Stability of Traffic Patterns in Broadband Networks

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1 Introduction

The efficient management and control of networks is getting increasing attention as networks become larger and more complex. For example, the growth of the internet brings with it an expanding base of users with demands for global connectivity and a good quality of service. At the same time, the protocols used for transmission of voice and data are being improved and new protocols such as ATM are being developed.

With the increase in complexity comes increasing difficulty of management. The more hops used in setting up a connection, the more likely it is that different protocols are being used and larger delays are encountered. With more complex protocols, verification of protocol performance in all conditions becomes increasingly impossible.

There may be a margin of stability with respect to network delays for traffic in narrowband and broadband networks and it would be of interest to network managers to see how small or large this margin of stability is. This issue may be examined using general models, network measurements or simulation studies.

In this paper, standard control theory is used to model the routing of telephone traffic. A model is developed to investigate the maximum delay in the transmission of routing information that will still allow stability. Simulations are used to validate the model, and to investigate the multi-service case. Finally conclusions are drawn about applicability of the results.

2 Present State of the Art

Much work has already been done in the application of fluid flow models to telecommunications networks. In a fluid flow model, stochastic variations of traffic levels are ignored and instead a solution is found for the change in the expected levels of traffic, using differential equations that relate the time varying call arrival rate, blocking rate and occupancy levels.

Kaniyil et al. in [1] examined structural instabilities in symmetric telecommunications networks with non-hierarchical routing using potential functions. In this work, time dependent average quantities were used to characterize the state of the system. The existence of two stable states at high traffic levels was shown.

Ohta in [2] used a fluid model of a symmetric network to predict the onset of congestion. The intention was to implement controls prior to congestion that would keep the network operating at full efficiency. A fluid flow model will show that there is a delay between the sudden increase in call arrivals and the onset of congestion. The feasibility of an advanced network management system which makes use of congestion prediction was shown.

Filipiak has been very active in the area of fluid flow models for telecommunications networks. Filipiak et al. in [3] present a framework for estimating future occupancy statistics in a communications network, based on present measurements of occupancy, arrival rate and holding time. Good results were obtained by comparing the model predictions with measured values taken from the French telephone network.

Filipiak et al. in [4] apply the same theory to the dynamic rerouting that was part of the Toronto Trial of Dynamically Controlled Rerouting (DCR) in the Canadian Network. Simulation showed that the results obtained were more accurate in the case of high load than the estimation and prediction methods used in the trial.

Krupp in [5] examines instability in telephone networks with alternate

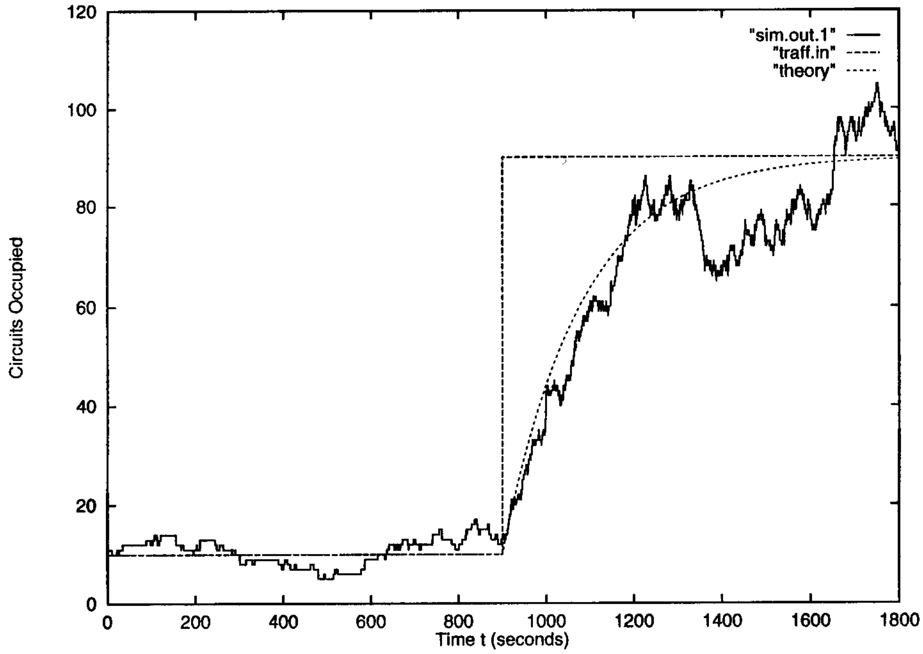

Figure 1: Step increase in Traffic at t = 900

routing. Stability criteria are derived in the paper.

For broadband networks the correct models of source traffic are still being discussed. Burstiness statistics, geometrically distributed burst lengths, switched Poisson processes, Markov Modulated Poisson processes and generally modulated deterministic processes are all being proposed [6]. The approach taken in this paper is to assume initially that the traffic carried is telephony traffic to show the existence of instabilities. A second simulation is then undertaken to show that the same instabilities will exist in a two service network.

3 Model of a Single Route

An important component of a network model is the model of a single route. Figure 1 shows the rise in traffic level following a step rise in offered traffic.

Using generating functions, Cooper[7] shows that the expected number of circuits occupied following a step increase in traffic from N_0 to N_1 is given by

$$N(t) = N_1 - (N_1 - N_0) * \exp(-t/T_h)$$

where T_h is the holding time, N_0 is the initial traffic level and N_1 is the new traffic level.

This system can be modelled as a linear time invariant system with a transfer function of

$$F(s) = \frac{1}{(1 + sT_h)}$$

In control theory terms, this is a system with a time lag T_h. The stochastic variation about the expected level is regarded as noise and not explicitly modelled. This is a standard assumption in control theory.

4 Model of Rerouting Algorithm

These studies originated from the development of a network management tool for telephone networks, called NOAA (Network Operations Analyzer and Assistant), which automated many of the controls that network management personnel put in the network to reroute traffic in the event of disaster or overload situations. As the reroute controls became more automated concerns arose about the stability of the system. In particular it was desirable to find out how big a margin existed between stable and unstable behavior, in terms of the parameters that specify the system.

For this purpose, we distinguish between IRR (Immediate Reroute) and ORR (Overflow Reroute) controls. An IRR control reroutes traffic before it attempts the problem route. Traffic is diverted elsewhere in the network where spare capacity exists. An ORR control reroutes traffic after it attempts the problem route and finds no capacity available. The ORR control offers that particular call an extra chance of completion.

From a stability viewpoint, we would expect to see fewer problems with ORR controls as each call tries the standard routing first and then tries

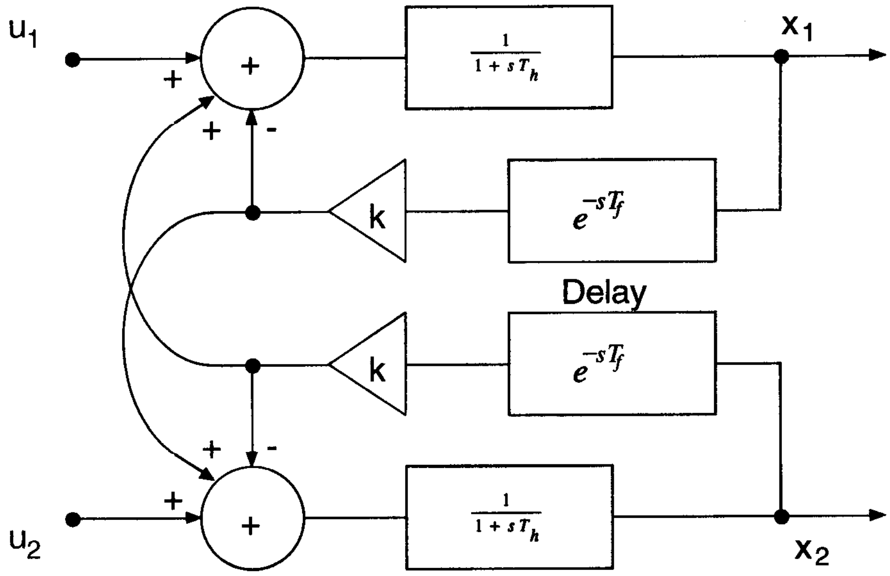

Figure 2: Rerouting Model

the added routing options specified by the control. For each call that tries the problem route, its chances of completion are always incremented by the implementation of an ORR control. In the case of small overloads, network throughput can only be expected to increase, as individual calls have more possibilities of completion.

For an IRR control, if too much traffic is diverted and the delays in obtaining the feedback about traffic information are too great, there is a possibility of instability. Traffic from route A could be diverted to Route B which may then experience a problem and find spare capacity on Route A. The overload situation could oscillate between route A and route B, causing an overall decrease in throughput.

The model in Figure 2 was used to analyze a system with two possible routes between some source destination pair. Observations about the traffic level on either route are used to decide on what percentage of new call arrivals to divert to the other route. It is assumed that IRR controls may be applied to either route. This model is simplified in two respects:

- Network Management uses sampled information. Traffic information from the switches is typically available every 5 minutes or 30 seconds and not continuously. This is not modelled here.
- Network Management takes no action until a route overflows. This could be modelled by an element in the feedback path such as a relay with deadspace. However that has not been done here.

The purpose of the analysis is to examine the order of magnitude of the time constants involved that could result in instability.

The gain factor k is a measure of how much traffic is diverted by the network management control from a full route to an empty one in steady state. If α is the fraction of traffic diverted from a full route to an empty one in steady state then

$$k = \frac{\alpha}{1 - 2\alpha}$$

This can be derived from the model by removing the lag factor and delay once steady state and constant inputs are assumed. It is assumed that $\alpha \leq 0.5$. In other words, the most aggressive traffic balancing would split the traffic equally between trunk groups.

In our network management application, we had $k = 0.187$ but typically k can vary from 0 to ∞ depending on the aggressiveness of the network management.

In our system, typical values for the holding time T_h and the feedback delay T_f are 3 minutes and 5 minutes respectively.

5 Analysis

The system shown in Figure 2 is a standard Multi-Input Multi-Output system from the control theory point of view. However the presence of the delay terms makes the analysis a little more difficult. Looking at the output of the adders we can write:

$$x_1(1 + sT_h) = u_1 - ke^{-sT_f}x_1 + ke^{-sT_f}x_2$$

$$x_2(1 + sT_h) = u_2 - ke^{-sT_f}x_2 + ke^{-sT_f}x_1$$

Grouping terms gives:

$$x_1(1 + sT_h + ke^{-sT_f}) = u_1 + ke^{-sT_f}x_2$$

$$x_2(1 + sT_h + ke^{-sT_f}) = u_2 + ke^{-sT_f}x_1$$

To check for stability, we set $u_1 = 0$ and multiply the first equation by $(1 + sT_h + ke^{-sT_f})$ to eliminate x_2. This gives:

$$x_1(1 + sT_h + ke^{-sT_f})^2 = ke^{-sT_f}(u_2 + ke^{sT_f}x_1)$$

This gives

$$\frac{x_1}{u_2} = \frac{ke^{-sT_f}}{(1 + T_h s + ke^{-sT_f})^2 - (ke^{-sT_f})^2}$$

Note that the transfer function for x_1/u_1 also has the same denominator. A sufficient condition for instability is for the denominator to be 0 for some value of s on the $s = j\omega$ axis. This critical threshold of stability is of interest to us. Looking for a 0 denominator gives:

$$(1 + sT_h + ke^{-sT_f}) = -(ke^{-sT_f})$$

or

$$1 + sT_h = -2ke^{-sT_f}$$

Setting $s = j\omega$ and equating real and imaginary parts gives:

$$1 = -2k\cos(\omega T_f)$$

$$\omega T_h = 2k\sin(\omega T_f)$$

These equations give some interesting results

- For $k < 0.5$, this mode of instability does not arise. This is a consequence of equation 1.
- The critical value of the feedback time can be solved for given some value of $k > 0.5$.

For example, if $k = 3$ and $T_h = 3$ minutes, then we can solve for $\omega = 3.416$ which leads to $T_{osc} = 1.840$ minutes for the period of oscillation. Also T_f, the critical value of the feedback delay is found to be 0.509 minutes. This suggests that if $T_f > 0.509$ we should see some signs of instability.

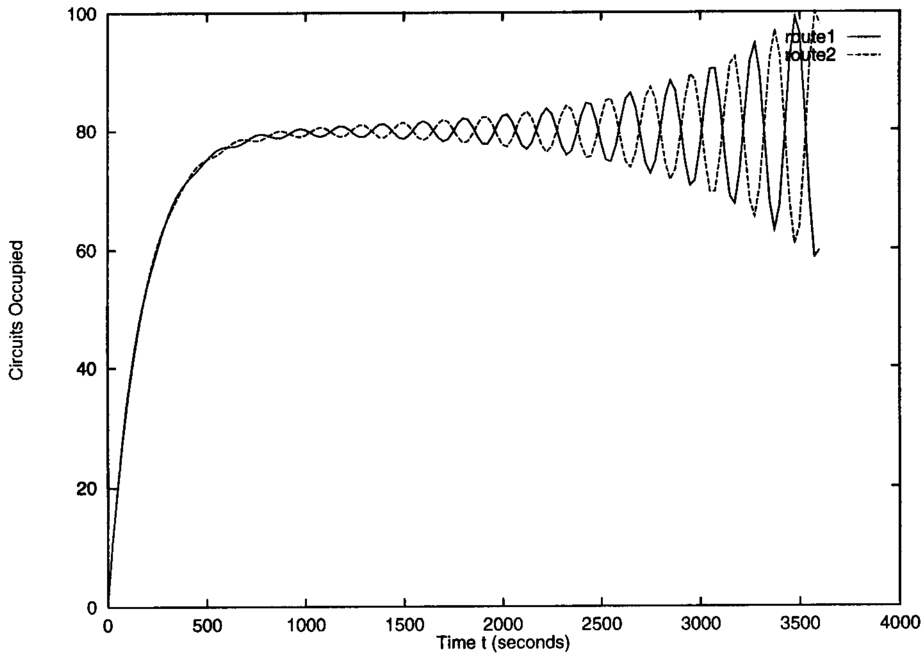

Figure 3: Route Occupancy assuming Automated Rerouting (T_f = 1 minute)

6 Simulation Study #1

To verify the effects found in the analysis, a simulation was carried out. 80 Erlangs of traffic were offered to each of two routes which were assumed to have 100 circuits. A holding time of 3 minutes, a variable feedback delay and a gain of $k = 3$ were assumed. The results are shown in Figures 3 and 4. Instability can clearly be seen for the larger value of T_f.

7 Simulation Study #2

To see how this situation is affected by the addition of an additional service with a longer holding time, a second service was added. The top half of the model in Figure 2 is replaced by the two service counterpart shown in Figure 5. The results indicate that the service with the shorter holding time

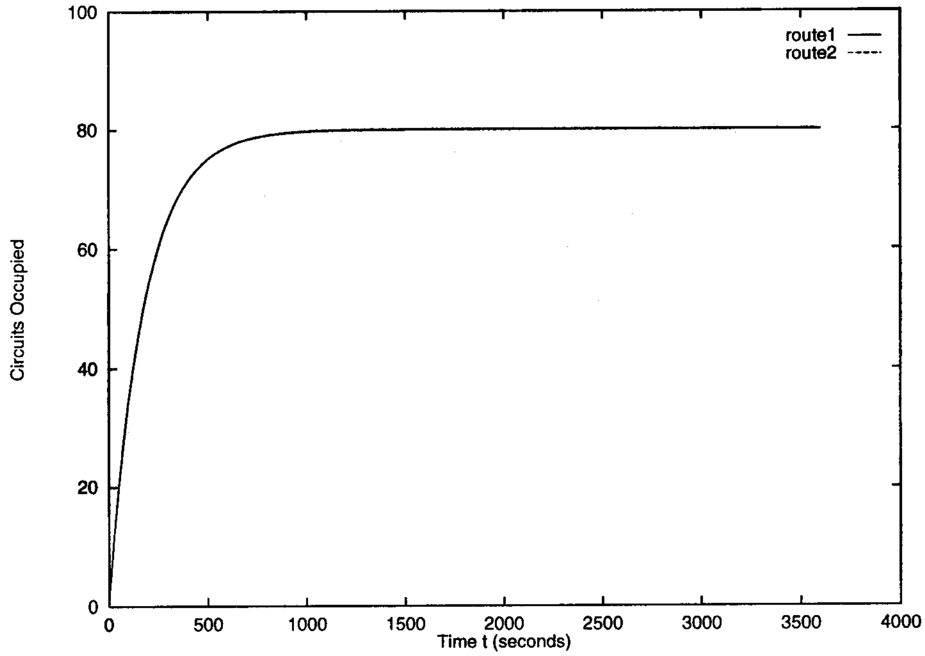

Figure 4: Route Occupancy assuming Automated Rerouting (T_f = 0.1 minute)

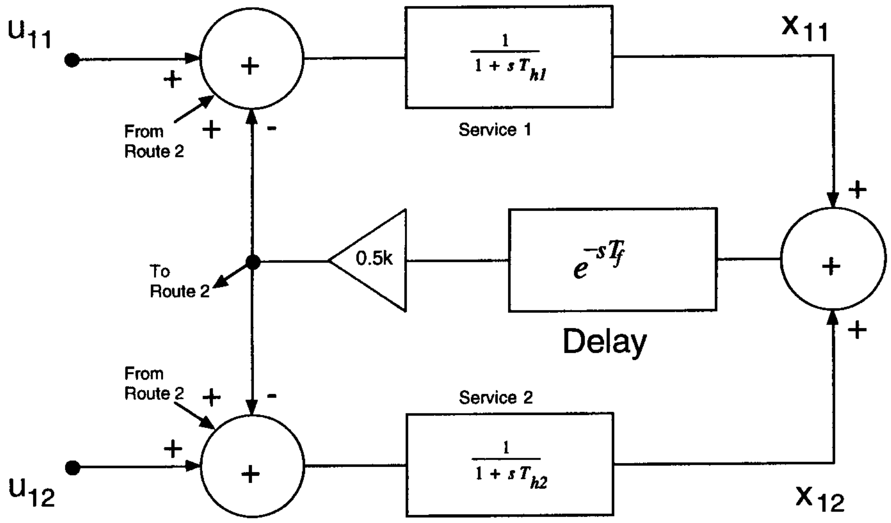

Figure 5: Rerouting Model

dominates.

This would seem to indicate that a network that carried speech and short data "conversations" would need feedback controls that had time constants with very small delay to avoid instabilities, assuming a control algorithm similar to those used today.

8 Conclusions

Standard control theory has been applied to a network management problem. The aim was to see whether the automation of network management controls could result in instabilities. The conclusion is that this can happen. Careful control of the delays in the feedback of information used to calculate routing strategy is necessary in order to prevent this.

This analysis should be applicable to control schemes such as RTNR (Real Time Network Rerouting) described in [8] and presently implemented

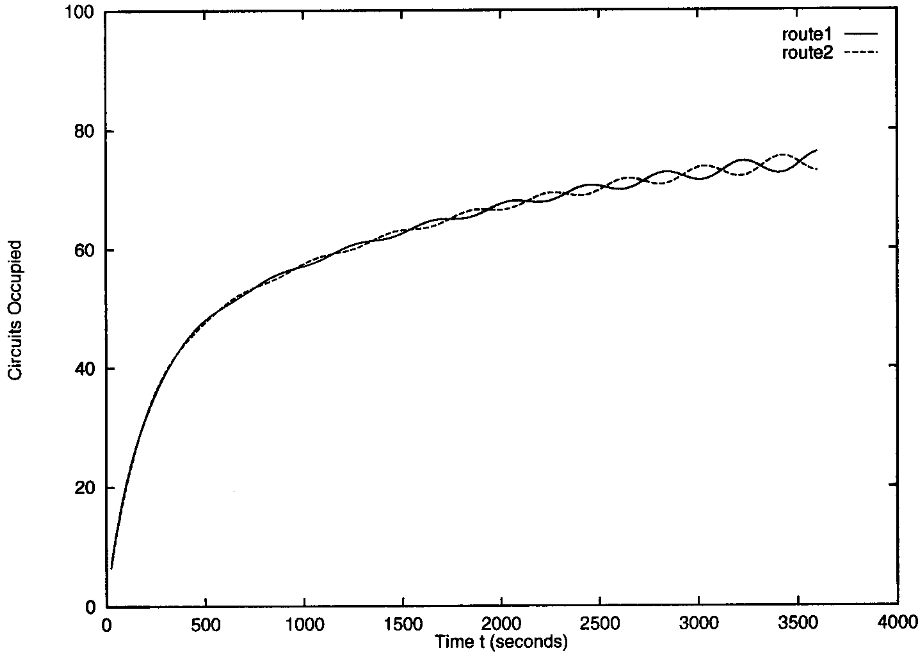

Figure 6: Route Occupancy assuming Automated Rerouting and Two Services ($T_f = 2.0$ minutes)

in the AT&T long distance network. The RTNR routing scheme is a dynamic routing scheme that makes use of cached information to decide the route to be taken for a call. This paper suggests that if the cache becomes too old (perhaps due to delays in the signalling network), instabilities can arise.

As new models of source traffic become available for ATM networks, these studies can be extended to cover these networks also. At the very least, it should be clear that close attention needs to be paid to the dynamics of the transmission of network management information to avoid instabilities in the network.

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