Fuzzy logic based Congestion control

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ABSTRACT: It is generally accepted that the problem of network congestion control remains a critical issue and a high priority, especially given the growing size, demand, and speed (bandwidth) of the increasingly integrated services networks[1]. Despite the research efforts spanning a few decades and the large number of different schemes proposed, there are no universally acceptable control solutions. Current solutions in existing networks are increasingly becoming ineffective, and it is generally accepted that these solutions cannot easily scale up – even with various proposed "fixes". In this paper we propose a fuzzy based congestion control approach to address the congestion control problem. The performance of the proposed controlled system is evaluated via simulation.

KEYWORDS: congestion control, fuzzy logic, integrated services networks.

1. INTRODUCTION:

Despite the many years of research efforts, the problem of network congestion control remains a critical issue and a high priority, especially given the growing size, demand, and speed (bandwidth) of the networks. Network congestion is becoming a real threat to the growth of existing packet-switched networks, and of the future deployment of integrated services communication networks. It is a problem that cannot be ignored.

Congestion is caused by saturation of network resources, (communication links, buffers, network switches, etc…). For example, if a communication link delivers packets to a queue at a higher rate than the service rate of the queue, then the queue size will grow. If the queue space is finite then, in addition to the delay experienced by the packets until service, losses will also occur. Observe that congestion is not a static resource shortage problem, but rather a dynamic resource allocation problem. Networks need to serve all users requests, which may be unpredictable and bursty in their behaviour (starting time, bit rate, and duration). However network resources are finite, and must be managed for sharing among the competing users. Congestion will occur, if the resources are not managed effectively. The optimal control of networks of queues is a well-known, much studied, and notoriously difficult problem, even for the simplest of cases. For example, Papathemetriou and Tsitsiklis [1] show that several versions of the problem of optimally controlling a simple network of queues with simple arrival and service distributions and multiple customer classes is complete for exponential time (i.e. provably intractable). The effect of network congestion is degradation in the network performance. The user experiences long delays in the delivery of messages, perhaps with heavy losses caused by buffer overflows. Thus there is degradation in the quality of the delivered service, with the need for retransmissions of packets (for services intolerant to loss). In the event of retransmissions, there is a drop in the throughput which leads to a collapse of network throughput when a substantial part of the carried traffic is due to retransmissions (in that state not much useful traffic is carried–waste of system resources).

Congestion is a complex process to define. It is felt by a degradation of performance. The choice of how to measure congestion and where, apart from the other practical problems such as cost and complexity, can influence to a great degree the achievable control approach, control strategy, and control location. Here we only highlight this potential problem

[1] Integrated services communication networks include high speed packet switching networks: ATM, current and future TCP/IP Internet, frame relay, etc…

through an example. In the TCP/IP congestion control scheme, packet loss is used to sense congestion. The observed congestion in this case is at an advanced state (has already happened and hence losses are starting to occur). Whereas sensing delay at a node (e.g. queue length) does not necessarily indicate that congestion has happened. (Actually, one may expect that with delay sensing a predictive model can be build to indicate the level of the expected state of congestion over a given future time horizon, thus enabling corrective measures to be taken). Also other factors may influence to a large degree the effectiveness and speed of response of a congestion algorithm. For example, in TCP/IP congestion sensing is binary (presence or absence of congestion), and the round trip time (and feedback delay) are significantly different. (For an in depth discussion of these issues, the effect of location on quality of control, as seen though the control horizon, as well as potential problems of control, and how these influence the design of the controls, see [2]). One may also identify other potential problems of control, such as Large scale; Distributed nature; Large geographic spread (at its limit it covers the globe); Increasingly processing delay at nodes gets smaller, in comparison to the propagation delay in the links. Large-bandwidth delay product makes the control of congestion through feedback potentially difficult; Diverse nature and behaviour of carried traffic (voice, video, www, ftp, ….); Unpredictable and time varying user behaviour ; Lack of appropriate dynamic models for control; and Expectation of the need for guaranteed levels of performance to each user, which can be negotiated with the network.

This array of potential control problems has caused a lot of debate as to what are appropriate control techniques for the control of congestion, and depending on one’s point of view, many different schools of thought were followed, with many published ideas and control techniques. For historical reasons, and due to fundamental philosophical differences in the (earlier) approach to congestion control, the research for control of traditional TCP/IP and ATM based networks proceeded separately. However some convergence between the classical TCP/IP and the ATM approach is evident (see RFC2309 [3], Internet draft-kksjf-ecn-03 and RFC2481 [4], Internet draft-salim-jhsbnns-ecn-00 [5], and ATM Forum [6]). It has become clear [3] that the existing TCP congestion avoidance mechanisms (for a description see RFC2001 [7]), while necessary and powerful, are not sufficient to provide good service in all circumstances. Basically, there is a limit as to how much control can be accomplished from the edges of the network (this is discussed in length in [2] where the concept of an effective control horizon is discussed). Some mechanisms are needed in the routers to complement the endpoint congestion avoidance mechanisms (need for gateway control was realised early; e.g. see [8], where for future work the gateway side is advocated as necessary). RFC2309 strongly recommends active queue management in routers and RFC2481 suggests Explicit Congestion Notification (ECN) control for IP [4]. Internet draft-salim-jhsbnns-ecn-00 [5] takes it a step further and proposes Backward ECN (BECN) and Multilevel ECN (MECN), in which the feedback signal can include information on the severity of the congestion. Note the similarity in concept with the Explicit Rate (ER) based schemes advocated by the ATM Forum Traffic Management specification [6] for managing Available Bit Rate traffic[2]. ATM switches (labeled Explicit Down Switches (EDS) in [6]) can calculate the maximum ER that they can accept over the next control interval, so that ABR traffic into the network can be regulated, for effective use of resources. This can be contrasted to the earlier preventive (open loop) based approaches [9], which were suggested then as the (only) effective way to control ATM (Broadband-ISDN) based networks. Several feedback based control schemes have been proposed for delay tolerant traffic, including: end-to-end window based flow control [10], end-to-end binary feedback [11], network edge rate control [12], end-to-end ECN based (forward or backward) flow rate control [13], [14], EPRCA (Enhanced Proportional Rate Control Algorithm) [15], ERICA and ERICA+ [16, 17], Predictive Adaptive control [18] [19], Fuzzy Backward Congestion Notification [20], Fuzzy Explicit Rate Marking (FERM) [21], hop-by-hop rate based [22], and credit-based control [23]. In contrast, the number of proposed congestion control schemes for delay sensitive traffic is much less: Fuzzy congestion control [24], and Neural based congestion control [25], Fuzzy based rate control for MPEG video [26].

Evolutionary, for TCP/IP and ATM we see a progressive shift of controls from the edges of the network (initially open loop then edge binary feedback based) to inside the network. The feedback signal has also shifted from implicit to explicit, from pure binary to multivalued and explicit. Furthermore, it should be pointed out that the congestion control problem in the Internet is exacerbated, as the Internet is transformed into an integrated services high-speed network. For Integrated Services [27], not many congestion control algorithms have appeared in the open literature. Its architecture is expected to provide a mechanism for protecting individual flows from congestion, and introduces its own queue management and scheduling algorithms. In [27] it is speculated whether a virtual circuit model should be adopted (i.e. abandonment of IP), as proposed in ATM and ST-II protocol. Debate is still at an early stage, but the approach to congestion control should be based on a congestion control framework and appropriate control techniques (the same comments apply for differentiated services in the Internet).

[2] Advocated by the ATM Forum, against an initial push advocating preventive open loop based control for Broadband-ISDN

In section 2 of the paper we present an example of the application of CI: the Fuzzy Logic Based approach for congestion control. In section 3 we present the FERM II congestion control algorithm, in section 4 the simulative evaluation of the proposed scheme, and finally in section 5 we offer our conclusions and recommendations.

2. FUZZY LOGIC APPLICATION FOR CONGESTION CONTROL

A network system is a large distributed complex system, with difficult often highly non-linear, time varying and chaotic behaviour. There is an inherent fuzziness in the definition of the controls (declared objectives and observed behaviour). Dynamic or static modelling of such a system for (open or closed loop) control is extremely complex. Measurements on the state of the network are incomplete, often relatively poor and time delayed. Its sheer numerical size and geographic spread are mind-boggling. For example, customers (active services) in the 10s of millions, network elements in the 100s of million, and global coverage.

Therefore, in designing the network control system, a structured approach is necessary. The traditional techniques of traffic engineering, queuing ana1ysis, decision theory, etc. should be supplemented with a variety of novel control techniques, including (nonlinear) dynamic systems, computational intelligence and intelligent control (adaptive control, learning models, neural networks, fuzzy systems, evolutionary/genetic algorithms), and artificia1 intelligence.

Computational Intelligence (CI) [28], [29] is an area of fundamental and applied research involving numerical information processing (in contrast to the symbolic information processing techniques of Artificial Intelligence (AI)). Nowadays, CI research is very active and consequently its applications are appearing in some end user products. The definition of CI can be given indirectly by observing the exhibited properties of a system that employs CI components [28]:

> “A system is **computationally intelligent** when it: deals only with numerical (low-level) data, has a pattern recognition component, and does not use knowledge in the AI sense; and additionally, when it (begins to) exhibit
>
> - computational adaptivity;
> - computational fault tolerance;
> - speed approaching human-like turnaround;
> - error rates that approximate human performance.
>
> The major building blocks of CI are artificial neural networks, fuzzy logic, and evolutionary computation.”

While these techniques are not a panacea (and it is very important to view them as supplementing proven traditional techniques), we are beginning to see a lot of interest not only from the academic research community [30], but also from telecommunication companies [31].

Fuzzy Logic Controllers (FLCs) may be viewed as alternative, non-conventional way of designing feedback controllers where it is convenient and effective to build a control algorithm without relying on formal models of the controlled system and control theoretic tools. The control algorithm is encapsulated as a set of commonsense rules. FLCs have been applied successfully to the task of controlling systems for which analytical models are not easily obtainable or the model itself, if available, is too complex and highly nonlinear.

In recent years, a handful of research papers have been published on the investigation of solutions to congestion control issues in ATM networks. Given the complexity of ATM networks, rich variety of traffic sources that operate on them, and difficulty of obtaining formal models for in depth analysis, it is not surprising to see that FLCs are favored by the researchers involved in ATM network development. Purely reactive congestion control techniques will not be effective in ATM based multimedia and multiservice networks. Therefore, the researchers who applied the computational intelligence methods to congestion control problem mostly looked at predictive congestion control schemes. In general, the schemes observe the short term behavior of a link to estimate the future of cell arrivals in order to predict the onset of congestion and take proactive measures to prevent its occurrence. Liu and Douligeris [32] have proposed a combination system consisting of a leaky bucket and a fuzzy logic cell rate controller. Jensen [33] has proposed a fuzzy system for controlling the transmission rate of sources to protect links against overload in the case of connections exceeding their negotiated traffic parameters. Cheng and Chang [34], [35] combine connection admission control (CAC) and congestion control mechanisms. The congestion control mechanism sends back coding rate control signals to video and audio sources, and congestion control signals to data sources to adjust the cell transmission rate of the sources, and subsequently the traffic density at the switches. Pitsillides et al. [36], [37], and Qiu [38] have proposed congestion control schemes which operate under similar principles. The schemes, by measuring the queue length and queue growth rates at the output buffer of a switch, attempt to estimate the future behaviour of the queue, and send explicit rate control signals to the traffic sources to avoid or alleviate congestion. The explicit rate control signals are calculated periodically by fuzzy inference engines located in the switches, and sent to the traffic sources in resource management (RM) cells. The scheme of Pitsillides et al. is used in Fuzzy Explicit Rate Marking (FERM) algorithm. They have analyzed its performance in detail regarding fairness, responsiveness, resource utilization and cell loss in LAN and WAN environments. The scheme has been further refined (FERM2) and as an adaptive scheme which has self tuning capabilities (A-FERM). A detailed overview of FERM2 is presented in the next section. Note that not many schemes are proposed for the control of real time traffic. A notable example is Tsang et al [26] who propose a fuzzy logic based scheme for real time MPEG video to avoid long delay or excessive load at the user interface in an ATM network. They control the input and output rates of a shaper whose role is to smooth the MPEG output traffic rate. This they do at the expense of variable picture quality, but in a controlled way (by allowing a small output variation, similar to an open loop which aims for constant picture quality at the expense of variable bit rate).

3. FERM2 CONGESTION CONTROL ALGORITHM

In this section the operation of FERM2 explicit rate congestion control scheme is summarized. FERM2 is very similar to FERM [37] and can be considered as a further refinement of the original scheme. The main difference between the two schemes is in the former one the desired queue length is implicit, in the later one it is set by a higher level control module to provide more dynamic resource utilization across the switches constituting the virtual connection. Figure 1 shows the block diagram FERM2. Similar to the original algorithm, FERM2 also uses the following five parameters

Parameter	Definition
PCR	Peak cell rate
ICR	Initial cell rate
AIR	Additive increase rate
MCR	Minimum cell rate
N_{fp}	Control interval

Overall operation of the scheme is compliant with the ATM Forum Traffic Management Specification, Version 4. Cell rates of data sources are adjusted by Explicit Rate (ER) information carried by Resource Management (RM) cells. RM cells are periodically generated by traffic sources, transmitted towards the destination end systems, and initial ER information is set by the ICR. The destination end systems bounce the RM cells back to the sources. During the return path, when a RM cell passes through an ATM switch, its ER value is examined and possibly modified. A data source, upon receiving a RM cell, adjusts its cell rate based on the value contained in the RM cell’s ER field. If the ER field contains a rate bigger than PCR, the cell rate is set to PCR. Similarly, the cell rate is set to MCR for the ER values less than MCR.

The scheme, in the calculation of the ER, monitors both the current queue length and its growth rate. The queue length captures the current state of the output buffer of the switch, and the rate of change of the queue length provides some form of prediction for the near future buffer behavior. Thus, the scheme could be expected to be more effective than schemes using feedback based on the queue length threshold, queue length, or the rate of change of the queue length alone. The scheme provides the ER to all the active VCs at all the time so that congestion and undesired resulting behavior can be avoided. The scheme does not need to keep the state of current VC connections sharing the same semi-static VP at the switch.

Periodical ER calculations are performed by the Fuzzy Congestion Controllers (FCCs) located in each ATM switch.

3.1. FUZZY CONGESTION CONTROLLER

Fuzzy Congestion Controller (FCC) is a fuzzy logic controller (FLC). Designing a FLC involves selection of suitable mathematical representations for t-norm, s-norm, defuzzification operators, fuzzy implication functions, and shapes of membership functions among a rich set of candidates. Particular selection of these operators and functions alter the nonlinear input-output relationship, or in other words, the behavior of a FLC. But, research has shown that same effects can be achieved by proper modification of the rule base [39]. Therefore, in practical applications, usually computationally lighter and well studied operators and functions are selected, and desired behavior of a FLC is obtained by altering the linguistic rules.

For the implementation of the FCC, the authors have chosen the most widely used and computationally lighter methods, which are

- singleton fuzzification
- t-norm algebraic product for the mathematical representation of the connective "and"
- Larsen's product rule of implication
- sup-product compositional rule of inference
- weighted mean of maximums defuzzification.

As can be observed from the control surface of the FCC (Figure 2), it is a nonlinear controller. For a certain queue length, it calculates different flow rate limits depending on the rate at which queue length varies.

At the end of the each filter period of N_{fp} cell times (control interval), two numerical values showing the average length of the ABR queue and the difference of the ABR queue length from the previous control interval (i. e. queue growth rate) are calculated and fed to FCC. Based on this data and the linguistic information stored in the rule base, FCC computes the Flow Rate Correction ($-1 < FRC < 1$) and an Explicit Rate $ER_{next} = ER_{current} + (FRC * \text{Link Cell Rate})$ for the sources feeding the ATM switch. If, within the current control interval, the ATM switch receives an RM cell traveling to the upstream nodes, it examines the ER field of the cell and if this rate is greater than the calculated flow rate, it modifies the ER field with the calculated value and retransmits the RM cell.

3.2. RULE BASE DESIGN

The selection of rule base is based on the designer's experience and beliefs on how the system should behave. Design of a rule base is two-fold: First, the linguistic rules (``surface structure'') are set; afterwards, membership functions of the linguistic values (``deep structure'') are determined.

The trade-off involving the design of the rule base is to have a set of minimum number of linguistic rules representing the control surface with sufficient accuracy to achieve an acceptable performance. Recently, in the fuzzy control literature, some formal techniques for obtaining a rule base by using Artificial Neural Networks or Genetic Algorithms have appeared. Nevertheless, the conventional trial and error approach under the guidance of some design rules of thumb [40] can be referred or a discussion of these) have been used in this study.

Usually, to define the linguistic rules of a fuzzy variable, Gaussian like, triangular or trapezoidal shaped membership functions are used. Selection of Gaussian like membership functions leads to smoother control surfaces.

Then, the rule base is fine tuned by observing the progress of simulation, such as cell loss occurrences and demand versus throughput curves. The tuning can be done with different objectives in mind. For example, any gain in throughput must be traded off by a possible increase in the delay experienced at the terminal queues. However, since the tuning of the fuzzy rules is intuitive, and can be related in simple linguistic terms with user's experience, it should be a straightforward matter to achieve an appropriate balance between a tolerable end-to-end delay, and the increase in throughput. Alternatively an adaptive fuzzy logic control method can be used which can tune the parameters of the fuzzy logic controller on line, using measurements from the system. The tuning objective can be based on a desired optimization criterion, for example, a trade-off between maximization of throughput with minimization of end-to-end delay experienced by the users. The set of linguistic rules shown below in Table 1 define the control surface of the FCC:

if ABR queue length is too short and queue is decreasing fast then increase flow rate sharply
if ABR queue length is too short and queue is decreasing slowly then increase flow rate moderately
if ABR queue length is too short and queue length is not changing then increase flow rate moderately
if ABR queue length is too short and queue is increasing slowly then decrease flow rate moderately
if ABR queue length is too short and queue is increasing fast then decrease flow rate moderately

if ABR queue length is acceptable and queue is decreasing fast then increase flow rate moderately
if ABR queue length is acceptable and queue is decreasing slowly then increase flow rate moderately
if ABR queue length is acceptable and queue length is not changing then do not change flow rate
if ABR queue length is acceptable and queue is increasing slowly then decrease flow rate moderately
if ABR queue length is acceptable and queue is increasing fast then decrease flow rate moderately

if ABR queue length is too high and queue is decreasing fast then do not change flow rate
if ABR queue length is too high and queue is decreasing slowly then do not change flow rate
if ABR queue length is too high and queue length is not changing then decrease flow rate moderately
if ABR queue length is too high and queue length is increasing slowly then decrease flow rate sharply
if ABR queue length is too high and queue length is increasing fast then decrease flow rate sharply

Table 1. Set of linguistic rules defining the control surface of the FCC

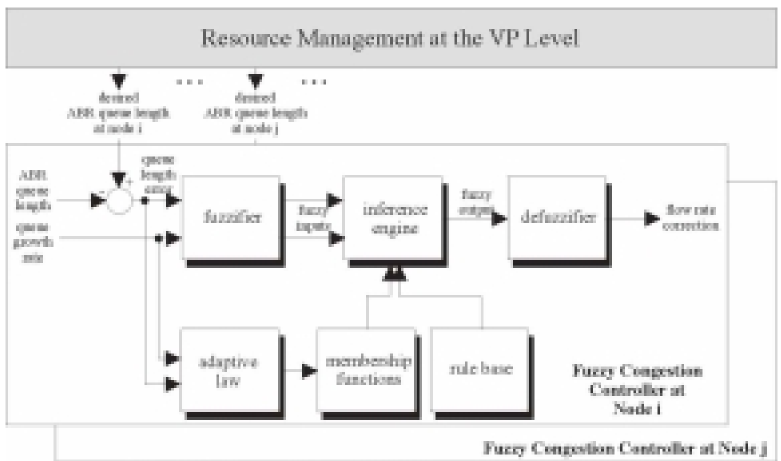

Figure 1. Block diagram of the Fuzzy Congestion Controller of the FERM2 scheme.

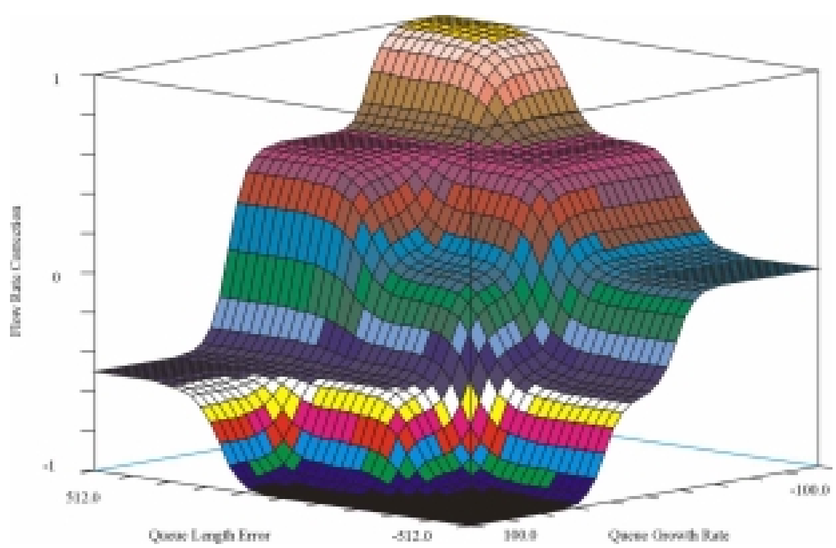

Figure 2. Control surface of the Fuzzy Congestion Controller. The control surface is shaped by the rule base and the linguistic values of the linguistic variables. By observing the progress of simulation, and modifying the rules and definitions of the linguistic values, FCC can be tuned to achieve better server utilization, and lower cell loss coupled with minimal end-to-end cell delay.

3.3. DESIGN CHALLENGES

The linguistic rules which determine the actions to be taken by the FLCs can sometimes pose challenges to the designers. Traditionally, the rules encapsulate the expert's experience or belief about the necessary control actions taken. It is possible that the expert's knowledge is not available, or not easily obtainable. In this case, if operational data is in hand, linguistic rules may be extracted from the data by using clustering methods. Cheng and Chang [34], [35] have adopted genetic algorithms to obtain linguistic rules from the operational data. Another challenge is, usually the rules are static: they do not change during the operation of the system. Naturally, this can lead to suboptimal control actions to be taken if system dynamics change in time. The solution to this problem is to use adaptive methods to modify a set of parameters which are used to define the linguistic rules in real-time.

Sugeno [41] has proposed a method for adaptive tuning of linguistic rules of a FLC. In his method, the controlled variable which determines the output action defined in the linguistic rules are chosen as polynomial expressions of some state variables whose coefficients are modified by adaptive techniques. This technique can be used for controlling very complex systems and has been successfully demonstrated by Sugeno to control the flight of a helicopter. For an illustrative example of this very interesting approach see [42] and [43]. Hu, Petr and Braun [44] have used this method to design an adaptive fuzzy congestion control scheme. In their approach, the level of network congestion is monitored through the queue length at the output buffer of the switch, with the control target being set at a desired queue length. Sekercioglu and Pitsillides have also designed an adaptive control scheme (A-FERM).

4. SIMULATIVE EVALUATION

The authors have done extensive simulations on a representative ATM network (Figure 3) and have compared the performance of FERM against enhanced proportional rate control algorithm (EPRCA). The results of this study has been reported in [37]. FERM2 yields yet better throughput results than FERM in an overloaded network for both LAN and WAN networks (Figure 4 and Figure 5).

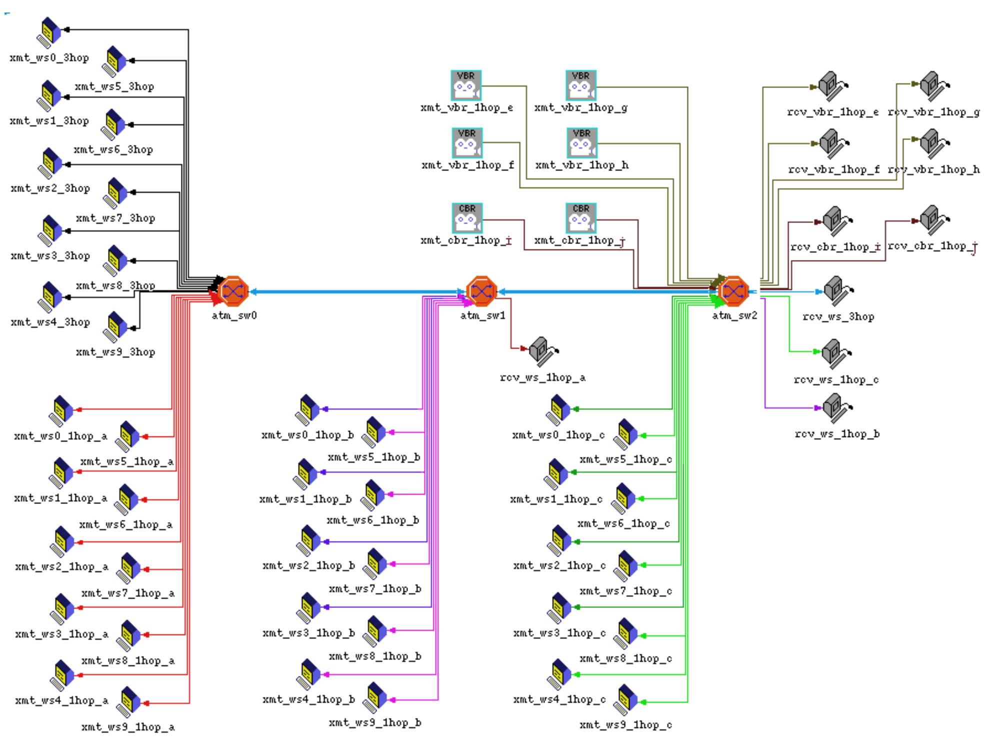

Figure 3. ATM network model used for performance analysis of FERM and FERM2 algorithm. Same network configuration has been used for the simulation of ATM WAN backbone and ATM LAN backbone except that the distances

between switches have been set to 1500 km and 10 km for WAN and LAN simulations respectively. All traffic (except 1hop (b) traffic) leaving ATM switch 2 travels to a fourth ATM switch and distributed. Since no cell buffering occurs at this switch, it has not been included into the simulation model. The speed of all links have been considered as 155 Mb/s.

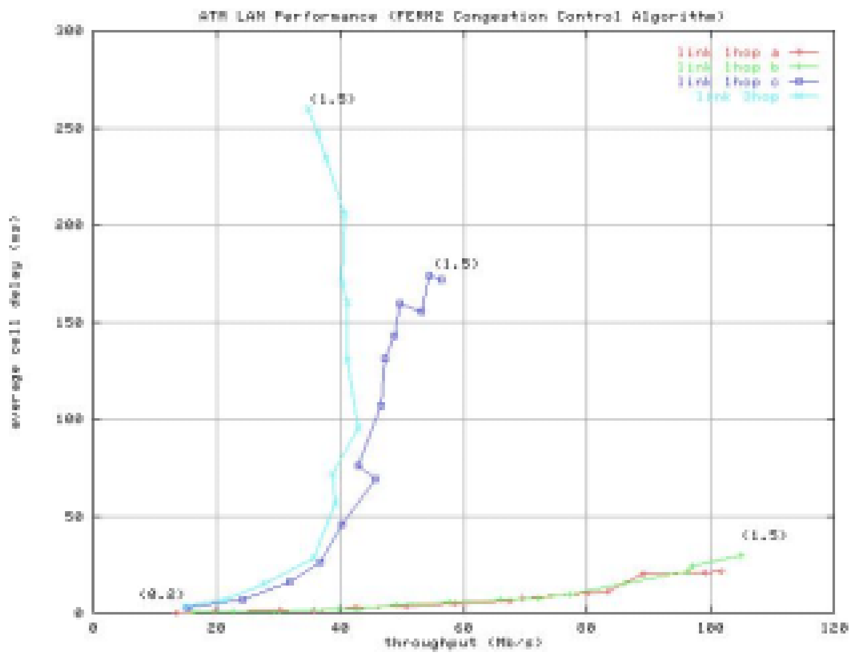

Figure 4. Plot of average end-to-end ABR cell delay vs. useful throughput of simulated ATM LAN under FERM2 congestion control. The graph has been produced by varying the offered link loads generated by the ABR traffic sources from 20% to 150% of the link capacities.

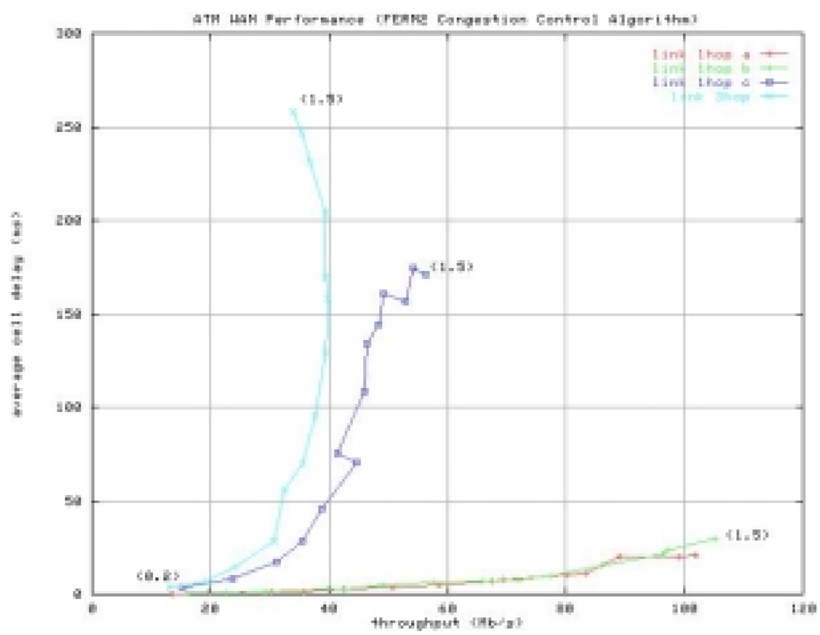

Figure 5. Plot of average end-to-end ABR cell delay vs. useful throughput of simulated ATM WAN under FERM2 congestion control. The graph has been produced by varying the offered link loads generated by the ABR traffic sources from 20% to 150% of the link capacities.

The following plots show the time evolution of the Explicit Rate, as calculated by FCC, for the case of a LAN (**Figure 6**) and a WAN network (Figure 8). The other two figures show the time evolution of the queue length for both LAN (Figure 7) and WAN (Figure 9), with the reference point set at 400 cell places. Please note the expected deterioration in performance of the controlled network for high bandwidth delay products (WAN), as opposed to the excellent controlled system performance for the case of very small propagation delay (LAN). Nevertheless even for the WAN case, the network system is well controlled and the network losses and retransmissions are limited. Note that the distances between switches are set at 1500km, with a maximum end-to-end round trip delay around 30 msec @ 6000 kms; compare with the 2.6 msec time it takes to fill or empty a buffer of 1000 cells @ 155 Mbits/sec.

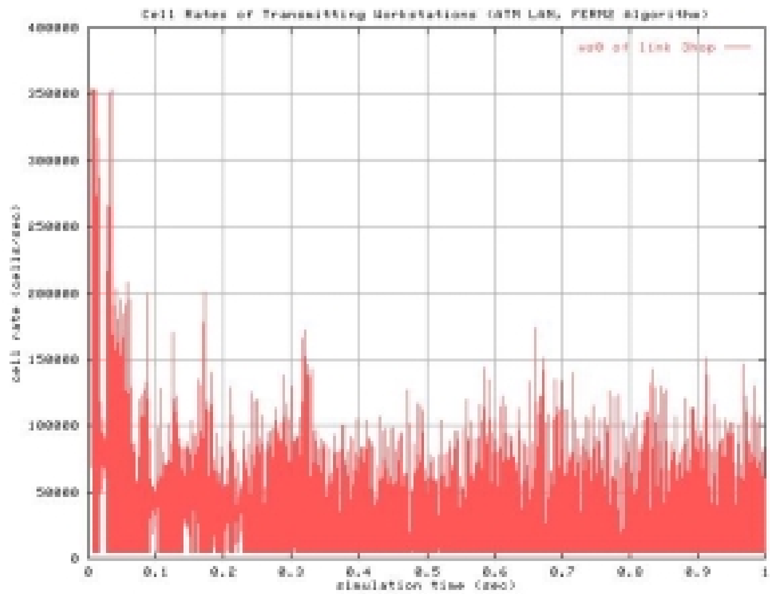

Figure 6 Time evolution of the Explicit Rate for the case of the LAN; calculated by the FCC

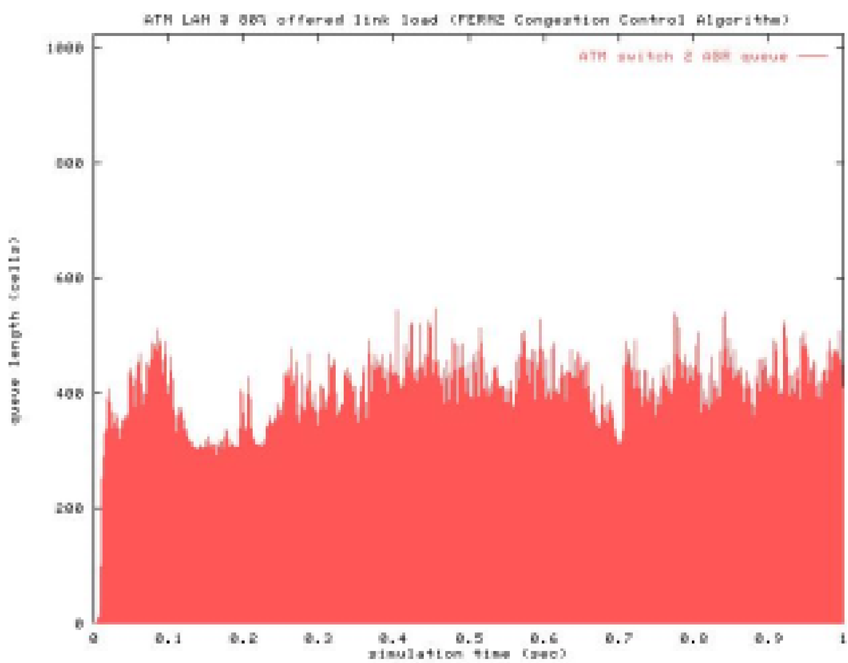

Figure 7. Time evolution of the queue length for the case of a LAN. Note that the reference value is set at 500 cell places.

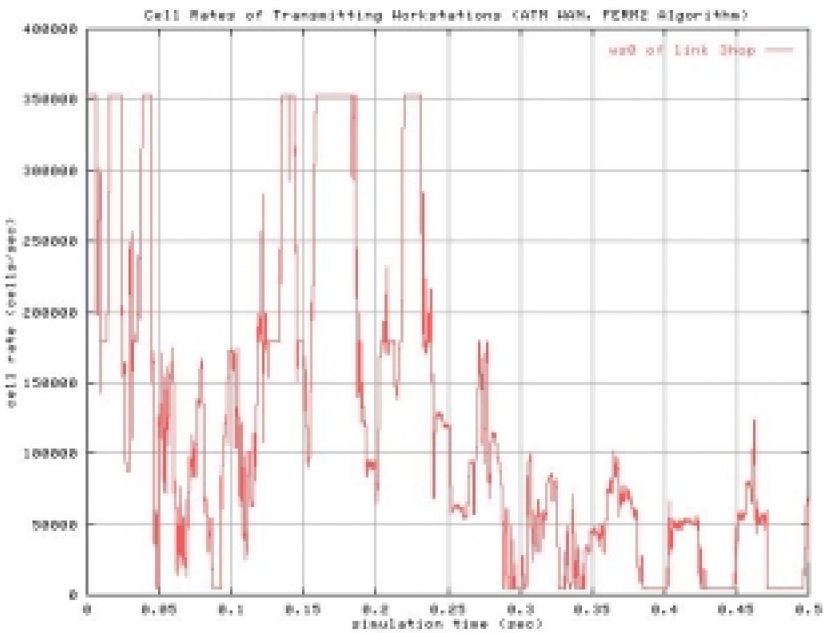

Figure 8. Time evolution of the Explicit Rate for the case of the WAN; calculated by the FCC

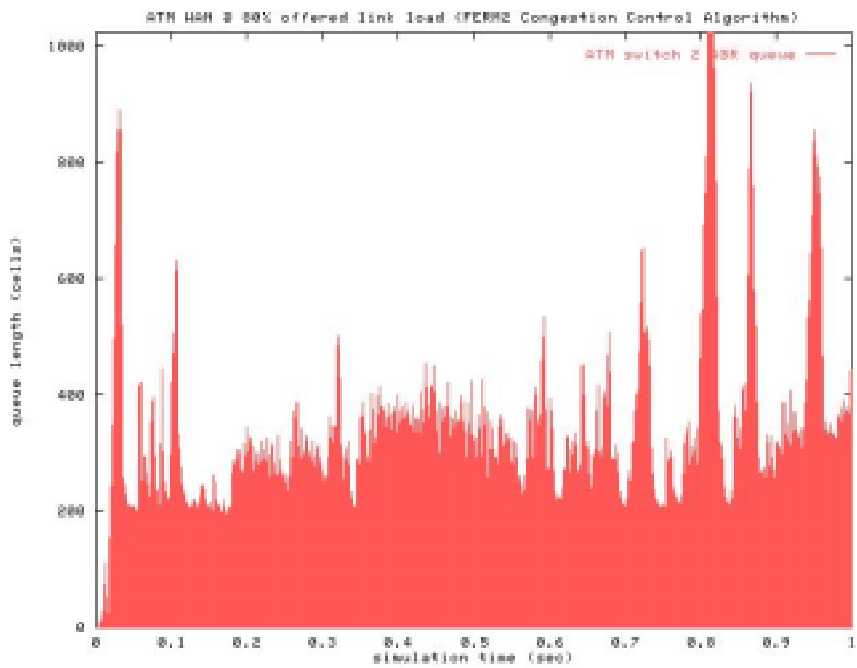

Figure 9. Time evolution of the queue length for the case of a WAN. Note that the reference value is set at 500 cell places.

5. CONCLUSIONS AND RECOMMENDATIONS

In the “fight” against congestion, despite the research efforts spanning a few decades and the large number of different schemes proposed, there are no universally acceptable solutions (a control strategy, a control system, or a “package” of control solutions). Congestion control remains a critical issue and a high priority, especially given the growing size, demand, and speed (bandwidth) of the increasingly integrated services network.

In this paper we have reviewed existing literature on IP and ATM congestion control. We have presented an illustrative example of using CI intelligence to control congestion using Fuzzy Logic. This and the literature we review on CI methods applied to ATM networks show that CI can be effective in the control of congestion. There is no doubt that we will see more and more use of these techniques, including their use in the IP world. We also expect that, as in other commercial products, CI techniques will finally make it into real products in this area, and we expect with tremendous success.

Of course many challenges to the control of congestion remain unresolved (after all the network control system is one of the most, if not the most, complex control system that man ever made—it is complex as well as large-scale). Challenges, include:

- Get agreement on a structured approach to congestion control for the network. Control theoretic concepts and techniques have an essential role to play.
- Engineer the network system with the network control system together in order to add another degree of flexibility.
- Deploy these control systems in the large scale, geographically distributed network system. Theoretical advances in handling large scale complex systems are required, including decomposition and organisation of controls (possibly hierarchical, multilayer, multilevel).
- Globally optimise the overall network objectives.
- Develop a framework for the evaluation of the performance of the controlled systems for different control solutions. The framework will possibly have to be simulative (a Common Simulative Framework, CSF). The CSF will have to define and include a number of predefined scenario of test loads, test networks and controlled system performance indices (these will include the indices discussed in [21], such as fairness, steady state response, transient response, rise time, settling time, and controller properties, as e.g. stability, robustness, efficiency, implementation complexity, ease of tuning, scalability, internetworking with other schemes, policing of connections, …).

In conclusion, there is a real challenge in the control of congestion in communication networks, especially the ones supporting video, voice and data applications simultaneously. Computational Intelligence techniques are expected to play a central role, especially in the large scale, geographically distributed network systems. Hybrids are also expected to supplement these techniques and prove useful, especially in optimising the overall network objectives.

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