Traffic Backlog and Impact on Network Dimensioning for Survivability for Wide-Area VP-based ATM Networks*

R. Cotter[a], D. Medhi[a] and D. Tipper[b]

[a]Department of Computer Networking, University of Missouri–Kansas City, Kansas City, MO 64110, USA. Email: {rcotter,dmedhi}@cstp.umkc.edu

[b]Department of Information Science and Telecommunications, University of Pittsburgh, Pittsburgh, PA 15260 USA. Email: tipper@tele.pitt.edu

It has been recently observed that the dominant factor on network performance after a failure in a packet switched network is the transient or nonstationary congestion period triggered by the backlog of packets due to retransmission after a failure. Given this observation, we address the survivable network design problem for VP-based ATM networks by introducing the transient time threshold to clear backlog as one of the quality-of-service parameters and present a design framework. Through computational work on test networks, we observe that if this parameter is not incorporated, a network (where services do backlog traffic after a failure) may be under designed resulting in noticeably longer transient period than any acceptable threshold.

1. INTRODUCTION

Designing networks for survivability has received considerable attention in recent years [2, 3, 9, 11, 13, 16, 17, 19, 21, 22, 26, 27]. For ATM-based broadband networks, multi-layer network survivability and restoration can be possible at the following levels: transmission-level, virtual path-level, and virtual circuit or connection/call-level. At transmission level, SONET self-healing ring for restoration is a viable alternative for a major failure such as a fiber cable cut [27]. However, it may not be possible to provide for such transmission level restoration for every type of networks or failures, especially in a wide-area networking environment (e.g. if the network is based on leased capacity from various vendors, all of whom may not have transmission restoration; or, it is not cost-effective to provide adequate transmission network restoration; or, transmission level restoration may not be applicable in certain failure scenarios, such as a line card or a device failure). This, in turn, means that survivability and restoration at VP and/or VC level would also be necessary. For call/virtual circuit-level restoration, the reader is directed to work such as [7, 21, 24, 25]. Our present paper concentrates on virtual-path level survivability and restoration.

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The virtual path concept for ATM networks design and management have been addressed by numerous researchers [5, 8, 10, 12, 15, 18, 20, 23]. For network design with virtual-path-level survivability, some work has been done recently – see, for example, [3, 16]. Our work is motivated by the recent observation that in connection-oriented packet-switched networks the dominant factor on network performance after a failure is the transient or nonstationary congestion period triggered by the *backlog of packets after a failure* [24]. This backlog is created since the connections wait till the fault has been identified and until a routing decision has been made. During this time delay, backlog occurs due to packet loss and retransmission, and/or packet accumulated due to the application layer requirement. It is, thus, desirable to minimize the transient period as much as possible; specifically, a bound on the transient period is desirable from a quality-of-service perspective. Thus, a noteworthy question to address is the impact on network dimensioning due to such a requirement. Additionally, there are other quality-of-service (QoS) parameters that need to be addressed, for example, grade-of-service parameter for connection blocking before and after the failure, any packet (cell) loss rate, network link utilization threshold before and after a failure (which, in turn, has impact on average network delay). Although capacity design for virtual path-based networks has been addressed [3, 16], none of the previous work has addressed such a range of QoS parameters; especially, the backlog issue has never been addressed before. Our work here addresses such a set of QoS requirements for virtual-path based ATM networks which is dynamically reconfigurable due to traffic load change [20]; our work also takes into account the transmission network topology in determining failure states and for capacity design.

The rest of the paper is organized as follows. In section 2, we present a network dimensioning model that takes into account a set of QoS parameters including an acceptable threshold on traffic backlog transient period. In section 3, we present computational results to show the network capacity requirement to address the traffic backlog issue.

2. MODEL

We first start by illustrating the network architecture considered here which consists of a VP-based traffic network and a transmission network for broadband networks. The traffic network is connected by ATM switching nodes where various traffic such as voice, data and video services are provided; the transmission network is connected by ATM cross-connect systems (nodes) [10, 15, 18, 20]. Following the specification by ATM forum [6], we use the following terminology: ATM cross connects provides virtual path switching function while ATM switching nodes act as virtual path terminators. The connection between two ATM switching nodes can be provided using virtual path connections (VPC). Since it is possible to have multiple VPCs for the same pair of switching nodes [6, p. 94], we use the term l-group to indicate this logical grouping of VPCs between two switching nodes since the ATM forum specification does not define this entity. Two ATM cross-connect nodes can have a Virtual Path Link (VPL) defined between them. Again, it is possible to define multiple VPLs between two cross-connect nodes which is provided on a physical link at the transmission network. Note that l-group is the same as VPC if there is only one VPC defined between a pair of switching nodes; similarly, physical link (p-link) is the same as VPL if there is only one VPL defined between a pair of cross-connect nodes.

Following [20], we assume that various services offered are categorized into a set of service classes and a single virtual path connection (VPC) is set up between origin and destination ATM switching nodes for each class separately which is reconfigurable depending on the traffic change during the day; Thus, an l-group between a pair of switching nodes contains as many VPCs as there are service classes, i.e. one VPC defined for each service class.

We consider the following set of QoS parameters: (a) for each service class s, grade-of-service (GoS) parameters through connection level blocking probability $\hat{b}_s$ for normal operating condition, and b_s^σ in the case of in failure state σ. (b) for each service class, a packet(cell) loss rate $\hat{p}_s$ for connections that are already set up, (c) link utilization threshold $\hat{\rho}$ for normal operating conditions and another utilization threshold, ρ^σ, for under a failure state [these thresholds, in turn, reflect on the average network delay for cells since increase in network utilization also increases average network delay; thus, specifying a different parameter for the failure state allows us to consider the possibility that it may be acceptable to have higher average delay under a failure state than under a normal state] and finally (d), the threshold time for acceptable transient recovery period $\hat{t}$ sec for clearing backlog of cells after a failure. [These and all other notations introduced later are all summarized in Appendix-A for clarity.]

We assume that each service class is homogeneous, and connection (call) arrival to be Poissonian. Further, we assume that cells generated by the source for each connection for a service class s has on-off behavior characterized by traffic descriptors $T_s = \{u_s, m_s, R_s\}$, where u_s is the source utilization, m_s is the average burst period, and R_s is the peak rate while the actual values of the parameters are different for different service classes.

It is well-known that the offered load in a network varies with the time of the day and we assume that the load is clustered into a set of load hours $\mathcal{H}$. A traffic pair k connecting two ATM switching nodes for service class s in load hour h is denoted by the tuple $\{k, s, h\}$. Let the traffic offered load in regard to connection arrival for $\{k, s, h\}$ be a_k^{sh} erl. To meet the GoS requirement for this tuple under normal network operating conditions, we need to provide at most n_k^{sh} connections where

$$n_k^{sh} = \lceil E^{-1}(a_k^{sh}, \hat{b}_s) \rceil = \min_n \{n \mid E(a_k^{sh}, n) \leq \hat{b}_s\}. \tag{1}$$

These connections are provided on a VPC between the end points for the tuple $\{k, s, h\}$. [Here, $E(.,.)$ is the Erlang-B loss formula]. Since the source for each connection for the tuple $\{k, s, h\}$ generates on-off traffic, the bandwidth requirement for the VPC required to carry n_k^{sh} connections can be obtained by using a procedure described in [20] which is based on the inverse of the fluid-flow approximation due to Anick et al [4]; this is denoted here by $InvFFA(n_k^{sh}, u_s, m_s, R_s, r, \hat{p}_s)$ (here, r is the buffer size at switching nodes, see [4, 20]; the reader is directed to [20] for details). For simplicity of notation, we can combine these two operations and write as EFFA, i.e.,

$$EFFA(a_k^{sh}, \hat{b}_s, T_s) = InvFFA(\lceil E^{-1}(a_k^{sh}, \hat{b}_s) \rceil, u_s, m_s, R_s, r, \hat{p}_s). \tag{2}$$

For brevity, this quantity is also denoted by w_k^{sh} for the tuple $\{k, s, h\}$. Under normal operating conditions, to meet the QoS requirement and the demand generated, we need to provide VPC routing for each service class which can change depending on offered traffic load hour using the following multi-commodity flow model where the total capacity cost is minimized (see [20]):

$$\min_{\{x,y\}} \quad \sum_{\ell \in \mathcal{L}} c_\ell y_\ell \tag{3a}$$

subject to

$$\sum_{j \in \mathcal{P}_k^{sh}} x_{kj}^{sh} = 1, \quad s \in \mathcal{S}, \quad k \in \mathcal{K}, \quad h \in \mathcal{H} \tag{3b}$$

$$\sum_{k \in \mathcal{K}} \sum_{s \in \mathcal{S}} w_k^{sh} \sum_{j \in \mathcal{P}_k^{sh}} \delta_{kj}^{s\ell h} x_{kj}^{sh} \leq \hat{\rho} \alpha y_\ell, \quad \ell \in \mathcal{L}, \quad h \in \mathcal{H} \tag{3c}$$

$$x_{kj}^{sh} = 0 \text{ or } 1, \quad j \in \mathcal{P}_k^{sh},\ s \in \mathcal{S},\ k \in \mathcal{K},\ h \in \mathcal{H} \tag{3d}$$

$$y_\ell \geq 0 \text{ and integer}, \quad \ell \in \mathcal{L} \tag{3e}$$

In this model (3), the objective function (3a) represents the total capacity cost on p-links (including cost for end-ports). (3b) and (3d) are the decisions of choosing a virtual path connection for a service class for a node pair at different times during the day; here, one out of several possible VPC routes is chosen. The left hand quantity in (3c) is the total link capacity required at a particular load hour for the VPCs that are set up using that physical link by different source-destination node pairs and services; thus, constraints (3c) say that the link flow in each load period is going to force the determination of capacity on p-links (and hence, on end termination ports)to cover for any time during the day meeting the criteria that (a) the link utilization does not exceed the threshold value $\hat{\rho}$ (where $0 < \hat{\rho} \leq 1$), and (b) the capacity of the links takes modular value with modularization parameter α. (Parameter $\hat{\rho}$ was not in [20] and is added here to bound the average network delay as discussed earlier). We will denote the solution to model (3) by $\{\bar{y}_\ell \mid \ell \in \mathcal{L}\}$.

Now consider the scenario of a failure which corresponds to losing all the capacity on a p-link — however, only one p-link fails at a time; we will denote a failure state by the notation σ. The network management system takes a certain amount of time to detect the failure and then needs to take any necessary action to reconnect by VPC rerouting; we denote this time to detection and action by τ sec. In our case, the VPCs that were using this p-link are all affected, and since it takes τ sec to take any action, affected connections on these affected VPCs in the mean time starts backlogging packets (cells) – this backlog is accumulated on the access link that connects to the originating switching nodes [24]. We denote the backlog for the affected pairs for the tuple $\{k, s, h\}$ by $Q_k^{sh\sigma}(\tau)$. Note that since a single VPC is set up for each tuple $\{k, s, h\}$, the total backlog for an affected VPC is then the ensemble of the backlog from all the affected connections on that VPC for that affected pair. The question is how much is the backlog for on-off traffic sources? Through initial preliminary simulation, we observe that for an ensemble of connections the backlog is approximated by the product of the time length and the average rate of all connections on the VPC as given below:

$$Q_k^{sh\sigma}(\tau) = \tau u_s R_s n_k^{sh} \xi_k^{sh\sigma} \tag{4}$$

where $\xi_k^{sh\sigma}$ is the indicator function, which is set to one if pair k for service class s is affected in the load hour h for the failure σ, 0 otherwise. Now this backlog is the "additional" amount that needs to be carried over and above the regular traffic as soon as the affected VPCs are reconnected around the failure. It is, then, desirable that this backlog be cleared off within a certain amount of time; this is the threshold time t sec as one of the QoS parameters which we have discussed earlier.

Finally, two other factors may/can also play a role under failure due to economic reason. First, the GoS to be provided to the affected pairs may be different/higher than the GoS under normal condition $\hat{b}_s$ which is denoted by b_s^σ; second, it may be acceptable to have higher link utilization threshold than under normal circumstances to reflect that some additional delay is acceptable under a failure — this is be denoted by ρ^σ.

The first factor along with the backlog to be cleared in a given time length t leads to the following demand requirements in failure state σ:

$$w_k^{sh\sigma} = \begin{cases} EFFA(a_k^{sh}, b_s^\sigma, T_s) + Q_k^{sh\sigma}(\tau)/t, & \text{if } \xi_k^{sh\sigma} = 1; \\ EFFA(a_k^{sh}, \hat{b}_s, T_s), & \text{if } \xi_k^{sh\sigma} = 0. \end{cases} \tag{5}$$

Given this estimate on bandwidth requirement for each failure state σ, the capacity required in the network at each failure state can be obtained using the following multi-commodity flow model:

$$\min_{\{x,z\}} \quad \sum_{\ell \in \mathcal{L}^\sigma} c_\ell z_\ell^\sigma \tag{6a}$$

subject to

$$\sum_{j \in \mathcal{P}_k^{sh\sigma}} x_{kj}^{sh} = 1, \quad s \in \mathcal{S}, \quad k \in \mathcal{K}, \quad h \in \mathcal{H} \tag{6b}$$

$$\sum_{k \in \mathcal{K}} \sum_{s \in \mathcal{S}} w_k^{sh\sigma} \sum_{j \in \mathcal{P}_k^{sh\sigma}} \delta_{kj}^{s\ell h\sigma} x_{kj}^{sh} \le \rho^\sigma \alpha z_\ell^\sigma, \quad \ell \in \mathcal{L}^\sigma, \quad h \in \mathcal{H} \tag{6c}$$

$$x_{kj}^{sh} = 0 \text{ or } 1, \quad j \in \mathcal{P}_k^{sh\sigma},\ s \in \mathcal{S},\ k \in \mathcal{K},\ h \in \mathcal{H} \tag{6d}$$

$$z_\ell^\sigma \ge 0 \text{ and integer}, \quad \ell \in \mathcal{L}^\sigma \tag{6e}$$

The interpretation of this model is the same as (3) except that this is now used for each failure state σ taking into consideration the requirements under the failure conditions such as the restricted set of links and candidate paths as well as the demand requirements. Model (6) needs to be solved for each failure state and we denote the set of all failure states (corresponding to all p-links) by $\mathcal{E}$. We will denote the solution for model (6) by $\{\bar{z}_\ell^\sigma \mid \ell \in \mathcal{L}^\sigma\}$. Once the normal as well as all the failure states are covered, then the capacity requirement on each p-link can be obtained as follows:

$$\bar{y}_\ell \leftarrow \max\left\{\bar{y}_\ell, \max_{\sigma \in \mathcal{E}} \left\{\bar{z}_\ell^\sigma\right\}\right\}, \quad \ell \in \mathcal{L} \tag{7}$$

and this y is used in computing the total network capacity cost through (3a).

Another approach is possible for network capacity determination. To distinguish, we will refer to the above method as 'max-heuristic'. In the second approach, we solve model (3) first, and then for each failure state σ, we solve model (6′) which differs from model (6) in that a slightly different constraint in place of (6c) is used as shown below:

$$\sum_{k \in \mathcal{K}} \sum_{s \in \mathcal{S}} w_k^{sh\sigma} \sum_{j \in \mathcal{P}_k^{sh\sigma}} \delta_{kj}^{s\ell h} x_{kj}^{sh} \le \rho^\sigma \alpha (\bar{y}_\ell + z_\ell^\sigma), \quad \ell \in \mathcal{L}^\sigma, \quad h \in \mathcal{H} \tag{6c′}$$

This constraint then means that in model (6′) we need to determine additional capacity for the failure state given that there is already $\bar{y}_\ell$ capacity in the network. Thus, in the second approach, expression (7) is replaced by

$$\bar{y}_\ell \leftarrow \bar{y}_\ell + \bar{z}_\ell^\sigma, \quad \ell \in \mathcal{L} \tag{8}$$

and this relation is updated after solving model (6′) for each failure state, and thus, the updated $\bar{y}_\ell$ is assumed in model (6′) when it is solved for the next state and the process continues for each failure state at a time. Thus, the capacity in the network is $\bar{y}_\ell$ after this incremental update is done for all failure states. We will refer to this method as the 'add-heuristic'.

We like to remark that given the above development, the entire problem that considers both the non-failure state as well as all failure states can be cast in a single model by appropriately (re)defining various notations. This is briefly discussed in Appendix-B.

3. COMPUTATIONAL RESULTS

Before we present our results, we first discuss the network data and the network scenarios. All configurations include switching nodes that can originate and terminate traffic, as well as cross connect nodes that relay traffic. We have considered two different network configurations for computational work. The 10 switching node network includes 18 cross-connect nodes and 27 transmission links and will be referred to as Net-1. The 15 switching node network includes 23 cross-connect nodes and 33 transmission links (Net-2). Network topologies for these two networks are shown in Figures 1 and 2. For both these network examples, asymmetric offered traffic, specified in Erlangs, was given between various switch node pairs for 3 separate load hours and for 3 different service classes, where each service class has Poissonian connection arrival and the source for each connection has on-off traffic descriptors (see [20] for a description on the traffic offered load data which has been extracted from actual networks). A set of candidate paths for each of the node pair was obtained using a k-shortest path algorithm and was provided as an input in solving optimization models (3) and (6) [or (6′)]. Combinatorial optimization models (3) and (6) [or (6′)] were then solved using a duality-based subgradient optimization procedure which is described in [20] where we have set the modularization parameter, α, to T1 rate (1.5 Mbps). The unit link cost c_ℓ consists of termination cost and distance-based cost (see Appendix-A). For clarity in the rest of the discussion, we will refer to our approach described in the previous section as the backlog-incorporated survivable network (BISNet) design option; similarly, the network which is designed for survivability for all the QoS parameters same as in BISNet design *except* that backlog is not taken into account (this can be obtained using our framework by setting $\xi_k^{sh\sigma}$ to zero in *all* cases) will be referred to as noBISNet design (marked with 'no' in figures); note that noBISNet design-based results are invariant of the value of t.

The normal operating condition GOS, $\hat{b}_s$, was specified as 1% connection blocking for all service classes, and the normal link utilization $\hat{\rho}$ was set to 0.7. The GOS under failure conditions, b_s^σ, was tested for two different values of 5% and 10% blocking to reflect that under a failure a higher level of connection blocking may be acceptable; similarly, the network link utilization, ρ^σ, under failure conditions was set to two different values, 0.7 and 0.8 — while the first value is the same as under the normal value, the second value is to say that a higher level of link utilization is acceptable under a failure mode (which may result in higher average network cell delay).

For all our computational work, we have set the detection and action time, τ, to 2 sec. This value is reasonable if the notion of the backup VP with zero bandwidth is used [16]. (It should be noted that if the value of τ is higher, the backlog accumulated will be more). For transient threshold time, t, we have considered the values of 2, 5, 10, 60, and 120 sec. First we discuss results for network Net-1 using the 'max-heurstic' for BISNet design and noBISNet design. (We found that the there is virtually no difference between the design obtained by max-heuristic and add-heuristic – hence results only from max-heuristic is reflected in the figures). In the first set of experiments, we consider that all traffic classes accumulate backlog for the affected VPCs. In Figure 3, we plot network cost for different values of t. As expected, a network designed for 5% connection blocking under failure and link utilization of 0.7 has higher cost than if the connection blocking is increased to 10% and/or the link utilization is increased to 0.8. One of the most important observation, however, is on the network cost as the value of transient time threshold, t, increases. As it can been for values of t set to 60 or 120 sec, there is virtually no cost difference between BISNet design and noBISNet design. This suggests that in most failure cases, if the noBISNet design is done, the transient behavior is not expected to last beyond 60 to 120 sec range. If this scenario is acceptable to network providers (and their customers), it is not necessary to take backlog into account in the survivable network design model. On the other hand, for threshold value of t set to 2 sec, we see that BISNet design cost is 51% to 56% higher than noBISNet design depending on $(b_s^\sigma, \rho^\sigma)$-combination. This additional cost may be too high given the fact that noBISNet design cost is already 58% to 89% more than the network design cost needed to provide for only normal operating condition, ie. no failure situation is considered [this means the cost for 'no failure' design is obtained by solving only model-(3)]. On the other if t is set to 10 sec, then BISNet design cost is only about 10% more than noBISNet design cost. This suggests that if the network provider wants to limit transient time to about 10 sec, this additional network cost would be required. Otherwise, the network provider has to be content with the transient time that may last 60 to 120 sec.

We also consider the scenario where only one traffic class may have backlog while the other classes may not; this may be the scenario if a traffic class has data-oriented loss-sensitive traffic in which case backlog is accumulated, while for another service class that has real-time loss-insensitive traffic almost all cells may be dropped. The results, again comparing BISNet design and noBISNet design, are shown in Figure 4 for Net-1 assuming that only the third service class has backlog. As expected, the cost is lower when a service class has backlog compared to all service classes having backlog (comparing Figure 3 and 4). When only one service class has backlog, at the threshold value of t set to 2 sec, BISNet design cost is between 20% to 22% higher than noBISNet design cost – see Figure 4. We found the results for Net-2 corresponding to Figures 3 and 4 to be quite similar and are shown in Figures 5 and 6 for all service case, and for service class 3, respectively.

4. DISCUSSION

Following the observation in [24] on the congestion/transient affect due to backlog after a failure, we embarked upon a way to address the backlog issue as a part of network design. Towards this end, we considered a QoS parameter to address transient time length threshold along with other QoS parameters such as connection blocking and link utilization, and provide a network dimensioning framework for on-offsource traffic. We observe that if the transient threshold is required to be small, such as 2 sec, the network cost can be over 50% higher than a survivable design where backlog is not taken into consideration. Looking from the other side, this means that a network designed for survivability, but without taking backlog into consideration may have a noticeably higher transient time period compared to network with a backlog-incorporated survivable network design.

In this study, we have considered each traffic class to be homogeneous and source traffic descriptors to be of on-off type. Certainly, more work is needed to understand the effect due to backlog in traffic classes that may have heterogeneous traffic and/or the source traffic descriptor is other than an on-off type. Particularly, it would be interesting to see the impact on dimensioning with TCP traffic over ATM and the backlog generated under a failure. Nevertheless, our work here has shed some light on the impact and network design cost due to the accumulation of backlog after a failure.

APPENDIX-A

Summary of notations:

$\mathcal{H}, h$	Set of load hours and index used
$\mathcal{K}, k$	Set of node (demand) pairs in the network and index used
$\mathcal{S}, s$	Set of Service/Traffic classes and index used
$\mathcal{L}$	Set of p-links in the network
σ	A failure state
$\mathcal{E}$	Set of all failure states

$\tilde{b}_s$	A QoS parameter: GoS connection blocking (in normal operating conditions)
b_s^σ	A QoS parameter: GoS connection blocking parameter in failure state σ
$\tilde{p}_s$	A QoS parameter: cell loss probability
$\tilde{\rho}$	A QoS parameter: link utilization threshold in normal state
ρ^σ	A QoS parameter: link utilization threshold in a failure state
t	A QoS parameter: transient backlog recovery period threshold
T_s	Traffic descriptor of sources for service class s
u_s, m_s, R_S	For on-off source for class s, utilization, burst period and peak rate, respectively
a_k^{sh}	Offered load in erlangs for the tuple $\{k, s, h\}$
n_k^{sh}	Number of connections corresponding to load a_k^{sh}
w_k^{sh}	Estimated bandwidth requirement to provide n_k^{sh} connections, each with on-off source
$\mathcal{P}_k^{sh}$	Set of possible candidate VPC routes for type $s \in \mathcal{S}$, $k \in \mathcal{K}$ used in all $h \in \mathcal{H}$
$\mathcal{P}_k^{sh\sigma}$	The set of valid candidate VPC routes for type $s \in \mathcal{S}$, demand pair $k \in \mathcal{K}$ used for all $h \in \mathcal{H}$ in failure state σ
x_{kj}^{sh}	Virtual path connection routing variables $-$ 1 if type $s \in \mathcal{S}_k$, $k \in \mathcal{K}$ uses possible route $j \in \mathcal{P}_k^{sh}$ in $h \in \mathcal{H}$; 0 otherwise
$\delta_{kj}^{s\ell h}$	Link-route incidence matrix; 1 if possible route $j \in \mathcal{P}_k^{sh}$ for $s \in \mathcal{S}$ and for pair $k \in \mathcal{K}$ in $h \in \mathcal{H}$ uses link $\ell \in \mathcal{L}$; 0 otherwise
$\delta_{kj}^{s\ell h\sigma}$	corresponds to $\delta_{kj}^{s\ell h}$ for failure state σ
y_ℓ	Sizing (topology) variables; the number of units of high capacity on p-link $\ell \in \mathcal{L}$
z_ℓ^σ	link capacity variable for ℓ in state σ
α	Modular capacity of a high capacity unit
c_ℓ	Cost of a high capacity unit on p-link $\ell \in \mathcal{L}$; this is defined to be 2 * termination_cost + 0.1 * distance, and we assume termination_cost to be 100
τ	Failure recovery detection and action time
$Q_k^{sh\sigma}(\tau)$	Backlog generated for the tuple $\{k, s, h\}$ in time τ sec in failure state σ
$\xi_k^{sh\sigma}$	indictor function set to 1 if the tuple $\{k, s, h\}$ in failure state σ is affected; 0 otherwise state σ
$\mathcal{L}^\sigma$	The set of operational links in failure state σ (i.e., all links except the failed link)

APPENDIX-B

To consider normal operating state as well as all the failure states in a single model, we define state $\sigma = 0$ to be the normal state and now consider the set $\mathcal{E}$ to include this state also. In this scenario, $w_k^{sh\sigma}$ with $\sigma = 0$ is given by (2). Similarly, $\rho^{\sigma(=0)} = \tilde{\rho}$, and $b_s^{\sigma(=0)} = \tilde{b}_s$. The constraints (6b)-(6e) will appear in the overall model with the modification that $\sigma \in \mathcal{E}$ is also included in each constraint set explicitly; further, we need the additional constraints

$$z_\ell^\sigma \leq y_\ell, \quad \sigma \in \mathcal{E}$$

with $y_\ell \geq 0$ and integer ($\ell \in \mathcal{L}$), as well as the following objective function in the overall model

$$\min_{\{x,z,y\}} \quad \sum_{\ell \in \mathcal{L}} c_\ell y_\ell .$$

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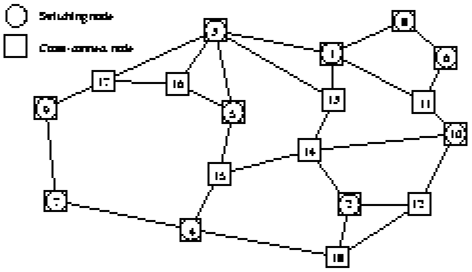

Figure 1: Topology of Net-1 (10 switching nodes, 18 ATM Cross-connect nodes)

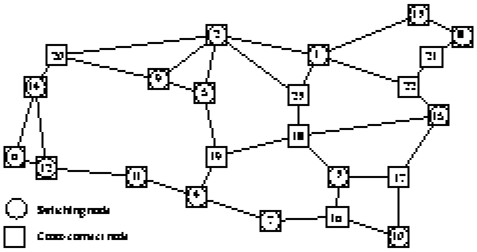

Figure 2: Topology of Net-2 (15 switching nodes, 23 ATM Cross-connect nodes)

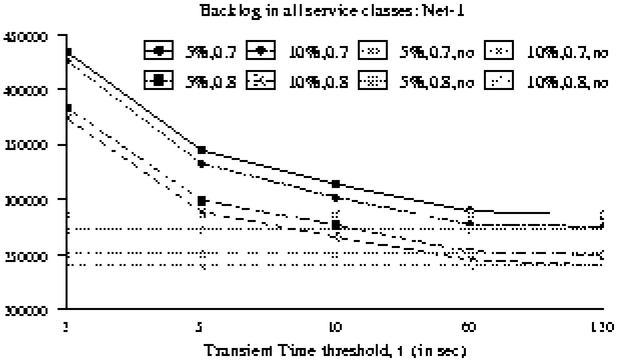

Figure 3: Comparison of BISNet and no-BISNet design costs for Net-1 for various values of $(b_s^\sigma, \rho^\sigma)$: all service backlog case

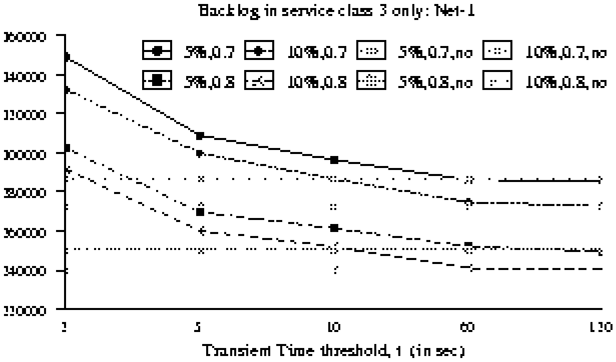

Figure 4: Comparison of BISNet and no-BISNet design costs for Net-1 for various values of $(b_s^\sigma, \rho^\sigma)$: only class 3 has backlog

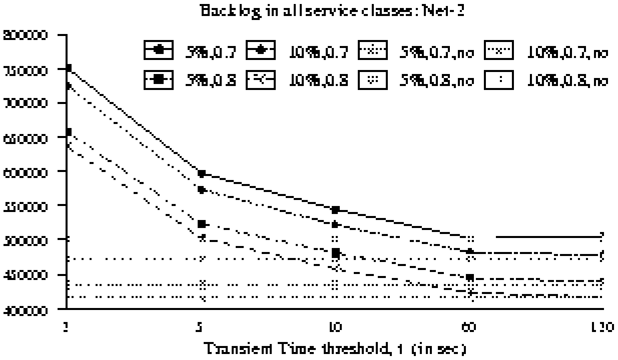

Figure 5: Comparison of BISNet and no-BISNet design costs for Net-2 for various values of $(b_s^\sigma, \rho^\sigma)$: all service backlog case

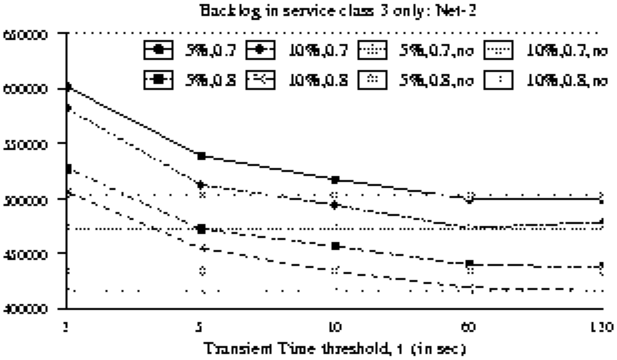

Figure 6: Comparison of BISNet and no-BISNet design costs for Net-2 for various values of $(b_s^\sigma, \rho^\sigma)$: only class 3 has backlog