STRATEGIES FOR DYNAMIC CAPACITY MANAGEMENT

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Abstract

We study networks based on virtual paths, *i.e.* rearrangable end-to-end transport network. Virtual paths networks are readily implemented in any network using the synchronous digital hierarchy and/or the asynchronous transfer mode. The concept and its advantages, for example cost savings, network operation simplification and enhanced network management capabilities, are discussed. Algorithms for virtual path designs are reviewed and a new algorithm is presented which is found to compare favourably with the algorithm providing the most similar features. Applying it to a real network, we turn to operational aspects of reconfigurable networks such as methods and parameters for traffic estimation and network updating. The validity of the results is demonstrated by means of simulations of a number of networks subject to variable traffics.

1 Virtual Path Networks

A virtual path (VP) is formed by reserving a certain amount of transmission capacity on a series of links and cross connecting the reserved channels through possible, intermediate transit nodes. Interconnecting all origin-destination pairs (OD-pairs) by means of VPs, a virtual path network is obtained, figure 1. Such a network forms a higher layer which is logically independent of the underlying physical network. The process of creating and/or rearranging a (logical) network of VPs between a number of end nodes is called capacity management [8], bandwidth management [16], bandwidth switching [1] or bandwidth control [25], and is performed at a network management centre (NMC).

VPs are engineered for each OD-pair respectively so that current traffic demands can be carried with an acceptable grade of service. However, it is not always possible to accomodate all demands to their full extent. Hence capacity allocation must be made in such a way that some performance metric, *e.g.* network profit from carried traffic minus carrying costs, is maximised.

Since the optimality of a certain VP configuration depends on link capacities and currently offered traffics, VP assignments must be re-evaluated in response to changes. We refer to this process as dynamic capacity management (DCM). DCM can be performed either in advance or on demand. The former means that assignments are predefined and changed in an independent manner while individual call attempts control rearranging in the latter. We focus on the former, as this is the one most favoured by low transmission-to-processing costs [8, 9].

Some of the motives behind VP networks and DCM [2, 7, 8, 9, 24, 25] are

- Reduced network costs resulting from simplified transit exchanges.
- Simplified multiplexing due to service-dedicated end-to-end VPs.
- Faster call handling by excluding intermediate node processing at set-up time.

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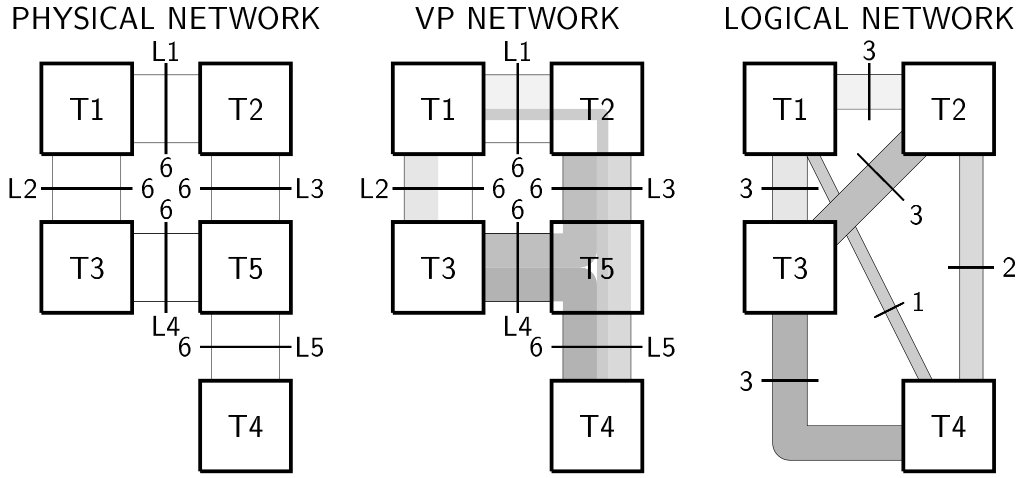

Figure 1: *Formation of a logical network of virtual paths.*

- Improved network management capabilities such as possibilities to redirect traffic in a congested or faulty network.
- A means for providing new services by setting up customer-dedicated (sub)networks as closed groups of VPs.

2 Algorithms for Dynamic Capacity Management

2.1 Existing Algorithms

DCM must be supported by efficient algorithms to compute VP capacity allocations. We have found DCM algorithms or algorithms closely related to DCM published by Gopal *et al.* [13, 14], Herzberg [16], Evans [10], Gersht *et al.* [11, 12, 19] and Mase *et al.* [21]. Algorithms are also outlined by Hui *et al.* [18]. Finally, Mase *et al.* [22] discuss such algorithms in terms similar to those in [10, 11, 12, 18, 19], but without going into any detail. Summing up on these it is found that

- most algorithms explicitly or implicitly presume a linear relationship between the capacity of a VP and its call carrying capability (linear equivalent bandwidth),
- most algorithms explicitly or implicitly presume the existence of predefined paths for all VP, and
- some algorithms produce real valued solutions which are not immediately useful in SDH-networks.

We have developed a new algorithm that does not require linear equivalent bandwidth nor predefined paths and that produces integer valued solutions. Moreover, the optimisation function can be chosen arbitrarily.

The algorithm is a heuristic and as such it does not guarantee that the final solution is a global optimum. On the other hand, the "optimality" guaranteed by some of the algorithms above is not entierly global, but only under the condition of a given set of paths.

2.2 Our Algorithm

Letting $t = 1, \ldots, T$ denote an arbitrary TC and $o = 1, \ldots, N$ ($d = 1, \ldots, N$) an arbitrary node of origin (destination), the main steps of the algorithm can be described as follows:

1. For $t = 1, \ldots, T$, read the table that provides the relationship between capacities and circuits.
2. Read the number of nodes N, link capacities $C_{o,d}$ (expressed as units of capacity) and offered traffics $A_{t,o,d}$ (expressed as Erlangs).
3. Assign high, initially acceptable call loss levels $\alpha(t, o, d)$ for all TCs t and all OD-pairs o, d.
4. Find the shortest paths available to each traffic t, o, d.
5. Compute the gain achieved for each traffic t, o, d if one unit of capacity was to be added to its shortest path.
6. Compute the loss paid for each traffic t, o, d if one unit of capacity was to be added to its shortest path.
7. Find the traffic $t_{\max}, o_{\max}, d_{\max}$ that would yield the highest gain/loss ratio.
8. If the highest gain/loss ratio is 0 then go to step 11, else proceed to step 9.
9. Assign one unit of capacity to the traffic $t_{\max}, o_{\max}, d_{\max}$.
10. Go to step 4.
11. If low, ultimately acceptable loss levels $\alpha(t, o, d)$ have been reached for all traffics or all capacity has been assigned then stop, else proceed to step 12.
12. Reduce currently acceptable loss levels $\alpha(t, o, d)$ for all t, o, d.
13. Go to step 4.

Available capacity is successively distributed to VPs so that a minimum amount of capacity is used in each step and that maximum value is obtained for each unit of capacity. The successive reductions of acceptable losses serve to ensure fairness in grade of service and that assigned capacity will be sufficiently utilised. The algorithm terminates when for every VP either (i) a final, predetermined, desirable loss level has been reached or (ii) no more capacity is available to VPs which still suffer from high losses.

The tables in step 1 give the number equivalent of circuits $N(t, i)$ for TC t and $C = i$ units of capacity, $i = 1, 2, \ldots$. The tables are computed from traffic characteristics, grade-of-service demands, buffer space and acceptable loss, see *e.g.* [4, 5, 15, 17, 22]. A "unit of capacity" is, for PDH an integer number of 64 kb/s channels, for SDH the smallest virtual container used, and for pure ATM a rate in cells/second large enough to carry a call of any TC.

In step 3, our initial loss level is 50%. In step 11, it is reduced to the ultimately acceptable level of 0.05% through two intermediate levels of 5% and 0.5% respectively.

Shortest paths in step 4 are determined using Floyd's algorithm [20] with the length l associated to link o, d designed to find the shortest path in number of links traversed, with preferential treatment to paths having more spare capacity left than other paths of equal length

$$l(o,d) = \begin{cases} 1 + \dfrac{1}{{C'_{o,d}}^4} & C'_{o,d} > 0 \\ \infty & C'_{o,d} = 0 \end{cases} \tag{1}$$

where $C'_{o,d}$ denotes the remaining, not yet assigned capacity on link o, d.

$G(t, o, d)$ in step 5 is the additional t-traffic that would be carried from o to d if one unit of capacity was added to its currently shortest path

$$G(t, o, d) = \tag{2}$$
$$= \begin{cases} A_{t,o,d}[E_{N'_{t,o,d}}(A_{t,o,d}) - E_{N_{t,o,d}}(A_{t,o,d})] \\ \quad \text{if } (E_{N_{t,o,d}}(A_{t,o,d}) > \alpha(t, o, d)) \text{ and } (l(o, d) < \infty) \\ 0 \\ \quad \text{if } (E_{N_{t,o,d}}(A_{t,o,d}) \leq \alpha(t, o, d)) \text{ or } (l(o, d) = \infty) \end{cases}$$

where $E_N(A)$ is the Erlang-B formula. $N_{t,o,d}$ is the present number of circuits available to t, o, d, while $N'_{t,o,d}$ refers to the case where one more unit of capacity has been added to the shortest path. Both N and N' are determined for each route of the VP individually, by means of the tables referred to in step 1, and then summed.

$L(t, o, d)$ in step 6 is the sum of all gains that can be achieved at the same point and that require some of the capacity also requested by t, o, d:

$$L(t, o, d) = \sum_{t'=1}^{T} \sum_{o'=1}^{N-1} \sum_{d'=o'+1}^{N} I(\mathcal{L}_{t,o,d} \cap \mathcal{L}_{t',o',d'} \neq \emptyset)\, G(t', o', d') \tag{3}$$

where $\mathcal{L}_{t,o,d}$ is the set of links traversed by the shortest path for t, o, d and $I(\cdot)$ is an indicator function taking the value of 1 if its argument is true, otherwise 0.

2.3 Discussion

An obvious advantage with the proposed algorithm is its robustness. That is, unlike methods based on mathematical programming, it will remain stable and converge at the same speed for all types of non-linearities and discontinuities in gain and loss functions and irrespective of the ways in which routes for VPs are chosen. These properties leave full freedom to modify and extend the algorithm to meet particular demands such as

- Biased selection of routes.
- A limitation to the number of distinct physical paths.
- Predetermined routes.
- Arbitrary profit maximisation function G.
- Traffic concentration.

2.4 Numerical Results

To investigate the power of the proposed algorithm (A), it was applied to a series of eight distinct networks, each consisting of ten nodes and subject to eight different traffic patterns, each summing up approximately 7,000 Erlangs. Details on the networks are found in appendix A of [6]. To enable comparisons to the comparable algorithm (B) of [13, 14], the number of TCs was set to one.[1] The predefined paths required by B were taken as the four most used ones found by A. The unit of capacity was set to 10 circuits for both algorithms.

Results are summarised in table 1. E_{Call} is the loss averaged over all calls in the network, $E_{\text{OD-pair}}$ is the loss averaged over all OD-pairs, U_{tot} is the mean carried traffic per seized unit of capacity and $P_{\text{OD-pair}}$ is the mean number of distinct routes used per

[1]Results on two TCs, voice and frame relaying, are found in [4, 5].

Algorithm	E_{Call}	$E_{\text{OD-pair}}$	U_{tot}	$P_{\text{OD-pair}}$	R_{tot}
A	39 (1.9)	59 (1.8)	64 (5.1)	(1.4)	5 (1.3)
B	25 (2.0)	5 (2.9)	0 (5.0)	(1.2)	3 (1.3)

Table 1: *Comparison of network performance using different DCM-algorithms.*

OD-pair. For each algorithm is given the number of times it produced the *best* result with the *mean* result over all 64 configurations within parenthesis. Loss is expressed in % and utilisation in carried Erlangs per unit of capacity. Finally, R_{tot} is the ratio between the virtual capacities of the rearranged networks and the actual capacities of the physical networks, averaged over all 8 networks.

The table suggests that, for the networks and traffic patterns considered, our algorithm results in a slightly better performance in terms of E_{Call} and even better in terms of $E_{\text{OD-pair}}$. Also, a distinct, slightly higher degree of network utilisation U_{tot} is recorded and we observe equal savings in transmission capacity R_{tot} of about 30% by means of different VP arrangements for different traffic patterns.

3 Applying Dynamic Capacity Management

3.1 Operational Considerations

Changing physical routes and altering capacity assignments of VPs will introduce a need to rearrange calls in progress. New physical routes will result in calls having to be moved from one physical path to another. Rearranging, or repacking, will not be given any further attention here. Altering capacities, however, may result in VPs being forced to drop some calls. Such calls must either be rerouted over tandem nodes or prematurely cleared. Neither of these alternatives are very attractive: The former means increased demands on node processing and transmission capacity, while the latter is unacceptable from subscribers' point of view.

Our policy is to provide one-hop rerouting if this is possible. The alternative route is selected according to the Least Busy Alternative (LBA) strategy [23]: For each pair of trunks between the nodes in question is the highest utilisation computed after which the pair with the lowest maximum utilisation is chosen. Tandem routing over more than one node is prohibited in the interest of utilisation efficiency. Hence, if all two-hop paths are blocked, premature clearing is used as a last resort. Further, rerouting is combined with limited repacking so that, at every network updating point, rerouted calls are moved back to direct routes as far as possible.

3.2 Traffic Dynamics

We consider Poissonian traffics of variable rate. Such a traffic exhibit two kinds of variations, those which follow from the stochastic nature of a Poisson process of constant rate (micro dynamics), and those which are caused by rate variations (macro dynamics). Micro dynamics is thus characterised by rapid, stochastic variations, while macro dynamics is slower and more regular. It follows that micro dynamics requires faster and more frequent network updating than macro dynamics.

Consider a link on which the average occupancy is m and let $T_{k,m}$ denote the expected time elapsed from the moment at which an occupancy of k, $k : k < m$, is detected until the occupancy is again m for the first time [3]. Figure 2 displays $T_{k,m}$ for links with $n = 100$ (left) and $n = 1000$ (right) circuits operating at engineered losses of 0.5%, 1.0%,

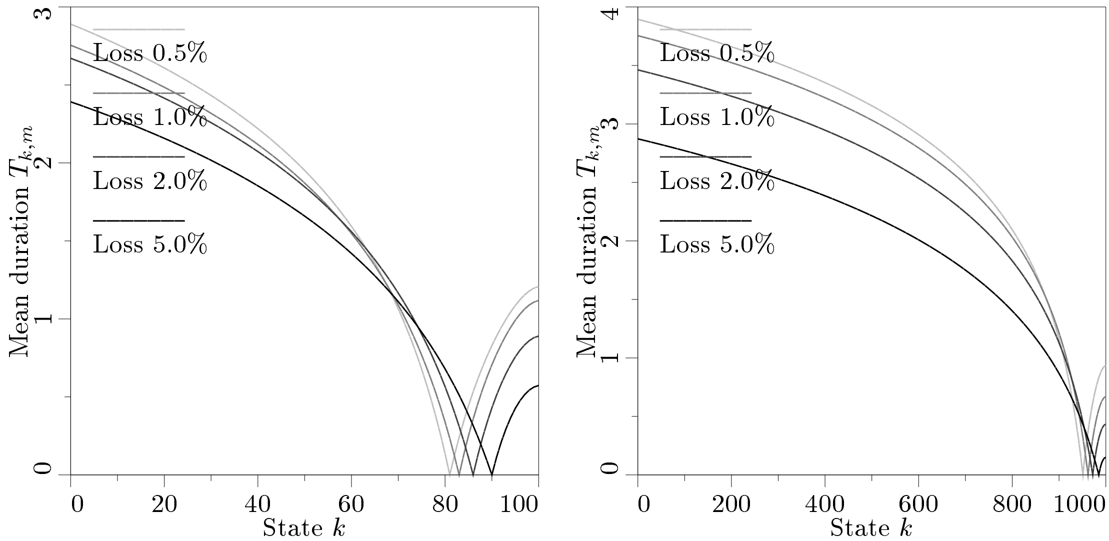

Figure 2: *Expected duration of load states.*

2.0% and 5.0%. It is observed that the expected time required to return to the average point of operation increases up to a maximum of 3 and 4 time units respectively for the largest initial deviation.

Assuming an updating frequency of ten times that of the variations and setting the mean call holding time to 100 s, the numbers above indicate DCM turn-around times of about 10 seconds. However, the design algorithm alone will most likely consume all of this time or more and, moreover, as we will se below, estimating offered traffics with a reasonable accuracy, also takes all of this time or more.

It is concluded that DCM cannot be accomplished in the time scale of micro dynamics. Instead, it appears that solutions traditionally employed to cope with this and other types of variations — various arrangements of overflow systems with alternative routing — would be adequate for rearrangable VP networks too. In fact, applying the two methods in parallel they will compliment each other: DCM rearranges the network on the macro scale and overflow arrangements rearrange calls on the micro scale.

3.3 Traffic Estimation

In a real environment, offered traffics are not known but must be estimated from forecasts and/or on-line measurements. This paper does not address traffic prediction and estimation explicitly, hence we restrict ourselves to giving some limited results on simple on-line measurement techniques and their performance. The focus on on-line measurements is motivated by a wish to device a fully automatic management system.

We distinguish between two methods of on-line traffic estimation: Arrival counting (AC) and carried traffic measurements (CT).[2]

In AC, the number of call attempts received during a measurement interval of length t, $N(t)$, is recorded from which the offered traffic A is estimated as $\hat{A} = N(t)/t$.

Denoting the true, offered traffic by A, we find the expectation E and the variance V of $\hat{A}$ as

$$E\{\hat{A}\} \;=\; A$$

[2] More advanced alternatives include *e.g.* moving average, filtering and adaptive filtering, possibly including forecasting.

$$V\{\hat{A}\} = \frac{A}{t}$$

In CT is the number of busy circuits at time τ, $a'(\tau)$ recorded during an interval of length t, $\int_t a'(\tau)\, d\tau$, from which the carried traffic A' is estimated as $\hat{A}' = \frac{1}{t}\int_t a'(\tau)\, d\tau$. Next, an estimate of the offered traffic $\hat{A}$ of A is computed by "backward Erlang computation", *i.e.* by solving for $\hat{A}$ in $\hat{A}' = \hat{A}(1 - E_N(\hat{A}))$.

First consider an infinite group for which the probability of loss is 0, hence $\hat{A} = \hat{A}'$. We find

$$\begin{aligned} E\{\hat{A}\} &= A \\ V\{\hat{A}\} &= \frac{2A}{t}\left(1 - \frac{1-e^{-t}}{t}\right) \end{aligned}$$

Comparing AC to CT, it is noted that the latter provide better accuracy if $t < 1.5936$.

For a finite group, however, loss is > 0 and $\hat{A} > \hat{A}'$. Given an estimate of $\hat{A}'$, an estimate of the offered traffic $\hat{A}$ may be obtained by solving for $\hat{A}$ in $\hat{A}' = \hat{A}(1 - E_N(\hat{A}))$. We will not attempt to analyse the procedure in detail. In short, $\hat{A}$ computed this way is asymptotically unbiased, but, because of the non-linearity of the Erlang loss function, it has a positive bias for finite observation intervals. In conclusion, AC is chosen as our estimation method.

3.3.1 Observation Interval

We turn to the problem of selecting a proper observation interval $t = t_{\mathrm{M}}$ for AC. Consider the traffic model in figure 3. Call arrivals follow a Poisson process the rate of which changes every Tth time unit. The arrival process is monitored for t_{M} time units after which the result is reported to the NMC where a new network design is computed in t_{E} time units. Hence, when completed, a network design is based on information the age of which spans from t_{E} to $t_{\mathrm{E}} + t_{\mathrm{M}}$.

We define the optimal observation interval as the one for which the expected, squared error of an estimate takes its minimum,

$$t_{\mathrm{M}}^{\mathrm{opt}} = \min_{t_{\mathrm{M}}} E\{(\hat{A} - A_k)^2\}$$

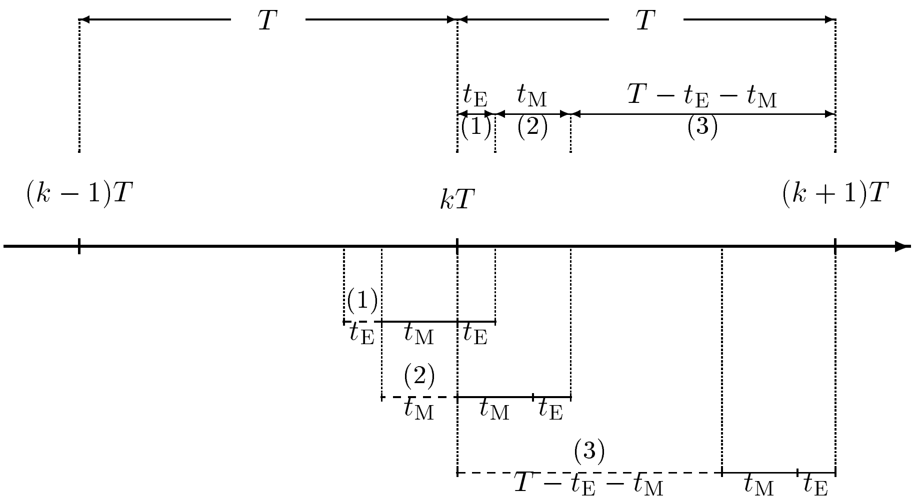

Figure 3: *Model for estimating a variable traffic.*

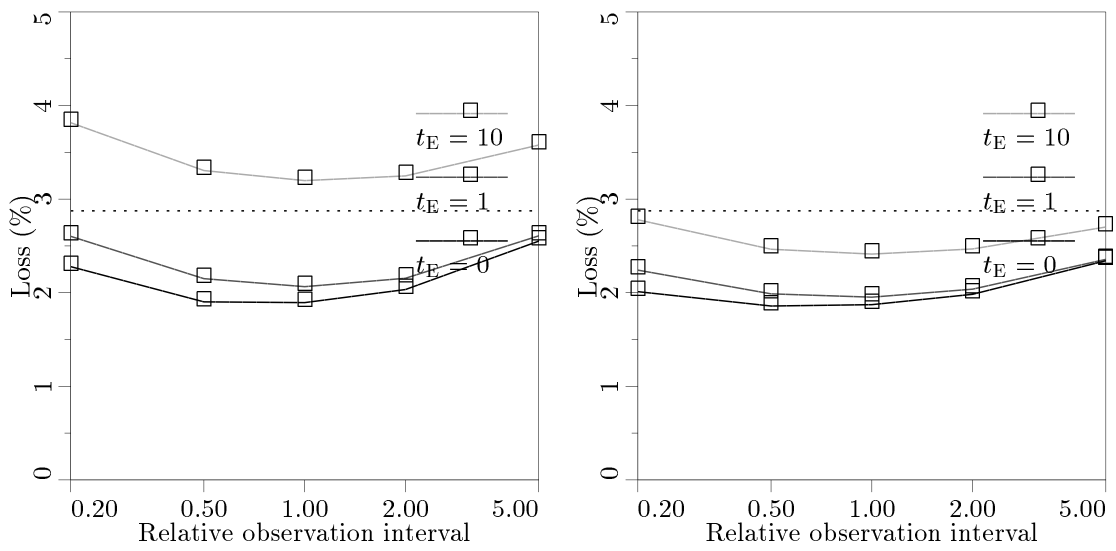

Figure 4: *Network loss versus observation interval for different durations of stable states.*

where A_k is the offered traffic during interval k. We find

$$t_M^{opt} = \frac{\sqrt{3A_kT + 3(A_{k-1} - A_k)t_E}}{|A_{k-1} - A_k|}$$

If the difference between A_{k-1} and A_k is small, we may get $t_M^{opt} > T - t_E$, a result for which our model is not valid. In this case, a sequence of more than two traffics must be considered to find the optimal observation interval. We refrain from this, but simply set t_M^{opt} as the minimum of $T - t_E$ and the above.

Extending the result to networks, and assuming cyclic traffic sequences for each OD-pair, we compute t_M^{opt} for each OD-pair and each interval k and compute an overall t_M^{opt} by weighting over the expected, absolute errors.

Figure 4 shows loss as a function of t_M/t_M^{opt}, as observed in simulations, for the same networks as in table 1 with $T = 20$ (left) and $T = 50$ (right) respectively. Solid lines refer to different values of t_E and dotted lines to networks which are permanently dimensioned for average traffics and for which no updating takes place.

We observe an overall insensitivity to t_M^{opt}: Setting t_M to $t_M^{opt}/2$ or $2t_M^{opt}$ has very little impact on loss. Another aspect of the robustness is that similar curves are obtained from simulations in which traffics are changed over 10 (for $T = 20$) and 20 (for $T = 50$) units of time respectively rather than at distinct points. Looking at $t_E = 10$ and $T = 20$, it is also noted that if the network updating time t_E is too long compared to the variations T, average dimensioning will perform better than repeated updating.

In a real network, T are A_k are neither known, nor do they actually exist. T can, however, be regarded as a target reflecting DCM ambitions. Further, fixing T to one hour, it is reasonable to assume that one would have a fair idea of average traffics per hour and OD-pair for a complete 24 hour period. From figure 4, it is concluded that the difference between "a fair idea" and the exact value is of no great importance.

4 Conclusions

VPs and DCM are two important issues in a broadband network based on ATM and/or SDH. We have presented an algorithm for DCM and discussed the application of DCM to a real network.

The concepts of micro and macro variations were introduced and it was concluded that DCM is limited to the latter. Two simple methods of on-line estimation of offered traffic were considered: direct by arrival counting and indirect by backward Erlang from carried traffic. We decided on the former since the latter provides biased estimates for finite observation intervals.

Next, an optimal observation interval for arrival counting was determined. It was found that the choice of observation interval for a complete network over a long period of time is not critical.

We have seen that less capacity is required to provide the same degree of service if DCM is used (table 1), or that the degree of service may be improved by improved by means of DCM (figure 4). It it thus concluded that DCM is well suited to meet "slow" variations in traffic, *i.e.* changes which take place on a time scale of several mean call holding times.

The present account is very condensed due to spatial restrictions. A more detailed version may be obtained from the author.

5 Further Work

The results presented above only represent a sample of important issues related to DCM algorithms and application strategies. The present paper, which is a part of a long term project, reports on results achieved so far. Further areas include, but are not limited to,

- Detection threshold under which successive samples are interpreted as originating from the same traffic and accumulated in order to reduce variance.
- Comparing alternate routing to DCM and study DCM-networks on which alternate routing is used.
- Speed improvement. There are numerous ways tio improve speed, all of which need to be evaluated.
- Exclusion of smaller traffics from individual VPs, but overflowing them to a network of highly efficient VPs for major OD-pairs.
- Algorithms for traffic estimates, their parameters and performance also require further attention.

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