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SERIES E: OVERALL NETWORK OPERATION, TELEPHONE SERVICE, SERVICE OPERATION AND HUMAN FACTORS

International routing plan

QoS routing and related traffic engineering methods – Capacity management methods

ITU-T Recommendation E.360.6

ITU-T E-SERIES RECOMMENDATIONS

OVERALL NETWORK OPERATION, TELEPHONE SERVICE, SERVICE OPERATION AND HUMAN FACTORS

For further details, please refer to the list of ITU-T Recommendations.

ITU-T Recommendation E.360.6

QoS routing and related traffic engineering methods – Capacity management methods

Summary

The E.360.x series of Recommendations describes, analyses, and recommends methods which control a network's response to traffic demands and other stimuli, such as link failures or node failures. The functions discussed and recommendations made related to traffic engineering (TE) are consistent with the definition given in the Framework document of the Traffic Engineering Working Group (TEWG) within the Internet Engineering Task Force (IETF):

Internet Traffic Engineering is concerned with the performance optimization of operational networks. It encompasses the measurement, modelling, characterization, and control of Internet traffic, and the application of techniques to achieve specific performance objectives, including the reliable and expeditious movement of traffic through the network, the efficient utilization of network resources, and the planning of network capacity.

The methods addressed in the E.360.x series include call and connection routing, QoS resource management, routing table management, dynamic transport routing, capacity management, and operational requirements. Some of the methods proposed herein are also addressed in, or are closely related to those proposed in ITU-T Recs E.170 to E.179 and E.350 to E.353 for routing, E.410 to E.419 for network management and E.490 to E.780 for other traffic engineering issues.

The recommended methods are meant to apply to IP-based, ATM-based, and TDM-based networks, as well as the interworking between these network technologies. Essentially, all of the methods recommended are already widely applied in operational networks worldwide, particularly in PSTN networks employing TDM-based technology. However, these methods are shown to be extensible to packet-based technologies, that is, to IP-based and ATM-based technologies, and it is important that networks which evolve to employ these packet technologies have a sound foundation of methods to apply. Hence, it is the intent that the methods recommended in this series of Recommendations be used as a basis for requirements for specific methods, and, as needed, for protocol development in IP-based, ATM-based, and TDM-based networks to implement the methods.

The methods encompassed in this Recommendation include traffic management through control of routing functions, which include QoS resource management. Results of analysis models are presented which illustrate the tradeoffs between various approaches. Based on the results of these studies, as well as established practice and experience, methods are recommended for consideration in network evolution to IP-based, ATM-based, and/or TDM-based technologies.

Source

ITU-T Recommendation E.360.6 was prepared by ITU-T Study Group 2 (2001-2004) and approved under the WTSA Resolution 1 procedure on 16 May 2002.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications. The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

CONTENTS

Introduction

In this Recommendation we discuss capacity management principles, as follows:

Link Capacity Design Models. These models find the optimum tradeoff between traffic carried on a shortest network path (perhaps a direct link) versus traffic carried on alternate network paths.

Shortest Path Selection Models. These models enable the determination of shortest paths in order to provide a more efficient and flexible routing plan.

Multihour Network Design Models. Three models are described including:

i) discrete event flow optimization (DEFO) models;

ii) traffic load flow optimization (TLFO) models; and

iii) virtual trunking flow optimization (VTFO) models.

Day-to-day Load Variation Design Models. These models describe techniques for handling day-to-day variations in capacity design.

Forecast Uncertainty/Reserve Capacity Design Models. These models describe the means for accounting for errors in projecting design traffic loads in the capacity design of the network.

See ITU-T Recs E.520 to E.529 and E.731 on dimensioning of TDM networks; E.735 and E.737 on dimensioning of ATM networks; E.733 on dimensioning of SS7 signalling networks and E.734 on dimensioning of IN network resources.

ITU-T Recommendation E.360.6

QoS routing and related traffic engineering methods – Capacity management methods

1 Scope

The E.360.x series of Recommendations describes, analyses, and recommends methods which control a network's response to traffic demands and other stimuli, such as link failures or node failures. The functions discussed and recommendations made related to traffic engineering (TE) are consistent with the definitions given in the Framework document of the Traffic Engineering Working Group (TEWG) within the Internet Engineering Task Force (IETF):

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Hence the methods encompassed in this series of Recommendations include:

- traffic management through control of routing functions, which include call routing (number/name translation to routing address), connection routing, QoS resource management, routing table management, and dynamic transport routing.
- capacity management through control of network design, including routing design.
- operational requirements for traffic management and capacity management, including forecasting, performance monitoring, and short-term network adjustment.

Results of analysis models are presented which illustrate the tradeoffs between various approaches. Based on the results of these studies, as well as established practice and experience, TE methods are recommended for consideration in network evolution to IP-based, ATM-based, and/or TDM-based technologies.

2 References

See clause 2 of ITU-T Rec. E.360.1.

3 Definitions

See clause 3 of ITU-T Rec. E.360.1.

4 Abbreviations

See clause 4 of ITU-T Rec. E.360.1.

5 Link capacity design models

As illustrated in Figure 1, link capacity design requires a tradeoff of the traffic load carried on the link and traffic that must route on alternate paths.

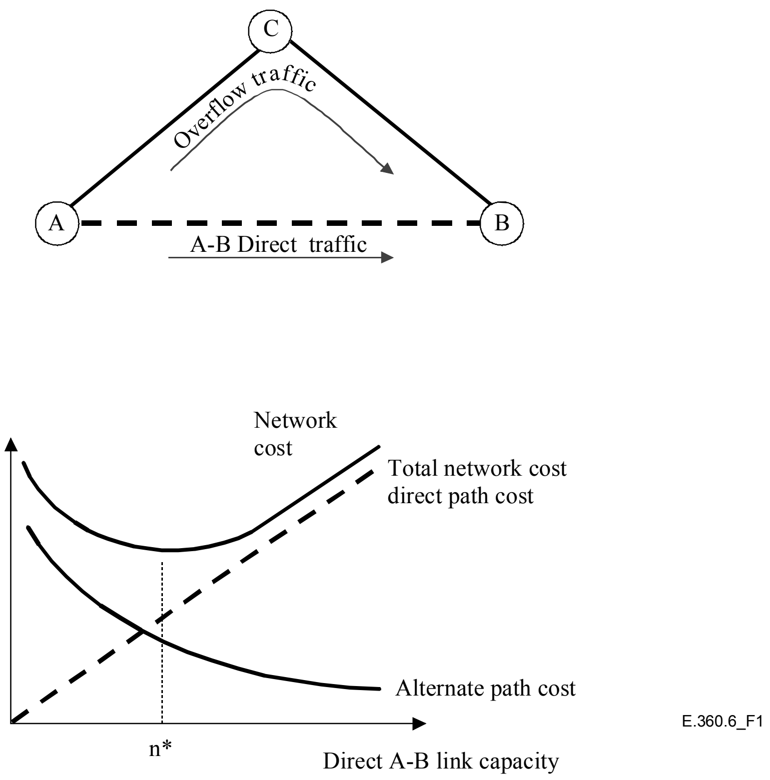

Figure 1/E.360.6 – Tradeoff between direct link capacity and alternate path capacity

High link occupancy implies more efficient capacity utilization, however high occupancy leads to link congestion and the resulting need for some traffic not to be routed on the direct link but on alternate paths. Alternate paths may entail longer, less efficient paths. A good balance can be struck between link capacity design and alternate path utilization. For example, consider Figure 1 which illustrates a network where traffic is offered on link A-B connecting node A and node B.

Some of the traffic can be carried on link A-B, however, when the capacity of link A-B is exceeded, some of the traffic must be carried on alternate paths or be lost. The objective is to determine the direct A-B link capacity and alternate routing path flow such that all the traffic is carried at minimum cost. A simple optimization procedure is used to determine the best proportion of traffic to carry on the direct A-B link and how much traffic to alternate route to other paths in the network. As the direct link capacity is increased, the direct link cost increases while the alternate path cost decreases as more direct capacity is added, because the overflow load decreases and therefore the cost of carrying the overflow load decreases. An optimum, or minimum, cost condition is achieved when the direct A-B link capacity is increased to the point where the cost per incremental unit of bandwidth capacity to carry traffic on the direct link is just equal to the cost per unit of bandwidth capacity to carry traffic on the alternate network. This is a design principle used in many design models, be they sparse or meshed networks, fixed hierarchical routing networks or dynamic nonhierarchical routing networks.

6 Shortest path selection models

Some routing methods such as hierarchical routing, limits path choices and provides inefficient design. This limits flexibility and reduces efficiency. If we choose paths based on cost, and relax constraints such as a hierarchical network structure, a more efficient network results. Additional benefits can be provided in network design by allowing a more flexible routing plan that is not restricted to hierarchical routes but allows the selection of the shortest nonhierarchical paths. Dijkstra's method [Dij59], for example, is often used for shortest path selection. Figure 2 illustrates the selection of shortest paths between two network nodes, SNDG and BRHM.

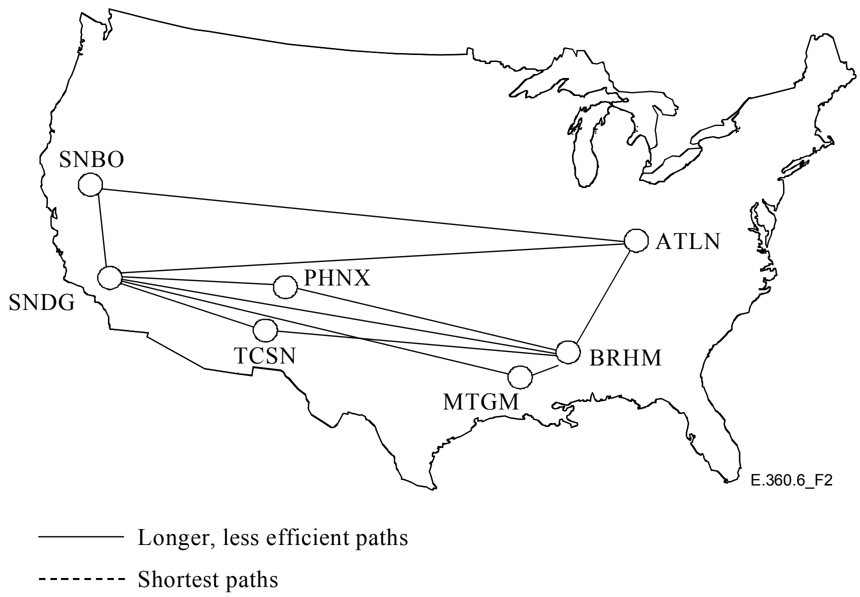

Figure 2/E.360.6 – Shortest path routing

Longer paths, such as SNDG-SNBO-ATLN-BRHM, which might arise through hierarchical path selection, are less efficient than shortest path selection, such as SNDG-PHNX-BRHM, SNDG-TCSN-BRHM, or SNDG-MTGM-BRHM. There are really two components to the shortest path selection savings. One component results from eliminating link splintering. Splintering occurs, for example, when more than one node is required to satisfy a traffic load within a given area, such as a metropolitan area. Multiple links to a distant node could result, thus dividing the load among links which are less efficient than a single large link. A second component of shortest path selection savings arises from path cost. Routing on the least costly, most direct, or shortest paths is often more efficient than routing over longer hierarchical paths.

7 Multihour network design models

Dynamic routing design improves network utilization relative to fixed routing design because fixed routing cannot respond as efficiently to traffic load variations that arise from business/residential phone use, time zones, seasonal variations, and other causes. Dynamic routing design increases network utilization efficiency by varying routing tables in accordance with traffic patterns and designing capacity accordingly. A simple illustration of this principle is shown in Figure 3, where there is afternoon peak load demand between nodes A and B, but a morning peak load demand between nodes A and C and nodes C and B.

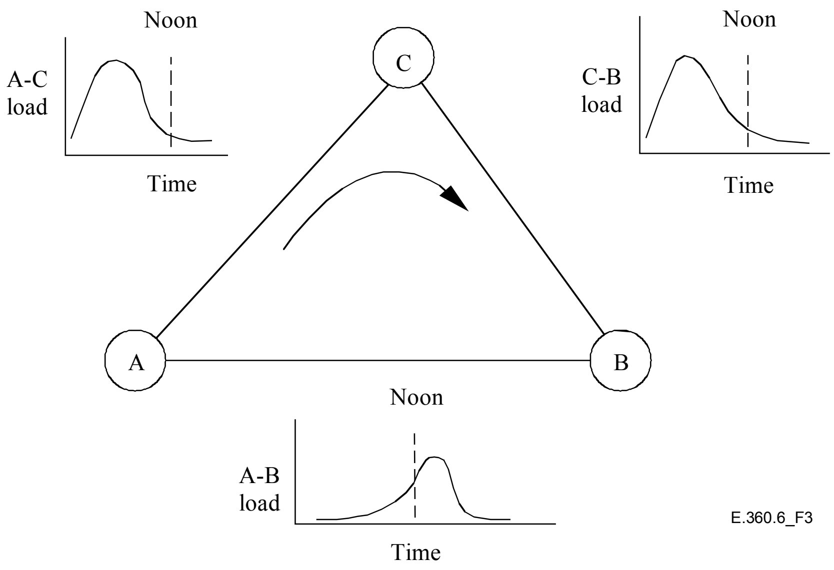

Figure 3/E.360.6 – Multihour network design

Here a simple dynamic route design is to provide capacity only between nodes A and C and nodes C and B but no capacity between nodes A and B. Then the A-C and C-B morning peak loads route directly over this capacity in the morning, and the A-B afternoon peak load uses this same capacity by routing this traffic on the A-C-B path in the afternoon. A fixed routing network design provides capacity for the peak period for each node pair and thus provides capacity between nodes A and B, as well as between nodes A and C and nodes C and B.

The effect of multihour network design is illustrated by a national intercity network design model illustrated in Figure 4. Here it is shown that about 20 percent of the network's first cost can be attributed to designing for time-varying loads.

As illustrated in Figure 4, the 17 hourly networks are obtained by using each hourly load, and ignoring the other hourly loads, to size a network that perfectly matches that hour's load. Each hourly network represents the hourly traffic load capacity cost referred to in Table 1/E.360.1. The 17 hourly networks show that three network busy periods are visible: where we see morning, afternoon, and evening busy periods, and the noon-hour drop in load and the early-evening drop as the business day ends and residential calling begins in the evening. The hourly network curve separates the capacity provided in the multihour network design into two components: Below the curve is the capacity needed in each hour to meet the load; above the curve is the capacity that is available but is not needed in that hour. This additional capacity exceeds 20 percent of the total network capacity through all hours of the day, which represents the multihour capacity cost referred to in Table 1/E.360.1. This gap represents the capacity of the network to meet noncoincident loads.

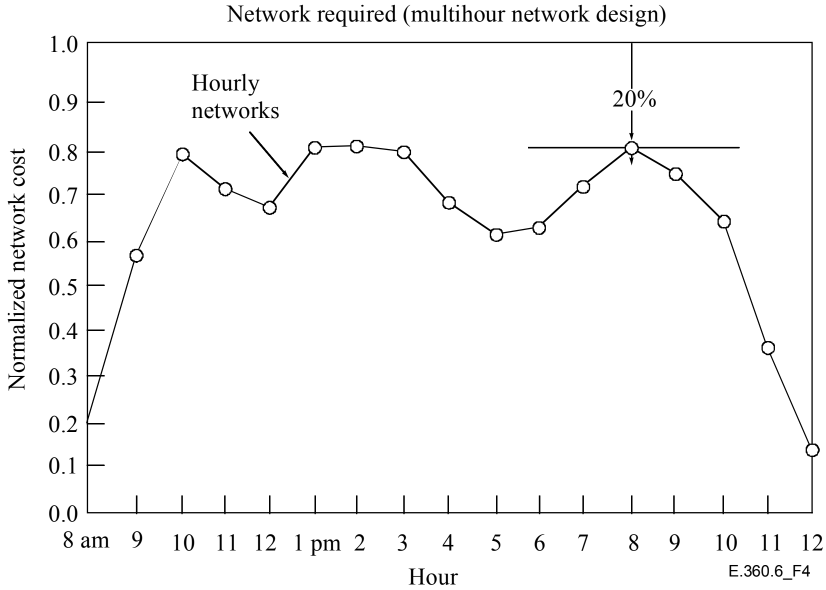

Figure 4/E.360.6 – Hourly versus multihour network design

We now discuss the three types of multihour network design models: discrete event flow optimization models, virtual trunking flow optimization models, and traffic flow optimization models, and illustrate how they are applied to various fixed and dynamic network designs. For each model, we discuss steps that include initialization, routing design, capacity design, and parameter update.

7.1 Discrete Event Flow Optimization (DEFO) models

Discrete event flow optimization (DEFO) models are used for fixed and dynamic traffic network design. These models optimize the routing of discrete event flows, as measured in units of individual connection requests, and the associated link capacities. Figure 5 illustrates steps of the DEFO model.

The event generator converts traffic demands to discrete connection-request events. The discrete event model provides routing logic according to the particular routing method and routes the connection-request events according to the routing table logic. DEFO models use simulation models for path selection and routing table management to route discrete-event demands on the link capacities, and the link capacities are then optimized to meet the required flow. We generate initial link capacity requirements based on the traffic load matrix input to the model. Based on design experience with the model, an initial node-termination capacity is estimated based on a maximum design occupancy in the node busy hour of 0.93, and the total network occupancy (total traffic demand/total link capacity) in the network busy hour is adjusted to fall within the range of 0.84 to 0.89. Network performance is evaluated as an output of the discrete event model, and any needed link capacity adjustments are determined. Capacity is allocated to individual links in accordance with the Kruithof allocation method [Kru37], which distributes link capacity in proportion to the overall demand between nodes.

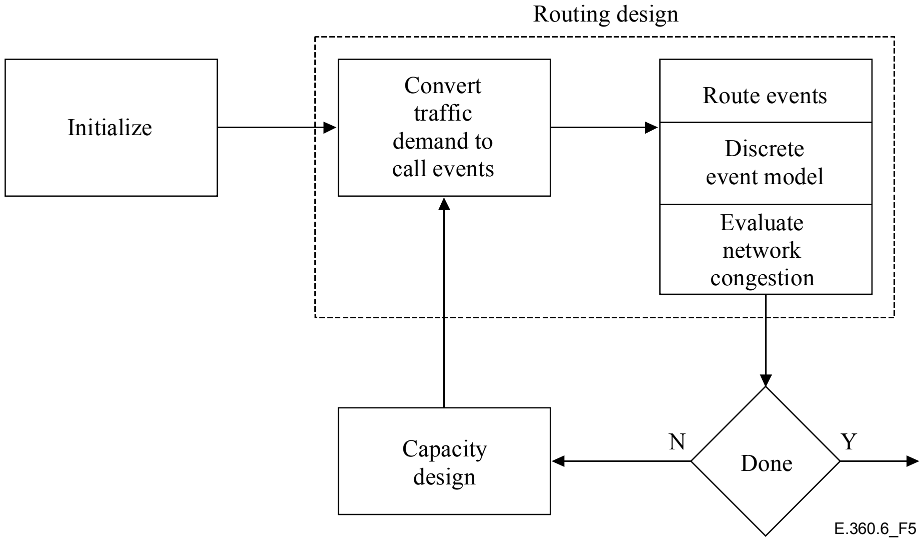

Figure 5/E.360.6 – Discrete Event Flow Optimization (DEFO) model

Kruithof's technique is used to estimate the node-to-node requirements p_{ij} from the originating node i to the terminating node j under the condition that the total node link capacity requirements may be established by adding the entries in the matrix P = $[p_{ij}]$. Assume that a matrix Q = $[q_{ij}]$, representing the node-to-node link capacity requirements for a previous iteration, is known. Also, the total link capacity requirements b_i at each node i and the total link capacity requirements d_j at each node j are estimated as follows:

$$b_i = \frac{a_i}{\gamma}$$

$$d_j = \frac{a_j}{\gamma}$$

where a_i is the total traffic at node i, a_j is the total traffic at node j, and γ is the average traffic-carrying capacity per trunk, or node design occupancy, as given previously. The terms p_{ij} can be obtained as follows:

$$f_i = \frac{b_i}{\sum_j q_{ij}}$$

$$f_j = \frac{d_j}{\sum_i q_{ij}}$$

$$E_{ij} = \frac{f_i + f_j}{2}$$

$$p_{ij} = q_{ij} \times E_{ij}$$

After the above equations are solved iteratively, the converged steady state values of p_{ij} are obtained.

The DEFO model can generate connection-request events according to a Poisson arrival distribution and exponential holding times, or with more general arrival streams and arbitrary holding time distributions, because such models can readily be implemented in the discrete routing table simulation model. Connection-request events are generated in accordance with the traffic load matrix input to the model. These events are routed on the selected path according to the routing table rules, as modelled by the routing table simulation, which determines the selected path for each call event and flows the event onto the network capacity.

The output from the routing design is the fraction of traffic lost and delayed in each time period. From this traffic performance, the capacity design determines the new link capacity requirements of each node and each link to meet the design performance level. From the estimate of lost and delayed traffic at each node in each time period, an occupancy calculation determines additional node link capacity requirements for an updated link capacity estimate. Such a link capacity determination is made, based on the amount of blocked traffic. The total blocked traffic Δa is estimated at each of the nodes, and an estimated link capacity increase ΔT for each node is calculated by the relationship

$$\Delta T = \frac{\Delta a}{\gamma}$$

where again γ is the average traffic-carrying capacity per trunk. Thus, the ΔT for each node is distributed to each link according to the Kruithof estimation method described above. The Kruithof allocation method [Kru37] distributes link capacity in proportion to the overall demand between nodes and in accordance with link cost, so that overall network cost is minimized. Sizing individual links in this way ensures an efficient level of utilization on each link in the network to optimally divide the load between the direct link and the overflow network. Once the links have been resized, the network is reevaluated to see if the performance objectives are met, and if not, another iteration of the model is performed.

We evaluate in the model the confidence interval of the engineered blocking/delay. For this analysis, we evaluate the binomial distribution for the 90th percentile confidence interval. Suppose that for a traffic load of A in which calls arrive over the designated time period of stationary traffic behavior, there are, on average, m blocked calls out of n attempts. This means that there is an average observed blocking/delay probability of:

$$p\ell = \frac{m}{n}$$

where, for example, $p\ell = .01$ for a 1 percent average blocking/delay probability. Now, we want to find the value of the 90th percentile blocking/delay probability p such that

$$E(n, m, p) = \sum_{r=m}^{n} C_n^r p^r q^{n-r} \geq 0.90$$

where

$$C_n^r = \frac{n!}{(n-r)!r!}$$

is the binomial coefficient, and

$$q = 1 - p$$

Then the value p represents the 90th percentile blocking/delay probability confidence interval. That is, there is a 90 percent chance that the observed blocking/delay will be less than or equal to the value p. Methods given in [Wei63] are used to numerically evaluate the above expressions.

As an example application of the above method to the DEFO model, suppose that network traffic is such that 1 million calls arrive in a single busy-hour period, and we wish to design the network to achieve 1 percent average blocking/delay or less. If the network is designed in the DEFO model to yield at most .00995 probability of blocking/delay, that is, at most 9950 calls are blocked out of 1 million calls in the DEFO model, then we can be more than 90 percent sure that the network has a maximum blocking/delay probability of .01. For a specific switch pair where 2000 calls arrive in a single busy-hour period, suppose we wish to design the switch pair to achieve 1 percent average blocking/delay probability or less. If the network capacity is designed in the DEFO model to yield at most .0075 probability of blocking/delay for the switch pair, that is, at most 15 calls are blocked out of 2000 calls in the DEFO model, then we can be more than 90 percent sure that the switch pair has a maximum blocking/delay probability of .01. These methods are used to ensure that the blocking/delay probability design objectives are met, taking into consideration the sampling errors of the discrete event model.

The greatest advantage of the DEFO model is its ability to capture very complex routing behavior through the equivalent of a simulation model provided in software in the routing design module. By this means, very complex routing networks have been designed by the model, which include all of the routing methods discussed in ITU-T Rec. E.360.2, TDR, SDR, and EDR methods, and the multiservice QoS resource allocation models discussed in ITU-T Rec. E.360.3. Complex traffic processes, such as self-similar traffic, can also be modelled with DEFO methods. A flow diagram of the DEFO model, in which DC-SDR logical blocks described in ITU-T Rec. E.360.2 are implemented, is illustrated in Figure 6. The DEFO model is general enough to include all TE models yet to be determined.

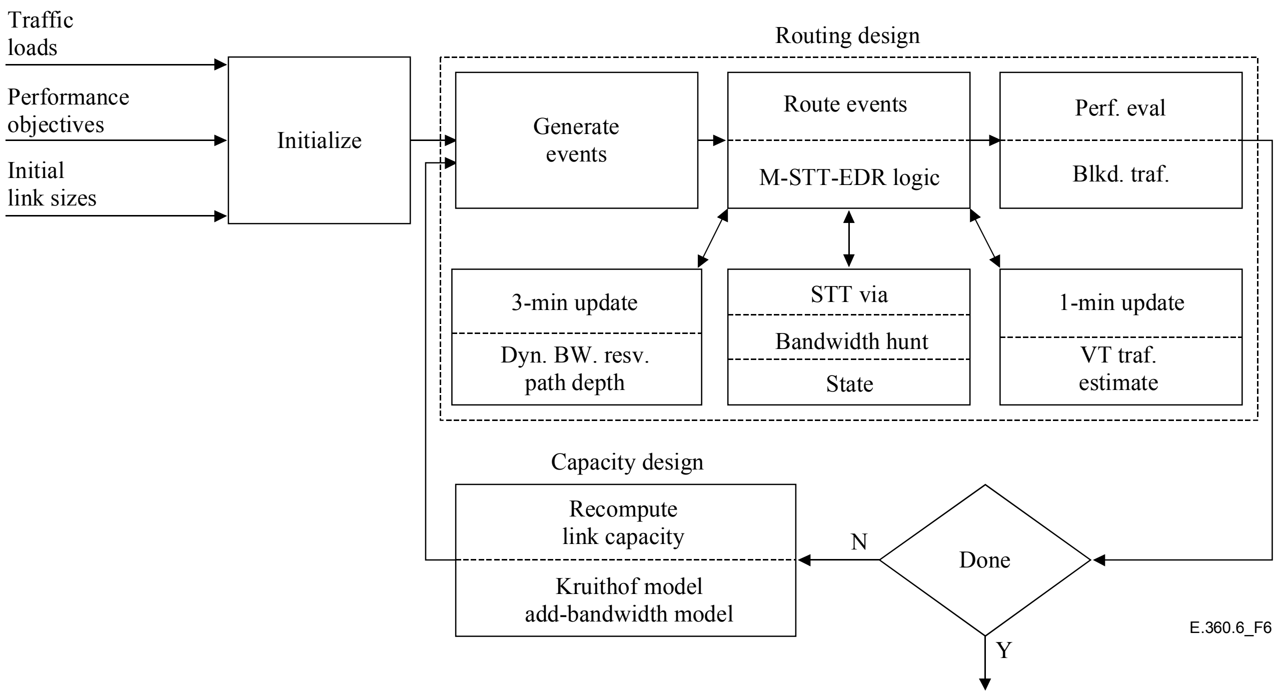

Figure 6/E.360.6 – Discrete event flow optimization model with multilink Success-to-the-Top Event Dependent Routing (M-STT-EDR)

7.2 Traffic Load Flow Optimization (TLFO) models

Traffic load flow optimization (TLFO) models are used for fixed and dynamic traffic network design. These models optimize the routing of traffic flows and the associated link capacities. Such models typically solve mathematical equations that describe the routing of traffic flows analytically and, for dynamic network design, often solve linear programming flow optimization models. Various types of traffic flow optimization models are distinguished as to how flow is assigned to links, paths, and routes. In fixed network design, traffic flow is assigned to direct links, and overflow from the direct links is routed to alternate paths through the network, as described above.

In dynamic network design, traffic flow models are often path-based, in which traffic flow is assigned to individual paths, or route-based, in which traffic flow is assigned to routes.

As applied to fixed and dynamic routing networks, TLFO models do network design based on shortest path selection and linear programming traffic flow optimization. An illustrative traffic flow optimization model is illustrated in Figure 7.

There are two versions of this model: route-TLFO and path-TLFO models. Shortest least-cost path routing gives connections access to paths in order of cost, such that connections access all direct circuits between nodes prior to attempting more expensive overflow paths. Routes are constructed with specific path selection rules. For example, route-TLFO models construct routes for multilink, or two-link, path routing by assuming crankback and originating node control capabilities in the routing. The linear programming flow optimization model strives to share link capacity to the greatest extent possible with the variation of loads in the network. This is done by equalizing the loads on links throughout the busy periods on the network, such that each link is used to the maximum extent possible in all time periods. The routing design step finds the shortest paths between nodes in the network, combines them into candidate routes, and uses the linear programming flow optimization model to assign traffic flow to the candidate routes.

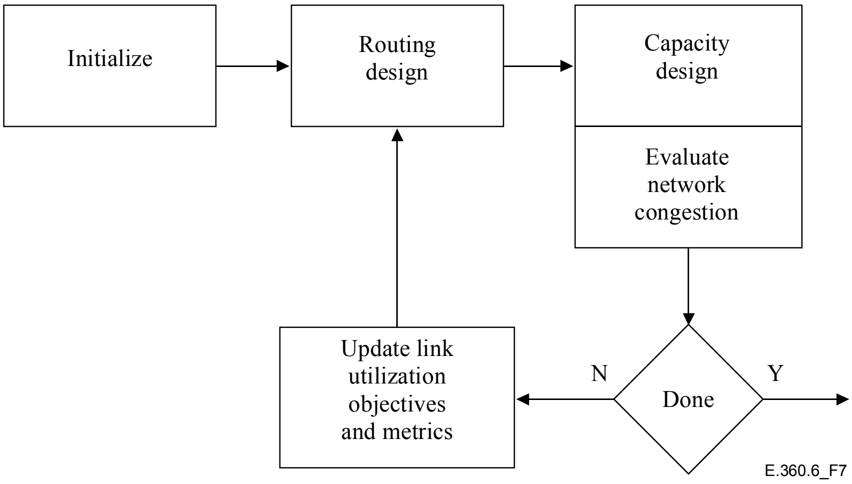

Figure 7/E.360.6 – Traffic Load Flow Optimization (TLFO) model

The capacity design step takes the routing design and solves a fixed-point traffic flow model to determine the capacity of each link in the network. This model determines the flow on each link, and sizes the link to meet the performance level design objectives used in the routing design step. Once the links have been sized, the cost of the network is evaluated and compared to the last iteration. If the network cost is still decreasing, the update module:

1) computes the slope of the capacity versus load curve on each link, which reflects the incremental link cost, and updates the link "length" using this incremental cost as a weighting factor; and

2) recomputes a new estimate of the optimal link overflow using the method described above.

The new link lengths and overflow are fed to the routing design, which again constructs route choices from the shortest paths, and so on. Minimizing incremental network costs helps convert a nonlinear optimization problem to a linear programming optimization problem. Yaged [Yag71], [Yag73] and Knepley [Kne73] take advantage of this approach in their network design models. This favors large efficient links, which carry traffic at higher utilization efficiency than smaller links. Selecting an efficient level of blocking/delay on each link in the network is basic to the route/path-TLFO model. The link overflow optimization model [Tru54] is used in the TLFO model to optimally divide the load between the direct link and the overflow network.

7.3 Virtual Trunking Flow Optimization (VTFO) models

Virtual trunk flow optimization (VTFO) models are used for fixed and dynamic traffic and transport network design. These models optimize the routing of "virtual trunking (VT)" flows, as measured in units of VT bandwidth demands such as 1.5 Mbit/s, OC1, OC12, etc. For application to network design, VTFO models use mathematical equations to convert traffic demands to VT capacity demands, and the VT flow is then routed and optimized. Figure 8 illustrates the VTFO steps. The VT model converts traffic demands directly to VT demands. This model typically assumes an underlying traffic routing structure.

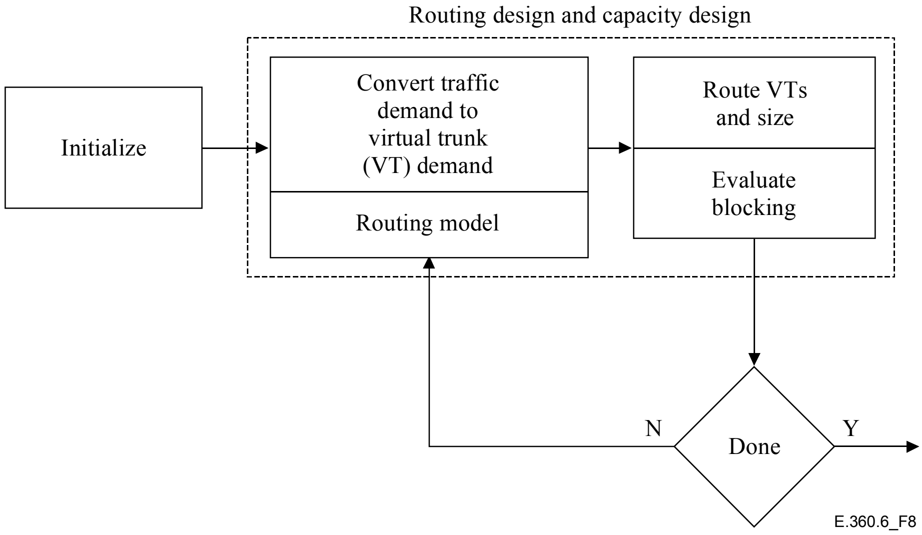

Figure 8/E.360.6 – Virtual Trunking Flow Optimization (VTFO) model

A linear programming VT flow optimization model can be used for network design, in which hourly traffic demands are converted to hourly VT demands by using, for example, TLFO network design methods described above for each hourly traffic pattern. The linear programming VT flow optimization is then used to optimally route the hourly node-to-node VT demands on the shortest, least-cost paths and size the links to satisfy all the VT demands. Alternatively, node-to-node traffic demands are converted to node-to-node VT demands by using the approach described above to optimally divide the traffic load between the direct link and the overflow network, but in this application of the model we obtain an equivalent VT demand, by hour, as opposed to an optimum link-overflow objective.

8 Day-to-day load variation design models

In network design we use the forecast traffic loads, which are actually mean loads about which there occurs a day-to-day variation, characterized, for example, by a gamma distribution with one of three levels of variance [Wil58]. Even if the forecast means loads are correct, the actual realized loads exhibit a random fluctuation from day to day. Studies have established that this source of uncertainty requires the network to be augmented in order to maintain the required performance objectives. Accommodating day-to-day variations in the network design procedure can use an equivalent load technique that models each node pair in the network as an equivalent link designed to meet the performance objectives. On the basis of day-to-day variation design models, such as [HiN76], [Wil58], the link bandwidth N required in the equivalent link to meet the required objectives for the forecasted load R with its specified instantaneous-to-mean ratio (IMR) and specified level of day-to-day variation phi is determined. Holding fixed the specified IMR value and the calculated bandwidth capacity N, we calculate what larger equivalent load Re requires bandwidth N to meet the performance objectives if the forecasted load had had no day-to-day variation. The equivalent traffic load Re is then used which in place of R, since it produces the same equivalent bandwidth when designed for the same IMR-level but in the absence of day-to-day variation.

9 Forecast uncertainty/reserve capacity design models

Network designs are made based on measured traffic loads and estimated traffic loads that are subject to error. In network design, we use the forecast traffic loads because the network capacity must be in place before the loads occur. Errors in the forecast traffic reflect uncertainty about the actual loads that will occur and, as such, the design needs to provide sufficient capacity to meet the expected load on the network in light of these expected errors. Studies have established that this source of uncertainty requires the network to be augmented in order to maintain the blocking/delay probability grade-of-service objectives [FHH79].

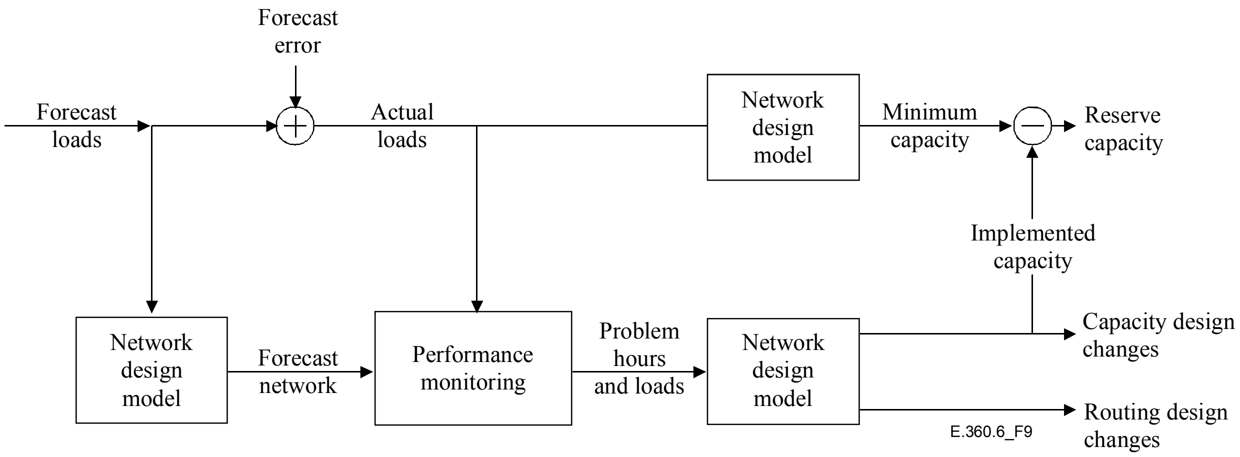

Figure 9/E.360.6 – Design model illustrating forecast error and reserve capacity trade-off

The capacity management process accommodates the random forecast errors in the procedures. When some realized node-to-node performance levels are not met, additional capacity and/or routing changes are provided to restore the network performance to the objective level. Capacity is often not disconnected in the capacity management process even when load forecast errors are such that this would be possible without performance degradation. Capacity management, then, is based on the forecast traffic loads and the link capacity already in place. Consideration of the in-service link capacity entails a transport routing policy that could consider:

1) fixed transport routing, in which transport is not rearranged; and
2) dynamic transport routing, as discussed in ITU-T Rec. E.360.5, which allows periodic transport rearrangement including some capacity disconnects.

The capacity disconnect policy may leave capacity in place even though it is not called for by the network design. In-place capacity, that is in excess of the capacity required to exactly meet the design loads with the objective performance, is called reserve capacity. There are economic and service implications of the capacity management strategy. Insufficient capacity means that occasionally link capacity must be connected on short notice if the network load requires it. This is short-term capacity management. There is a trade-off between reserve capacity and short-term capacity management. Reference [FHH79] analyses a model that shows the level of reserve capacity to be in the range of 6-25 percent, when forecast error, measurement error, and other effects are present. In fixed transport routing networks, if links are found to be overloaded when actual loads are larger than forecasted values, additional link capacity is provided to restore the objective performance levels and, as a result, the process leaves the network with reserve capacity, even when the forecast error is unbiased. Operational studies in fixed transport routing networks have measured up to 20 percent and more for network reserve capacity. Methods such as the Kalman filter [PaW82], which provides more accurate traffic forecasts and rearrangeable transport routing, can help reduce this level of reserve capacity. On occasion, the planned design underprovides link capacity at some point in the network, again because of forecast errors, and short-term capacity management is required to correct these forecast errors and restore service.

The model illustrated in Figure 9 is used to study network design of a network, on the basis of forecast loads, in which the network design accounts for both the current network and the forecast loads in capacity management. Capacity management can make short-term capacity additions if network performance for the realized traffic loads becomes unacceptable and cannot be corrected by routing adjustments. Capacity management tries to minimize reserve capacity while maintaining the design performance objectives and an acceptable level of short-term capacity additions. Capacity management uses the traffic forecast, which is subject to error, and the existing network. The model assumes that the network design is always implemented and, if necessary, short-term capacity additions are made to restore network performance when design objectives are not met.

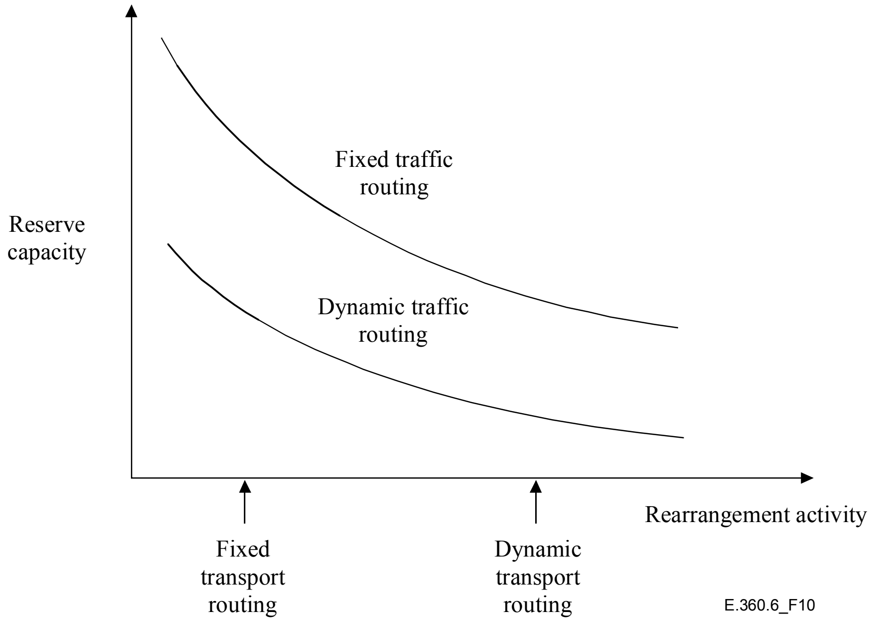

Figure 10/E.360.6 – Trade-off of reserve capacity vs. rearrangement activity

With fixed traffic and transport routing, link capacity augments called for by the design model are implemented, and when the network design calls for fewer trunks on a link, a disconnect policy is invoked to decide whether trunks should be disconnected. This disconnect policy reflects a degree of reluctance to disconnect link capacity, so as to ensure that disconnected link capacity is not needed a short time later if traffic loads grow. With dynamic traffic routing and fixed transport routing, reduction in reserve capacity is possible while retaining a low level of short-term capacity management. With dynamic traffic routing and dynamic transport routing, additional reduction in reserve capacity is achieved. With dynamic traffic routing and dynamic transport routing design, as illustrated in Figure 10, reserve capacity can be reduced in comparison with fixed transport routing, because with dynamic transport network design the link sizes can be matched to the network load.

10 Meshed, sparse, and dynamic-transport design models

In the meshed network designs we assume an overlay network structure, such as for example MPLS traffic trunk formed by label switched paths (LSPs) or ATM virtual paths (VPs). Such LSPs are formed through use of label switched routers (LSRs) to establish the paths. VPs are formed through use of ATM switches, or perhaps might involve the use of ATM cross-connect device. In the meshed network case, traffic is aggregated to many logical links, and the links therefore need to have a bandwidth granularity below OC3 level. Such an overlay network cross-connecting capability is able to establish a mesh of layer-2 logical links, which are multiplexed onto the higher capacity fiber backbone links. With the highly connected mesh of logical links, 1- and 2-link routing methods, such as 2-link STT-EDR and 2-link DC-SDR, can be employed if VPs or LSPs can be used in tandem.

For the sparse network case, as illustrated in Figure 11, logical links are established by use of cross-connect switching, such as with optical cross connects (OXCs), as discussed in ITU-T Rec. E.360.5. In the sparse network case, the traffic is aggregated to a fewer number of logical links in which case the links have larger bandwidth granularity, OC3, OC12, OC48, and higher. For the dynamic transport network design, the traffic is aggregated to an even smaller number of fiber backbone links, and in that case the bandwidth granularity is larger, OC48, OC192, and larger, corresponding to a single wavelength on a DWDM fiber channel.

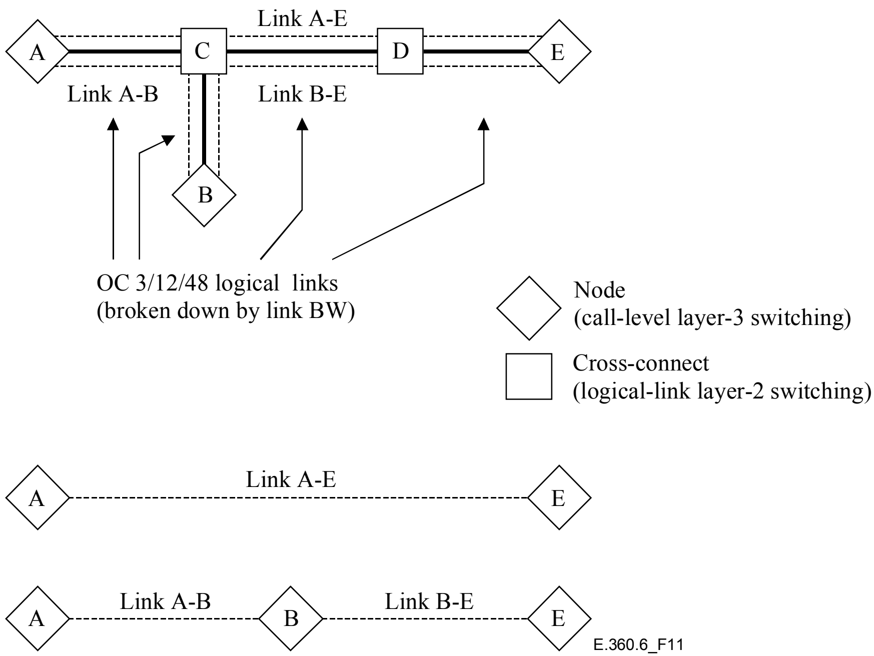

Figure 11/E.360.6 – Mesh logical network topology with logical-link layer-2 switching and call-level layer-3 switching

For design of the dynamic transport routing network, as described in ITU-T Rec. E.360.5, the logical links are controlled dynamically within the OXC network by switching bandwidth on the fiber backbone links to the logical links. As a result, the design procedure for dynamic transport networks can be relatively simple. The traffic demands of the various node pairs are aggregated to the backbone fiber transport links, which overlay the logical links, and then each transport link is sized to carry the total traffic demand from all node pairs that use the backbone fiber transport link for voice, data, and broadband traffic. As illustrated in Figure 12, one subtlety of the design procedure is deciding what performance objectives (e.g. blocking objective) to use for sizing the backbone transport links. The difficulty is that many node pairs send traffic over the same backbone transport link, and each of these node pairs has a different number of backbone transport links in its path. This means that for each traffic load, a different level of performance (e.g. blocking) on a given backbone transport link is needed to ensure, say, a 1% level of blocking end-to-end. With many kinds of traffic present on the link, we are guaranteed an acceptable blocking probability grade-of-service objective if we identify the path through each transport link that requires the largest number of links, n, and size the link to a 1/n blocking objective. In Figure 12, link L1 has a largest number n equal to 6, and link L2 has a largest number n equal to 4. If the end-to-end blocking objective is 1%, then the link-blocking objectives are determined, as given in Figure 12. We show that the dynamic transport routing network sized in this simple manner still achieves significant efficiencies.

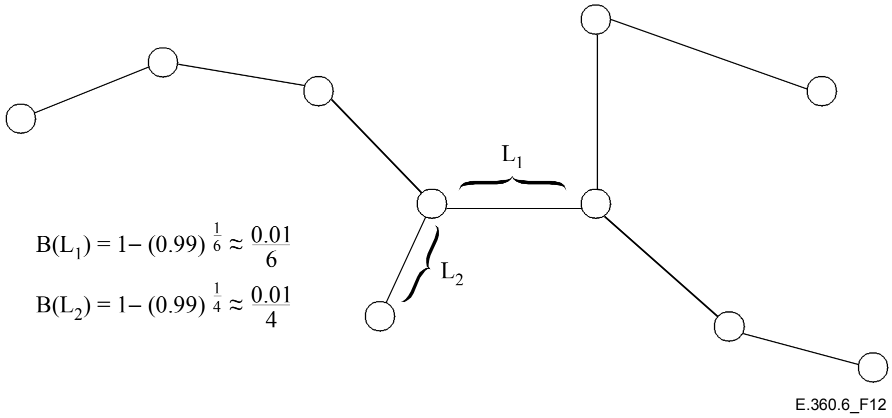

Figure 12/E.360.6 – Dynamic transport routing network design model

11 Conclusions/recommendations

The conclusions/recommendations reached in this Recommendation are as follows:

- Discrete event flow optimization (DEFO) design models are recommended and are shown to be able to capture very complex routing behavior through the equivalent of a simulation model provided in software in the routing design module. By this means, very complex routing networks have been designed by the model, which include all of the routing methods discussed in ITU-T Rec. E.360.2 (FR, TDR, SDR, and EDR methods) and the multiservice QoS resource allocation models discussed in ITU-T Rec. E.360.3.
- Sparse topology options are recommended, such as the multilink STT-EDR/DC-SDR/DP-SDR options, which lead to capital cost advantages, and more importantly to operation simplicity and cost reduction. Capital cost savings are subject to the particular switching and transport cost assumptions. Operational issues are further detailed in ITU-T Rec. E.360.7.
- Voice and data integration is recommended and:
  a) can provide capital cost advantages; and
  b) more importantly, can achieve operational simplicity and cost reduction; and
  c) if IP-telephony takes hold, and a significant portion of voice calls use voice compression technology, this could lead to more efficient networks.
- Multilink routing methods are recommended and exhibit greater design efficiencies in comparison with 2-link routing methods. As discussed and modelled in ITU-T Rec. E.360.3, multilink topologies exhibit better network performance under overloads in comparison with 2-link routing topologies; however, the 2-link topologies do better under failure scenarios.
- Single-area flat topologies are recommended and exhibit greater design efficiencies in termination and transport capacity, but higher cost and, as discussed and modelled in ITU-T Rec. E.360.3, better network performance in comparison with multi-area hierarchical topologies. As illustrated in ITU-T Rec. E.360.4, larger administrative areas can be achieved through use of EDR-based TE methods as compared to SDR-based TE methods.

- EDR methods are recommended and exhibit comparable design efficiencies to SDR. This suggests that there is not a significant advantage for employing link-state information in these network designs, especially given the high overhead in flooding link-state information in SDR methods.
- Dynamic transport routing is recommended and achieves capital savings by concentrating capacity on fewer, high-capacity physical fiber links and, as discussed in ITU-T Rec. E.360.5, achieves higher network throughput and enhanced revenue by their ability to flexibly allocate bandwidth on the logical links serving the access and inter-node traffic.

Annex A

Modelling of traffic engineering methods

In this annex, we again use the full-scale national network model developed in ITU-T Rec. E.360.2 to study various TE scenarios and tradeoffs. The 135-node national model is illustrated in Figure A.1/E.360.2, the multiservice traffic demand model is summarized in Table A.1/E.360.2, and the cost model is summarized in Table A.2/E.360.2.

A.1 Per-virtual-network vs. per-flow network design

Here we illustrate the use of the DEFO model to design for a per-flow multiservice network design and a per-virtual-network design, and to provide comparisons of these designs. The per-flow and per-virtual network designs for the flat 135-node model are summarized in Table A.1.

Table A.1/E.360.6 – Design comparison of per-virtual-network and per-flow bandwidth allocation – Multilink STT-EDR connection routing – Sparse single-area flat topology (135-node multiservice network model; DEFO design model)

Network design parameters		Per-virtual-network bandwidth allocation design	Per-flow bandwidth allocation design
Number of links	OC3 links	583	482
	OC12 links	294	389
	OC48 links	104	111
	Total links	981	982
Termination capacity (equivalent DS0s, millions)	OC3 links	3.16	2.30
	OC12 links	6.07	6.64
	OC48 links	7.30	7.50
	Total	16.5	16.4
Transport capacity (equivalent DS0-miles, millions)	OC3 links	1536.3	1185.5
	OC12 links	3876.0	4105.4
	OC48 links	3952.9	3994.5
	Total	9365.2	9285.3
Termination cost ($ millions)	OC3 links	61.0	44.4
	OC12 links	58.5	64.0
	OC48 links	28.6	29.4
	Total	148.1	137.7

Table A.1/E.360.6 – Design comparison of per-virtual-network and per-flow bandwidth allocation – Multilink STT-EDR connection routing – Sparse single-area flat topology (135-node multiservice network model; DEFO design model)

Network design parameters		Per-virtual-network bandwidth allocation design	Per-flow bandwidth allocation design
Transport cost ($ millions)	OC3 links	299.6	229.8
	OC12 links	621.3	659.6
	OC48 links	237.3	240.0
	Total	1158.1	1129.5
Total cost ($ millions)	OC3 links	360.6	274.2
	OC12 links	679.8	723.6
	OC48 links	265.8	269.5
	Total	1306.2	1267.2
Routing analysis (network busy hour)	Average links/connection	1.84	1.86
	# Node-pairs 1 link/connection	982	982
	# Node-pairs 2 links/connection	3698	3698
	# Node-pairs 3 links/connection	4365	4365

We see from the above results that the per-virtual network design compared to the per-flow design yields the following results:

- the per-flow design has 0.996 of the total termination capacity of the per-virtual-network design;
- the per-flow design has 0.991 of the total transport capacity of the per-virtual-network design;
- the per-flow design has 0.970 of the total network cost of the per-virtual-network design.

These results indicate that the per-virtual-network design and per-flow design are quite comparable in terms of capacity requirements and design cost. In ITU-T Rec. E.360.3 we showed that the performance of these two designs was also quite comparable under a range of network scenarios.

A.2 Integrated vs. separate voice/ISDN and data network designs

The comparative designs for separate and integrated network designs under multilink, STT-EDR, per-flow routing are given in Table A.2 for the following cases:

- voice/ISDN-only traffic (VNETs 1-8 in Table A.1/E.360.2)
- data-only traffic (VNETs 9-11 in Table A.1/E.360.2)
- integrated voice/ISDN and data design (VNETs 1-11 in Table A.1/E.360.2)

Table A.2/E.360.6 – Comparison of voice/ISDN-only design (VNETs 1-8), data-only design (VNETs 9-11), and integrated voice/ISDN and data design (VNETs 1-11) – Multilink STT-EDR connection routing; per-flow bandwidth allocation – Sparse single-area flat topology (135-node multiservice network model; DEFO design model)

Network design parameters		Voice/ISDN-only design	Data-only design	Integrated voice/ISDN and data design
Number of links	OC3 links	92	393	482
	OC12 links	159	294	389
	OC48 links	3	109	111
	Total links	254	796	982
Termination capacity (equivalent DS0s, millions)	OC3 links	0.36	1.87	2.30
	OC12 links	2.76	4.99	6.64
	OC48 links	0.20	7.34	7.50
	Total	3.31	14.2	16.4
Transport capacity (equivalent DS0-miles, millions)	OC3 links	380.1	937.7	1185.5
	OC12 links	1284.4	3025.8	4105.4
	OC48 links	160.0	3853.4	3994.5
	Total	1824.5	7816.9	9285.3
Termination cost ($ millions)	OC3 links	6.92	36.0	44.4
	OC12 links	26.6	48.1	64.0
	OC48 links	0.78	28.7	29.4
	Total	34.2	112.8	137.7
Transport cost ($ millions)	OC3 links	70.0	182.2	229.8
	OC12 links	211.1	486.8	659.6
	OC48 links	9.33	231.9	240.0
	Total	290.4	900.9	1129.5
Total cost ($ millions)	OC3 links	76.9	218.3	274.2
	OC12 links	237.7	534.9	723.6
	OC48 links	101.2	260.6	269.5
	Total	324.7	1013.8	1267.2
Routing analysis (network busy hour)	Average links/connection	2.32	1.96	1.86
	# Node-pairs 1 link/connection	254	796	982
	# Node-pairs 2 links/connection	2895	3350	3698
	# Node-pairs 3 links/connection	5806	4899	4365
	# Node-pairs 4 links/connection	90	0	0

We see from the above results that the separate voice/ISDN and data designs compared to the integrated design yields the following results:

- the integrated design has 0.937 of the total termination capacity as the separate voice/ISDN and data designs;
- the integrated design has 0.963 of the total transport capacity as the separate voice/ISDN and data designs;
- the integrated design has 0.947 of the total cost as the separate voice/ISDN and data designs.

These results indicate that the integrated design is somewhat more efficient in design owing to the economy-of-scale of the higher-capacity network elements, as reflected in the cost model given in Table A.2/E.360.2.

The comparative designs for separate and integrated network designs under 2-link STT-EDR connection routing with per-flow QoS resource management are given in Table A.3 for the following cases:

- voice/ISDN-only traffic (VNETs 1-8 in Table A.1/E.360.2)
- data-only traffic (VNETs 9-11 in Table A.1/E.360.2)
- integrated voice/ISDN and data design (VNETs 1-11 in Table A.1/E.360.2)

Table A.3/E.360.6 – Comparison of voice/ISDN-only design (VNETs 1-8), data-only design (VNETs 9-11), and integrated voice/ISDN and data design (VNETs 1-11) – 2-link STT-EDR connection routing; per-flow bandwidth allocation – Sparse single-area flat topology (135-node multiservice network model; DEFO design model)

Network design parameters		**Voice/ISDN-only design**	**Data-only design**	**Integrated voice/ISDN and data design**
Number of links	OC3 links	170	61	47
	OC12 links	169	92	100
	OC48 links	0	186	192
	Total links	339	339	339
Termination capacity (equivalent DS0s, millions)	OC3 links	0.65	0.35	0.28
	OC12 links	3.85	2.02	2.22
	OC48 links	0.0	20.1	23.1
	Total	4.50	22.5	25.6
Transport capacity (equivalent DS0-miles, millions)	OC3 links	1031.0	611.4	501.0
	OC12 links	9823.5	3401.0	3600.2
	OC48 links	0.0	6133.9	7529.4
	Total	2013.4	10,146.3	11,630.6
Termination cost ($ millions)	OC3 links	12.6	6.84	5.44
	OC12 links	37.1	19.5	21.4
	OC48 links	0.0	78.8	90.6
	Total	49.7	105.1	117.4

Table A.3/E.360.6 – Comparison of voice/ISDN-only design (VNETs 1-8), data-only design (VNETs 9-11), and integrated voice/ISDN and data design (VNETs 1-11) – 2-link STT-EDR connection routing; per-flow bandwidth allocation – Sparse single-area flat topology (135-node multiservice network model; DEFO design model)

Network design parameters		Voice/ISDN-only design	Data-only design	Integrated voice/ISDN and data design
Transport cost ($ millions)	OC3 links	186.7	110.4	90.4
	OC12 links	173.7	522.0	553.1
	OC48 links	0.0	392.5	477.5
	Total	360.4	1024.9	1120.9
Total cost ($ millions)	OC3 links	199.3	117.2	95.8
	OC12 links	210.8	541.5	574.4
	OC48 links	0.0	471.3	568.1
	Total	410.1	1130.0	1238.4
Routing analysis (network busy hour)	Average links/connection	2.77	2.77	2.77
	# Node-pairs 1 link/connection	340	340	340
	# Node-pairs 2 links/connection	3249	3249	3249
	# Node-pairs 3 links/connection	8487	8487	8487
	# Node-pairs 4 links/connection	14	14	14

We see from the above results that the separate voice/ISDN and data designs compared to the integrated design yields the following results:

- the integrated design has 0.948 of the total termination capacity as the separate voice/ISDN and data designs;
- the integrated design has 0.956 of the total transport capacity as the separate voice/ISDN and data designs;
- the integrated design has 0.804 of the total cost as the separate voice/ISDN and data designs.

These results indicate that the integrated design is somewhat more efficient in design termination and transport capacity. It is about 20 percent more efficient in cost owing to the economy-of-scale of the higher-capacity network elements, as reflected in the cost model given in Table A.2/E.360.2.

The comparative designs for separate and integrated network designs under 2-link DC-SDR connection routing with per-flow QoS resource management are given in Table A.4 for the following cases:

- voice/ISDN-only traffic (VNETs 1-8 in Table A.1/E.360.2)
- data-only traffic (VNETs 9-11 in Table A.1/E.360.2)
- integrated voice/ISDN and data design (VNETs 1-11 in Table A.1/E.360.2)

Table A.4/E.360.6 – Comparison of voice/ISDN-only design (VNETs 1-8), data-only design (VNETs 9-11), and integrated voice/ISDN and data design (VNETs 1-11) – 2-link DC-SDR connection routing; per-flow bandwidth allocation – Sparse single-area flat topology (135-node multiservice network model; DEFO design model)

Network design parameters		Voice/ISDN-only design	Data-only design	Integrated voice/ISDN and data design
Number of links	OC3 links	170	63	48
	OC12 links	169	90	99
	OC48 links	0	186	192
	Total links	339	339	339
Termination capacity (equivalent DS0s, millions)	OC3 links	0.65	0.37	0.29
	OC12 links	3.83	2.00	2.20
	OC48 links	0.0	20.1	23.17
	Total	4.48	22.5	25.66
Transport capacity (equivalent DS0-miles, millions)	OC3 links	1029.7	638.3	501.2
	OC12 links	976.0	335.7	3599.6
	OC48 links	0.0	613.4	7528.9
	Total	2005.7	10128.9	11,629.8
Termination cost ($ millions)	OC3 links	12.5	7.12	5.60
	OC12 links	36.9	19.3	21.2
	OC48 links	0.0	78.8	90.7
	Total	49.4	105.2	117.5
Transport cost ($ millions)	OC3 links	186.4	115.2	90.5
	OC12 links	172.6	515.2	552.9
	OC48 links	0.0	392.5	477.6
	Total	359.0	1023.0	1238.5
Total cost ($ millions)	OC3 links	199.0	122.4	96.1
	OC12 links	209.5	534.5	574.1
	OC48 links	0.0	471.3	568.3
	Total	408.4	1128.1	1238.5
Routing analysis (network busy hour)	Average links/connection	2.77	2.77	2.77
	# Node-pairs 1 link/connection	340	340	340
	# Node-pairs 2 links/connection	3249	3249	3249
	# Node-pairs 3 links/connection	8487	8487	8487
	# Node-pairs 4 links/connection	14	14	14

We see from the above results that the separate voice/ISDN and data designs compared to the integrated design yields the following results:

- the integrated design has 0.951 of the total termination capacity as the separate voice/ISDN and data designs;
- the integrated design has 0.958 of the total transport capacity as the separate voice/ISDN and data designs;
- the integrated design has 0.806 of the total cost as the separate voice/ISDN and data designs.

These results indicate that the integrated design is somewhat more efficient in design termination and transport capacity. It is about 20 percent more efficient in cost owing to the economy-of-scale of the higher-capacity network elements, as reflected in the cost model given in Table A.2/E.360.2.

A.3 Multilink vs. 2-link network design

We see from the results in Tables A.2 and A.3 that the multilink EDR network design compared to 2-link EDR design yields the following results:

- the voice/ISDN-only multilink-EDR design has 0.735 of the total termination capacity of the 2-link design;
- the voice/ISDN-only multilink-EDR design has 0.906 of the total transport capacity of the 2-link design;
- the voice/ISDN-only multilink-EDR design has 0.792 of the total cost of the 2-link design;
- the data-only multilink-EDR design has 0.631 of the total termination capacity of the 2-link design;
- the data-only multilink-EDR design has 0.770 of the total transport capacity of the 2-link design;
- the data-only multilink-EDR design has 0.897 of the total cost of the 2-link design;
- the integrated multilink-EDR design has 0.640 of the total termination capacity of the 2-link design;
- the integrated multilink-EDR design has 0.798 of the total transport capacity of the 2-link design;
- the integrated multilink-EDR design has 1.023 of the total cost of the 2-link design.

These results show that the multilink designs are generally more efficient than the 2-link designs in transport and termination capacity, and have lower cost for the separate designs and comparable cost for the integrated design.

A.4 Single-area flat vs. 2-level hierarchical network design

In Table A.5 we illustrate the use of the DEFO model to design for a per-flow 2-level hierarchical multiservice network design and a 2-level hierarchical per-virtual-network design, and to provide comparisons of these designs. Recall that the hierarchical model, illustrated in Figure A.1/E.360.2, consists of 135-edge-nodes and 21 backbone-nodes. The edge-nodes are homed onto the backbone nodes in a hierarchical relationship. The per-flow and per-virtual network designs for the hierarchical 135-edge-node and 21-backbone-node model are summarized in Table A.5.

Table A.5/E.360.6 – Design comparison of per-virtual-network and per-flow bandwidth allocation multilink STT-EDR connection routing – 135-edge-node and 21-backbone-node sparse multi-area 2-level hierarchical topology (multiservice network model; DEFO design model)

Network design parameters		Per-virtual-network bandwidth allocation design	Per-flow bandwidth allocation design
Number of links	OC3 links	60	40
	OC12 links	97	113
	OC48 links	186	187
	Total links	343	340
Termination capacity (equivalent DS0s, millions)	OC3 links	0.36	0.21
	OC12 links	2.09	2.18
	OC48 links	19.62	18.72
	Total	22.08	21.12
Transport capacity (equivalent DS0-miles, millions)	OC3 links	654.4	377.2
	OC12 links	3462.2	3608.0
	OC48 links	5870.9	5923.6
	Total	9987.5	9908.8
Termination cost ($ millions)	OC3 links	70.0	4.1
	OC12 links	20.2	21.0
	OC48 links	76.8	73.3
	Total	104.0	98.5
Transport cost ($ millions)	OC3 links	118.0	68.0
	OC12 links	531.6	554.0
	OC48 links	376.7	377.1
	Total	1026.3	991.2
Total cost ($ millions)	OC3 links	125.0	72.2
	OC12 links	551.8	57.5
	OC48 links	453.5	450.4
	Total	1130.3	1097.6
Routing analysis (network busy hour)	Average links/connection	2.90	2.77
	# Node-pairs 1 link/connection	344	340
	# Node-pairs 2 links/connection	2706	3249
	# Node-pairs 3 links/connection	6703	8487
	# Node-pairs 4 links/connection	2158	14
	# Node-pairs 5 links/connection	179	0

We see from the above results that the hierarchical per-virtual network design compared to the hierarchical per-flow design yields the following results:

- the hierarchical per-flow design has 0.956 of the total termination capacity of the hierarchical per-virtual-network design;
- the hierarchical per-flow design has 0.992 of the total transport capacity of the hierarchical per-virtual-network design;
- the hierarchical per-flow design has 0.971 of the total network cost of the hierarchical per-virtual-network design.

These results indicate that the hierarchical per-virtual-network design and hierarchical per-flow designs are quite comparable in terms of capacity requirements and design cost. In ITU-T Rec. E.360.3 we showed that the performance of these two designs was also quite comparable under a range of network scenarios.

By comparing Tables A.1 and A.5, we can find the relative capacity of the single-area flat network design and the multiple-area, 2-level hierarchical network design (per-flow case):

- the single-area flat design has 0.776 of the total termination capacity of the multi-area 2-level hierarchical design;
- the single-area flat design has 0.937 of the total transport capacity of the multi-area 2-level hierarchical design;
- the single-area flat design has 1.154 of the total network cost of the multi-area 2-level hierarchical design.

In this model, the single-area flat designs have less total termination and transport capacity as the multi-area hierarchical designs, and are therefore more efficient in engineered capacity. However, the hierarchical designs appear to be less expensive than the flat designs. This is because of the larger percentage of OC48 links in the hierarchical designs, which is also considerably sparser than the flat design and therefore the traffic loads are concentrated onto fewer, larger, links. As discussed in ITU-T Rec. E.360.2, there is an economy of scale built into the cost model which affords the higher capacity links (e.g. OC48 as compared to OC3) a considerably lower per-unit-of-bandwidth cost, and therefore a lower overall network cost is achieved as a consequence. However, the performance analysis results discussed in ITU-T Rec. E.360.3 show that the flat designs perform better than the hierarchical designs under the overload and failure scenarios that were modelled. This is also a consequence of the sparser hierarchical network and lesser availability of alternate paths for more robust network performance.

A.5 EDR vs. SDR network design

Next, we examine the meshed network designs for the 2-link STT-EDR network and the 2-link DC-SDR network, which were discussed in ITU-T Rec. E.360.2. The designs for the 2-link STT-EDR and 2-link DC-SDR connection routing networks, with per-flow QoS resource management, are given in Table A.6, which again are obtained using the DEFO model on the 135-node model.

Table A.6/E.360.6 – Design comparison of 2-link STT-EDR and 2-link DC-SDR connection routing per-flow bandwidth allocation – Meshed single-area flat topology (135-edge-node multiservice network model; DEFO design model)

Network design parameters		2-link STT-EDR design	2-link DC-SDR design
Number of links	OC3 links	47	48
	OC12 links	100	99
	OC48 links	192	192
	Total links	339	339
Termination capacity (equivalent DS0s, millions)	OC3 links	0.28	0.29
	OC12 links	2.22	2.20
	OC48 links	23.14	23.17
	Total	25.64	25.66
Transport capacity (equivalent DS0-miles, millions)	OC3 links	501.0	501.2
	OC12 links	3600.2	3599.6
	OC48 links	7529.4	7528.9
	Total	11,630.6	11,629.8
Termination cost ($ millions)	OC3 links	5.44	5.60
	OC12 links	21.4	21.2
	OC48 links	90.6	90.7
	Total	117.4	117.5
Transport cost ($ millions)	OC3 links	90.4	90.5
	OC12 links	553.1	552.9
	OC48 links	477.5	477.6
	Total	1120.9	1121.0
Total cost ($ millions)	OC3 links	95.8	96.1
	OC12 links	574.4	574.1
	OC48 links	568.1	568.3
	Total	1238.4	1238.5
Routing analysis (network busy hour)	Average links/connection	2.77	2.77
	# Node-pairs 1 link/connection	340	340
	# Node-pairs 2 links/connection	3249	3249
	# Node-pairs 3 links/connection	8487	8487
	# Node-pairs 4 links/connection	14	14

We see from the above results that the EDR network design compared to the SDR design yields the following results:

- the EDR design has 0.999 of the total termination capacity of the SDR design;
- the EDR design has 1.000 of the total transport capacity of the SDR design;
- the EDR design has 0.999 of the total network cost of the SDR design.

We note that the designs are very comparable to each other and have essentially the same total network design costs. This suggests that there is not a significant advantage for employing link-state information in these network designs, and given the high overhead in flooding link-state information, EDR methods are preferred.

A.6 Dynamic transport routing vs. fixed transport routing network design

Finally we examine the design comparisons of dynamic transport routing compared with the fixed transport routing. In the model we assume multilink STT-EDR connection routing with per-flow QoS resource management, and once again use the DEFO design model for the flat 135-node network model. The results are summarized in Table A.7.

Table A.7/E.360.6 – Design comparison of fixed transport routing and dynamic transport – Routing multilink STT-EDR connection routing; per-flow bandwidth allocation – Sparse single-area flat topology (135-node multiservice network model; DEFO design model)

Network design parameters		Fixed transport routing design	Dynamic transport routing design
Number of links	OC3 links	482	0
	OC12 links	389	0
	OC48 links	111	173
	Total links	982	173
Termination capacity (equivalent DS0s, millions)	OC3 links	2.30	0
	OC12 links	6.64	0
	OC48 links	7.50	18.0
	Total	16.4	18.0
Transport capacity (equivalent DS0-miles, millions)	OC3 links	1185.5	0
	OC12 links	4105.4	0
	OC48 links	3994.5	9731.0
	Total	9285.3	9731.0
Termination cost ($ millions)	OC3 links	44.4	0
	OC12 links	64.0	0
	OC48 links	29.4	70.6
	Total	137.7	70.6
Transport cost ($ millions)	OC3 links	229.8	0
	OC12 links	659.6	0
	OC48 links	240.0	584.2
	Total	1129.5	584.2
Total cost ($ millions)	OC3 links	274.2	0
	OC12 links	723.6	0
	OC48 links	269.5	654.8
	Total	1267.2	654.8

Table A.7/E.360.6 – Design comparison of fixed transport routing and dynamic transport – Routing multilink STT-EDR connection routing; per-flow bandwidth allocation – Sparse single-area flat topology (135-node multiservice network model; DEFO design model)

Network design parameters		Fixed transport routing design	Dynamic transport routing design
Routing analysis (network busy hour)	Average links/connection	1.86	2.49
	# Node-pairs 1 link/connection	982	173
	# Node-pairs 2 links/connection	3698	2371
	# Node-pairs 3 links/connection	4365	6085
	# Node-pairs 4 links/connection	0	416

We see from the above results that the fixed transport network design compared to the dynamic transport design yields the following results:

- the dynamic transport design has 1.097 of the total termination capacity of the fixed-transport-network design;
- the dynamic transport design has 1.048 of the total transport capacity of the fixed-transport-network design;
- the dynamic transport design has 0.516 of the total network cost of the fixed-transport-network design.

These results indicate that the dynamic transport design has more termination capacity and transport capacity than the fixed transport network design, but substantially lower cost. The larger capacity comes about because of the larger fiber backbone link bandwidth granularity compared to the logical link granularity in the fixed transport routing case. The lower cost of the dynamic transport network comes about, however, because of the economies of scale of the higher capacity transport and termination elements, as reflected in Table A.2/E.360.2. In ITU-T Rec. E.360.3 we showed that the performance of these two designs was also quite comparable under a range of network scenarios.

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