a small value of time, say 1ms. Note that the bounded buffer size does not provide the bounded delay for a specific value of  $\sigma$  in a queueing system with deterministic service time. Delay bound is a function of channel rate as well. We assume that the loss bound is probabilistic. The definition of probabilistic loss bound is as follows.

$$\Pr[\text{Loss}] < \varepsilon \quad (2)$$

where  $\varepsilon$  is a small value, say  $10^{-6}$ . We assume that the arrivals are of fixed size. The arrivals with variable size can be treated as batch arrivals.

There are two objectives in our design. The major objective is providing different QoS guarantees to satisfy the different requirements of heterogeneous applications. The second objective is maximizing the resource utilization of the network. Multiplexing wide-range traffic sources on the same network will increase the utilization of the network resource. The higher the resource utilization is, the lower the call blocking probability is. Therefore, the objective of the capacity planning is to minimize the call blocking probability of connection-oriented services with QoS guarantees.

### **1.1 Resource Allocation and Call Admission Control**

Bae [2] classified congestion control in ATM networks into two categories, reactive control and preventive control. The scheme can be applied to general integrated services networks as well. Figure 1 illustrates a classification on congestion control.

For services with reactive control, the source will adjust its input rate based on the feedback from the network. The examples are TCP/IP in ISPN and ABR service in ATM networks.

However, preventive control tries to prevent congestion before it happens. The objective of preventive control is to ensure that network traffic will not reach the level, which causes unacceptable congestion. The most common and effective approach is to control traffic flow at the entry points to the network. Preventive control can be performed in two ways: call admission control and bandwidth enforcement. Call admission control determines whether to accept or reject a new connection at the time of call setup. This decision is based on traffic characteristics of the new connection and the current network load. The bandwidth enforcement monitors individual connections to ensure that the actual traffic flow conforms with that reported at call establishment.

The network can allocate the bandwidth and buffers to each connection to meet its QoS requirements. To increase network resource utilization and thus reduce call blocking probability, network needs an efficient resource management scheme. The resource allocation can be either static or dynamic. Static resource allocation allocates a fixed amount of resource at the beginning of the call request. Dynamic resource allocation changes its allocation over the duration of the call. Static resource allocation is independent of network status. We need a probabilistic reference model for the traffic source. The model is usually simple and is able to capture the statistical characteristics of the traffic. From the traffic model, the effective bandwidth for this stream can be calculated in advance and we are able to predict the worst-case scenario that could happen in the network. Dynamic resource allocation depends on current traffic load and network condition to adjust its allocation. Therefore, it is necessary to monitor traffic and network status. The captured results could be instant network load or the statistics during the previous monitoring window. Resource reallocation is then according to monitored results.

To provide QoS, we have to prevent network from overload. Therefore, call admission control needs to be enforced for new connections. Call admission control determines which connection requests are accepted by the network. The decision to

accept a new call should be based on the number of active connections in the network and on the characteristics of the bit streams carried by these connections. Call admission control policy depends on bandwidth management policy and buffer management policy. Bandwidth management policy is responsible to schedule the delivering order of output streams among different classes of traffic or different connections. Buffer management policy is responsible to partition buffer space for different classes of traffic or different connections.

Figure 2 shows a framework of resource allocation in integrated services networks. The resource allocation scheme discussed here can be applied to either ATM networks or ISPN. Network traffic is classified into three categories, *Constant-Bit-Rate* (CBR) connections, *Variable-Bit-Rate* (VBR) connections and *Best Effort Traffic*.

CBR and VBR connections are connection-oriented with QoS guarantees. These traffic sources are not adaptive to network status and could possibly overload the network. Therefore, we need the call admission control to maintain QoS requirements. In order to meet QoS constraints, CBR and VBR connections are assigned high priority so that network will provide all possible resources to support these types of service. The examples are Real Time Protocol (RTP)/ReSerVation Protocol (RSVP) on ISPN, and CBR/VBR services on ATM networks.

To achieve full utilization of the network resource, network should also provide best effort traffic. The best effort traffic can be connection-oriented or connectionless. There are no QoS guarantees. The traffic sources have flow control protocol and are adaptive to network status. Since the best effort traffic will obtain the network resource that is left over, it is assigned low priority. The examples are TCP/IP on ISPN, and ABR services on ATM networks.

## 1.2 Problem Formulation

It is necessary to estimate the effective bandwidth required for certain QoS. Figure 3 illustrates several performance issues to be investigated. In integrated services networks, we have a number of heterogeneous sources fed into the networks. Each source has its own traffic characteristics. The aggregate traffic is just the superposition of all traffic sources. A single node of the network can be modeled as a queueing system with a finite buffer. The buffer can be either shared among all sources or partitioned for individual source. The service discipline can be either *First-In-First-Out* (FIFO) or *Weighted-Fair-Queueing* (WFQ). There are two important issues to be studied.

- 1) *What is the traffic characteristics of the aggregate traffic?*
- 2) *Suppose the buffer space is shared among sources and FIFO service discipline is applied, this queueing system is equivalent to a G/D/1/K queue with batch arrivals. What is the performance of this G/D/1/K queue fed with the aggregate traffic?*

To understand how the aggregate traffic behaves, we need to realize the effective bandwidth for a given traffic stream. Effective bandwidth is the minimum bandwidth required for a traffic stream fed into a queueing system with fixed buffer size to meet its

QoS constraints. Note that the effective bandwidth should be a function of queue size, delay constraint, and loss constraint.

### 1.3 Traditional Approach and Its Drawbacks

In the past the performance evaluation is done through the following procedures.

- 1) *Finding a probabilistic model for a specific application.*
- 2) *Matching the parameters of the stochastic model for a specific application.*
- 3) *Evaluating multiplexing gain for the aggregate traffic based on the stochastic model of individual source traffic.*
- 4) *Solving queueing performance for arbitrary arrival traffic.*

There are many problems associated with traditional approach.

- 1) *Network traffic is more chaotic than we expect.*

Multimedia traffic will be delivered on broadband networks. Hypertext documents are already everywhere on *World Wide Web* (WWW). We expect more audio and video streams on today's Internet. The diversity of traffic types will be further in the future.

In a global networking environment, as more and more new networking technologies are developed, heterogeneous protocols will be employed. TCP/IP protocol suite has been the most widely accepted protocol. Recently, HTTP contributes a significant amount of traffic on Internet. In the future, we expect more UDP/IP traffic, which delivers real-time audio/video streams over the network. In general, there are two categories for protocols. One type of traffic source performs the flow control function, which depends on network status, for example, TCP protocol on Internet and ABR service on ATM networks. The other is totally independent of network status, for example, UDP protocol on Internet and CBR/VBR service on ATM networks.

In 1990s, network researchers explore that network traffic may exhibit *long range dependence* (LRD) [18, 24]. The well-known famous example is the LAN packet trace collected at Bellcore in 1989, which we will call it Bellcore LAN trace pAug. They have shown that the trace can be approximated as an asymptotic second-order self-similar process with Hurst parameter between 0.5 and 1 [18]. Besides, the movie trace of Star Wars, which is encoded by MPEG-1 standard, also exhibits LRD [8]. Recent study has also demonstrated that WWW traffic also exhibits self-similarity [4]. Unfortunately, traditional Markovian model does not capture the heavy-tailed autocorrelation function of the LRD traffic.

Another issue of network traffic is that whether network traffic is a stationary process or not is still unclear. The traffic running on the network includes connection-oriented traffic and connectionless traffic. The traffic delivered on each connection depends on the underlying coding scheme, the protocol used, user behavior, and network status if network-dependent flow control is applied. In such a heterogeneous environment, we could not conclude that network traffic is stationary. In case that

network traffic is not stationary, all analysis based on stochastic models will be inappropriate and invalid.

2) *Source model is unclear and matching the parameters is not trivial.*

In order to predict the performance, we need to find a probabilistic model for a given application. However, it is hard to justify that the probabilistic model would capture the statistical behavior of the source.

Another issue of traffic modeling is matching the parameters. For some stochastic processes, the procedure of parameter matching is not trivial.

3) *Solving queueing models is difficult.*

Suppose we have a probabilistic model for a given application. The next question is “What is the queueing performance for this application on a queue with channel rate  $C$ , and buffer size  $K$ ?” The queueing solution exists only for some simple models. For the rest of models, the solution is still under studying.

4) *Evaluating the multiplexing gain of multiple homogeneous/heterogeneous sources is still unknown.*

The last issue is multiplexing. To efficiently utilize the network resources, we need to multiplex many sources on the same link with shared buffer space. How to evaluate the multiplexing gain is the key to estimating maximum connections we can support on this link. We want to realize how the aggregate traffic behaves. Unfortunately, the existing solution only applies to a few simple models, for example, Bernoulli process, Poisson process, and MMPP. We know that the aggregation of Bernoulli process is Binomial process. Also, the aggregation of Poisson processes is still a Poisson process, and the aggregation of MMPP's is still an MMPP.

#### **1.4 The Organization of the Paper**

This paper is organized as follows. In section 2 the G/D/1/K queue is discussed. We propose a new method to speed up loss probability evaluation. We also present the *Loss probability – Buffer size – Channel capacity* (LBC) matrix to characterize the source traffic and resource requirement. From LBC matrix, we are able to plot *Buffer size – Channel capacity* (BC) curve for various loss probability. Several examples of BC curve for various traffic models and real traces are also present. In section 3, the issues on dynamic resource management are discussed. We then propose a dynamic resource allocation scheme for ISN. We also propose a measurement-based call admission control policy which evaluate multiplexing gain from the measured traffic trace during a fixed interval. Different policies for predicted sources and unpredicted sources are discussed. Traffic policing mechanism is also discussed. We then present the possible algorithms to speed up the simulation for BC curve. In section 4, we conclude our initial results and point out the contributions of our research work. The future research is also discussed.

## 2 THE G/D/1/K QUEUE

For a single node in the network, the performance evaluation is equivalent to a G/D/1/K queueing system. The G/D/1/K queue is a queueing system with arbitrary arrival process, deterministic service time, single server, and a buffer of size  $K$ . To analyze the queueing performance, we studied the properties of G/D/1/K queue. The important finding is that a G/D/1/K queue is bounded by its queue size  $K$ , and the queueing analysis can be obtained from the unfinished work. We will continue the discussion in Section 3.2.

### 2.1 The Mystery of G/D/1/K Queue

The queueing analysis of G/D/1/K queue can be obtained from the unfinished work. Figure 4 shows the unfinished work analysis for a G/D/1/K queue. The traffic trace is divided by channel rate into two groups which are illustrated in shaded area. We call it hill series  $A_i$  and valley series  $B_i$ . The series  $U_i$  is composed of the unfinished work at each starting point of series  $A_i$  and  $B_i$ .

Assume that the available buffer space is the “credit” of the queueing system. When the traffic trace is in valley area  $B_i$ , the arrival rate is less than the channel rate. The system can accumulate credits, which are illustrated in the crossed area of the valley. The maximum credit the system can accumulate is the unfinished work  $U_{2i}$  at the starting point of  $B_i$  if  $B_i > U_{2i}$ , or the area  $B_i$  if  $B_i < U_{2i}$ . When the traffic trace is in hill area  $A_i$ , the arrival rate is greater than the channel rate and the credits are consumed. When the system runs out of credit, it starts losing arrivals. Number of arrivals lost in area  $A_i$ , denoted as  $L_i$ , depends on the unfinished work  $U_{2i-1}$  and the area  $A_i$ . In figure 3.1,  $L_i$  is illustrated in the crossed area of the hill.

We summarize the property of G/D/1/K queueing system as follows.

$$\begin{aligned}
 U_1 &= 0 & L_1 &= \max(U_1 + A_1 - K, 0) \\
 U_2 &= \min(U_1 + A_1, K) \\
 U_3 &= \max(U_2 - B_1, 0) & L_2 &= \max(U_3 + A_2 - K, 0) \\
 U_4 &= \min(U_3 + A_2, K) & & \\
 U_5 &= \max(U_4 - B_2, 0) & L_3 &= \max(U_5 + A_3 - K, 0) \\
 U_6 &= \min(U_5 + A_3, K) \\
 &\vdots & &\vdots
 \end{aligned} \tag{3}$$

The loss probability is defined as

$$\text{Loss probability} = \frac{\sum_i L_i}{\text{Total number of arrivals}} \tag{4}$$

The mystery of G/D/1/K queueing system is that  $L_i$  depends on the unfinished work  $U_{2i-1}$  and the area  $A_i$ . However, the unfinished work  $U_{2i-1}$  depends on the previous unfinished work  $U_{2i-2}$  and the area  $B_{i-1}$ . Intuitively, there is no analytical solution for a G/D/1/K queue. The good news from these properties is that we can speed up the simulation for the loss probability of a G/D/1/K queue with fixed channel rate and variable buffer size as long as we have obtained the full hill and valley series. The bad news is that when the channel rate is changed, we have to simulate the whole trace again to update hill and valley series. There is no easy way we can obtain new hill and valley series from the ones associated with the old channel rate.

## 2.2 The LBC Matrix

For a traffic model to be useful, it must be able to predict the queueing performance with a finite buffer space. The complete queueing analysis of a given traffic trace can be represented in a *Loss probability – Buffer size – Channel rate* (LBC) matrix. A typical LBC matrix is shown in Figure 5.

The channel rate in the first row ranges from the mean arrival rate to the peak arrival rate. The buffer size in the first column ranges from 0 to maximum buffer size for mean rate allocation. The size of LBC matrix depends on the granularity of channel rate and buffer size.

## 2.3 The BC Curve

From the LBC matrix, we can determine the required resources, which are the channel bandwidth and the buffers, allocated to a specific connection that desires a certain degree of QoS.

To illustrate this, we present the BC curve, which is buffer size versus channel rate for a certain QoS requirement, say, the loss probability less than  $10^{-3}$ . Intuitively, if we extend the loss probability in the third dimension, we will have a 3-D surface called LBC surface. We then have the complete knowledge of resource allocation for any desired QoS.

If no loss is allowed in the network, we have a lossless BC curve. From the lossless BC curve, we can obtain some properties of traffic. Figure 6 shows a BC curve for various traffic sources, including Bellcore LAN trace pAug, Star Wars MPEG-1 trace, a 30-minute videoconferencing trace, and the Poisson process. Each curve starts at the mean arrival rate, and ends at the peak arrival rate. We note that, in most cases, there exists a “knee” for each curve. The curve above the “knee” is called the upper region. The curve below the “knee” is called the lower region. Also note that the curve of Bellcore LAN trace pAug does not have an obvious “knee”.

Lower region is not important for the queueing analysis. The shape of the lower region is according to the transient behavior of the peak arrival rate. For example, the peak rate of Star Wars MPEG-1 trace is 483. For a queueing system with buffer size 100 to support this trace without losing any arrivals, the channel rate must be at least 383.

Upper region shows how worse the traffic is. The smaller the slope of upper region, the worse the traffic is. For example, the Star Wars MPEG-1 trace has the same

mean as Poisson process. For the same buffer size, the required channel rate to support Star Wars MPEG-1 trace is much higher than the one to support the Poisson process.

If a probabilistic loss bound is allowed in the network, we will have BC curve. The shape of BC curve will vary for various loss probability requirements. More examples of BC curve are shown in the following section.

BC curve provides an accurate way to estimate effective bandwidth. However, the problem is that the computation to get this BC curve from the history of the traffic within window  $T$  is very complicated and may not be computed in real time.

The following derivation shows how to obtain the channel rate and the buffer size from the BC curve, given the delay constraint. We know that

$$\sigma = \frac{B^*}{C^*} \quad (5)$$

where  $D$  is the maximum delay at a node,  $B$  is the buffer size for the connection, and  $C$  is the channel rate. That is,

$$B^* = C^* \times \sigma \quad (6)$$

From the BC curve, we also know that

$$B^* = f(C^*) \quad (7)$$

Combine (6) and (7), we then have

$$C^* \times \sigma = f(C^*) \quad (8)$$

Given the maximum delay  $\sigma$ , we are able to find the channel rate  $C^*$  to satisfy QoS constraint. Substitute the channel rate  $C^*$  back in (6), we can find the corresponding buffer size  $B^*$ .

The above derivation is illustrated in Figure 7. A typical BC curve for a given loss constraint is shown in the figure. On the same plot, the dotted curve is  $B/C$  versus  $C$ . Suppose the delay constraint is  $\sigma$ . From the dotted curve, we can find the corresponding  $C^*$ , which is the minimum channel rate required to meet the QoS requirements. From the BC curve, we can obtain the corresponding  $B^*$ , which is the required buffer size for  $C^*$  to meet the QoS requirements.

## 2.4 Simulation Results

We have performed a series of discrete-time simulations to obtain the BC curve for various traffic models and real traces collected from the network. For probabilistic models, we generate 1,000,000 samples. For real traces, they are split into 10ms time slots. Arrivals are in fixed size, composed of 48-byte information, which is the payload of an ATM cell.

We choose the same mean arrival rate for all probabilistic models, and we then compare the BC curve for loss probability from 0, 0.1, to 0.000001. The probabilistic model we illustrated here are the Poisson process, the first-order the *AutoRegressive* (AR) process, and the heavy-tailed (Pareto distributed) on-off process. The real traces we simulated include Bellcore LAN traffic trace – pAug, Star Wars MPEG-1 trace. The statistics of traffic sources are shown in Table 1. In the following examples, we present the distribution of number of arrivals, the autocorrelation function, and the BC curve for all traffic sources.

### Example 1: The BC Curve of Poisson Process

In this example, the arrival process is the Poisson process. Number of arrivals in each time slot is Poisson distributed as

$$P(k) = \frac{\lambda^k}{k!} e^{-\lambda} \quad (9)$$

The mean arrival rate is 10. The peak arrival rate is 25. However, the theoretical peak rate of a Poisson process is infinity providing that number of samples is sufficiently large. The variance of all samples is 10.

From Figure 8, we know that Poisson process is an independent arrival process. From Figure 9, we note that the required buffer size is very small since arrivals are independent and the variance is small.

### Example 2: The BC Curve of First-Order Autoregressive Process

In this example, the arrival process is first-order *autoregressive* (AR) process. In each time slot, source generates an arrival based on the following equation.

$$z(t) = \phi \times z(t-1) + a(t) \quad (10)$$

where  $\phi$  is the AR parameter and  $a(t)$  is a white noise with zero mean. In our simulation, the AR parameter is 0.9, and the variance of white noise is 144. The mean arrival rate is 9.9. The peak arrival rate is 124. The variance of all samples is 222.

From Figure 10, we know that first-order autoregressive process exhibits SRD among arrivals. From Figure 11, we note that the required buffer size for AR process is much worse than that for Poisson process due to higher interarrival correlation and variance of AR process.

### Example 4: The BC Curve of Heavy-Tailed On-Off Process

In this example, the arrival process is heavy-tailed on-off process. The only difference between the on-off process and the heavy-tailed on-off process is that the sojourn time in each state follows Pareto distribution instead of geometric distribution.

The Pareto parameter for on state is 1.11, and the Pareto parameter for off state is also 1.11. Therefore, the mean sojourn time in on state is the same as the mean sojourn

time in off state, which is 10. The mean arrival rate is 9.66, and the peak arrival rate is 20. The variance of all samples is 99.89.

From Figure 12, we know that the heavy-tailed on-off process exhibits strong LRD among arrivals. From Figure 13, we note that the required buffer size is the worst case in our simulation study. We conclude that the interarrival correlation has very strong impact on traffic behavior and queuing performance

#### **Example 4: The BC Curve of Star Wars MPEG-1 Trace**

In this example, the arrival process is the MPEG-1 trace of Star Wars. The mean arrival rate is 9.87, and the peak arrival rate is 483. The variance of all samples is 845.47.

From Figure 14, we know that Star Wars MPEG-1 trace exhibits periodicity. It is possibly due to underlying coding scheme. From Figure 15, we note that the shape and the magnitude of BC curve is very close to the first-order autoregressive process, which confirms that the first-order autoregressive process is a good candidate to model VBR video trace.

#### **Example 6: The BC Curve of Bellcore LAN Trace – pAug**

In this simulation, the arrival process is the Bellcore LAN trace – pAug. The mean arrival rate is 30.25, and the peak rate is 284. The variance of all samples is 2219.71. [18] has shown that the LAN trace pAug exhibits second-order self-similarity with Hurst parameter 0.83.

From Figure 16, we know that the Bellcore LAN trace pAug does exhibit strong LRD. From Figure 17, we note that it is of no use to increase buffer size to maintain QoS requirements. The required bandwidth to support LRD traffic is much larger than its mean arrival rate.

### **3 DYNAMIC RESOURCE ALLOCATION AND CALL ADMISSION CONTROL**

In this section, we discuss the requirements for dynamic resource allocation and propose a dynamic resource allocation scheme. We then establish a measurement-based call admission control policy algorithm for ISN.

#### **3.1 Dynamic Resource Allocation**

Dynamic resource allocation must consider the following issues.

##### *1) What to Monitor*

The information to be collected from the network depends on the usefulness of the information to the traffic characterization. Intuitively, the statistics we should collect is the distribution of number of arrivals. We can obtain mean, variance, and peak of the arrival rate from it. For interarrival correlation, we may collect the autocorrelation function of traffic trace, but it is not very useful for the derivation of effective bandwidth.

To obtain BC curve for performance analysis, however, we need to collect the complete traffic trace during a window of size  $T$ .

### 2) *The Actual Required Resource*

From the information we collect, we have to determine the effective bandwidth of the traffic during the previous measurement window  $T$ . Once the complete traffic trace is collected, we can obtain LBC matrix by simulation. However, the simulation is very time-consuming. The actual simulation time depends on the size of measurement window and the granularity of LBC matrix.

### 3) *Resource Reallocation*

Our philosophy is predicting the trend of the future from the history of the past. We assume that the traffic characteristics are invariant from measurement window to measurement window. The network resource allocated in the next measurement window depends on the traffic characteristics in the previous measurement window. Therefore, we need to perform a resource reallocation at the end of each measurement window.

### 4) *Reallocation Cycle*

The reallocation cycle is exactly the measurement window size. If the window size is too small, we may update the traffic status too frequently and possibly waste too much CPU power on resource reallocation. If the window size is too large, the dynamics of the traffic can not be fully captured and realized.

### 5) *Sharing or Isolation*

To maintain the QoS in the network and simplify the management issues, we suggest that network resource should be isolated among different classes of services. However, to increase the utilization of network resource, the resource should be shared within the same class of traffic.

Statistical multiplexing is employed for connections with the same QoS requirement, since the resource utilization will be benefited from multiplexing gain. Theorem 1 states the inequality of the sum of effective bandwidth and the effective bandwidth of the sum (aggregate traffic).

#### **Theorem 1**

*A connection  $i$  requires  $(B_i, C_i)$  to meet its QoS requirements. Suppose we have  $n$  connections which has the same QoS requirements. The aggregate traffic requires  $(\hat{B}, \hat{C})$  to meet the same QoS requirements. Then*

$$\hat{B} \leq \sum_{i=1}^n B_i \quad (11)$$

$$\hat{C} \leq \sum_{i=1}^n C_i \quad (12)$$

When a new connection requests for the network resources, it should specify the worst-case resources it may require. However, the actual resource allocated is decided by the current characteristics of the aggregate traffic, that is, it may be changed dynamically over the active period. Therefore, VBR connections may “steal” resources from best effort traffic to handle unexpected traffic from VBR sources.

### 3.2 A Dynamic Resource Allocation Scheme for ISN

Figure 18 shows a dynamic resource allocation scheme for ISN in which we have best effort connections, VBR connections, and CBR connections.

A fixed buffer of size  $\hat{B}_b$  is assigned to best effort connections. Best effort connections may or may not reserve channel bandwidth. However, when the traffic rate of CBR and VBR connections are below their reserved channel bandwidth, best effort connections can get the channel bandwidth which is left over.

VBR connections are processed separately based on their QoS requirements. The connections that require different QoS requirements are put into different queues. In other words, all connections in the same queue have the same QoS requirements. The resource requirement for individual VBR connection  $i$  in class  $j$  is denoted as  $(B_{v,i}^{(j)}, C_{v,i}^{(j)})$ . The resource requirement for aggregate VBR traffic in class  $j$  is denoted as  $(\hat{B}_v^{(j)}, \hat{C}_v^{(j)})$ .

CBR connections are assigned with bandwidth  $\hat{C}_c$ . Since CBR connections are well behaved and the input traffic rate is equal to the channel rate assigned to the connections, no buffers are assigned to CBR connections.

The service discipline is *Weighted Fair Queueing* (WFQ). The server is work-conserving. All CBR/VBR servers have an upper bound of channel rate that can be obtained. The best effort connections take all the bandwidth which is left over by CBR/VBR connections. The only exception for maximum channel rate that CBR/VBR connections could obtain happens when there is no best effort arrivals waiting to be delivered in the queues.

### 3.3 A Measurement-Based Call Admission Control Algorithm

The basic assumption for measurement-based call admission control is that the traffic characteristics is invariant from measurement window to measurement window. Our objective is to accurately estimate the required resource to deliver the instant traffic and obtain the available bandwidth for new connections so that we can utilize network resource more efficiently and therefore reduce the call blocking probability. To increase network resource utilization, the admission decision should be made based on the effective bandwidth for each class of traffic during the previous measurement window  $T$ .

Suppose we have the complete traffic trace over the previous measurement window  $T$ , then we are able to obtain its BC curve and determine the traffic characteristics by the required resource to support QoS requirements.

### 3.3.1 Connection Setup

We characterize the traffic by the resource it requires in a queueing system with a finite buffer space. BC curve provides an intuitive look of the traffic characteristics.

Figure 19 illustrates connection setup procedures for CBR/VBR connections. A new connection must request resources  $(B,C)$  from the network. If the request can be supported by the network, then it is admitted; otherwise, it is rejected.

The requested network resource can be an array of  $(B,C)$  pairs. If both buffers and channel bandwidth can not be supported by the network, the request is rejected. In case that network does not have enough channel bandwidth to support the new traffic, but has more buffers than the requested buffers, the network will try a different combination of  $(B,C)$  again to see if the request can be supported.

The call admission control policy is different for predicted sources and unpredicted sources. The traffic characteristics of predicted sources can be fully studied and realized in advance. However, for unpredicted sources, we have very limited knowledge of the incoming traffic. The traffic characteristics may vary from time to time.

### 3.3.2 Call Admission Control Policy for Predicted Sources

For predicted sources, the traffic characteristics can be fully understood in advance. Therefore, it is easier for network to manage the resource and control congestion.

1) *Conservative call admission control policy:*

Reject the new connection request if

$$\sum_i C_{c,i} + \sum_i \sum_j C_{v,j}^{(i)} + C_{new} < C_{max} \quad (13)$$

$$\hat{B}_b + \sum_i \sum_j B_{v,j}^{(i)} + B_{new} < B_{max} \quad (14)$$

Advantages and disadvantages of this policy are stated as follows.

- Admission control policy is simple, we don't need to measure the multiplexing gain of heterogeneous aggregate traffic.
- The admission control policy may be too conservative.
- The effective bandwidth allocation for individual source is still much better than the peak bandwidth allocation.
- There will be absolutely no QoS violation.

2) *Efficient call admission control policy:*

Reject the new connection request if

$$\hat{C}_c + \sum_i \hat{C}_v^{(i)} + C_{new} < C_{max} \quad (15)$$

$$\hat{B}_b + \sum_i \hat{B}_v^{(i)} + B_{new} < B_{max} \quad (16)$$

Advantages and disadvantages of this policy are stated as follows.

- The efficient call admission control policy takes advantage of the multiplexing gain from the same class of traffic.
- The efficient call admission control policy reduces the call blocking probability.
- The resource utilization can be maximized.
- Networks may have the risk of violating QoS requirements.

### 3.3.3 Call Admission Control Policy for Unpredicted Sources

For unpredicted sources, the traffic characteristics can not be realized in advance. Therefore, we propose a recursive procedure to obtain the accurate resource allocation in the following steps.

*Step 1: Request the initial resource (B,C).*

*Step 2: Monitor the incoming traffic of the connection within an interval of T.*

*Step 3: Update (B,C) based on the traffic characteristics of the measured result.*

### 3.4 Traffic Policing

We don't include traffic policing mechanism in our proposed resource management scheme. However, the source may cheat the network and request less resource to get admitted. It turns out that the network may be overloaded than we expect. In case there is a need to implement traffic policing mechanism, the *Leaky Bucket* mechanism can be implemented at the entry point of the network.

For conservative call admission control policy, the WFQ can be employed for isolating resources among connections. The traffic policing is automatically enforced by WFQ scheduling algorithm.

For efficient call admission control policy, the additional policing mechanism may be applied on the individual connection to monitor its behavior.

### 3.5 Measurement Process and Fast Simulation for BC Curve

In this section, we discuss some issues related to measurement process and traffic estimation.

#### 3.5.1 Fast Simulation to Obtain Effective Bandwidth

It is not necessary to simulate every point of BC matrix. If the assigned channel rate is close to the peak rate, then the required buffer size will drop significantly. That is, the required simulation time will be reduced.

The granularity of LBC matrix will also affect the simulation time. Therefore, we may choose a large increment for buffer size and channel rate. The rest of the curve can be obtained by estimation. Since number of simulations is reduced, the simulation will also be reduced significantly.

For the loss probability for a given channel rate and various buffer size, we can apply the property of G/D/1/K queue we studied in section 2.1 to speed up the simulation. In the first run, we simulate the measured trace with given channel rate and obtain the hill sequence and valley sequence. We then are able to perform fast simulation for any given buffer size.

### 3.5.2 Another Heuristic Approach to Estimate $(B,C)$

Another heuristic approach to obtain the required  $(B,C)$  for given QoS requirements is summarized in the following four steps.

*Step 1: Choose  $C$ .*

*Step 2: Run simulation to see how much the QoS is violated.*

*Step 3: If the QoS is violated, increase  $C$ , otherwise, decrease  $C$ . If the QoS is close enough to the target QoS, stop the simulation.*

*Step 4: Run simulation again.*

Advantages and disadvantages of this policy are stated as follows.

- General speaking, the allocated bandwidth in the next measurement window is close to the allocated bandwidth in the previous measurement window. Therefore, if we use the previous allocated bandwidth as an initial point in simulation, we will save a lot of unnecessary simulation.
- How fast the process will converge to the optimal point depends on the bandwidth update policy, namely, from the old value to the new value. This policy must be established to make this approach work. However, this study is still under investigation.

## 4 CONCLUSIONS

Modern network traffic is more chaotic than people expect. Long range dependent traffic have a significant impact on network performance. Simple models and traffic parameters are fairly inadequate to characterize the traffic and evaluate the required network resources to handle the traffic. In this paper, we propose a clear definition of QoS requirements and required resources (buffers and channel bandwidth) to support the QoS. We build an infrastructure in delivering QoS in integrated services networks and propose a measurement-based CAC algorithm, which can accurately characterize the network traffic and utilize the network resource in an efficient way. The proposed framework can provide multiple classes of services with QoS guarantees. The contribution is summarized as follows.

- We have established a practical framework to manage resources in integrated services networks.
- We have characterized the behavior of G/D/1/K for a given traffic trace by obtaining hill and valley series. The queueing performance can then be analyzed by the unfinished work at the starting point of hill and valley series..
- We have investigated queueing behavior of traffic by obtaining its LBC matrix and BC curve.
- We have been developing fast algorithms to obtain the effective bandwidth by simulation.

There are several interesting issues to be studied in the future. Although many properties of G/D/1/K queue have been explored, we still do not have a quick solution to the performance analysis. The current results are obtained by simulation. However, the results may not be obtained in real time without enough CPU power. Therefore, the development of solutions to the G/D/1/K queue is necessary.

Stochastic traffic models are still valid and can be applied to many applications. Fast approximations of BC curve for various traffic models, including Markovian traffic models and fractional traffic models, need to be developed.

Multiplexing gain for homogeneous traffic is also an interesting issue. The multiplexing gain for various models can be obtained from the BC curve of aggregate traffic. By comparing the multiplexing gain under various traffic load and traffic parameters, it is possible to approximate the multiplexing gain by a stationary function.

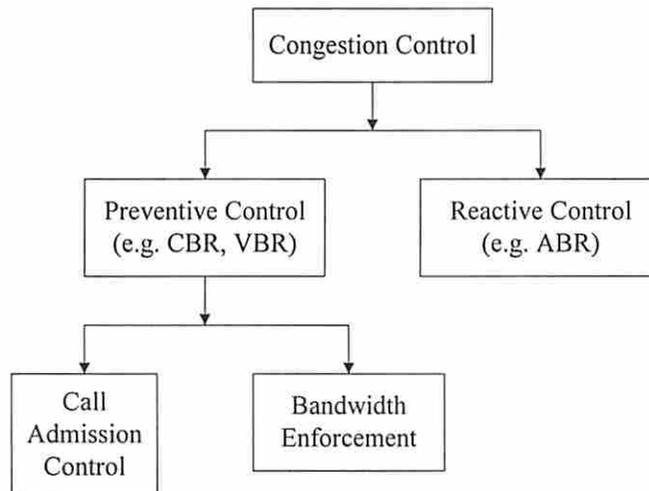
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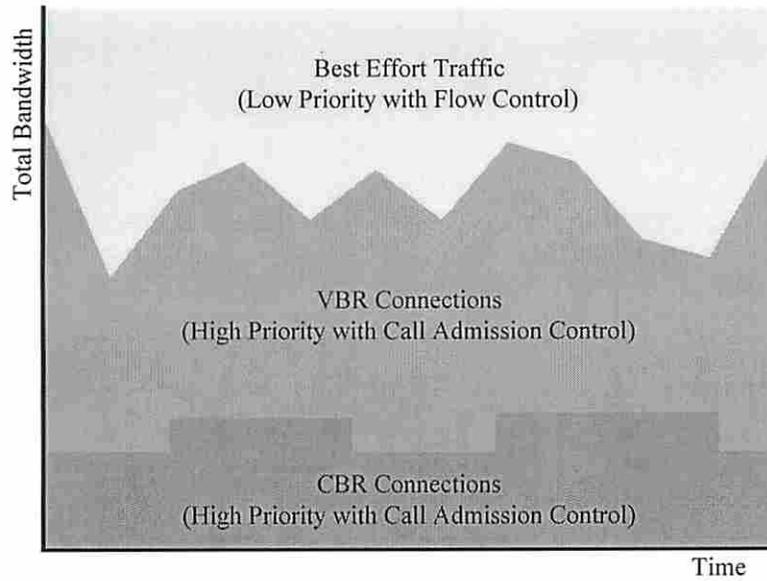
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**Table 1:** The statistics of source traffic.

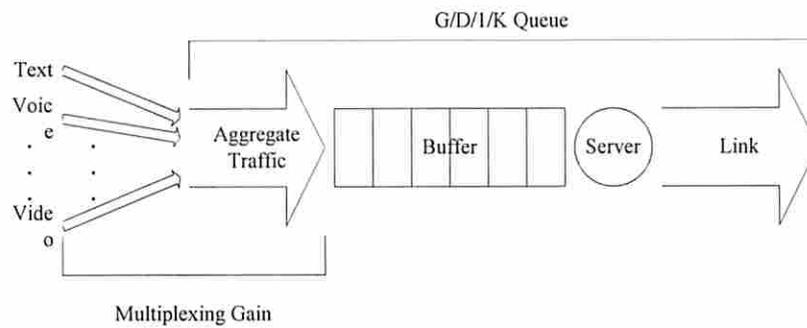
Source	Mean	Peak	Variance	Correlation
Poisson Process	10	25	10	Independent
AR(1) Process	9.9	124	222	$r(k) > 0$ $k < 55$
Two-State MMPP	10	28	18	$r(k) > 0$ $k < 34$
Heavy-Tailed On-Off Process	9.66	20	99.89	$r(k) > 0.15$ for all $k < 1000$
Star Wars MPEG-1 Trace	9.87	483	854.47	Periodic
Bellcore LAN Traffic – pAug	30.25	284	2219.71	$r(k) > 0.037$ for all $k < 1000$



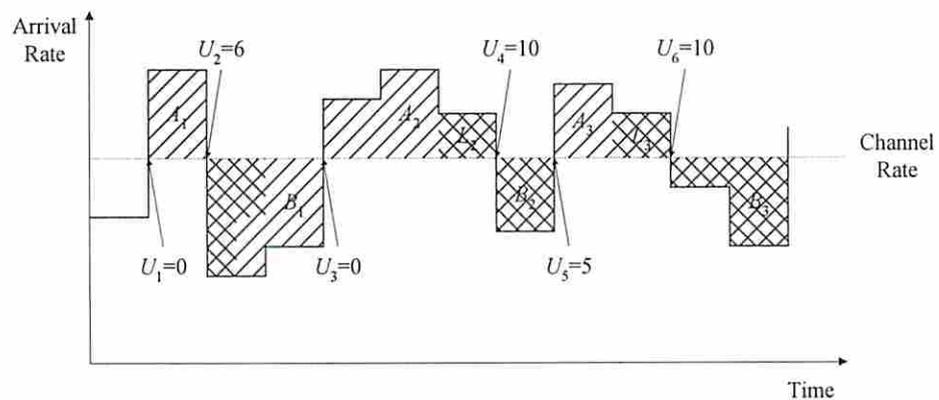
**Figure 1:** A classification on congestion control.



**Figure 2:** A framework of resource allocation in integrated services networks.



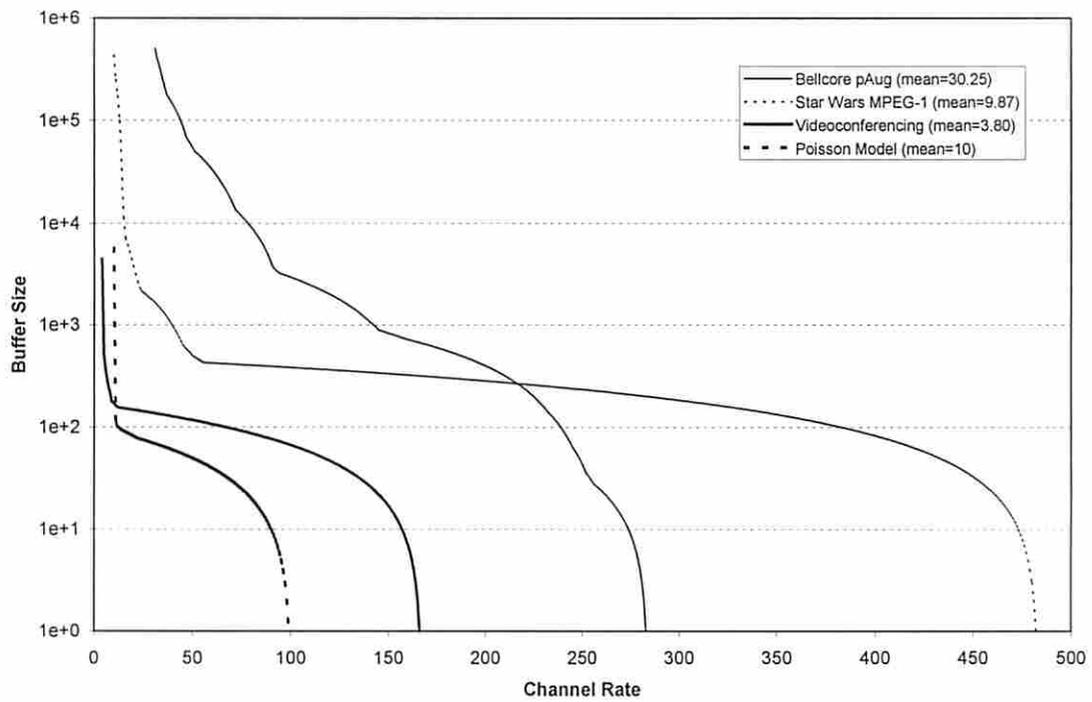
**Figure 3:** An abstract model for network performance analysis.



**Figure 4:** The unfinished work in a G/D/1/K queue.

Buffer Size	Channel Rate				
	B/C	10	20	30	...
10		0.0012	0.0003	0.0001	...
20		0.001	0.0002	0.00005	...
30		0.0008	0.0001	0.00002	...
...		...	...	...	...

**Figure 5:** The LBC matrix.



**Figure 6:** The lossless BC curve.

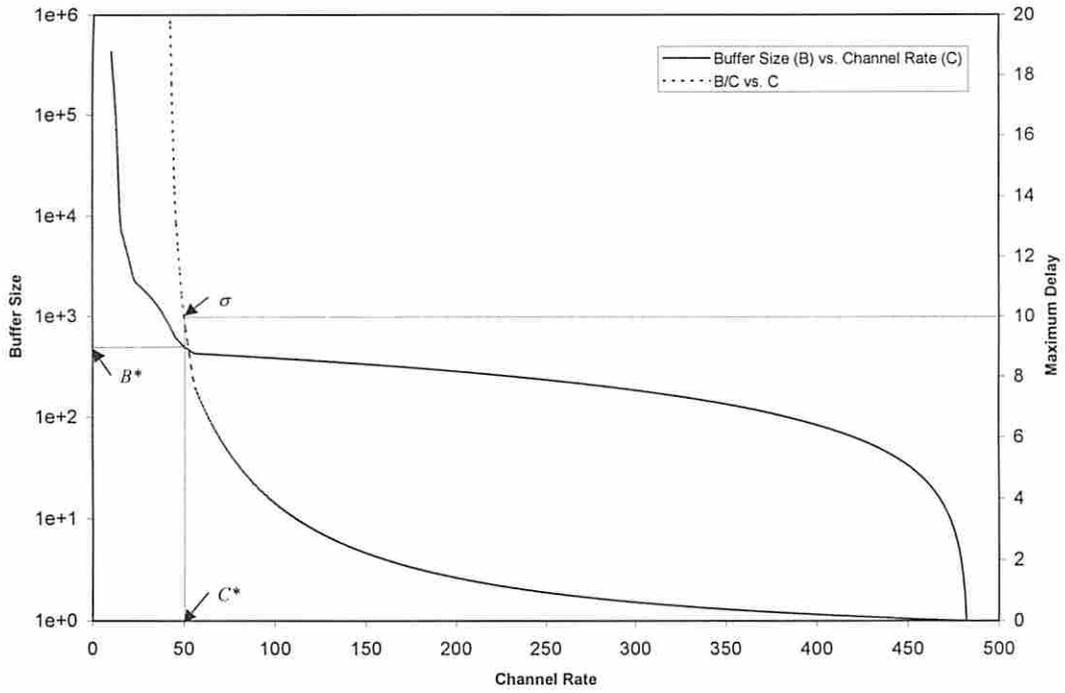


Figure 7: B/C versus C on the same plot as the BC curve.

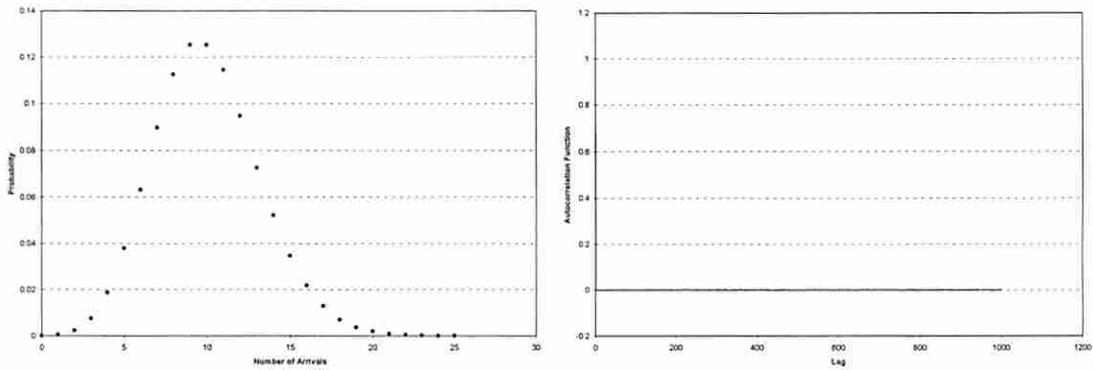
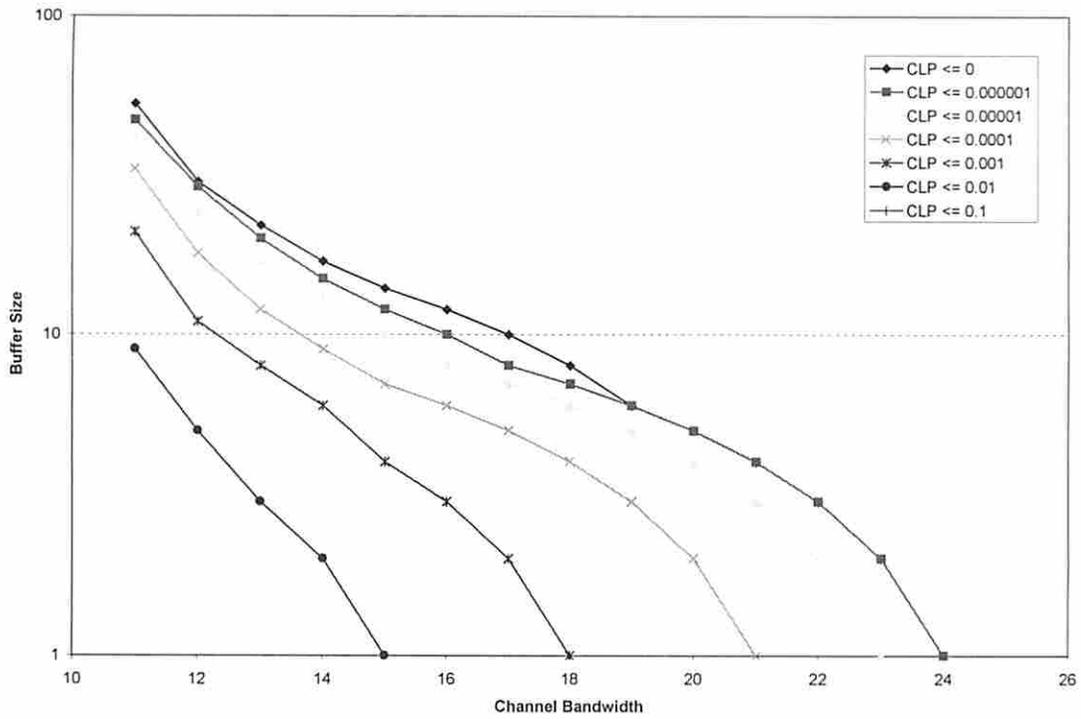
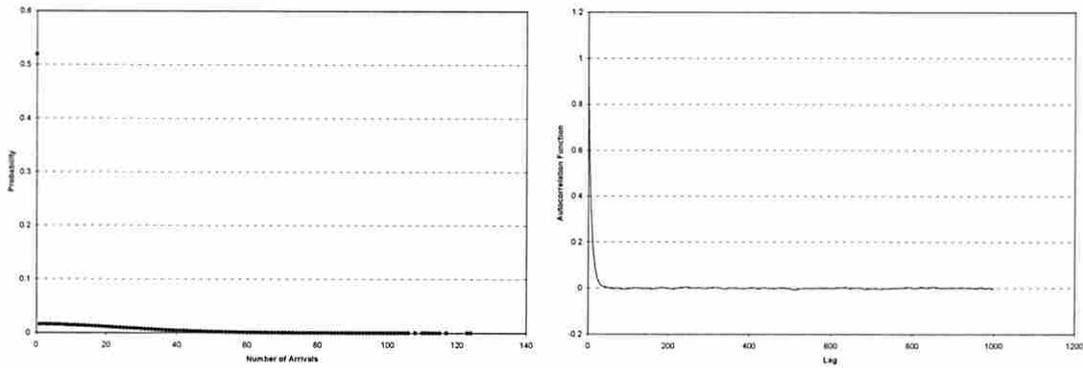


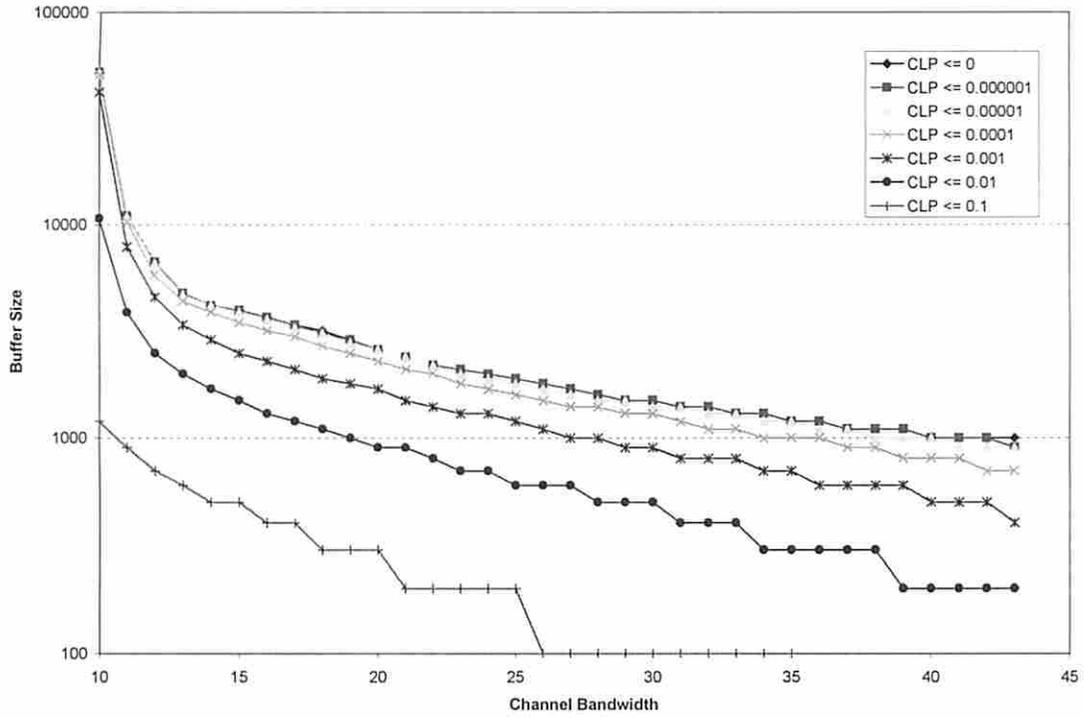
Figure 8: The distribution of number of arrivals and autocorrelation function of Poisson process.



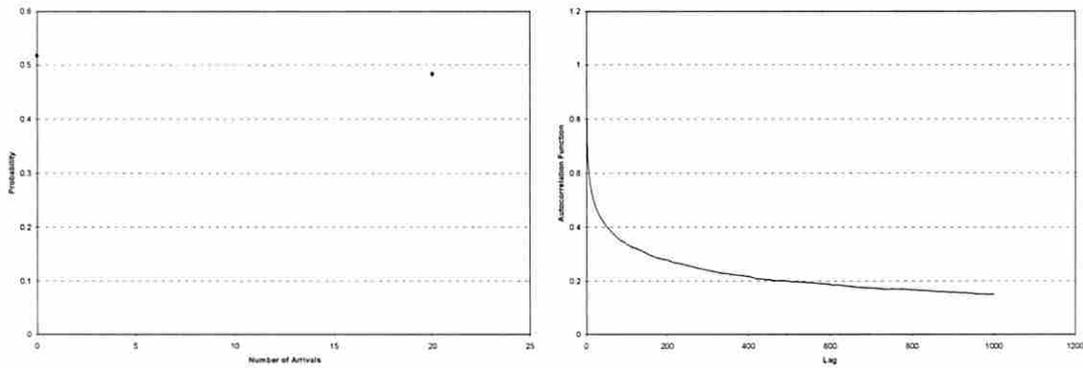
**Figure 9:** The BC curve of Poisson process.



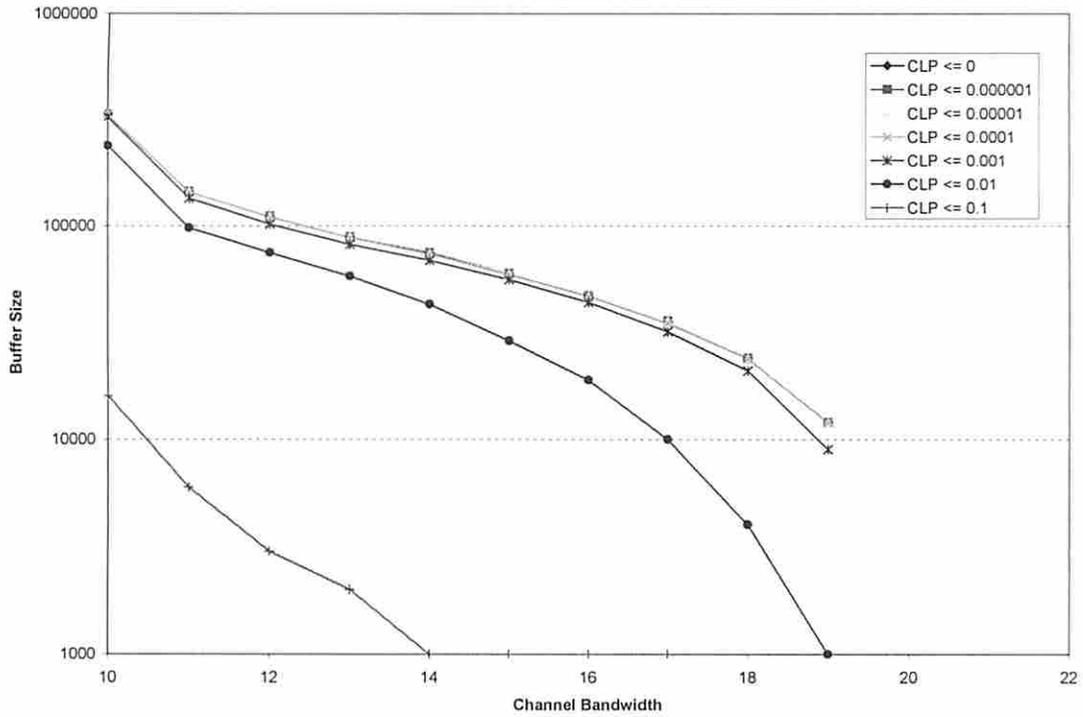
**Figure 10:** The distribution of number of arrivals and autocorrelation function of first-order autoregressive process.



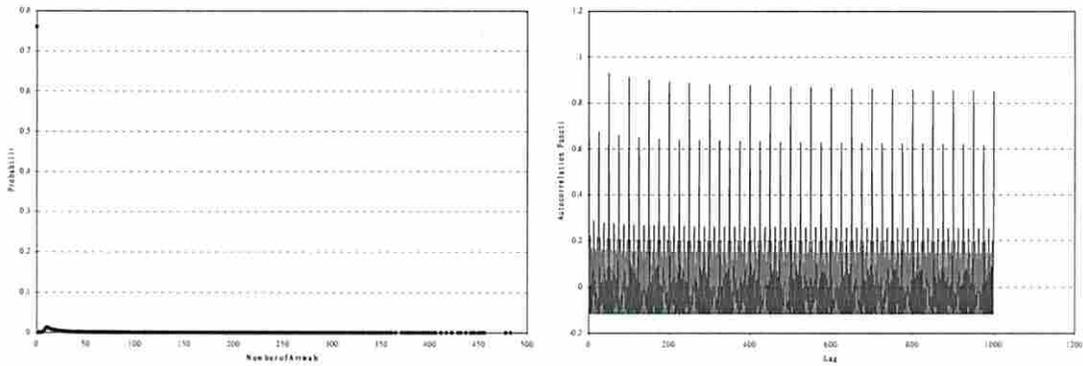
**Figure 11:** The BC curve of first-order autoregressive process.



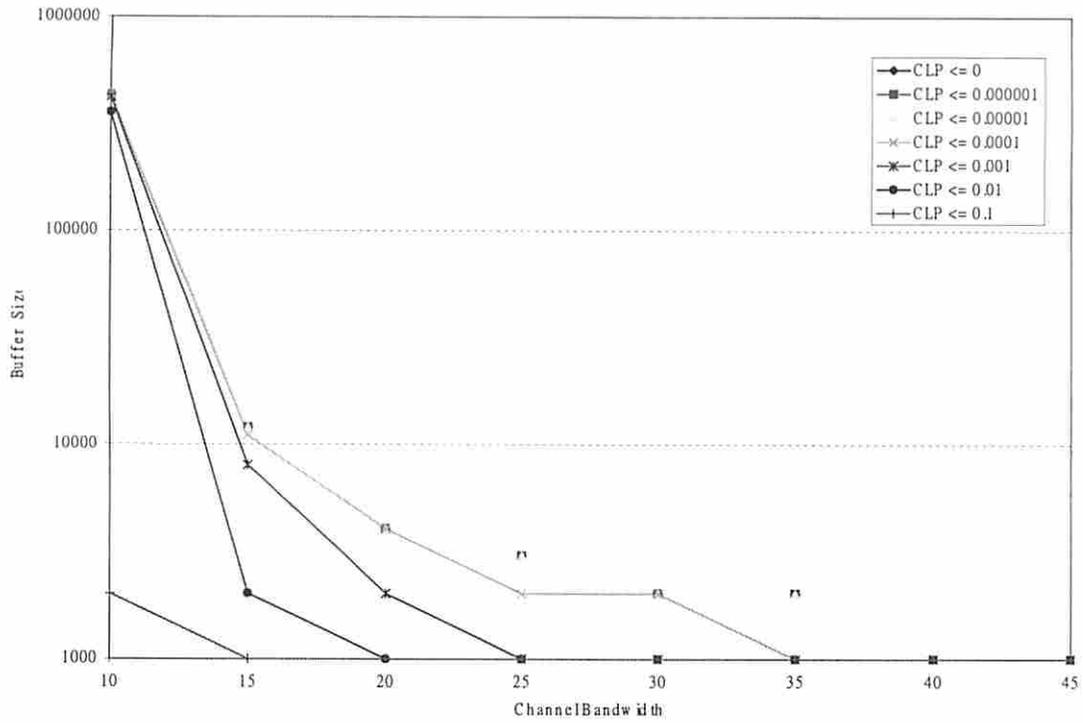
**Figure 12:** The distribution of number of arrivals and autocorrelation function of heavy-tailed on-off process.



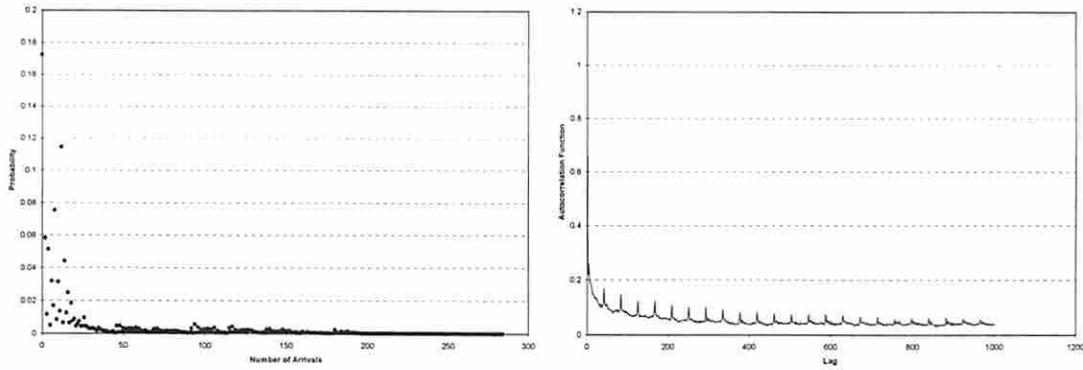
**Figure 13:** The BC curve of heavy-tailed on-off process.



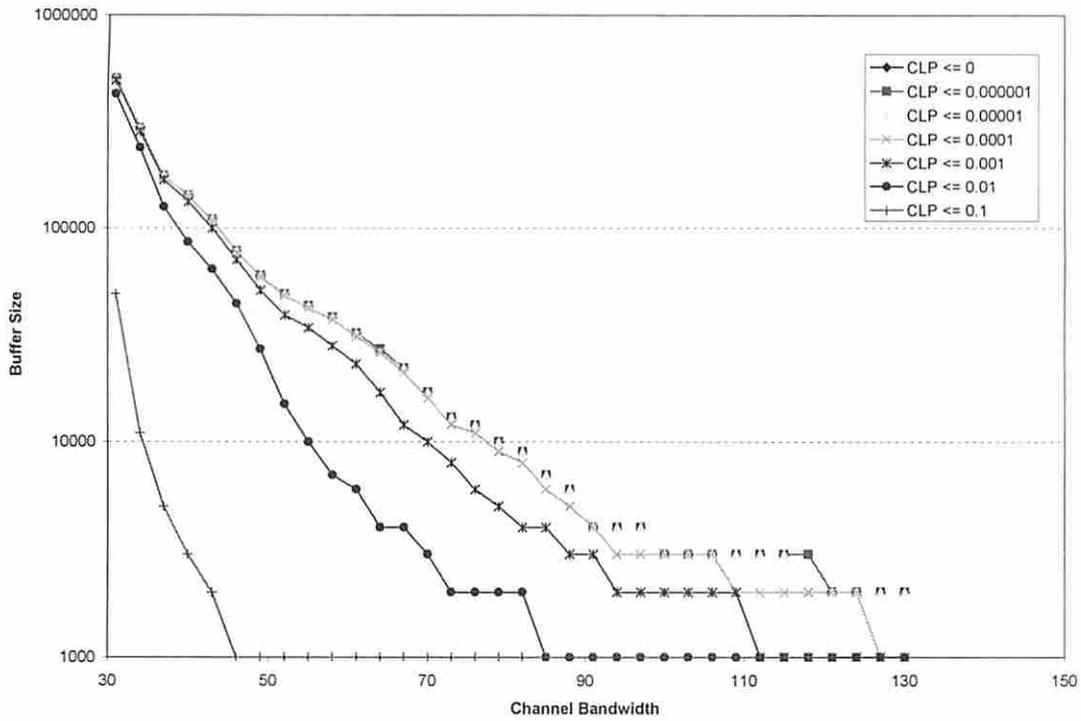
**Figure 14:** The distribution of number of arrivals and autocorrelation function of Star Wars MPEG-1 trace.



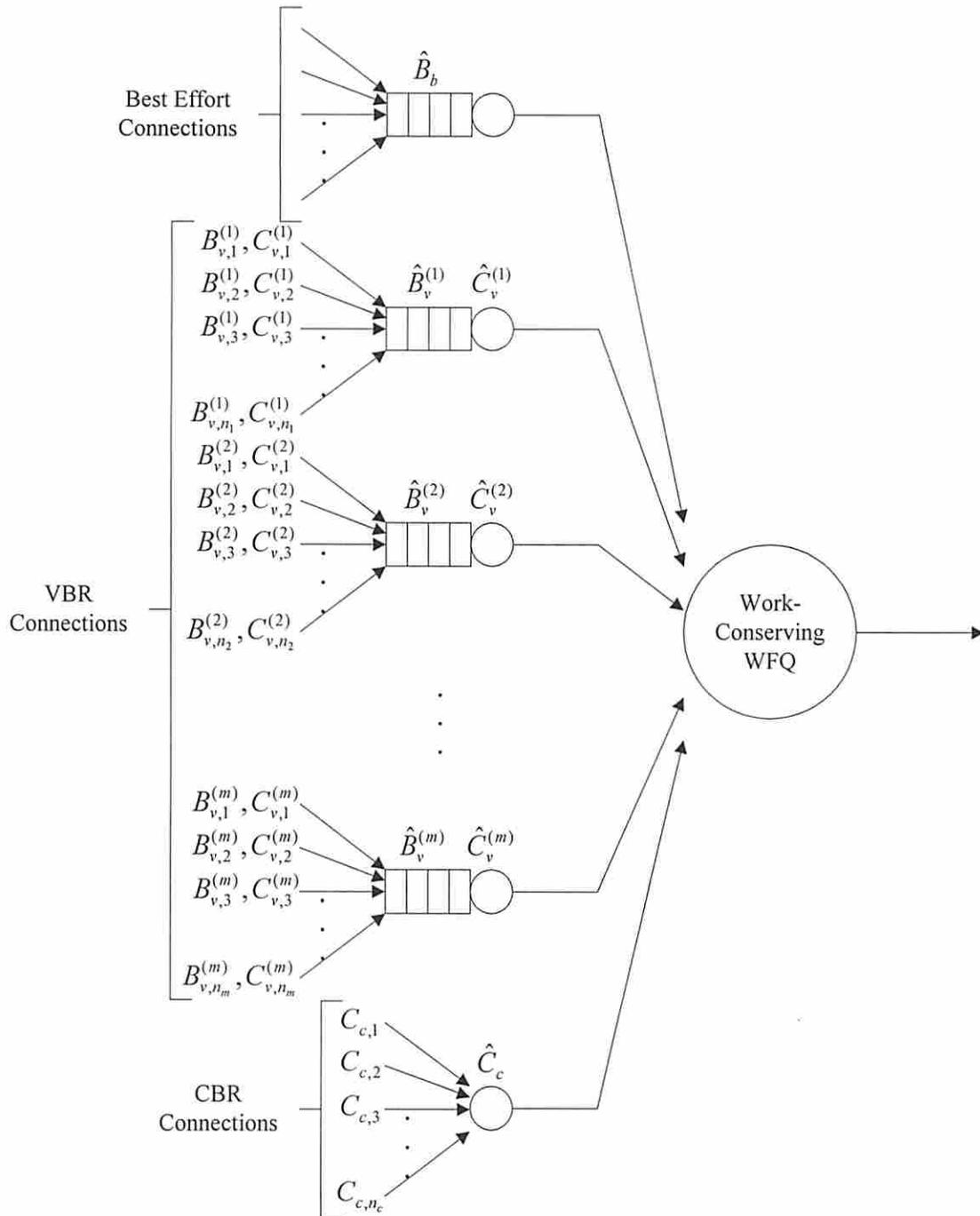
**Figure 15:** The BC curve of Star Wars MPEG-1 trace.



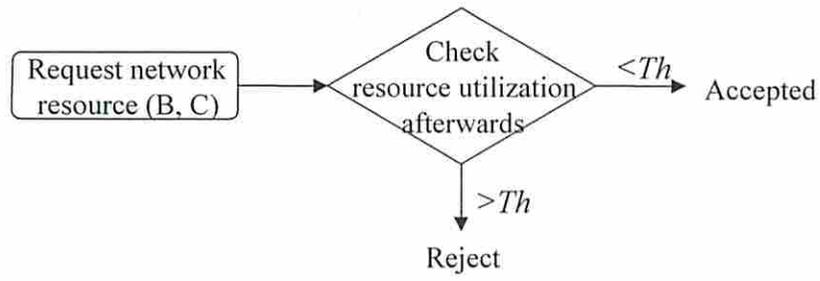
**Figure 16:** The distribution of number of arrivals and autocorrelation function of Bellcore LAN trace – pAug.



**Figure 17:** The BC curve of Bellcore LAN trace – pAug.



**Figure 18:** A dynamic resource allocation scheme for ISN.



**Figure 19:** Connection setup procedures.