[132]. This problem was recognized quite early [22], references [44,110] provide a detailed review of these. control scheme [117]. Control Protocol (TCP) [21,108] and to recover from it [63]. and interactive video [35,154]. endpoints, for example, two BSD sockets [21,23]. *Virtual Circuits* (VCs) (such as in Datakit [41]). not make such demands [35]. [68], increasing the load on the bottleneck [101]. [63,114]. standstill [132]. The first definition is used in references [66,117], the second in reference [63], and the third in reference [85]. over the resources [140]. [37,48]. [35,68]. in a common pool [62]. a day [13,105]. data transfer [20,155], peak hours than during off-peak hours [7,111,130]. the recent past [32,146], For example, the SPAWN system [146] users to declare their resource needs accurately [20]. [80]. been extensively studied by Sanders [121-123]. [29,77,92]. [29], determine the effect of its sending rate on the network [117]. [54,63,96,117]. [44], [51,52,104], [1,38,66,79,133,137,138]. [63,117], [126,137,138]. Examples are the Virtual Clock scheme [154], Delay-EDD [37] and Stop-and-Go queueing [47]. game [125]. [6], Sanders [121-123], Douligeris and Majumdar [25-27] and Lazar *et al* [59]. several orders of magnitude larger [84]. and perhaps have catastrophic effects [101,132]. [112] themselves overload the congested network. of the recent past (45000 kbps to 56 kbps) [69]. network allocates its resources [23]. [43,55,106,107,115,139,149]. criterion to adopt [44]. Nevertheless, it is necessary to negotiation and enforcement mechanism [20,155]. e.g. [63]. the switches [117]. Still others assume complete control but no control over source traffic [54]. having hardware support for rapid switching [100] optimizing for the average case [18] removing signaling information from the data path [41] choice of scheduling algorithm [156] an efficient call processing architecture [131]. peer entities (for example, [117]) For example, a Fair Queueing [23] switch has the responsibility for [66]). very bursty [52,104]. and high bandwidth off-line bulk data transfer [12]. Gerla and Kleinrock [44] and Pouzin [110] transient spikes in queue occupancy [116,117]. (as in CIGALE or Cyclades) [61,88]. and possible congestion [66]. not acknowledged 'in time' [108]. When the alarm goes off, congestion is suspected [153]. the switch sends information in

packet headers [115] or Source Quench packets [112], choke packets [88], state-exchange packets [79,120], rate-control messages [148], or throttle packets [70] probe values [75], retransmission timers [153], throughput monitoring [147], or delay monitoring [66] such as a hardware problem [153]. [14,110]. The Loss-load curve scheme [148] and the selective DECbit scheme [115] seek to attention in the literature, and is surveyed in [44]. Other schemes, such as Input Buffer Limit [81], Channel Queue Limit [70], Buffer Class [45] and Matsumoto's X.75 proposal [91] packet switches [100]. reservation-oriented networks [156]. Some exceptions are in the DEC scheme [115], the Loss-load curve approach [148] and the Random dropping scheme [90]. scheme does not reduce congestion [90]. [63,88]. either using a window adjustment scheme [117] or a rate adjustment scheme [17,75]. of the future, such cooperation can no longer be assumed [118]. For example, in the DECbit scheme [117], The same is true for the Jacobson-Karels TCP scheme [63]. [90], and completely by the Loss-load curve method [148]. developed for the Datakit network [41]. This is the approach taken by Zhang in the Flow Network [154], [37], by Topolcic *et al* in the ST-II proposal [134] and by Cidon *et al* for the PARIS network [16]. In a hybrid scheme described in reference [24] The two-window scheme proposed by Hahne *et al* [54] this requirement can be reduced even further [96]. user to obey some traffic profile [34]. at the time of call set-up, and doing admission control [37]. [37]. [35]. their data can be dropped or violation-tagged [5]. [87,128,136,141]. In the Flow network, the Virtual Clock mechanism is used [154], distributed flow control [37]. Ferrari and Verma [36] and Kanakia [68] have proposed mechanisms based on calendar queues [11] that have a similar effect. though this was not studied in any depth [113]. [46,47,68]. [37,142]. performance guarantee [83]. is also relevant [19,31]. simulator [73]. congestion [44]. even if a universal standard such as ISO (12) Nagle [101] proposed a *fair queueing* (FQ) fairly [55,72]. Recently Morgan [98] has examined the role such queueing and has been analyzed extensively [42,86]. Similar work has been presented by Zhang [154]; the fair queueing algorithm presented here [156]. The max-min fairness criterion [43,55,115]

[115].

(this emulation discrepancy bound is proved in reference [50]). The IP protocol [109] does have a field for type-of-service, Recent work [57] raises questions about the { 1˜+˜{1 over {N}} ({k sup 2} ˜+˜ k(2 epsilon -1)) right }˜˜for˜˜{P sub F} left { 1˜+˜{1 over {N}} ({k sup 2} ˜+˜ k(2 epsilon -1)) right } found in reference [23]. There are few analytical results here, but Hahne [55] is crucial in the design of switch algorithms [101]. queueing algorithms to do so [125]. Prue and Postel [113] [94,95] the packet to be dropped is chosen at random [90]. [39,56,124,154]. [154]. at 1.2 Gbps [69]. [50,57,89,93,125,126]. such as NetBlt [17], and the technology for this is well known [65]. [93]. since $N sub ac$ is strictly non-increasing in ($t sub chk$, t). has been proposed [57]. [58,78]. traffic in the sense of [57], TCP protocol [108] with the modifications made by Jacobson [63]. we used the REAL network simulator [73] Along with the work done by McKenney [93] and Heybey et al [57], this work provides the practitioner Queueing, such as the Virtual Clock algorithm [154]. `i_min[k]` is the position in `max` of the swap(min[a], min[b]); swap(i_max[i_min[a]], i_max[i_min[b]]); swap(i_min[a], i_min[b]); pointer consistency, i.e. that `i_min[i_max[a]] = a` and `i_max[i_min[a]] = a`. `i_min[n] = i_max[n] = n`. min[ptr] = data; for (; (ptr/2 >= 1) &&(min[ptr] < min (ptr/2]); ptr /=2) min[1] = INFINITY; save = i_min[1]; max[save] = -1; if (min[a] < min[a/2]) smaller = a/2; smaller_son = (min[lson(a)] < min[rson(a)]) ? lson(a) : rson(a); if (min[smaller_son] < min[a]) smaller = smaller_son; attendant inefficiencies [50]. of Bessel functions [135]; of data traffic in current networks [13,51], [129]. [144,145]. analyzed in [129]. [143,145]. flow control scheme [17]. scheme modified an idea described by Clark et al. for NETBLT [17], and sent to the source using a state exchange protocol [120]. [64,97]. so, unlike TCP [63,153], [64]. [$T0 ,˜ T1 $] if in every time interval [$ t sub 1 , ˜ t sub 2 $] $ member $ [$ T0 , ˜ T1 $], [$ T0 ˜ + ˜ 2 R (0), ˜ T1 $]. conditions are trivially satisfied in [$ T0 ˜+˜ 2 R (0),˜ T1 $]. For example, the Jacobson-Karels version of TCP [63] and so will lose bandwidth when V increases [64]. Jain’s delay based scheme [66] will respond [129]. In recent work [156], we have shown that the FQ discipline is similar to the Virtual Clock [154] and Delay-EDD [37] service disciplines. though not using packet pairs, is described in reference

[53], [63, 108] or Jain's delay-based approach [66]. As mentioned in [2], Separation Theorem [3]. In recent work, Mitra et al [96, 97] Processor Sharing [50], [13, 51]. [B/2 mi nb (k) mi sk pl mu (k) RTT(k) pl mu (k+1) RTT (k + 1)] [B/2 mi n hat sub b (k) mi sk pl mu hat (k) RTT(k) pl mu hat (k+1) RTT hat (k + 1)] [B/2 mi n hat sub b (k) mi sk pl 2 mu hat (k) RTT(k)] [B/2 mi n hat sub b (k) mi sk pl 2 mu hat (k) RTT(k)] [B/2 mi n hat sub b (k) mi sk pl 2 mu hat (k) RTT(k)] Similar studies are mentioned in [30]. chosen to lie inside the range [0,B], such as the second method of Liapunov ([102] page 558). known and robust technique [49]. bold "x" eq left [pile { nb ˜ above mu ˜ above mu sub -1 ˜} right] **G** = $left [pile { { 1 ˜-Rtt ˜ 0 ˜ } above { 0 ˜ 1 ˜ 0 ˜ } above { 0 ˜ 1 ˜ 0 ˜ } } right] $ **H** = $left [pile { Rtt ˜ above 0 ˜ above 0˜ } right] $ $nu sub 1 $ = $ left [pile { 0 ˜ above omega ˜ above 0 ˜ } right] $ **C** = [0 0 1] $ E ([˜ x hat (t) mi x (t)] sup T [x hat (t) mi x (t)])$, to yield many other types of filters [49]. right] [nu sub 1 sup T (theta) nu sub 2 (theta)] ˜ right } eq left [pile { { Q ˜ S˜ } above { S sup T ˜ R˜ } } right] ˜delta **Q** = E$ left [pile { {0 ˜ 0 ˜ 0 ˜ } above {0 ˜ omega sup 2 ˜0˜ } above {0 ˜ 0 ˜ 0˜ }} right] $ **S** = E $ left [pile { 0 above omega nu sub 2 ˜ above 0 } right] $ system. We follow the derivation in [49] (pg 249). bold "K" (k) eq [bold "G" SIGMA (k) bold "C" sup T pl bold " S "] [bold [82, 152, 158]. [151], found in reference [76]. We also make the fluid approximation [1], This approximation is commonly used [8, 133], and both analysis [97] and simulations show time interval [t, t+J], but in fact can work together [67]. scheme proposed by Hahne *et al* [54] is attractive. [6, 9, 10, 27, 126]. work by Jain [116] and Jacobson [63], In recent work, Ko *et al* [79] described originally by Agnew [1], and since extended by Filipiak [38] and Tipper *et al* [133]. Vakil, Hsiao and Lazar [138] Vakil and Lazar [137] have considered Robertazzi and Lazar [119] and Hsiao and Lazar [60] in the benchmark suite described in reference [23] is comparable to that of the DECbit scheme [117], [63, 117]), messy and only partially understood [157]. experimental high speed network testbed [69]. lk1 eq 1 over { RTT(k)} [B/2 mi nhat-1 mi sk pl mu RTT(k) pl mu RTT (k)] lk1 eq 2 mu mi lk pl 1 over { RTT(k)} [B/2 mi nhat-1] lambda (2) eq 2 mu mi mu pl 1 over { RTT (2)} [B/2 mi B/2] lambda (3) eq 2 mu mi mu pl 1 over { RTT(3)} [B/2 - B/2] We follow the description of LQG presented in [102] (pg. 835). bold "Q" eq left [pile { { 1 ˜0 ˜0 ˜ } above { 0 ˜0 ˜0 ˜ } above { 0 ˜0 ˜0 ˜ } } right] [99] [93, 117, 154], [33]. as in reference [12]. traffic [13, 51, 105]. [33, 103], [4, 28] [73, 74]. transport flow control protocol [108, 150], [63, 127, 154, 157], the DECbit scheme [114-117]. as

implemented in XNS's SPP [150] or in TCP (before 4.3 Tahoe BSD) [108], Jacobson and Karels' (JK) modified TCP [63] [15, 115-117], [63, 71]). protocols such as NETBLT [17] congestion avoidance scheme [66]. [115, 148], (see reference [115] and the simulation results below), on the description in references [115, 116]. of 40 and 570 bytes in the Internet [12]. Floyd and Jacobson in [39, 40]). [39, 40]. [54]. (though global tradeoffs are still possible [6]). and has also been studied exhaustively in references [39, 40]. [101]). by Prof. S. Singh and Prof. A. Agrawala [129]). laws is a well known problem [49]. thesis by D. Verma [141].

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