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ASYMPTOTIC EFFICIENCY AND ADMISSION CONTROL FOR DISCRETE COMMUNICATION NETWORKS

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ABSTRACT

The problem of reducing the effects of traffic uncertainties on the efficiency of digital communication networks is considered. The emphasis is on maximizing the efficiency of high capacity communication networks, subject to traffic uncertainties with unmodeled statistics. The note concentrates on the optimal selection of the data admitted into the network.

1. INTRODUCTION

A discrete (or digital) communication network is used to transmit digitized data, computer files, digitized phone calls, digitized video signals, and other forms of discrete information. To improve the efficiency of a discrete communication network, traffic control algorithms are used to direct the data traffic through the network. The present note deals with the development of traffic control algorithms that aim to maximize the amount of data passing through the network.

The traffic entering a digital communication network is random and varied in nature. Large portions of the traffic lack comprehensive statistical models, as the characteristics of their random nature have not been fully validated. Among the important classes of network traffic that lack comprehensive statistical models, one finds the substantial class of digitized video and multimedia data, as well as other classes (e.g., ECKBERG [1979], DAIGLE and LANGFORD [1986], HUI [1988], PAXSON and FLOYD [1994], and SCHWARTZ [1996]).

The lack of comprehensive statistical models diminishes the benefits of using filtering techniques for the design of traffic control algorithms. It gives rise to a need to develop traffic control methodologies that do not depend on detailed statistical models of the traffic. The present note addresses this need by introducing a traffic control theory that does not require detailed statistical models of network traffic. This theory is analogous to the theory of robust control, which helps overcome the effects of unmodeled uncertainties on control systems.

While the theory of robust control is intended to deal mainly with relatively small uncertainties, traffic control must deal with large uncertainties as well. To emphasize this distinction, we replace the adjective "robust" by the adjective "sturdy" in the present context, and refer to our current topic as *sturdy traffic control*. Sturdy traffic control deals with the development of traffic control algorithms that operate under the influence of large unmodeled uncertainties, characterized by amplitude bounds.

When discussing traffic control algorithms, one must address the issue of data loss. Sturdy traffic control completely prohibits data loss. In contrast, statistical traffic control techniques often incur some data loss during rare traffic events (e.g., ATKINS [1980], GOLESTANI [1991], and CHANG [1994]). Notwithstanding its prohibition of data loss, sturdy traffic control leads to full network utilization in many common situations. This comes to show that data loss is not a "necessary evil" along the path to high network efficiency.

The techniques discussed in the present note are intended for large capacity networks. In fact, we concentrate on network efficiency at the limit, when the volume of traffic tends to infinity. This leads us to the notion of *asymptotic efficiency*. Asymptotic efficiency is pertinent to the large capacity networks (called *backbones*) currently used for long distance digital communication. An important advantage of using asymptotic efficiency as the criterion for network optimization is that it leads to scalable traffic control algorithms. These algorithms adjust easily as a communication network expands.

This note is an extended summary and refinement of HAMMER [2000a]. It concentrates on the process of optimizing the selection of the data allowed into a network. The control of the data flow within the network is further discussed in HAMMER [2000b and 2001].

1.1 Some terminology.

The discrete elements transmitted through a digital communication network are called *cells*. Most often, all cells of a given network contain the same volume of data (i.e., the same number of bits; e.g., ATM FORUM [1997]). In such case, the volume of data passing through the network is determined by the number of cells. For the sake of simplicity, we shall restrict our discussion exclusively to such networks.

A *call* is a collection of cells that form a complete data record. Each cell carries information that identifies the call to which it belongs, as well as the relative position of the cell's data within the call's record. Whence, it is not necessary to keep the cells in a particular order as they pass through the network. The cells can be put back into correct order at the destination.

The calls entering a network are divided into different categories called *call classes*. Digitized phone calls, computer file transfers, and digitized video signals are examples of call classes. Each call class has its own transmission-fidelity requirements. For example, classes of real-time signals, like digitized video and digitized phone calls, exhibit high sensitivity to transmission delays and jitter. On the other hand, computer data file transfers are relatively insensitive to transmission delays.

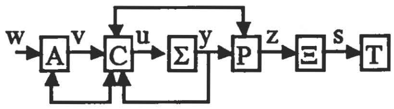
The transmission-fidelity requirements of a class form its *service requirements*. The most common service requirement specifies the maximal delay (or jitter) a cell of the class may experience while passing through the network. Detailed descriptions of service requirements are given in ATM FORUM [1997] (see also HANDEL, HUBER, and SCHRODER [1994]).

We shall use the term *network capacity* to indicate the largest number of cells the network can transmit during each unit of time. Inasmuch as calls enter the network from independent sources having random transmission rates, the number of cells entering the network may exceed network capacity. When this occurs, we have *network congestion*. An important role of traffic control algorithms is to resolve conditions of network congestion. Sturdy traffic control algorithms resolve network congestion without incurring cell loss.

2. BASICS.

We represent the flow of cells through a network by a sequence of integers. An element of the sequence corresponds to the number of cells that flow through a point of the network during a specified interval of time $\Delta > 0$. In particular, for an integer $k \geq 1$, the symbol v_k indicates the number of cells that flow through the point v of the network during the time interval $((k-1)\Delta, k\Delta]$. The interval $((k-1)\Delta, k\Delta]$ is referred to as *step* k. Note that for a network turned on at the time zero, the first significant step is $k = 1$. The length of the time interval Δ is selected to be short compared to network time constants and delays. This interpretation allows us to regard the network as a discrete time system acting on sequences of integers. The following diagram represents the main elements of a network.

(1)



Here, w represents the pool of calls requesting admission into the network, and A represents the network gate. The gate implements the call admission process: it selects the calls that are allowed to enter the network. The symbol Σ represents the short network link connecting the source to the backbone, while Ξ represents the backbone, a large capacity network segment. The controller C controls the flow of cells from the source, and is called the *source controller*. The flow of cells into the backbone is controlled by the router controller P. Both C and P contain buffers that can temporarily store cells when the incoming cell flow rate exceeds network capacity. Finally, T represents the destination of the cells. The operation of A, C, and P is controlled by the traffic control algorithm.

The signals v, u, y, z, and s of diagram (1) are sequences of non-negative integers that represent the cell flow through the network. Their values at (the end of) step k are v_k, u_k, y_k, z_k, and s_k, respectively. Assuming the network is turned on at the time zero, we take $k \geq 1$. The network link Σ induces a delay of κ steps, so that

$$y_k = u_{k-\kappa}, k = 1, 2, \ldots$$

Let $\phi > 0$ be the maximal number of cells that can pass through the backbone during a time interval of length Δ. We call ϕ the *capacity* of the backbone. Then, the backbone input sequence z must satisfy the requirement

$$0 \leq z_k \leq \phi, k = 1, 2, \ldots$$

In practice, Σ represents a large number of links feeding the backbone, and the combined capacity of these links usually exceeds the backbone capacity. Consequently, we shall assume that Σ does not impose a capacity limitation on the network. We shall concentrate on the optimization of backbone use, to best utilize the most costly part of the network.

2.1 The calls.

We consider calls of finite duration $T \geq 1$ whose flow rates are bounded by piecewise constant sequences. Each call extends then over the interval $[1, T]$. This interval is called the *call cycle*.

The integer T may represent a common multiple of the durations of all calls of interest, so all calls become compatible with the call cycle. In the case of very long calls, T

may indicate a convenient breakpoint of a call. The interval $[T+1, 2T]$ is the *second call cycle*, and so on.

Given an integer $q \geq 1$, partition the call cycle into q disjoint sub–intervals $I_1 := [1, t_1], I_2 := [t_1+1, t_2], ..., I_q := [t_{q-1}+1, T]$, where $t_1 = T$ when $q = 1$. The sub-intervals $I_1, ..., I_q$ are called *segments*. Let λ_i be the number of steps included in the segment I_i. Now, given a list of q integers $\varphi(1), \varphi(2), ..., \varphi(q)$, define the piecewise constant sequence

$$(2) \qquad \varphi_k := \begin{cases} 0 & \text{for} \quad k \leq 0 \\ \varphi(1) & \text{for} \ 1 \leq k \leq t_1, \\ \varphi(2) & \text{for} \ t_1+1 \leq k \leq t_2, \\ ..., & \\ \varphi(q) & \text{for} \ t_{q-1}+1 \leq k \leq T, \\ 0 & \text{for} \ T+1 \leq k. \end{cases}$$

The integers $t_1, t_2, ..., T$ are called the *switching times* of the sequence. Note that by using segments of length 1, every sequence with finite support can be represented in the form (2).

A call c is represented as a sum of two piecewise constant sequences over the partition $\{I_1, ..., I_q\}$:

$$c = \chi + \upsilon.$$

The sequence χ represents the nominal flow rate, whereas υ represent an uncertainty about the flow rate of the call. The sequence υ may vary from one sample of the call c to another. The only a–priori information available about υ is an amplitude bound $\rho \geq 0$:

$$0 \leq \upsilon(j) \leq \rho, j = 1, 2, ... q.$$

No statistical model of the uncertainty is presumed.

The calls attempting entry into the network are classified into m service classes $C^1, ..., C^m$. Each class has its own nominal waveform and uncertainty characteristics. A call of the class C^i will be denoted by

$$(3) \qquad c^i = \chi^i + \upsilon^i,$$

where χ^i represents the nominal part, and υ^i represents the uncertain part. At the step k, the value of the call is written as $c^i_k = \chi^i_k + \upsilon^i_k$; the value of the call c^i on the segment I_j is written as $c^i(j) = \chi^i(j) + \upsilon^i(j)$. We shall assume that

$$c^i_k > 0 \text{ for at least one } k \in [1, T],$$

i.e., that none of the calls is identically zero.

The term *call pool* refers to the population of calls awaiting admission into the network. We assume that the peak flow capacity required to transmit the entire call pool exceeds backbone capacity; otherwise, all waiting calls can be transmitted directly, and there is no place for optimization. The optimization process depends, among other factors, on the composition of the call pool. To simplify notation, we assume that the admission process is performed at the compensator P, and that admitted calls start entering the backbone at the time step $k = 1$.

3. ASYMPTOTIC EFFICIENCY AND COMPLETE FAMILIES

Asymptotic efficiency is a measure of backbone utilization in the limit, as backbone capacity tends to infinity. The term "efficiency" refers to the fraction of backbone capacity that is filled by the flow of cells. For a large capacity backbone, asymptotic efficiency of 1 indicates that the fraction of unused backbone capacity is close to zero. The notion of asymptotic efficiency leads to traffic control algorithms that are *scalable* in the sense that their basic mode of operation does not change when backbone capacity is increased.

Optimization of the backbone flow involves two processes: (i) selection of the calls that are admitted into the network, and (ii) reshaping the waveforms of the admitted calls by buffering. The present note concentrates on call admission, while HAMMER [2000b and 2001] address the issue of call reshaping.

To gain insight into the call admission process without undue complication, we adopt at first the simplifying assumption that the call waveforms are deterministic, namely that $\upsilon^i = 0$ in (3).

Another preliminary simplifying assumption we make is that there are no restrictions on the call supply. In practical terms, this means that for each call class C^i, $i = 1, ..., m$, the number of calls contained in the call pool is larger than the number of calls that can be simultaneously transmitted through the backbone.

The final simplifying assumption we make is that no buffering is performed. Then, backbone efficiency is controlled entirely through the call admission process, by selecting the calls that best fill the backbone. Note that an analysis of flow without buffering can be regarded as an analysis of the output of the compensator P, after all buffering has been completed. Accordingly, this preliminary discussion will lead us to a characterization of the optimal output of the compensator P. The issues of limited call supply, buffering, and call uncertainties are addressed later in this note and in HAMMER [2000b, 2001].

Let $\alpha_i \geq 0$ be the number of calls of the class C^i that have been admitted into the backbone. Then, the total number of cells injected into the backbone at the step k is given by

$$z_k = \Sigma_{i=1}^{m} \alpha_i c_k^i.$$

The admission process determines the integers $\alpha_1, ..., \alpha_m$. We refer to $\alpha_1, ..., \alpha_m$ as the *call populations*. For an unlimited call pool, there is no restriction on the selection of the call populations, other than the backbone capacity.

Letting ϕ be the backbone capacity, it follows that the maximal number of cells the backbone can carry during the call cycle $[1, T]$ is given by $T\phi$. For a backbone capacity of ϕ, let $\alpha_1(\phi), ..., \alpha_m(\phi)$ be the call populations admitted into the backbone; the total number of cells entering the backbone at the step k is

$$z_k(\phi) = \Sigma_{i=1}^{m} \alpha_i(\phi) c_k^i \leq \phi.$$

We refer to $z(\phi)$ as the *traffic control algorithm*; it is a rule that assigns populations $\alpha_1(\phi), ..., \alpha_m(\phi)$ to each backbone capacity $\phi \geq 1$. The *efficiency* $\eta(z(\phi))$ of the traffic control algorithm $z(\phi)$ is defined by

(4) $$\eta(z(\phi)) := \frac{\Sigma_{k=1}^{T} z_k(\phi)}{T\phi}.$$

Clearly, the efficiency is simply the fraction of backbone capacity being utilized by the traffic control algorithm $z(\phi)$, and we have

$$0 \leq \eta(z(\phi)) \leq 1.$$

The *asymptotic efficiency* $\eta(z)$ of the traffic control algorithm $z(\cdot)$ is defined by

$$\eta_\infty(z) := \lim_{\phi \to \infty} \eta(z(\phi)).$$

The asymptotic efficiency approximates the efficiency of the traffic control algorithm $z(\phi)$ when executed on backbones with large capacity ϕ. Maximization of the asymptotic efficiency is the basic optimization criterion in our discussion.

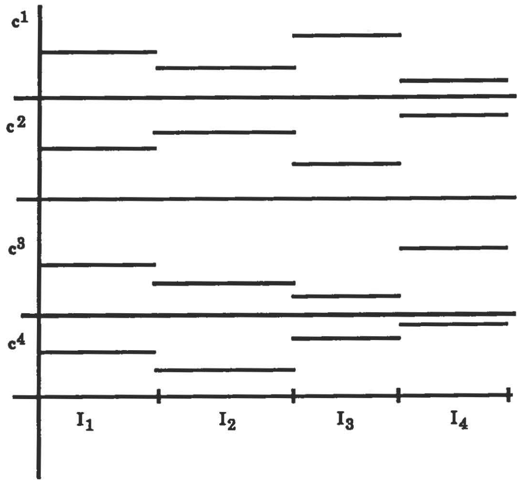
Now, let $F = \{c^1, ..., c^m\}$ be the family of call classes approaching the backbone. We say that the family F is *complete* if there are integers $\alpha_1, ..., \alpha_m \geq 0$ such that the linear combination $\Sigma_{i=1}^{m} \alpha_i c^i = c$ is a non-zero constant function over the interval $[1, T]$. The following statement characterizes the basic requirement for achieving asymptotic efficiency of 1 (HAMMER [2000a]).

(5) THEOREM. Let $F := \{c^1, ..., c^m\}$ be a family of piecewise constant call classes over the partition $\{I_1, ..., I_q\}$. Then, the following two statements are equivalent.

(i) There is a traffic control algorithm with asymptotic efficiency of 1 for the family F.

(ii) The family F is complete. ♦

In other words, asymptotic efficiency of 1 is possible if and only if the calls entering the backbone constitute a complete family. Complete families are the only families of call classes capable of utilizing the entire capacity of large backbones. HAMMER [2000a] contains some algorithms that generate complete families of calls. Here is an example of waveforms for a complete family of 4 calls.



5. INCOMPLETE CALL FAMILIES.

Consider a family $F = \{c^1, ..., c^m\}$ of call classes over the partition $\{I_1, ..., I_q\}$ of the interval $[1, T]$. Let α_i be the number of calls of the class c^i that enter the backbone. The total number of cells z_k entering the backbone at the step k is

(6) $$z_k := \Sigma_{i=1}^{m} \alpha_i c_k^i, k = 1, ..., T.$$

The *amplitude* $A(z)$ of the stream z is

$$A(z) := \max \{z_k : k = 1, ..., T\}.$$

As cell loss is disallowed, we require $A(z) \leq \phi$, where ϕ is the backbone capacity. The *relative efficiency* $\eta_r(\alpha_1, ..., \alpha_m)$ of the cell stream (6) is defined by

(7) $$\eta_r(\alpha_1, ..., \alpha_m) := \frac{\Sigma_{k=1}^{T} z_k}{TA(z)}, A(z) > 0.$$

Clearly,

$$0 \leq \eta_r(\alpha_1, ..., \alpha_m) \leq 1.$$

Comparing with (4), we have

$$0 \leq \eta(z) \leq \eta_r(\alpha_1, ..., \alpha_m),$$

so that the efficiency cannot exceed the relative efficiency. In the special case when $A(z) = \phi$, we get $\eta(z) = \eta_r(\alpha_1, ..., \alpha_m)$. We denote the maximal relative efficiency by $\eta_r^*(F)$, so that

$$\eta_r^*(F) := \sup\{\eta_r(\alpha_1, ..., \alpha_m) : \alpha_1, ..., \alpha_m \in Z^+\},$$

where Z^+ is the set of all non-negative integers. The next statement shows that there is a traffic control algorithm that achieves maximal relative efficiency (HAMMER [2000a]).

(8) THEOREM. Let $F = \{c^1, ..., c^m\}$ be a family of call classes over the partition $\{I_1, ..., I_q\}$, where none of the call classes $c^1, ..., c^m$ is identically zero. Let $\eta_r^*(F)$ be the maximal relative efficiency of the family F. Then, the following are true.

(i) There are finite integers $\alpha_1^*, ..., \alpha_m^* \geq 0$ such that $\eta_r^*(F) = \eta_r(\alpha_1^*, ..., \alpha_m^*)$.

(ii) The maximal relative efficiency $\eta_r^*(F)$, as well as the call populations $\alpha_1^*, ..., \alpha_m^*$ that yield it, are determined by the solution of a linear programming problem. ♦

The specifics of the linear programming problem that yields call populations for maximal relative efficiency are described in HAMMER [2000a].

There is an intimate connection between relative efficiency and asymptotic efficiency. In fact, as the next statement indicates, the maximal asymptotic efficiency associated with a family $F = \{c^1, ..., c^m\}$ is equal to its maximal relative efficiency (HAMMER [2000a]).

(9) THEOREM. Let $F = \{c^1, ..., c^m\}$ be a family of non-empty call classes transmitted over a backbone of capacity ϕ. Let $z^* := \Sigma_{i=1}^m \alpha_i^* c^i$ be a flow that achieves maximal relative efficiency $\eta_r^*(F)$ for the family F. Then, the following are true.

(i) For any flow z of the family F, the efficiency satisfies $\eta(z) \leq \eta_r^*(F)$.

(ii) For an integer $\beta > 0$, define the traffic flow $z_\beta := \beta z^*$, and let $\eta^* := \lim_{\beta\to\infty} \eta(z_\beta)$. Then, η^* is the maximal asymptotic efficiency, and $\eta^* = \eta_r^*(F)$. ♦

As Theorem 9 indicates, the flow that achieves maximal asymptotic efficiency consists of fixed proportions of the call classes. These proportions are characterized by the integers $\alpha_1^*, ..., \alpha_m^*$ of Theorem 8. The flow that achieves maximal asymptotic efficiency is obtained through a scalable process, by using integer multiples of the basic flow package $z^* = \alpha_1^* c^1 + ... + \alpha_m^* c^m$. Thus, when backbone capacity is increased, one only needs to scale the flow upward, leaving the consistency unchanged.

Of course, in order to achieve the maximal asymptotic efficiency with the family F, the pool of calls waiting for admission into the backbone must contain a sufficient number of calls of each class: there must be at least $\beta\alpha_i^*$ calls of the class c^i, for each $i = 1, ..., m$, in the notation of Theorem 9. The next section addresses situations where this requirement is not met.

6. INCOMPLETE CALL FAMILIES WITH LIMITED CALL SUPPLY.

We turn now to the more common situation, where the supply of calls in each class may be limited. Let $F = \{c^1, ..., c^m\}$ be a family of call classes to be transmitted through a backbone of capacity ϕ. Let p_i the number of calls of the class c^i that are in the call pool at the initial time. We call $p_1, ..., p_m$ the *call pool populations*. When considering the asymptotic case as ϕ approaches infinity, one has to let the call pool populations approach infinity as well. To this end, define the ratios

$$\rho_i := \frac{p_i}{\phi}, i = 1, ..., m,$$

called the *call pool parameters*. We assume that the call pool parameters remain constant as $\phi \to \infty$. In this way, the proportions among the different call populations, as well as their relation to the backbone capacity, remain constant. The call pool parameters are specified system parameters, characterizing the demand on the network. We assume, of course, that not all call parameters are zero. Clearly, any flow $z := \Sigma_{i=1}^m \alpha_i c^i$ through the backbone must satisfy

$$\alpha_i \leq p_i = \rho_i\phi, i = 1, ..., m.$$

When one attempts to transmit all calls of the call pool simultaneously through the backbone, one obtains the flow $z_\theta = \Sigma_{i=1}^m \rho_i\phi c^i$. The amplitude of this flow is $A(z_\theta) = \phi A(\Sigma_{i=1}^m \rho_i c^i)$. In order for the backbone optimization problem to be meaningful, one must have $A(z_\theta) > \phi$; otherwise, all waiting calls can be transmitted simultaneously, and there is no place for optimization. This yields the condition

$$(10) \quad A(\Sigma_{i=1}^m \rho_i c^i) > 1.$$

We regard (10) as a constraint on the call pool parameters. Recall that $A(z)$ denotes the amplitude of a flow z. Note that by (7), the maximal relative efficiency η_r^* that can be achieved under the present conditions is

$$\eta_r^* := \sup\{\eta_r(\alpha_1, ..., \alpha_m) : \alpha_i \leq p_i, A(z) \leq \phi, \alpha_i \in Z^+, i = 1, ..., m\}.$$

A call family $F = \{c^1, ..., c^m\}$ is *linearly independent* if the equation $\Sigma_{i=1}^m a_i c^i = 0$ (the constant zero function over [1, T]) is valid only when $a_i = 0, i = 1, ..., m$. This definition conforms to the usual notion of linear independence. In practice, most call families are linearly independent, since each call class usually represents a completely different application (e.g., telephony and video). We can list now the basic characteristics of a flow that maximizes asymptotic efficiency when the call supply is restricted (HAMMER [2000a]).

(11) THEOREM. Let $F = \{c^1, ..., c^m\}$ be a family of linearly independent call classes over the partition $\{I_1, ..., I_q\}$, and let $\rho_1, ..., \rho_m$ be the call pool parameters. Then, there is a list of integers $\alpha_1^*, ..., \alpha_m^* \geq 0$ for which the following are true.

(i) For the traffic flow $z_\beta := \beta(\Sigma_{i=1}^m \alpha_i^* c^i)$, where $\beta > 0$ is an integer, let $\eta^* := \lim_{\beta \to \infty} \eta(z_\beta)$. Then, η^* is the maximal asymptotic efficiency achievable with the family F and the call pool parameters $\rho_1, ..., \rho_m$.

(ii) The integers $\alpha_1^*, ..., \alpha_m^*$ can be obtained from the solution of a linear programming problem. ♦

As Theorem 11 indicates, the optimal flow is obtained by using multiple copies βz^* of the basic call "package" $z^* := \Sigma_{i=1}^m \alpha_i^* c^i$. This provides a scalable solution to the backbone optimization problem under call supply restrictions. A detailed description of a method for calculating the integers $\alpha_1^*, ..., \alpha_m^*$ is provided in HAMMER [2000a].

To summarize, we have taken in this note a functional approach to the issue backbone optimization, viewing it as a global optimization problem. In comparison, the classical approach to admission control tilts more toward an instant-by-instant evaluation of the network load (compare to DECINA and TONIATTI [1990], RATHGEB [1991], CCITT [1992]).

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