CONGESTION CONTROL I N COMPUTER NETWORKS: I SSUES AND TRENDS

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Abstract

Popular myths that cheaper memory, high-speed links, and high-speed processors will solve the problem of co in computer networks are shown to be false. A simple definition for congestion based on supply and dema resources is proposed and is then used to classify various congestion schemes. The issues that make the problema difficult one are discussed, and the architectural decisions that affect the design of a congestion presented. It is argued that long-, medium-, and short-term congestion problems require different soluti of the recent schemes are briefly surveyed, and areas for further research are suggested.

Congestion control is concerned with allocating the congrestion occurs when the demand is greater than the

Introduction 1

Myths About Congestion Control

sources in a network such that the network can openvailable resources. Therefore, it is believed that as ate at an acceptable performance level when the decources become less expensive, the problem of congesmand exceeds or is near the capacity of the networtk on will be solved automatically. This has led to th resources. These resources include bandwidths of linksowing myths: buffer space (memory), and processing capacity at intermediate nodes. Although resource allocation is nef- Congestion is caused by a shortage of buffer space essary even at low load, the problem becomes more important as the load increases because the issues of fairness and low overhead become increasingly important. Without proper congestion control mechanisms 2. Congestion is caused by slowlinks. The problem the throughput (or network) may be reduced considerably under heavy load.

and will be solved when memory becomes cheap enough to allow infinitely large memories.

will be solved when high-speed links become availabl e.

In this paper, we begin with several myths about con-3. Congestion is caused by slow processors. gestion and explain why the trend toward cheaper memproblemwill be solved when the speed of the proory, higher-speed links, and higher-speed processors hagessors is improved. intensified the need to solve the congestion problem

We then describe a number of proposed solutions and 4. If not one, then all of the above developments wil present a classification of congestion problems as well ascause the congestion problem to go away.

their solutions. In Section 4 we explain why the prob-

lemis so difficult. In Section 5, we discuss the protector to these beliefs, without proper protocol r design decisions that affect the design of a congestion, the above developments may lead to more concontrol scheme. Finally, we describe our recent propostion and, thus reduce performance. The following als and suggest areas for future research. discussion explains why.

> The congestion problem can not be solved with a large buffer space. Cheaper memory has not helped the congestion problem It has been found that networks with

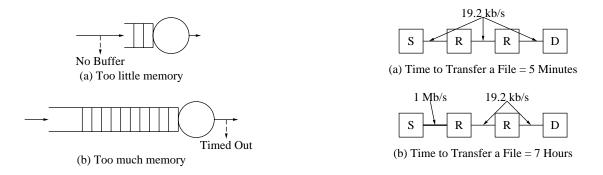
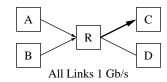


Figure 1: Too much memory in the intermediate nodes Figure 2: Introducing a high-speed link may reduce the is as harmful as too little memory.

infinite-memory switches are as susceptible to congestion as networks with low-memory switches [26]. For the latter, it is obvious that too much traffic will lead to buffer overflow and packet loss, as shown in Figure 1a. On the other hand, with infinite-memory switches, as shown in Figure 1b, the queues and the delays can get so long that by the time the packets come out of the switch, most of them have already timed out and

sources.



have been retransmitted by higher layers. In fact, Ftgore 3: A balanced configuration with all processors much memory is more harmful than too little memory and links at the same speed is also susceptible to consince the packets (or their retransmissions) have gesbeon. dropped after they have consumed precious network re-

The point is that high-speed links cannot stay in isolar the congestion problem can not be solved with high-speed tion. The low-speed links do not go away as the high-links. In the beginning, the telephone links connecting links are added to a network. Introduction of computers had a speed of a mere 300 bits per second high-speed links has increased the range of speeds that Slowly, the technology improved, and it was possible have to be managed. The protocols have to be designed get dedicated links of up to 1.5 Mbits per second. The precifically to ensure that this increasing range of links are anetworks (LANs), such as Ethernestpeeds does not degrade the performance. with a speed of 10 Mbits per second. It was precisely at

this point that the interest in congestion control The congestion problem can not be solved with high-speed niques increased. This is because the high-speed LANCessors. The argument for processors is similar to were now connected via low-speed, long-haul links, that for links. Introduction of a high-speed process congestion at the point of interconnection became na existing network may increase the mismatch of problem

The following experiment, although a contrived of congestion occurs even if all links and processors are of shows that introducing high-speed links without propersame speed. Our arguments above may lead some congestion control can lead to reduced performance [17] believe that a balanced configuration with all process Figure 2 shows four nodes serially connected by the ges and links at the same speed will probably not be 19.2 kbits per second links. The time to transfer a parceptible to congestion. This is not true. Consider the links are greatly as a parceptible to congestion. This is not true. Consider the links are greatly as a parceptible of the balanced configuration shown in Figure 1 two nodes was replace by a fast 1 Mbits per secoll 1 and 1

The conclusion is that congestion is a dynamic problem It cannot be solved with static solutions alone. We need protocol designs that protect networks in the event of congestion. The explosion of high-speed networks has led to more unbalanced networks that are causing congestion. In particular, packet loss due to buffer shortage is a symptomnot a cause of congestion.

Adassification of Congestion Problems and Solutions

In simple terms, if, for any time interval, the total sum of demands on a resource is more than its available capacity, the resource is said to be congested for that 1 n-Resource Creation Schemes: Such schemes interval. Mathematically speaking:

$$\Sigma Demand > Available Resources$$
 (1)

In computer networks, there are a large number of resources, such as buffers, link bandwidths, processor times, servers, and so forth. If, for a short interval, the Power increases on satellite links to increas buffer space available at the destination is less than that required for the arriving traffic, packet loss occurs. Similarly, if the total traffic wanting to enter a link is more than its bandwidth, the link is said to be congested.

The above definition of congestion, although simplistic, With all of the above schemes, users of the reis helpful in classifying congestion problems as well asource do not need to be informed, as they may solutions. Depending upon the number of resources involved, a congestion problemcan be classified as a single work. The network is solely responsible for solvin resource problemor a distributed resource problem as the congestion problem shown in Figure 4. The single resource involved may be a dumb resource, such as a LAN medium in which case, all the intelligence required to solve the congetry to reduce the demand to the level of the availtion problem has to be provided by the users. Various LAN access methods, such as CSMA/CD (Carrier Sense Multiple Access with Collision Detection), token access, about the load condition in the network so they register insertion, and so on, are examples of solutions an adjust the traffic. There are three basic classes to the problem of single, dumb resource congestion. If of such schemes: the resource is intelligent, for example, a name server, it • Service Denial Schemes: These schemes do can allocate itself appropriately. The problemis more difficult if the resource is distributed as in the case of a store and forward network. For example, considerint the links as the resources, the user demands have to be limited so that the total demand at each link is less than its capacity. It is this set of problems dealing with distributed resource congestion that we are concerned with in this paper.

The simple definition of congestion above also allows us to classify all congestion schemes into two classes: those that dynamically increase the available resource, and those that dynamically decrease the demand. Some examples of both these types of schemes are described below.

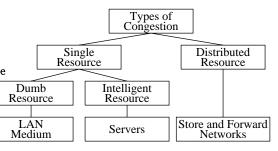


Figure 4: Types of congestion problems.

crease the capacity of the resource by dynamically reconfiguring them Examples of such schemes are:

- Dial-up links that can be added only during high usage.
- their bandwidths.
- Path splitting so that extra traffic is sent via routes that may not be considered optimal under lowload.

not even be aware of the congestion in the net-

2. Denand Reduction Schenes: These schemes

able resources. Most of these schemes require that the user (or other control points) be informed

- not allow new sessions to start up during congestion. The busy tone provided by the telephone company is an example of such a scheme. Connection-oriented computer networks also use similar schemes where congestion at any intermediate node would prevent newsessions from starting up.
- Service Degradation Schemes: These schemes ask all users (existing as well as new users) to reduce their loads. Dynamic window schemes in which the users increase or decrease the number of packets outstanding in the network based on the load are examples of this approach.

• Scheduling Schemes: These schemes ask users to schedule their demands so that the total demand is less than the capacity. Various contention schemes, and polling, priority, and reservation schemes are examples of this approach. It must be pointed out that all scheduling schemes are a special case of the service degradation approach.

In connectionless networks, starting a newsession does not require that all intermediate resources be Probe Packets: This requires sources to send probe informed, so the service denial approach cannot be effectively used. Such networks generally use service degradation and scheduling techniques.

All congestion control schemes, resource creation as well the overhead caused by feedback messages by inas demand reduction schemes, require the network to measure the total load on the network and then to take some remedial action. **feedback**, while the second part is called **control**. Depending upon the load, a feedback signal is sent from ward direction (towards the destination), which the congested resource to one or more control points, then relays the information back to the source [19] which then take remedial action. In demand reduction schemes, the control point is generally the source node of Anumber of alternatives for the location of control have the traffic, while in resource creation schemes, the con-also been proposed: trol points may be other intermediate nodes (or sources) on the network. Anumber of feedback mechanisms have been proposed, for example:

- Feedback Messages: Explicit messages are sent from the congested resource to the control point. Such messages have been called choke packets, source quench messages, or permits. The sources reduce their loads upon the receipt of choke packets [24] or source quench messages and increase it if these are not received. In the isarithmic scheme to-DCE) instead of between the end systems. [6], the sources have to wait to receive a permit before sending a packet. Critics of this approach Network Access: Like traffic lights at the entrance argue that the extra traffic created by the feedback messages and permits during heavy load may worsen the congestion.
- Feedback in Routing Messages: Each intermediate resource sends its load level (typically in terms queue length or delay) to all neighboring nodes who then adjust the level of traffic sent to that resource. ARPAnet at one time is an example of this approach. This method was found to generate too many routing messages, since the rate of change of delay through a node was much faster than the rate at which control could be affected.
- Rejecting Further Traffic: In this approach, no explicit messages are sent. However, incoming packets are either lost or not acknowledged, thereby, feedback signal.

creating a backpressure. This results in queues be ing built at other nodes, which then backpressure their neighbors. The backpressure slowly travels towards the source. This technique is useful only if the congestion lasts for a very short dura tion. Otherwise, the traffic that is not even using the congested resources is unfairly affected b the backpressure propagating throughout the net-

packets through the network and to adjust their loads depending upon the delay experienced by the probe packets.

• Feedback Fields in Packets: This approach avoids cluding the feedback in a special field in all pack ets. The feedback may be included either in pack-The first part is often called ets going in the reverse direction (towards the source of congesting traffe) [9,29] or in the for

• Transport Layer: The traffic is generated by the end systems, therefore, they are in the best position to adjust the load in an efficient manner. Dynamic windowschemes are an example of such controls at the transport layer. If the networl and the end systems are under different administrative control, such as in public networks, t control may be exercised between the first and the last intermediate systems (entry-to-exit or DCE-

ramps of some highways, the access controls at the network layer of the source node allow new traffic to enter the network only if the network is not congested. For example, the input limit scheme [23] does this by setting appropriate limit obn buffers allocated to the traffic originating at the node and to the transit traffic.

The delay adaptive routing used in • Network Layer: The routers and gateways, if congested, can take immediate action by reducing service to the sources that are sending more than their fair share. The fair queueing scheme [7], var ious buffer class schemes, and the leaky bucket algorithm[31] are examples of this approach. These schemes are particularly useful for public net works, which may not be able to ensure that the end systems will reduce the load on a congestion

• Data Link Layer: The control can also be exert traffic that has traveled a long distance (more hops), cised at the data link level at each hop using dwhale others want to give equal throughput to all users link level flow control mechanisms. Backpressuffhe definition of users is also not clear. on buffer exhaustion [3] is one such scheme. searchers treat each source-destination pair as a use Giving equal throughput to all source-destination pair

There are a number of other policies at the transpopats, sing through an intermediate node does not autonetwork, and data link layers that can be helpfulmathically guarantee that all connections from a singl congestion control. These policies are discussed later den will be treated fairly. Section 5.

Why Is the Problem Difficult?

next section.

The scheme must be responsive. The available capacity on a network is a constantly changing quantity. As the nodes and links go up or down, the available capacity is increased or decreased. As the users start and sto the demand also increases or decreases. The congestion

Despite the fact that a number of schemes have beencontrol scheme is required to match the demand dyproposed for congestion control, the search for manerwically to the available capacity. Thus, it should as schemes continues. The research in this area has baseurs to increase the demand when additional capacity going on for at least two decades [10]. There are becomes available and to decrease it if the demand exreasons for this. First, there are requirements forecosn-the capacity. The demand curve should follow the gestion control schemes that make it difficult to getapacity curve very closely. satisfactory solution. Second, there are several network policies that affect the design of a congestion scheme congestion scheme must work in bad environments. Thus, a scheme developed for one network may not work Under congestion, the rate of transmission errors, ou on another network with a different architecture. In Phisequence packets, deadlocks, and lost packets is section, we elaborate on the first issue of requirementeses considerably. The congestion scheme must con-The second issue of network policies is discussed in the to work in spite of these conditions.

Finally, the scheme must be socially optimal. That is, the scheme must allow the total network performance The scheme must have a low overhead. In particular, type be maximized. Schemes that consider each user in it should not increase traffic during congestion. is one of the reasons why explicit feedback messaigeglation may be individually optimal, but not social are considered undesirable. Some researchers have stimul [30, 21]. For example, if each user attempted gested that feedback be sent only during lowload, thos maximize its throughput, it may lead to an unstable the absence of feedback would automatically indicate tauation where total network load keeps increasing. high load. Even such schemes are not desirable, since It should be clear from the above list of requirement the network resources are also used for nonnetworking designing a congestion control scheme is not a triv applications. Therefore, resources consumed to proc these additional messages could have been better used by these other applications.

Policies That Affect the Congestion The scheme must be fair. Fairness may not be im-Control Schene portant during low load when everyone's demands can be satisfied. However, during congestion when the resources are less than the demand, it is important that the available resources be allocated fairly. Defining Pair in tectural or implementation decision that af ness is not trivial. A number of definitions have been either side of Equation 1 affects the design of proposed [1, 11, 15, 16]. However, no one definition has been widely accepted. For example, some researcher's consider starvation of a few users to be unfair [1] be considered a part of the overall congestion control allocating any research from the network. allocating any resources to a user is called starvation. These decisions are called poly By this definition, if all users get a nonzero share, of the resources, the scheme is fair. Others argue that I. a scheme without starvation can still be unfair if The hemost important network policy is the connecresources are allocated unevenly. The key problemism mechanism There are two types of networks: defining what is an even distribution of resources in a nection-oriented and connectionless. In connection

wide-area network where different users are traveling orlented networks, when a new session is set up, each

different distances. Some want to give preference to

Table I. Policies That Affect Congestion

1. Network Layer:

- Connection mechanism
- Packet queuing and service policy
- Packet drop policy
- Packet routing policy
- Lifetime control policy

2. Transport Layer:

- Round-trip delay estimation algorithm
- Time out algorithm
- Retransmission policy
- Out-of-order packet caching policy
- Acknowledgment policy
- Flow control policy
- Buffer management policy

3. Data Link Layer:

- Data link level retransmission policy
- Data link level packet drop policy
- Data link level acknowledgment policy
- Data link level flow control policy

two [23]. In some networks, there is a separate queue for each source and, thus, fairness among all sources ca be guaranteed. However, this does not ensure fairness among users from the same source going to different destinations. If a separate queue is maintained for ea source-destination pair, fairness among users from the same source to different destinations can be obtained. Several schemes to efficiently maintain and service such queues have been proposed. One scheme is to serve queues in a round-robin order [12]. This will cause th queues with large packets to get a larger share of th bandwidth than those with small packets. Schemes to tackle this inequity have also been proposed [7].

The packet drop policy deals with the issue of which packet is dropped if there is insufficient buffer space i a queue. Some of the alternatives are the first packet in the queue, the last packet in the queue (the arriv ing packet), or a randomly selected packet. The choice depends upon the type of application. For real-time communications, the older the message, the less valuable it is. Therefore, it is better to drop packets at head of the queue. This type of traffic has been called 'milk' and is contrasted with file and terminal traffic, which has been called 'wine' because older messages are more valuable than newer ones [5]. To ensure fairness, some have proposed random dropping, but others have argued its effectiveness [32].

• Data link level queuing and service policy, in particular, affect the resource alloca The route selection policy, in general, and the path spl and, hence, congestion in the network. In most networks today, a low-speed path will be totally unused even if parallel high-speed path is congested. Path splitting performed only across paths of the same speed or across parallel links connecting the same nodes (one hop).

Lifetime control policies affect the length of time packet stays in the network before being dropped. intermediate node in the path to be used is asked to Theere may be too many unnecessary retransmissions serve certain resources for the session. If the resonneces ence, load) if the lifetime is either too short

nectionless networks, newsessions can be started with-out any resource reservations at the intermediate nodes. This also allows the flexibility to dynamically change computation algorithms used by the transport prothe paths of existing connections. It is clear that cone also have a significant inpact. In fact, finding service denial schemes will work in connection-oriented algorithm for estimating round-trip delay in the networks, but not in connectionless networks. Similarly, finding a solution for congestion control [14, 17, 22]. It splitting, if required, should be set up at session start up time in connection- oriented networks. While thing the probability of false timeout alarms using the connectionless networks, it can be dynamically started as well as the variance of the round-trip delay also improves the efficiency of congestion control mechanisms using timeouts [14].

Packet queuing and service policies in the intermediate nodes affect resource allocation among users. The number of packets retransmitted on a packet loss afintermediate node may have separate queues for eachers the stability of timeout-based congestion scheme output link, each input link, or a combination of the optimal number may depend upon the out-of-order

are not available, the session is not started. Interchang. and stopped during a session.

packet caching policy at the destination. If the recent wilnes destination and, hence, the congestion level in t transport does not cache out-of-order packets, los next fiwark [13]. The buffers may be located in the system single packet may require retransmission of the enst pace or user space. They may be shared or nonshared. window. However, a comparison of several alternation of the enst packet one size or multiple sizes. The credit showed that if the packet loss is due to congestion, altiosation policy may be pessimistic or optimistic. In best to retransmit just one packet regardless of the pesse mistic case, the sum of all the windows permitted caching policy at the destination.

by that node will never be greater than the available

space. In an optimistic scheme, the node will allocate The packet acknowledgment policy affects the feedbackfore windows than available buffer space. This allows a delay in congestion information reaching back to fine throughput with a smaller probability of loosing source. If every packet is acknowledged, there mays been packets in cases where all the windows are being too much traffic but the congestion feedback is fast used. If the buffers are located in user space, sharing some acknowledgments are withheld, the load due tand optimismare less likely than if they are in system acknowledgments is less, but the congestion feedback space. delayed more.

The flow control policy used at the transport layer alsoer policies except that they apply to each hop in the affects the design of the congestion control scheme. New ork. For example, the intermediate systems in the a comparison of various flow control policies see Maxeret work may have their own packet caching, acknowl-chuk and Zarki [25]. Briefly, there are two major classificants, retransmission, and flow control policies. Al of flow control schemes: window-based and rate-based these will affect the design of the congestion control a window-based scheme, the destination specifies the me. number of packets that a source can send. This helps solve the problem of buffer shortage at the destinations unmary, there are a large number of architectural The source can further reduce the window in responsible cisions that affect the design of a congestion control a congestion feedback signal from the network. Instableme. This is why analysts comparing the same set of rate-based scheme, the destination specifies a maximulaternatives may reach different conclusions. A scheme rate in terms of packets per second or bits per sectional works for one network may not work equally well

that the source is allowed to send. The current trenfobit so ther networks. Some parameters or details of the

scheme may have to be changed.

The choice between window-based and rate-based flow control schemes depends partially upon the bottleneck **AFundamental Principle of Control** resource at the destination. Memory capacity is measured by the number of packets that can be stored; the

towards rate-based flow control schemes.

processing capacity is measured by the rate at whiAshthe name indicates, the problem of congestion conpackets can be processed; link bandwidth is measurtentblis basically a control problem. Most congestion co in terms of the number of bits per second that can beol schemes consist of a feedback mechanismand a contransmitted; and so on. Thus, if the destination is temperature chanism. In control theory, it is well known that ing the received packets on a disk, it may be limited bey control frequency should be equal to the feedback the transferrate of the disk, therefore, it is bett firetopure sney. As shown in Figure 5, if the control is fast a rate-based flow control schemes. On the other hand han the feedback, the system will have oscillations as if the destination has very little memory, it may wamitmuschability. On the other hand, if the control is slow use a window-based flow control scheme and limit the han the feedback, the system will be tardy and slow to number of packets that it can receive at a time. Simirleas pond to changes. In designing congestion schemes i considerations apply in choosing the metric for expresisnportant to apply this principle and to carefully s ing the rate. The choices are packets per second or bits the control interval. In many existing schemes th per second. If the bottleneck or a similar device with so siegnored, and although a feedback mechanism such as capacity is expressed in bits per second in the link het hource quench is specified, the issue of how often t rate limit should be specified in bits per second. sond feedback and howlong to wait before acting is left the other hand, if the bottleneck device is a processes opecified. This leads to schemes that are later found which takes a fixed amount of time per packet regardineffective. less of the size, the rate should be expressed in packets

per second.

Another lesson to learn from the control theory princi
ple is that no scheme can solve congestion that last les
Buffer management policy at the destination transpothanits feedback delay. Transport level controls, such

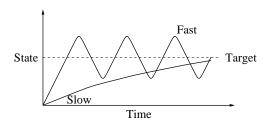


Figure 5: The rate of control and feedback delay are related.

gestion lasts for a few round-trip delays. For congestion that lasts for a shorter duration, data link and network level controls, such as priority classes, buffer classes, and input buffer limiting, are required. For longer-term congestion, either a session level control (such as session denial) or a resource creation scheme discussed earigue 6: Network performance as a function of the should be used. If congestion lasts indefinitely, it ligades Broken curves indicate performance with deterto solve the problemby installing extra resources mippistic service and interarrival times.

namic schemes are good only for transient congestion. Also, since the duration of congestion can not be detentimeout is remembered, and the increase is linear up

mined in advance, it is best to use a a combination $\inf W_o/2$ and parabolic thereafter. Other combinations, schemes operating at different layers.

such as decreasing to/WZ and increasing linearly after every five packets, have also been proposed [8].

Cliff

Knee

Load

Load

Load

Throughput

Roundtrip delaŷ

Power

Our Recent Proposals

In this section, we briefly describe three congestion schemes that we have recently proposed.

Timeout-Based Congestion Control

gardless of the window. Later, the windowis increased the this point. from Wto W-1 after receiving acknowledgments for Ascheme that allows the network to operate at the knee the window is increased linearly, that is by one affrethe network layer header is summarized in [19] and

DEChit Scheme for Congestion Avoidance

Another recent development in the area of congestion control is the introduction of the concept of congestion avoidance. Figure 6 shows general patterns of response time and throughput of a network as the network load increases. If the load is small, throughpu The timeout-based congestion control schemes are based. As the load increases on the idea that packet loss is a good indicator of congestion and, therefore, on a timeout, the load on the capacity, throughput stops increasing. This poin network should be reduced. Later, if there is no further loss, the load is increased slowly. In one time out, the queues start building, potentially resulting based scheme called CUTE (Congestion Using Timeout packets being dropped. Throughput may suddenly drop at the End-to-end layer), the windowis decreased to one, the load increases beyond this point. This point i on a timeout, and only one packet is retransmitted re-

the number of packets acknowledged in this case follows a parabolic curve and, therefore, this increase policy is called a congestion control scheme, which tries to keep called a parabolic increase. The complete scheme is described in Tain [18]. scribed in Jain [18]. In a similar scheme by Bux [As; mple congestion avoidance scheme using a single bit

every eight packets. Recently, Jacobson [14] prop@asedribed infurther detail in [4, 20, 27, 28]. another version called 'slowstart' where the window W

8

Del ay - Based Schene for Congestion Avoidance

levels. Schemes are required that prevent congestion at one level from affecting the traffic at other levels Thus, congestion of a backbone network should not af-

One problem with schemes requiring explicit feedback to ther networks and vice versa. from the network is that they cannot be used on heter congestion control in integrated networks with voice, geneous networks that consist of networks with several data, and several other types of traffic is also an interdifferent architectures. Since all the major networks of the world are slowly becoming interconnected, a packet traffic, a commonly proposed solution, does not suite may traverse several different types of networks before all environments. In some cases, such as real-time apartiting at the destination. In such cases, the freed-time the delay and throughput requirements are back provided by one network may not be meaningful plications, the delay and throughput requirements are to sources on other networks. Also, some intermedical trol scheme is nontrivial. As the telecommunication in ate nodes, for example, bridges, are susceptible to con-dustry is moving towards asynchronous transfer mode gestion, but cannot let their presence be known. (ATM), which uses short, fixed-size packets (cells), the such cases, only schemes with implicit feedback can be congestion control schemes for such networks are being used. The timeout-based scheme described earlier is an heatedly debated in several standards committees. example of an implicit feedback scheme for congestion control. To achieve congestion avoidance using implification general networks consisting of networks using feedback schemes is currently an unsolved problem Queveral different architectures need implicit feedback tentative proposal calls for measuring delay and adjustemes for congestion control and avoidance. ing the traffic depending upon the delay [21]. Morproblemwas mentioned earlier. research in this area is required before this proposal can Dynamic link creation schemes that require the dialbe implemented into networks. ing up of a new link need to be developed. When a

All three schemes discussed in this section have two kak should be dialed up or disconnected depends upon features. First, they do not require any additional PAE k-ariff structure. Now that high-speed, dial-uplin ets. As discussed earlier, processing of packets is a PAPBE coming available, it would be interesting to hav sive, and any attempt to increase network performanged delines regarding their usage. by introducing more packets may not be fruitful. Second, all parameters of the schemes are dimensionl Segver congestion is a recent problem that started occur-In particular, the schemes do not use any timers. Thing with the introduction of distributed systems. Aft correct value for any timer depends upon the networkpower failure, all nodes in a building need access t size and the link speed. Ascheme without any dimenthe name server, boot server, and so on. Unless the ac-

sional parameters is applicable to a wider range of clessis regulated properly, the server can get congest with requests and may be so late in responding that the requests are retransmitted, thus causing an unnec essary additional load on the servers. Schemes to solv this problemneed to be developed.

Areas for Further Research 8

speeds and network sizes.

Although congestion control is not a newproblem there Surmary are considerable opportunities for research. In this sec tion, we point out several issues that need to be resolved.

Congestion is not a static resource shortage problem Path splitting among long paths of differing capacities rather it is a dynamic resource allocation problem Sin is not well understood. In most networks today, plyplacing more memory in the nodes, or creating faster traffic from a given source to a given destination eitherks or faster processors will not solve the congest passes through the same path or is split equally among oblem. In any intermediate system where the total different paths of equal capacities. Thus, if the optiment rate is higher than the output rate, queues wil path is congested and a slower path is available, thind dup. Therefore, explicit measures to ensure tha slower path is not used. Designing a scheme that allows input rate is reduced should be built into the pro slower paths to be used depending upon the load levelocol architectures. on all paths is a topic for further research.

Insulating one level of network hierarchy from congeslarge networks are organized hierarchically into several

Congestion occurs whenever the total demand is more than the total available resources of memory, links, pr tion in other levels is another area for research. Mostsors, and so on. Therefore, congestion schemes can

be classified as resource creation schemes or demand 165.] D. Cohen, "Flow Control for Real-Time Commuduction schemes. Demand reduction schemes can be further subdivided into service denial, service degrap, No. 1-2, January/April 1980, pp. 41-47. dation, and scheduling schemes. Several schemes that feedback the network load information to the sources, "The Control of Congestion in who in turn control traffic, have been proposed.

Congestion control is not a trivial problem because of the number of requirements, such as lowoverhead, fai[7] A. Demers, S. Keshav, and S. Shenker, "Analyness, responsiveness, and so on. In particular, congesis and Simulation of a Fair Queueing Algorithm," tion schemes are called to work under unfavorable network conditions and are required to ensure that the re-nications Architectures and Protocols, Austin, TX, sult is socially optimal.

A number of network policies affect the choice of con-8] B. T. Doshi and H. Q. Nguyen, "Congestion Congestion control schemes. This is why one scheme may not be suitable for all networks. Given a set of protocopical Journal, November/December 1988, pp. 35design decisions, the congestion control scheme has t 4^6 .

be tuned to work appropriately with that set.

congestion control schemes is that the control and feed tem Journal, Vol. 21, No. 2, 1982, pp. 179-210. backrates should be similar. Otherwise, the system wid M Gerlaand L. Kleinrock, "Flow Control: A Comhave oscillatory or irresponsive behavior. This is why parative Survey," IEEE Transactions on Commucombination of schemes working at data link, network-nications, Vol. COM 28, No. 4, April 1980, pp. 553ing, and transport layers are required, along with proper 74. capacity planning to overcome congestion lasting a short duration to a very long duration.

Finally, as the networks become larger and heterogeneous, with higher speeds and integrated traffic, the congestion problem becomes more difficult to handle and more important than ever.

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