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**Summary:**

In the spirit of the CAREER, progress was made on the educational and research front. On the research front, I have been looking at the adaptive admission control problem. The problem can be broken down into a static and dynamic component. The static question asks whether a given combination of traffic will meet quality of service (QoS) requirements (a.k.a. a QoS decision function). Related is the question of what QoS will be observed by a given traffic combination (a.k.a. a QoS estimator). This question has been addressed in [4][6][9]. The key difficulty to this problem is estimating loss rate metrics given the $10^{-6}$ and smaller desired loss rates, the long correlations in the traffic sources, and the relatively short duration that a particular traffic combination exists. Two maximum likelihood statistical function approximation approaches are developed that combine the many sparse monitoring measurements into either a QoS decision function [9] or a QoS estimator [4]. These specifically treat the small samples and the correlated measurements. Through a survey of possible realistic traffic types it is shown that a tractable, robust (do not accept too many calls and violate QoS), and efficient (do not reject too many calls that could have been accepted without violating QoS) admission control decision model can be made only with adaptive methods such as the above [6]. The significance of these results is that we can use relatively sparse monitoring information to derive not just point estimates of QoS for a single traffic configurations, but QoS estimates for the entire space of traffic configurations. These estimates can be made for any type of traffic and not just for simple Poisson or MMPP processes. These estimates provide a solid basis for admission control under realistic conditions.

The dynamic question asks what set of accept decisions will meet the QoS requirements (the static question) and maximize network revenue. For example, given the revenue generated by carrying a call and its impact on the network, should the call be accepted or should it be rejected so that more valuable calls could be accepted later. Finding an optimal admission control policy is a dynamic programming problem. Since the size of the problem becomes very large quickly, we look at approximation methods based on a machine learning technique known as reinforcement learning (RL). Our work differs from others since we simultaneously estimate the QoS decision function (usually assumed a given) and the admission control policy. Results on simple examples show 30% more revenue for the RL policy compared to a simple greedy accept all policy [2][5]. The intra-call QoS (so called cell-level QoS) depends only on the long-term statistics of a given call combination. Other call-level QoS can be defined such as maximum blocking rates, fairness in blocking rates between service types, or limits in packet loss rates averaged over all policy decisions. A formulation and testing of these policy-level criteria is given in [10]. There are several technical preconditions to the use of dynamic programming and RL techniques. A rigorous formulation of the admission control problem within these conditions is given in [11]. These results provide an integrated framework to meeting QoS and optimizing network performance/ revenue.

Maximizing revenue and meeting QoS in wireline networks must contend with the variability of

traffic across time. Wireless networks add spatial traffic variability and channel variability due to end user mobility. Static admission control in wireless adds guarantees on QoS not only on the current connection on the current radio link, but also on the future radio links to which the user may be handed off. Dynamic QoS in wireless adds call-level QoS such as dropped calls due to poor channels or attempts to handoff to overloaded radio links. The interaction of cell level QoS and call-level QoS becomes more tightly coupled and can utilize the integrated approach developed for wireline above. Preliminary results were presented in [1]. This work is coupled with another NSF grant (*High-Performance, Low-Power Wireless Communication*) which is funding a student. The study of wireless QoS has led to addressing a related problems in cellular system design where we show that ad hoc networks of randomly-placed base stations have performance near to ideal hexagonal cellular systems [3][8]. This somewhat surprising result follows from the fact that the regularity of the ideal system is masked by the variability in the received signal strengths due to terrain, clutter, and shadowing. More surprising is that randomly based base stations have performance that is independent of the signal variability. This suggest that random-cellular design procedures are robust.

In wireline we are also looking at the relationship between switching and QoS. We have been studying several queueing architectures based on ideal input and output queued non-blocking switches. The first result is an architecture for large packet switches composed of smaller input and output queued packet switches that simultaneously reduces the switch complexity and increases performance. For instance in a 1024 input 1024 output ATM switch, at high loads queueing delays approach the minimum delays of a single large output queued switch with shared output buffers [7]. Another area is looking at the difference between input and output queueing. One result shows that simpler input-queued switches are equivalent to the optimal output-queued shared buffer switches for 2-input switches and nearly equivalent for larger switches [12]. The equivalence requires the input-queued switch to have information about future arrivals which requires additional computation to predict or deduce, but this provides a trade-off between switch fabric and computation cost. These results offer better designs for broadband switches and resurrect input queueing as a viable switch design.

In education, a simulation lab has been set up that is using industry donations (described in last report). The labs are in the areas of cellular communication systems using PlaNet, satellite communication labs using Satellite Toolkit and SaVi, and data networks using OpNet. As noted in the proposal the ITP program has both engineering and non-engineering students. These simulation tools have allowed students to experiment with realistic scenarios without the concern that they will break something. The labs have greatly enhanced their respective courses.

The grant has funded two students during the period. The first, Hui Tong, is a graduate student working towards his Ph.D. he has been making great progress in the wireline admission control problem and will likely finish his thesis in the coming year. The second, Mike Christman, is an undergraduate working on an REU. He worked this past summer on the random cellular systems learning about wireless systems and statistics and produced a graphical random-cellular analysis tool.

Approximately 43% of the four year project's expenses were spent by the end of this second year. A web version of this report is available at `http://ece-www.colorado.edu/~timxb/sponsor.html`. The project was supported by a university sponsored Junior Faculty Development Award: *Adaptive Network Control for Wireless Multimedia Communication*.

**Project Sponsored Publications and Presentations:**


[1] Brown, T.X, *Wireless Network Management*, presented at NIST, Gathersburg, Jan. 1998.

[2] Brown, T.X, "Reinforcement Learning for Admission Control," presented at *Machines that Learn*, Snowbird, Utah, April, 1998.

[3] Brown, T.X, "Analysis and Coloring of a Shotgun Cellular System," presented at *RAWCON '98*, Colorado Springs, Aug., 1998.

[4] Tong, H., Brown, T.X, "Estimating Loss Rates in an Integrated Services Network by Neural Networks," Accepted in *GLOBECOM '98,* Sydney, Nov., 1998.

[5] Brown, T.X, Tong, H., Singh, S., "Optimizing admission control while ensuring quality of service in multimedia networks via reinforcement learning," accepted in *NIPS 11*, Denver, Dec. 1998.

[6] Brown, T.X, "Adaptive Statistical Multiplexing for Broadband Communications," Recommended for publication in *Computer Networks and ISDN Systems*.

[7] Brown, T.X, "A High Performance Two-Stage Packet Switch Architecture," Submitted to *IEEE T. on Comm.*, Feb. 1998.

[8] Brown, T.X, "Analysis of Shotgun Cellular Systems," submitted to *IEEE JSAC*, May, 1998.

[9] Brown, T.X, "Classifying Loss Rates with Small Samples," submitted to *INFOCOMM '99*, New York, April, 1999.

[10]Tong, H., Brown, T.X, "Optimizing admission control and routing while ensuring quality of service in multimedia networks via reinforcement learning," submitted to *INFOCOMM '99*, New York, April, 1999.

[11]Tong, H., Brown, T.X, "Adaptive Call Admission Control: Semi-Markov Decision Process Formulation and Reinforcement Learning Solution," submitted to *ITC '99*, Edinburgh, June, 1999.

[12]Brown, T.X, "Input vs. Output Queueing," submitted to *ITC '99*, Edinburgh, June, 1999.


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