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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 on a given set of network resources (a.k.a. a QoS decision function). The last progress report described a number of advances in this area. Two papers describing these advances which were submitted at the time of the last report have now been published [1, 3]. An inverse version of the problem is to decide what resources are necessary to carry a given traffic combination at a given QoS. A method based on a unified view of our QoS framework is given in [13]. This is relevant for protocols such as RSVP which require a method for setting aside resources as new request arrive. Since our approach assumes very little about the traffic or the underlying network, it side steps the debate on traffic and network models, and adaptively over time finds optimal decision functions.

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. Two papers, described in the last report, have also now been published [2, 4]. The problem, so far, has treated controlling the traffic on a single link. This has been extended to finding routes in the multi-link network case [10]. Like the static case, it assumes very little about the traffic and adaptively matches a routing policy to the current situation.

The student who has been working on both the static and dynamic problem is Hui Tong. He has gone on to work for AT&T. A comprehensive look at the framework and theory that he has developed for these problems appears in [7].

At a lower level we have looked at the relationship between switching architectures and QoS. A paper in this area described in the last report will be published shortly [9]. Our current work is examining the trade off between computational complexity in switching and performance, specifically as it relates to input queued switches. In addition to results in the last report, a collaboration with Hal Gabow in CS has resulted in a more clear definition of the hard (i.e. NP-Hard) and easy switch designs [12]. For instance, using future information in packet arbitration of input-queued switches is NP-Hard. If the switch size is fixed then it is polynomial (with a large exponent), and it is  $O(1)$  computations per time slot for 2-input switches.

We are applying the dynamic QoS framework to the wireless environment [5]. We are looking at two versions of this problem. The first version, looks for optimal call acceptance and handoff policies in a cellular system that will meet a constraint on maximum call dropping rates. The work is coupled with another NSF grant (*High-Performance, Low-Power Wireless Communication*) which is funding two REU students looking at the problem. A related problem considers the case

of finding a radio transmission policy on a wireless data link that minimizes energy usage at the physical layer, while meeting QoS at the application layer [8]. For instance, an e-mail application could wait until the mobile is closer to a base station to transmit (at lower power). A web-browsing application could turn the transmitter off until efficient size chunks of data are collected and then turn on to transmit these chunks. A real-time application would be forced to turn on periodically to meet delay requirements. The goal of the work is for the physical-layer radio to discover the best policy using minimal interaction with the higher layers. On a simple model, our methods find a policy that saves 75% of the maximum potential savings. We are implementing this now on a pair of wireless LAN cards.

In education, a wireless lab has been set up based on \$100k funds from the Colorado Commission on Higher Education (CCHE). With the CCHE money, some money from this CAREER award, and industry donations, we have put together a lab course with an initial 10 students. Students study both physical layer (e.g. propagation and modulation) and higher layer (e.g. multiple access, and messaging) aspects of wireless. I am the University of Colorado's representative on the Global Wireless Education Consortium (GWEC). I am a co-PI on \$655,000 joint NSF and Industry award to develop wireless curriculum.

The CAREER award has funded three students during the period. The first, Hui Tong, has completed his PhD in electrical engineering this year. His thesis is the corner stone for the results from this award [7]. The second, Nerendra Ravula, has worked on the problem of switching, queueing, and future information. After receiving his Masters Degree, he has gone on to work for Intel. The third, Mike Christman, is an undergraduate working on an REU. He worked this summer writing the basic Linux control functions of a WavLan wireless LAN card so that we can implement the low-power wireless communication.

Approximately 78% of the four year project's expenses were spent by the end of this third year. A web version of this report is available at <http://ece-www.colorado.edu/~timxb/sponsor.html>.

### **Project Sponsored Publications and Presentations:**

- [1] Tong, H., Brown, T.X., “Estimating Loss Rates in an Integrated Services Network by Neural Networks,” in *Proc. GLOBECOM '98*, Sydney, Nov., 1998.
- [2] Brown, T.X, Tong, H., Singh, S., “Optimizing admission control while ensuring quality of service in multimedia networks via reinforcement learning,” in *Advances in Neural Information Processing Systems 11*, ed. M. Kearns et al., MIT Press, 1999.
- [3] Brown, T.X, “Classifying Loss Rates with Small Samples,” in *Proc. INFOCOMM '99*, New York, April, 1999.
- [4] Tong, H., Brown, T.X, “Adaptive Call Admission Control under Quality of Service Constraints in Multimedia Networks,” in *Engineers Conference Notes Network+Interop 99*, Las Vegas, May 12–13, 1999.
- [5] Brown, T.X, Tong, H., “Adaptive resource allocation for telecommunications,” Invited paper in *SPIE International Symposium on Optical Science, Engineering, and Instrumentation*, Denver, July 18–23, 1999.
- [6] Brown, T.X., “Dynamic Channel Assignment in Shotgun Cellular Systems,” in *Proc. of 1999 IEEE Radio and Wireless Conference (RAWCON 99)*, pp. 147–50.
- [7] Tong, H., *Adaptive Admission Control and Routing under Quality of Service Constraints in Broadband Communications*, Ph.D. Thesis, University of Colorado, Boulder, August, 1999

### **Project Sponsored Submissions and Future Publications:**

- [8] Brown, T.X, “Low Power Wireless Communication via Reinforcement Learning,” to be presented at *NIPS 12*, Denver, Dec. 1999.
- [9] Brown, T.X, “A High Performance Two-Stage Packet Switch Architecture,” to appear in *IEEE T. on Comm.*
- [10] Tong, H., Brown, T.X, “Adaptive Call Admission Control under Quality of Service Constraints: a Reinforcement Learning Solution,” to appear in *IEEE JSAC*.
- [11] Brown, T.X, “Practical Cellular Performance Bounds via Shotgun Cellular Systems,” submitted to *IEEE JSAC*, Jan., 1999.
- [12] Brown, T.X, Gabow H.N., “Future Information in Input Queueing,” submitted to *IEEE T. on Comm.*, Feb., 1999.
- [13] Brown, T.X, Tong, H., “Adaptive Quality of Service Decision Functions,” submitted to *IEEE JSAC*.

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