MTPT 2006

Leiria, September 2006

A multiobjective routing optimisation framework for multiservice networks- a heuristic approach

(part - I)

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Summary

- **Overview of explosive evolution of network technologies - new challenges and issues for OR**
- **Why multicriteria modelling is an actual issue in telecommunication network routing**
- **A multiobjective routing optimisation framework for multiservice networks :**
  - ***Why multicriteria routing models***
  - ***Overview of multicriteria routing approaches***
  - ***MODR-S - a multiobjective dynamic routing method for muliservice networks***
  - ***A general multiobjective routing framework for MPLS networks***
- **Future trends and issues**

1

Overview of major trends in network evolutions

Major Trends

- Driven by (*cf*. [El Sayed & Jaffe, 02], […..,0?]):

  - **very fast pace of technological evolution**

  -traffic growth:

  - rate of 60-80% in 2000/01 for IP traffic
  - 9% and 14% annual growth, in value, for Internet and mobile services in 2000/04)

  - **demand for new services** (namely broadband services)

  - **rapid liberalization since the 90's**

Mega Technological Trends:

- The convergence of **Internet** wired infrastructure towards an **intelligent optical network**

supporting technologies:

-*MPLS/GMPLS* (new multiservice Internet technologies)

-*DWDM* combined with new OXCs (very high capacity optical transport technologies in the order of 10^{12}=Tb/s).

- The evolution of **3G+ wireless** network in the direction of an **all IP converged network**

◈ Major Technological Trends (cont.)

- The <u>increasing relevance</u> of **multidimensional QoS** (Quality of Service) issues in the new technological platforms.

◈**Evolution of Network Architectures** [*cf.* Banergee *et al.*,01] - functional layers technologies evolution….>>

From

- IP over ATM over SDH over DWDM (Dense Wavelength Division Multiplexing).

*... **To***

- IP/GMPLS directly DWDM (with full optical switching)

2

Why Multicriteria Analysis ?

◈ Why Multicriteria Analysis ?

Generic factors to be considered for the development of OR tools:

✓ **Extremely fast pace and sometimes unpredictable rhythm of technological innovation**

✓ **Increasing demand for new and innovative services of different types required by residential and business subscribers**

✓ **A decisive change in market structures characterized by a steady transition to full liberalization and increasing competition among operators of different networks and services**

✓ **Planning and management decision processes may involve various decision agents and negotiation processes**

◈ Why Multicriteria Analysis ?

Generic factors to be considered for the development of OR tools (cont.):

- ✓ **distributed character of networks and services**

- ✓ **The emphasis on the short range in opposition to traditional “long-range” perspective**

- ✓ **The great uncertainty associated with these factors**

◈ Why Multicriteria Analysis ?

- **In particular MCDA models can be very useful in the new network platforms (e.g: in MPLS/GMPLS or DWDM optical networks) having in mind the increasing relevance of multidimensional issues, in particular those which refer to QoS and economic factors.**

◈ Why Multicriteria Analysis ? (cont.)

Major advantages:

✓ **It enables the OR models used for decision support to become more realistic and effective by reflecting explicitly different evaluation criteria.**

✓ **To enable the decision maker to grasp more easily the conflicting nature of the criteria and the trade-offs to be made in order to find a satisfactory compromise solution.**

▪ **In Multicriteria Analysis the concept of optimal solution gives place to the concept of *nondominated solution*: *feasible solutions for which it is not possible to improve on any criteria/objective without sacrificing on at least one of the others***

3

A multiobjective routing optimisation framework for multiservice networks

3.1 WHY MULTICRITERIA ROUTING MODELS ?

- Classical formulations of the problem in circuit-switched networks seek to optimise network cost while satisfying certain grade of service (GoS) constraints or to optimise GoS criteria under network cost constraints.

- In traditional packet-switched data networks routing aims at optimising a single metric, such as hop count or delay, generally based on shortest path algorithms.

- **Modern multiservice network functionalities deal with multiple, heterogeneous GoS requirements.**

WHY MULTICRITERIA ROUTING MODELS ? (cont.)

▪ A new routing concept - **QoS routing** - involves the calculation of a path satisfying certain GoS requirements and seeking simultaneously to optimise the associated metrics

⇒ In common QoS routing models path selection is generally formulated as a shortest path problem with a single objective function, either a single metric or a single function encompassing different metrics.

QoS requirements can be incorporated into these mathematical models by means of additional constraints:

⇒ destroys the network structure

⇒ heavier computational burden

WHY MULTICRITERIA ROUTING MODELS ?(cont.)

THERE ARE ADVANTAGES IN CONSIDERING THE ROUTING PROBLEM SUBJECT TO MULTIPLE CONSTRAINTS AS A MULTIPLE CRITERIA PROBLEM:

1. Besides cost, other aspects, namely QoS parameters, such as delay, blocking probability, bandwidth or jitter can be **addressed explicitly by the mathematical model** as objective functions which could be pursued to their optimum extent.

WHY MULTICRITERIA ROUTING MODEL?(cont.)

2. Multiple objective routing models enable to grasp in a rationalised manner the trade-offs among distinct QoS requirements and conflicting objectives.

$\Rightarrow$ QoS requirements may be expressed as adittional constraints

3.2 OVERVIEW of MULTICRITERIA ROUTING APPROACHES

⇒ From a **methodological** point of view we may distinguish:

I - "Mitigated approaches"

(a) Constraint-based QoS routing models, where all the criteria except one (which is taken as objective function) are transformed into side constraints, *e.g. shortest path constrained models* (see [Kuipers el, *2002a,b*])

(b) Models based on the *a priori* articulation of preferences in the path selection, *e.g.* widest-shortest and shortest-widest approaches, see *e.g.* in [G. Hasslinger and S. Schnitter, 03]

OVERVIEW of MULTICRITERIA ROUTING APPROACHES cont.

II - More explicit multicriteria approaches, as in**:**

(a) [Antunes *et al* , 99] - A static routing problem formulated as a bi-objective shortest path problem

(b) [Craveirinha *et al*, 01], [Martins *et al*, *03,05,06*]- network multiobjective hierarchical dynamic routing models based on a bi-objective constrained shortest path algorithm

(c) [Pornavalai *et al*, 98], [Clímaco *et al*, *03,04,05*],- Multicriteria routing models for multimedia applications in multiservice networks, applied to a node to node video traffic routing problem, formulated as a bi-objective shortest path problem with multiple constraints

(d) [Thirumalasetty and Medhi ,01] - A new routing problem in MPLS networks concerning "look ahead" guaranteed services

OVERVIEW of MULTICRITERIA ROUTING APPROACHES cont.

II - More explicit multicriteria approaches (cont.) examples

(e) [Knowles *et al*, 00], [Erbas, S. and Erbas, C. 03] - multiobjective formulations for QoS “off-line” routing models with application to MPLS networks, using evolutionary algorithms

(f) [Resende and Ribeiro *et al*, 03] - A bi-objective model for a private virtual circuit routing problem in the Internet

(g) [Aboella and Douligeris, 99] - A multiple objective routing model for B-ISDN (based on ATM), using a fuzzy optimisation approach

OVERVIEW of MULTICRITERIA ROUTING APPROACHES cont.

II - More explicit multicriteria approaches (cont.)

(i) [Anandalingam and Nam, 97] - A game theoretic approach to deal with a dynamic alternative routing problem in international circuit-switched networks

(j) [Zhu, 00] - A multiple objective approach to deal with a specific routing problem in WDM optical networks

(k) [Akkaren and Nurminem, 01] - Regarding multicriteria analysis, the authors develop a routing optimisation model involving a trade-off between route length and disjointness

OVERVIEW of MULTICRITERIA ROUTING APPROACHES cont.

⟹ From the point of view of the **routing modelling framework** we may distinguish:

❑ Routing **optimisation framework**:

- **Network-wide**: where the objective function(s) depend explicitly on all network traffic flows *(e.g. total expected revenue, network average blocking probability, network average blocking probability, network average packet delay)*

- **Flow-oriented**: where the objective function(s) are formulated at the level of each node-to-node traffic flow separately *(e.g. end-to-end flow blocking probability, mean end-to-end packet stream delay)*

OVERVIEW of MULTICRITERIA ROUTING APPROACHES cont.

- **Nature of the model** in terms of several instances:

• **key features of the underlying routing system** *(e.g. on-line/off line; static/dynamic; point-to-point/multipath routing)*

• **specified objective functions** and constraints and their technical-economic meaning

OVERVIEW of MULTICRITERIA ROUTING APPROACHES cont.

❑ **Nature of the model** in terms of several instances (cont.):

- **representation of the traffic to be routed** concerning:

  ❖ **level/granularity** of the representation (*e.g.traffic flow/"call" or connection request)*

  ❖ **nature of the representation***:*

  ➢ **deterministic** *(typical in multicommodity network formulations)*

  ➢ **stochastic** *(using some form of point process approximation to model the traffic flows)*

3.3 MODR-S - a multiobjective dynamic routing method for multiservice networks

Having in mind that:

• **Multiple objective routing** models enable to grasp eventual trade-offs among distinct QoS requirements and conflicting objectives.

• **Network-wide optimisation** models enable an integrated representation of all the traffic flows in the network and their interactions

• **Dynamic routing** has a significant impact on network performance and cost, namely considering time varying traffic patterns, overload and failure conditions

MODR-S (cont.)

• It is desirable, in multiservice networks to represent and distinguish, in terms of relative importance, **objective functions formulated at network level and at service level**

⟹ A **Multiobjective Dynamic Routing Method** for single service (MODR) and multiservice networks (**MODR-S**) was developed by our research team, that is described in: [Craveirinha *et al*. 03,], [L. Martins *et al*. 03,04, 05, 06].

MODR-S (cont.)

Next:

• A review of the **hierarchical multiobjective routing model** (basis of MODR-S).

• Analysis and discussion of the issues related to the great **complexity** of the model and to other sources of **imprecision** and **uncertainty** in this model.

• Overview of the main features of a **heuristic approach** enabling the effective treatment of those issues when searching for ‘good’ compromise network routing solutions.

Main features of MODR-S

- it is based on a **bi-hierarchical multiobjective network-wide optimisation** model

- it is a new type of ***periodic state dependent*** routing method, with alternative routing

- present formulation for networks equivalent, in the traffic plane, to multirate loss networks, uses ***implied costs*** and ***blocking probabilities*** as path metrics, in the search for candidate paths

Main features of MODR-S (cont.)

- a ***heuristic procedure*** is used to obtain ‘good’ compromise routing solutions for every node-to-node network flow of different service classes.

- this heuristic is based on the resolution of a ***bi-objective constrained shortest-path problem***, for obtaining candidate alternative paths for each traffic flow.

- This problem is solved by a very efficient algorithm (**MMRA-S**) based on the ***k-shortest path algorithm*** (*MPS*- [Martins *et al*, *99*] to compute non-dominated solutions

  - it uses, in this context, *dynamically changing preference regions* in the search for a sequence of R candidate alternative solutions (paths) for each O-D pair.

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL

Basis of the Model:

Periodic state dependent routing method where

$R_t(f_s) = \{r^1(f_s), r^2(f_s), ..., r^M(f_s)\}$ - ordered set of paths (or routes) which may be used by traffic flow f_s in time t ($M = 2$)

$R_t(s) = \cup_{all\, f_s \in F_s} R_t(f_s)$

$\overline{R}_t = \cup_{s=1}^{|S|} R_t(s)$

Change periodically as a function of a measure of

$A_t(f_s)$ - traffic offered by flow f_s from v_s to $v_t \in V$ at period t (in Erlangs)

$A_s^o = \sum_{f_s \in F_s} A_t(f_s)$ - total traffic offered by service s

A_s^c - total traffic carried by service s

$\overline{A_t} = \left(A_t(f_{i_j})\right)_{i,j}$

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

$B(f_s)$ - the mean point-to-point blocking probability for traffic flow f_s

d_{ks} - bandwidth required by service *s* calls on link l_k
(effective bandwidth)

$w(f_s)$ - expected revenue for an accepted call of traffic flow f_s

$$W_s = \sum_{f_s \in F_s} A_t(f_s)(1 - B(f_s))w(f_s)$$

Lets consider, for tractability purposes that:

$$d_{ks} = d_s \ (\forall l_k \in L \wedge \forall s \in S) \text{ and } w(f_s) = d_s, (\forall f_s \in F_s \wedge \forall s \in S)$$

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

• A **dynamic alternative routing problem** for multiservice networks is formulated as a **bi-level multiple objective optimisation problem**:

(Problem $\mathcal{P}^{(2)}_{G_2}$)

$$NL: \quad \min_{\overline{R}_t} \quad -W_T = -\sum_{s \in S} d_s A^c_s = -\sum_{s \in S} d_s A^o_s (1 - B_{ms})$$

$$\min_{\overline{R}_t} \quad B_{Mm} = \max_{s \in S}\{B_{ms}\}$$

$$SL: \quad \min_{\overline{R}_t(s)} \quad B_{ms} = (A^o_s)^{-1} \sum_{f_s \in F_s} A_t(f_s) B(f_s), \quad s = 1, 2, \ldots, |S|$$

$$\min_{\overline{R}_t(s)} \quad B_{Ms} = \max_{f_s \in F_s}\{B(f_s)\}, \quad s = 1, 2, \ldots, |S|$$

s.t. equations of the teletraffic model enabling to calculate $\{B(f_s)\}$ in terms of $\{A_t(f_s)\}$ and $\overline{R}_t$

- **network level** objectives (NL) have priority over **service objectives** (SL)

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

• in this formulation of a bi-level multiple objective optimisation problem:

▪ **network level** objectives:

W_T= ***total expected revenue*** associated with the traffic carried of all the different services

B_{Mm}= ***maximum of the average blocking probabilities*** of all the different services

- this is a *fairness* objective at network level ie referring to all network services

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

- **service level** objectives:

B_{ms}= ***average blocking probability for traffic flows of service type s*** ε *S*

B_{Ms}= ***maximum of the blocking probabilities $B(f_s)$*** of the traffic flows of service type s

- this is a *fairness* objective at service level ie referring to all traffic flows of each type of service

➢ **network level** objectives (NL) *have priority* over **service objectives** (SL)

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

• The calculation of candidate paths is based on a ***bi-objective shortest path model*** which uses as metrics **implied cost** and **blocking probability**:

(Problema $\mathcal{P}^{(2)}$)

$$\min_{r \in \mathcal{D}(f)} \; m^n(r) = \sum_{l_k \in r} m_k^n \quad n = 1, 2$$

where:

$m_{ks}^1 = c_{ks}$ (*implied cost* resulting from the acceptance of a call of flow f_s in link l_k)

$m_{ks}^2 = -\log(1 - B_{ks})$ (*blocking probability* of a call of flow f_s on link l_k)

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

• The ***implied cost*** *resulting from the acceptance of a call of flow f_t in link l_k* is a powerful mathematical concept in routing optimisation, was originally proposed by [Kelly , 88] and extended to single route multirate traffic networks [Faragó *et al.*, *95*, *Mitra et al.*, *99*]

✓it is the expected value of the loss of revenue in all network traffic flows which may use link l_k resulting from the acceptance of a call from f_t associated with the decrease on the capacity of the link

✓*Conjecture:* we propose the adaptation of this concept to multirate networks with (one-stage) alternative routing, leading to:

$$c_{kt} = \sum_{s} (1 - B_{ks})^{-1} \zeta_{kts} [\sum_{f_s : l_k \in r^1(f_s)} \lambda_{r^1(f_s)} (s_{r^1(f_s)} + c_{ks}) + \sum_{f_s : l_k \in r^2(f_s)} \lambda_{r^2(f_s)} (s_{r^2(f_s)} + c_{ks})]$$

$$s_{r^2(f_s)} = w(f_s) - \sum_{l_j \in r^2(f_s)} c_{js}$$

$$s_{r^1(f_s)} = w(f_s) - \sum_{l_j \in r^1(f_s)} c_{js} - (1 - L_{r^2(f_s)}) s_{r^2(f_s)}$$

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

$s_{r^i(f_s)} =$ surplus value of a call on route $r^i(f_s)$ (i = 1,2)

$\lambda_{r^i(f_s)} =$ marginal traffic of flow f_s carried in route $r^i(f_s)$

$\mathrm{B}_{\mathrm{ks}} =$ blocking probability of calls of service s on link l_k :

$$\mathrm{B}_{\mathrm{ks}} = \Gamma_s(\overline{d_k}, \overline{\rho}_k, C_k)$$

Γ_s represents the traffic calculation procedure, based on an adequate traffic model that enables the computation of the B_{ks}

$\zeta_{kts} =$ increase in the blocking probability for type s calls on link l_{k} because of the acceptance of a type t call :

$$\zeta_{kts} = \Gamma_s(\overline{d_k}, \overline{\rho}_k, C_k - d_t) - \Gamma_s(\overline{d_k}, \overline{\rho}_k, C_k)$$

$\overline{d_k}, \overline{\rho}_k$ are the vectors of efective bandwidths $[\mathrm{d}_{\mathrm{ks}}]$ and marginal traffics $[\rho_{\mathrm{ks}}]$ on link l_k

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

$L_{r^i(f_s)} =$ blocking probability on route $r^i(f_s)$:

$$L_{r^i(f_s)} = 1 - \prod_{f_s \in r^i(f_s)} (1 - B_{js})$$

assuming that routes $r^1(f_s)$ and $r^2(f_s)$ are disjoint:

$$\lambda_{r^1(f_s)} = A_t(f_s)(1 - L_{r^1(f_s)})$$

$$\lambda_{r^2(f_s)} = A_t(f_s) L_{r^1(f_s)} (1 - L_{r^2(f_s)})$$

- a simplified traffic model to calculate these parameters, based on the [Kaufman, 81] and [Roberts, 83] iterative algorithms enabling the estimation of the B_{ks} is shown in [L. Martins *et al*, *03*]

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

- For the computed implied cost and blocking probability coefficients the candidate paths for each $R_t(f_s)$ are obtained by resolving the **bi-objective shortest path** problem previously presented:

$$(\text{Problema } \mathcal{P}^{(2)})$$

$$\min_{r \in \mathcal{D}(f)} \; m^n(r) = \sum_{l_k \in r} m_k^n \quad n = 1, 2$$

Where for each $r(f_s)$ of a given flow f_s of service type s:

$$m_{ks}^1 = c_{ks} \qquad\qquad m_{ks}^2 = -\log(1 - B_{ks})$$

The log function is just used to obtain an additive metric m^2

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

- This problem $P^{(2)}$ is tackled by a very efficient algorithmic approach designated as **MMRA-S** (Modified Multiobjective Routing Algorithm), enabling to calculate a candidate solutions for $R_t(f_s)$

- $P^{(2)}$ is a particular case of the **multiobjective shortest path problem** for multimedia networks:

$$\min_{p \in D} m^n(p) \quad \mathrm{n} = 1, 2, \ldots, \mathrm{M}$$

where D is the feasible solution set

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

✓ The aggregation function to compute the value of a path p with respect to the metric m^n depends on the type of metric:

- The metric is additive if $$m^n(p) = \sum_{l_k \in p} m_k^n(p)$$

- The metric is multiplicative if $$m^n(p) = \prod_{l_k \in p} m_k^n(p)$$

- The metric is concave if $$m^n(p) = \min_{l_k \in p} m_k^n$$

OVERVIEW OF THE MULTIOBJECTIVE DYNAMIC ROUTING MODEL (cont.)

- **Delay, hop-count** and **cost** follow the additive aggregation function.

- **Path bandwidth** (*bottleneck bandwidth*) and throughput use the concave aggregation rule.

- **Blocking probability** metric can be transformed into an additive metric:
  value for arc l_k<>$-\log(1-B_k)$

FEATURES of MMRA -S

i) It uses a very **efficient sub-algorithm for calculating k-shortest paths,** a variant of **MPS** [Martins et al, 99] for paths with a maximum number of arcs, that is applied to a convex combination of the 2 objective functions, enabling the search for non-dominated (supported or unsupported) solutions

i) **Automatic representation of the system of preference** : it uses **preference thresholds** as a tool for ordering and selecting solutions in the bi-objective shortest path model, in the form of <u>required</u> and/or <u>accepted values</u> for each metric which define **preference regions** in the objective function space

ii) The **preference regions** for alternative path selection **are dynamic** ie have a flexible configuration that varies in time, reflecting current network working conditions.

iv) It allows the selection of two candidate paths for each traffic flow f_s

FEATURES of MMRA -S (cont.)

- Resolution of this static routing problem aims at finding a "best" compromise path
- Nondominated solutions can be computed by optimizing the scalar function ***z***:

$$z = \varepsilon_1 m^1(r) + \varepsilon_2 m^2(r)$$

•The search for non-dominated solutions located in the interior of the convex-hull follows the algorithm approach [Antunes *et al.*, *99*] that uses an extremely efficient *k*-shortest path algorithm, MPS [Martins *et al.*, 99]

FEATURES of MMRA -S (cont.)

•An example of the working of this sub-algorithm, using as metrics **delay** and **cost** (e.g. in packet-switched network):

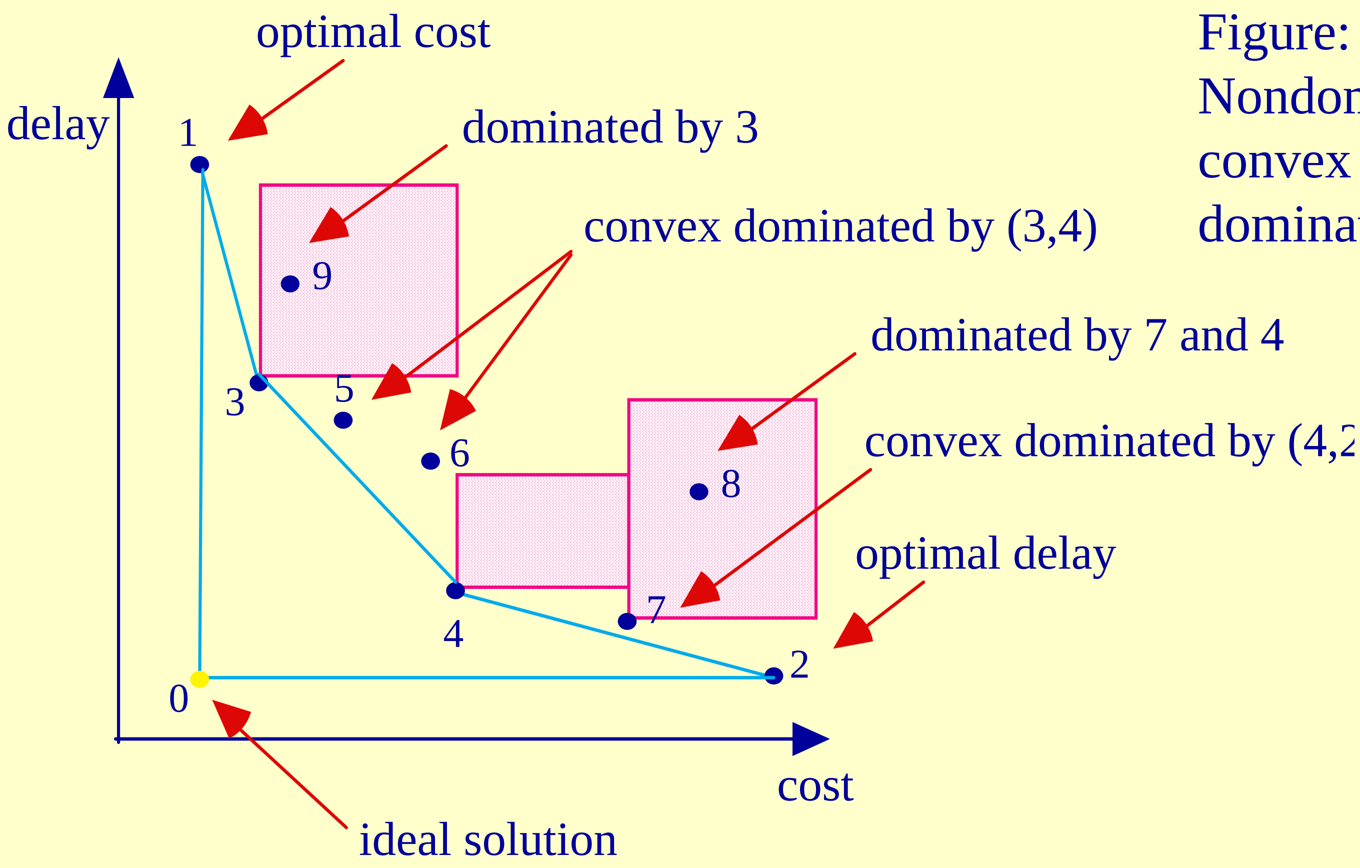


Figure:
Nondominated, convex dominated and dominated solutions

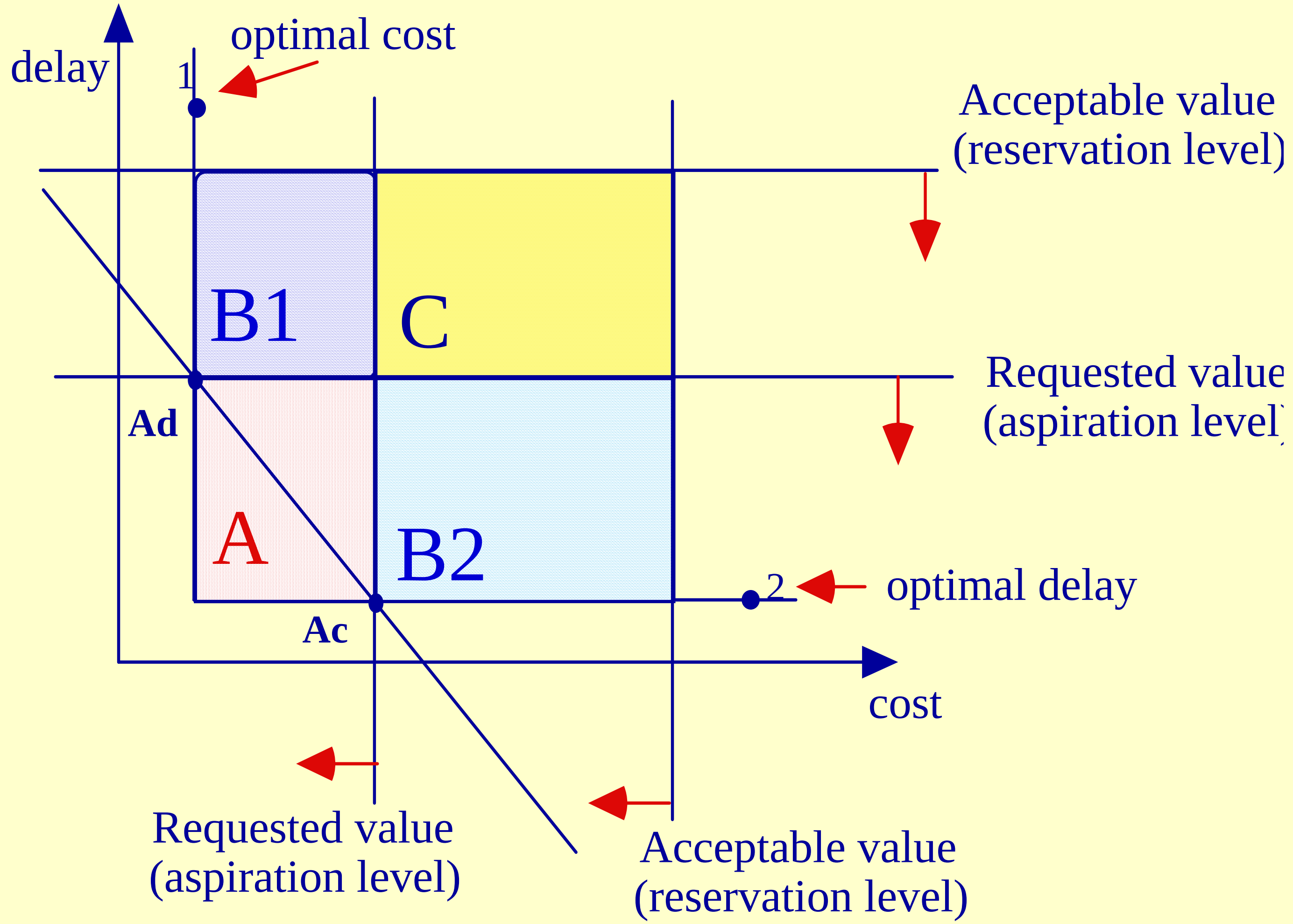
FEATURES of MMRA -S (cont.)

- **Preference thresholds** (sometimes designated as soft constraints i.e. constraints not directly incorporated in the mathematical formulation) are defined: in terms of **requested** (aspiration level) and **acceptable** (reservation level) thresholds for each metric, which define **preference regions** in the objective function space.

- These regions are then searched to determine satisfactory compromise paths (if they exist) respecting those preference thresholds

FEATURES of MMRA -S (cont.)

Example of definition of priority regions:



FEATURES of MMRA -S (cont.)

FEATURES OF THE ALGORITHMIC APPROACH
(two-objective case)

1 The nondominated solutions which optimise each objective function are computed, by solving 2 scalar shortest path problems (Dijsktra Alg.)

2 QoS requirements for each of those metrics are specified by means of the thresholds:

- requested value (aspiration level): Mreq

- acceptable value (reservation level):
  Macc (Mreq<Macc).

FEATURES of MMRA -S (cont.)

FEATURES OF THE ALGORITHMIC APPROACH
(two-objective case)

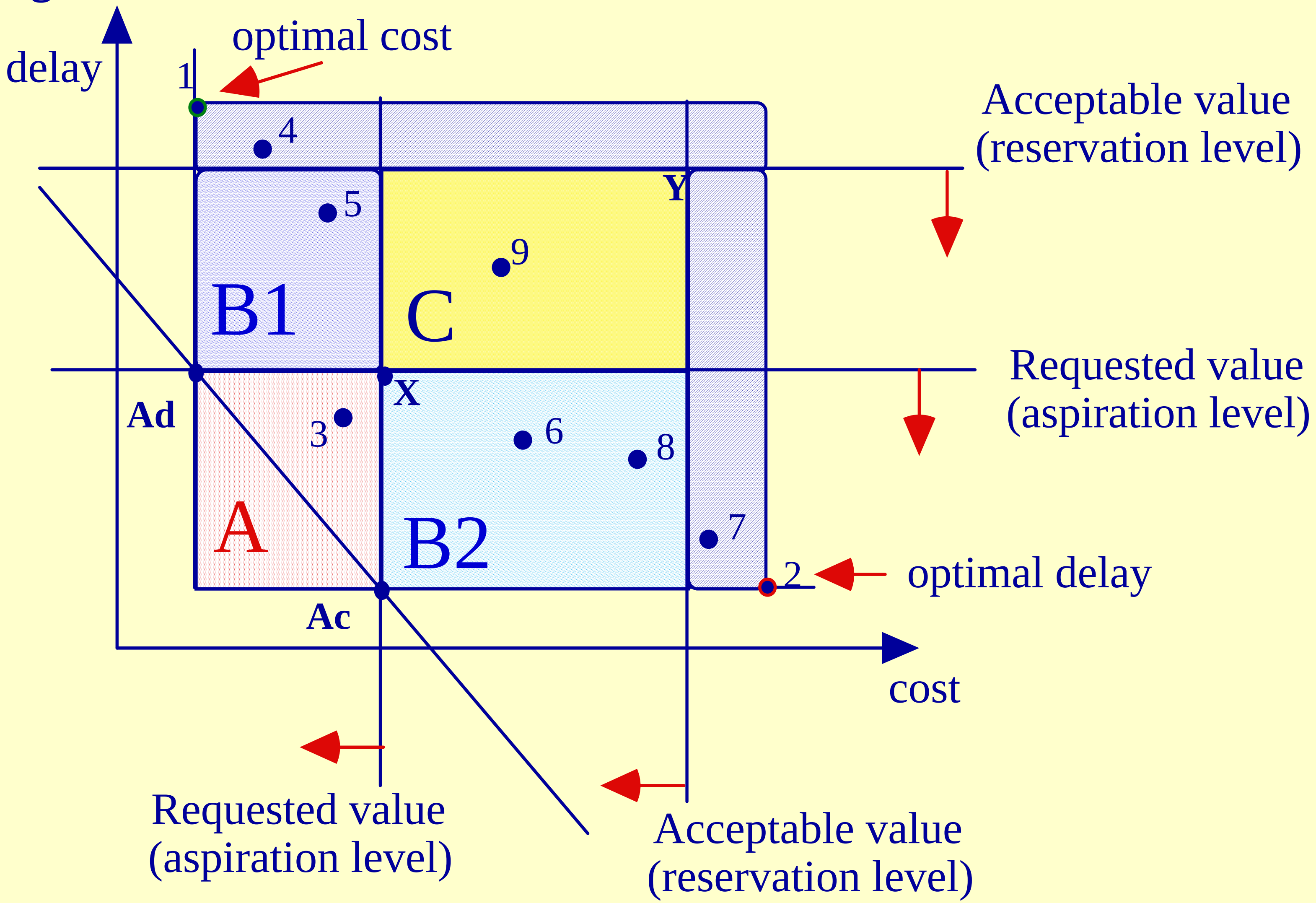
3 The auxiliary o. f. which is used to search for nondominated solutions is a weighted sum of the original o.f.s where the weights are calculated from the optimal solutions and the requested metric values(*e.g*. see isocost line passing through Ac and Ad in next figure)

FEATURES of MMRA -S (cont.)

- FEATURES OF THE ALGORITHMIC APPROACH

(two-objective case)

Example of calculated solutions and priority regions:



FEATURES of MMRA -S (cont.)

FEATURES OF THE ALGORITHMIC APPROACH
(two-objective case)

Bandwidth requirements:

Consideration of **bandwidth (or throughput)** as metrics implies preference thresholds for bandwidth in terms of the thresholds - requested value b_{req} and acceptable value b_{ac}

✓This algorithmic approach can be easily adapted to this type of metric with concave aggregation rule, by prunning all links which do not satisfy the considered requirements.

The Route Calculation Algorithm MMRA-S

It is a variant of the previous algorithm:

- computes and selects non-dominated and, in some cases, dominated paths for alternative routing purposes

- uses as basic sub-algorithm a very efficient k-shortest path algorithm constrained on the maximum number of arcs per path [T. Gomes *et al, 01*]

- the preference regions for path selection vary dynamically with the objective function coefficients, reflecting diverse network woking conditions

The Route Calculation Algorithm MMRA-S (cont.)

Preference Regions

required values and aceptable values for each service type s:

$$B_{av}(s) = \frac{1}{|L|}\sum_{l_k \in L} B_{ks} \qquad c_{av}(s) = \frac{1}{|L|}\sum_{l_k \in L} c_{ks}$$

D = maximal number of arcs per path

Blocking probabilities:

$$B_{req}(s) = 1-(1-B_k^-(s))^D \quad B_{acc}(s) = 1-(1-B_k^+(s))^D$$

$$B_k^-(s) = B_{av}(s) - \Delta B_k(s) \quad B_k^+(s) = B_{av}(s) + \Delta B_k(s)$$

$$\Delta B_k(s) = (B_{av}(s) - \min\{B_{ks}\})/2$$

Implied costs:

$$C_{req}(s) = Dc_k^-(s) \quad C_{req}(s) = Dc_k^+(s)$$

$$c_k^-(s) = c_{av}(s) - \Delta c_k(s) \quad c_k^+(s) = c_{av}(s) + \Delta c_k(s)$$

$$\Delta c_k(s) = (c_{av}(s) - \min\{c_{ks}\})/2$$

The Route Calculation Algorithm MMRA-S (cont.)

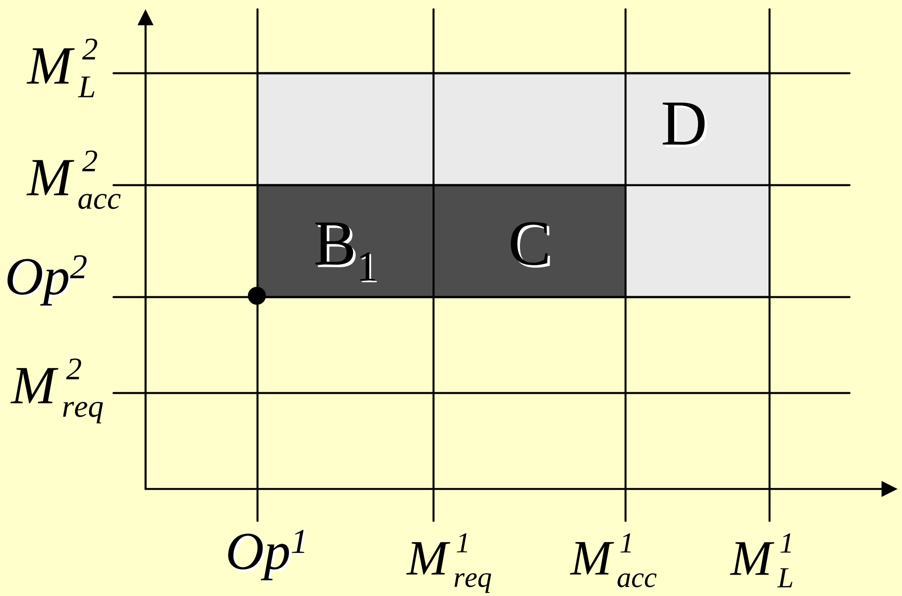
Preference Regions - Example

A $\rightarrow$ where M^{n}_{req} and M^{n}_{acc} are satisfied (n=1,2)

$B_n \rightarrow$ M^{n}_{req} is satisfied but only M^{m}_{acc} ($m \neq n$) is satisfied

C $\rightarrow$ M^{n}_{acc} is satisfied but not M^{n}_{req} (n=1,2)

D $\rightarrow$ last choice region: M^{n}_{acc} is not satisfied (n=1,2); it covers the space exterior to B_n, C up to the more relaxed bound M^{n}_{L} for z^n



$Op^1 < M^{1}_{req} < M^{1}_{acc}$; $M^{2}_{req} < Op^2 < M^{2}_{acc}$

• represents the ideal optimum

Estimation of the metric coefficients in P$^{(2)}$

➢ The used approach was to calculate the coefficients from the network teletraffic model using as input estimates of the point to point traffic offered of each service type obtained from periodic measurements, by recurring to a first order moving average iteration:

$$\tilde{x}_{f_s}(n) = (1-b)\tilde{x}_{f_s}(n-1) + b\tilde{X}_{f_s}(n-1)$$

$\tilde{x}_{f_s}(n)$ = estimated traffic offered of flow f_s in the n^{th} time interval

$\tilde{X}_{f_s}(n-1)$ = estimate of the offered traffic of f_s obtained from real-time measure

in the previous $(n-1)^{th}$ interval

The Route Calculation Algorithm MMRA-S (cont.)

EXAMPLE OF APPLICATION of MMRA-for a single service case

- Fully-meshed 6 node circuit-switched network dimensioned for B_m=0.5% (average node to node congestion for single-channel traffic); R=2; D=2

- Search direction associated with $z = 45^0$

Node Pair	Direct link capac.	Offered traffic	Intermediate node
1-2	36	27	3
1-3	13	6	4
1-4	33	25	5
1-5	27	20	6
1-6	31	20	2
2-3	29	25	4
2-4	17	10	5
2-5	37	30	6
2-6	25	20	1
3-4	17	11	5
3-5	14	8	6
3-6	19	13	1
4-5	13	9	6
4-6	27	20	1
5-6	18	12	1

Table: Network of the application example

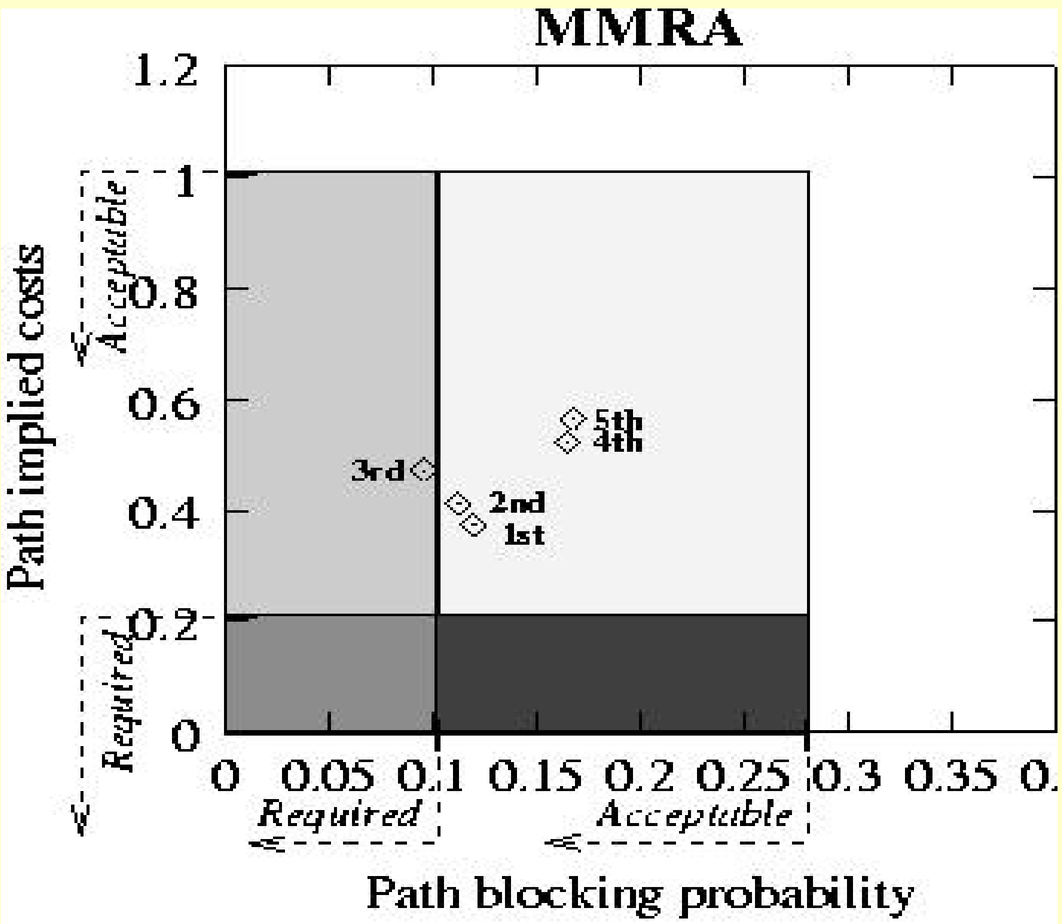
EXAMPLE OF APPLICATION of MMRA-for a single service case

Case a): **Network with 5% overload**

➢ **NOTE**: the direct link whenever exists is always selected for r^1 MMRA is just used to obtain candidate paths for r^2

i	Blocking	Implied Cost	Generated paths	Selected paths	Type	Preference region type
1	0.119621	0.371881	$2 \rightarrow 3$	$r^1(f)$	non-dominated	C
2	0.112106	0.410792	$2 \rightarrow 1 \rightarrow 3$		non-dominated	C
3	0.0953536	0.471365	$2 \rightarrow 5 \rightarrow 3$	$r^2(f)$	non-dominated	B_1
4	0.164738	0.521878	$2 \rightarrow 6 \rightarrow 3$		dominated	C
5	0.167548	0.563675	$2 \rightarrow 4 \rightarrow 3$		dominated	C

EXAMPLE OF APPLICATION of MMRA-for a single service case (cont.)



EXAMPLE OF APPLICATION of MMRA-for a single service case (cont.)

Case b): **Network with 10% overload in traffic flows from node 1**

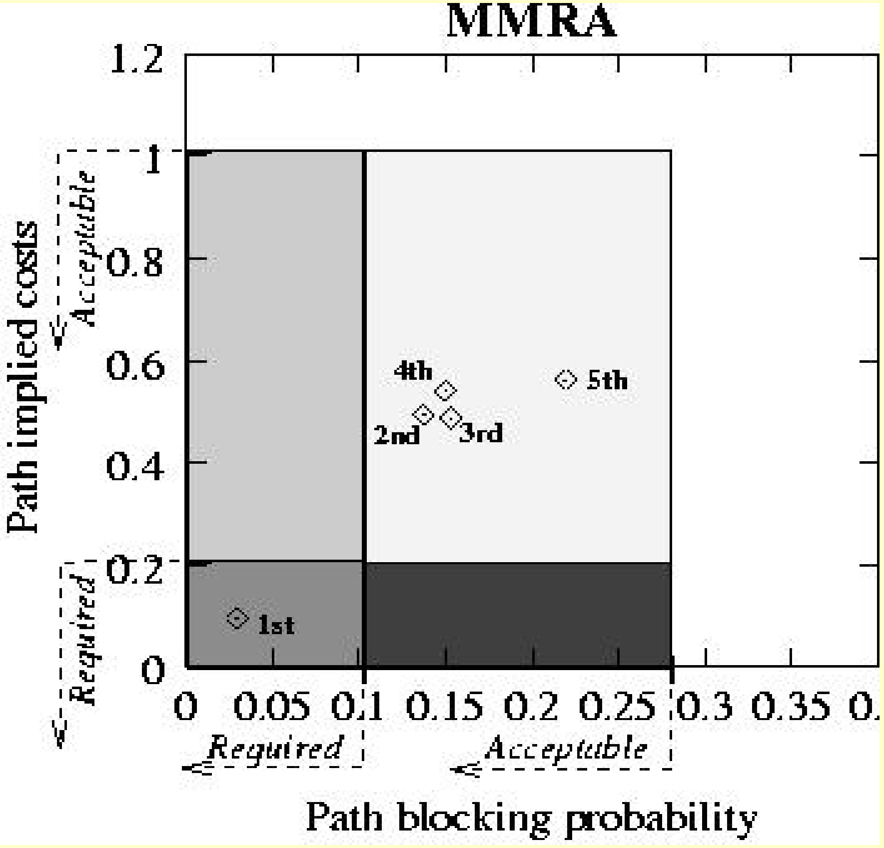
i	Blocking	Implied Cost	Generated paths	Selected paths	Type	Preference region type
1	0.0292787	0.0950544	$5 \rightarrow 3$	$r^1(f)$	**ideal solution**	*A*
2	0.137195	0.493963	$5 \rightarrow 2 \rightarrow 3$	$r^2(f)$	dominated	*C*
3	0.152468	0.487164	$5 \rightarrow 6 \rightarrow 3$		dominated	*C*
4	0.149753	0.541269	$5 \rightarrow 1 \rightarrow 3$		dominated	*C*
5	0.218845	0.562676	$5 \rightarrow 4 \rightarrow 3$		dominated	*C*

In this case:

- the direct link corresponds to the *ideal solution* (which is feasible) and assigned to r^1
- It is justified to consider the 2nd computed solution (*dominated* by the former) as a candidate to r^2 since solution since it is a next priority feasible solution.
- Solution 3 might also be chosen as a candidate to r^2 since it is in the same priority region

EXAMPLE OF APPLICATION of MMRA-for a single service case (cont.)

Case b):**Network with 10% overload in traffic flows from node 1 (cont.)**



EXAMPLE OF APPLICATION of MMRA-for a single service case (cont.)

COMMENTS ON THE EXPERIMENTAL RESULTS

- **<u>Blocking probability and implied cost may be conflicting criteria</u>** (although they are not ortogonal)

- In case (a) the three first generated solutions are non-dominated and $r^2(f) \in B_1$

- In case (b) the ideal solution is feasible and the next generated solutions are dominated; the second route was selected by giving preference to the path blocking criteria

- In more than *50%* of node pairs the two criteria are conflicting hence justifying potential advantages of the MODR approach

DEALING WITH COMPLEXITY AND UNCERTAINTY IN MODR-S

BASIS of THE RESOLUTION APPROACH:

- **Minimising m^1 (m^2) (in problem P_2), for each flow corresponds to minimising B_{ms} (B_{Ms}), which justifies that MMRA-S can be the basis for the resolution of the network-wide routing optimisation problem $P_{G2}^{(2)}$**

\- but this only true by assuming all remaining conditions in the network remain unchanged (unrealistic!)

- There are interdependencies between the objective function coefficients, $\{c_{ks}\}$ and $\{B_{ks}\}$, and between these two sets and the current total route set, $\bar{R}_t$

DEALING WITH COMPLEXITY AND UNCERTAINTY IN MODR-S

BASIS of THE RESOLUTION APPROACH (cont.)

- Problem $P_{G2}^{(2)}$ is **NP-complete in the strong sense** even in the simplest 'degenerated' case (single-objective and no alternative routes)

- **Routing solutions have to be calculated and selected in an automated manner in a short period of time**

BASIS of THE RESOLUTION APPROACH (cont.)

$\overline{C}$ - vector of the arc capacities C_k

$\overline{c}$ - vector of the arc implied costs

$\overline{B}$ - vector of link blocking probabilities

- A system with $2.|L|.|S|$ *implicit non-linear equations* may be obtained expressing the interdependencies between link metrics and the current routing plan

$$\begin{cases} B_{ks} & = \beta_{ks}\left(\overline{B}, \overline{C}, \overline{A_t}, \overline{R_t}\right) \\ c_{ks} & = \alpha_{ks}\left(\overline{c}, \overline{B}, \overline{C}, \overline{A_t}, \overline{R_t}\right) \\ (k & = 1, 2, \ldots, |L|; s = 1, 2, \ldots, |S|) \end{cases}$$

- Fixed point iterative schemes enable to compute $\overline{B}$ and $\overline{c}$ for given $\overline{C}$, $\overline{A}_t$ and $\overline{R}_t$

B_{ks} - Calculated by Kaufman (or Roberts) algorithm or uniform asymptotic approximation (UAA) for large values of the capacities [Mitra,94]

Complexity issues ...

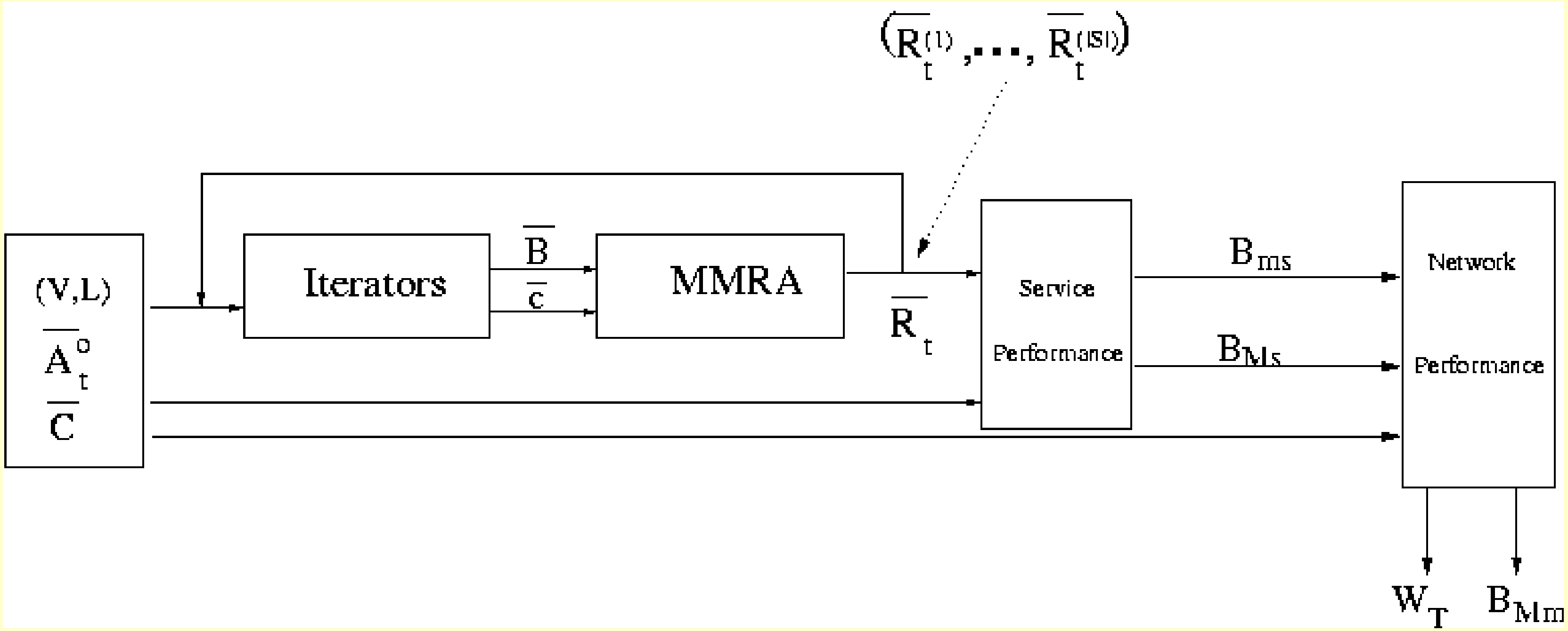


Fig.1 - Functional relations among the main mathematical entities of MODR-S

BASIS of THE RESOLUTION APPROACH (cont.)

Direct application of MMRA - S generates <u>unstable</u> solutions which may lead to poor network global performance

❖This is a new and specific case, in a multiobjective model, of a known *instability* problem in single objective adaptive shortest path routing models

➢ To overcome this problem and select ‘good’ compromise routing solutions at network level (at instants, t=n*T*; n=1,2,…; *T=routing up-date period*) a **heuristic for synchronous path selection** was developed (**MODR-S heuristic**)

BASIC FEATURES OF A HEURISTIC FOR SYNCHRONOUS PATH SELECTION - MODR-S Heuristics

Basis of the procedure : *to search for a subset of the alternative path set:*

$$\overline{R}^a_{t-\mathcal{T}} = \cup_{s=1}^{|S|} \overline{R}^a_{t-\mathcal{T}}(s) \quad : \qquad \overline{R}^a_{t-\mathcal{T}}(s) = \left\{ r^2(f_s), \quad f_s \in F_s \right\}$$

the elements of which should possibly be changed in the next updating period t in order to guarantee a "good" global compromise solution

Criterion for choosing candidate paths:

$$\begin{aligned} \xi(f_s) = F_{1s}F_{2s} &= \left(2c_{r^1(f_s)} - c_{r^2(f_s)}\right)\left(1 - L_{r^1(f_s)}L_{r^2(f_s)}\right) \\ c_{r^i(f_s)} &= \sum_{l_k \in r^i(f_s)} c_{ks} \end{aligned}$$

F_1 < > to favour the traffic flows for which the 2nd route has a high implied cost and the 1st route a low implied cost

F_2 < > to favour the flows with worse node-to-node blocking probability

MODR-S Heuristics (cont.)

▪ *The second issue addressed by the heuristic is to specify how many and which of the second choice routes of the different flows of each service type should possibly be changed by applying MMRA-S once again*

✓For this purpose the candidate routes $r^2(f_s)$ are ordered according to ζ and those with lower value of ζ are given preference for possible alteration.

Criterion for choosing which candidate paths should be changed:

✓ It results from applying MMRA-S once again and to select only candidate routes which lead to solutions which dominate the previous ones (in terms of W_T and B_{Mm}) and respect a certain relaxation criterion on the value of B_{Ms}

MODR-S Heuristics (cont.)

✓ The heuristic seeks the improvement of the current best solution by ‘scanning’ all flows of each service type, considering the services by decreasing order of the effective bandwidth and by applying two cycles of “solution improvement” such that the number of candidate flows for possible improvement in $r^2(f_s)$ decreases iteratively.

- A specific service protection scheme (APR) was imbedded in the heuristic in order to prevent excessive performance degradation in overload conditions, resulting from the utilisation of alternative routes for all node-to-node traffic flows

MODR-S Heuristics (cont.)

✓ This mechanism **APR** ("**Alternative Path Removal**") consists in the *elimination of the alternative paths r_s for which the objective functions of problem P_2 are worse than certain values obtained from an auxiliary empirical variable z_{APR}:*

$$m^2(r_s) > -log(1-0.3) * z_{APR} \quad \wedge \quad m^1(r_s) > d_s * z_{APR}$$

z_{APR} - parameter which varies dynamically in the heuristic

• Details on MODR-S and its sub-models/procedures are described in [Craveirinha *et al, 04*], [L. Martins *et al, 03, 06*],

Dealing with Imprecision and Uncertainty in MODR-S

• Difficulty associated with the <u>intrinsic uncertainty</u> of the coefficients of the objective functions of which have a *stochastic nature* (they are estimated from real-time measurements of stochastic variables).

⇒ to tackle this we used <u>time varying preference thresholds</u> calculated from current coefficient estimates, in order to reflect current network working conditions.

Dealing with Imprecision and Uncertainty in MODR-S (cont.)

⟹ The calculation model for those preference thresholds must:

i) prevent situations of inconsistency resulting from the great variability of the coefficients namely guaranteeing the correct inequality relations between optimal, required and acceptable values;

ii) maintain the basic effectiveness in the calculation of the candidate alternative routes for each node-to-node traffic flow of each service class.

Dealing with Imprecision and Uncertainty in MODR-S (cont.)

$\Longrightarrow$ Adequate **estimation procedures** have to be used for estimating the implied costs and the blocking probabilities on the links, resulting from real-time network measurements

• Several approaches based on known statistical methods were considered

- The implemented approach is based on the estimation of node-to-node traffic offered $A_t(f_s)$ at the beginning of each path updating period based on first order moving average iterations for the traffic offered of f_s .

Dealing with Imprecision and Uncertainty in MODR-S (cont.)

• Another source of imprecision has to do with the *simplifications assumed in the traffic calculation model*, a single parameter stochastic model, based on the superposition of independent Poisson processes representing the marginal traffic flows in each link, associated with the different traffic flows which use the link..

✓This simplifications lead to an underestimation of the blocking probabilities and in principle less imprecise stochastic approximations (namely two-parametric models based on the mean and variance of the traffic flows) could be used

✓ nevertheless more realistic traffic representations would turn the model rapidly *untractable* even for small networks…

Dealing with Imprecision and Uncertainty in MODR-S (cont.)

▪ Note that the importance of the accuracy of the results given by the traffic calculation model, in MODR-S, is in terms of relative values of the associated route metrics rather than in terms of absolute errors

⟹ These factors justify the need for the use of a traffic calculation approach of the type used in MODR-S, albeit simplistic

MODR-S Network Performance

•A network based in [Mitra,91] was engineered with three services with call durations of 1, 5 and 10 minutes and $\bar{d} = [1, 6, 10]$

•A discrete-event simulator has been developed for a comparative study with MODR, RTNR and DAR routing methods

•DAR method was adapted for the multiservice case with a dynamic trunk reservation mechanism based on the one used in RTNR to improve its performance in overload conditions.

•For the MODR-S method, the estimated offered traffic in the n^{th} time interval is obtained from offered traffic measurements $\tilde{X}$ with $b = 0.9$

$$\tilde{x}_{f_s}(n) = (1-b)\tilde{x}_{f_s}(n-1) + b\tilde{X}_{f_s}(n-1)$$

MODR-S Network Performance (cont.)

Overload Factor	MODR–S Analytical Model	MODR–S	RTNR Simulational Model	DAR
	W_T		$W_T \pm \Delta$	
-20%	22588.8	22588.7 ± 31.67	**22596.5 ± 29.12**	22583.1 ± 30.18
-10%	23146.8	23108.3 ± 25.43	**23113.6 ± 28.58**	23097.8 ± 26.56
0%	23526.8	**$23510.8. \pm 46.66$**	23378.9 ± 63.23	23470.7 ± 34.42
10%	23692	**23762.7 ± 32.61**	23450.7 ± 55.87	23604.2 ± 54.16
20%	23965.9	**23966.6 ± 36.00**	23503.1 ± 44.65	23594.1 ± 37.04
30%	23909.4	**24133.2 ± 39.35**	23606.6 ± 33.39	23733.2 ± 38.22
40%	24145.7	**24266.5 ± 48.92**	23704.1 ± 32.76	23840.8 ± 40.03
	B_{Mm}		$B_{Mm} \pm \Delta$	
-20%	0.00061	$0.0009 \pm 2.9 \times 10^{-4}$	**$0.0007 \pm 2.4 \times 10^{-4}$**	$0.0016 \pm 3.2 \times 10^{-4}$
-10%	0.001	**$0.0030 \pm 5.4 \times 10^{-4}$**	$0031 \pm 3.7 \times 10^{-4}$	$0.005 \pm 4.0 \times 10^{-4}$
0%	0.010	**$0.011 \pm 2.0 \times 10^{-3}$**	$0.017 \pm 3.2 \times 10^{-3}$	$0.015 \pm 1.6 \times 10^{-3}$
10%	0.036	**$0.028 \pm 1.1 \times 10^{-3}$**	$0.042 \pm 2.9 \times 10^{-3}$	$0.032 \pm 1.9 \times 10^{-3}$
20%	0.068	**$0.045 \pm 1.7 \times 10^{-3}$**	$0.078 \pm 5.4 \times 10^{-3}$	$0.117 \pm 2.0 \times 10^{-3}$
30%	0.104	**$0.063 \pm 2.6 \times 10^{-3}$**	$0.140 \pm 1.1 \times 10^{-3}$	$0.183 \pm 8.0 \times 10^{-4}$
40%	0.133	**$0.084 \pm 1.9 \times 10^{-3}$**	$0.188 \pm 1.2 \times 10^{-3}$	$0.240 \pm 2.3 \times 10^{-4}$

Table 2: Global Performance: the best results for each metric are indicated in bold.

Table 2: Network performance metrics: first level objective function values-comparison with RTNR and DAR-S

• The simulation results are the mid points of a 95% confidence intervals obtained by the method of the independent replications.

MODR-S Network Performance (cont.)

Factor Sobrec.	MODR–S Modelo Analítico		MODR–S Modelo Simulacional		RTNR Modelo Simulacional	
	B_{ms}	B_{Ms}	$B_{ms} \pm \Delta$	$B_{Ms} \pm \Delta$	$B_{ms} \pm \Delta$	$B_{Ms} \pm \Delta$
Serviço $s = 1$						
-20%	0.002	0.009	$0.002 \pm 2.6 \times 10^{-4}$	$0.009 \pm 2.8 \times 10^{-3}$	$\mathbf{< 10^{-3}}$	$\mathbf{< 10^{-3}}$
-10%	0.003	0.013	$0.003 \pm 6.3 \times 10^{-4}$	$0.009 \pm 1.6 \times 10^{-3}$	$\mathbf{0.001 \pm 3.3 \times 10^{-4}}$	$\mathbf{0.003 \pm 8.5 \times 10^{-4}}$
0%	0.004	0.018	$\mathbf{0.004 \pm 6.1 \times 10^{-4}}$	$\mathbf{0.014 \pm 2.6 \times 10^{-3}}$	$0.005 \pm 4.9 \times 10^{-4}$	$0.014 \pm 2.9 \times 10^{-3}$
10%	0.004	0.020	$\mathbf{0.005 \pm 9.5 \times 10^{-4}}$	$\mathbf{0.017 \pm 3.6 \times 10^{-3}}$	$0.019 \pm 3.9 \times 10^{-3}$	$0.053 \pm 1.4 \times 10^{-2}$
20%	0.005	0.017	$\mathbf{0.006 \pm 4.0 \times 10^{-4}}$	$\mathbf{0.017 \pm 2.6 \times 10^{-3}}$	$0.069 \pm 6.9 \times 10^{-3}$	$0.164 \pm 1.4 \times 10^{-2}$
30%	0.006	0.020	$\mathbf{0.008 \pm 9.3 \times 10^{-4}}$	$\mathbf{0.021 \pm 6.4 \times 10^{-3}}$	$0.131 \pm 1.6 \times 10^{-3}$	$0.257 \pm 7.8 \times 10^{-3}$
40%	0.008	0.031	$\mathbf{0.009 \pm 1.2 \times 10^{-3}}$	$\mathbf{0.022 \pm 3.3 \times 10^{-3}}$	$0.178 \pm 1.6 \times 10^{-3}$	$0.307 \pm 1.1 \times 10^{-2}$
Serviço $s = 2$						
-20%	0.001	0.002	$\mathbf{0.003 \pm 1.2 \times 10^{-3}}$	$0.011 \pm 3.5 \times 10^{-3}$	$0.003 \pm 2.1 \times 10^{-3}$	$\mathbf{0.008 \pm 4.3 \times 10^{-3}}$
-10%	0.004	0.007	$\mathbf{0.012 \pm 2.7 \times 10^{-3}}$	$\mathbf{0.032 \pm 9.7 \times 10^{-3}}$	$0.021 \pm 4.0 \times 10^{-3}$	$0.040 \pm 7.5 \times 10^{-3}$
0%	0.029	0.092	$\mathbf{0.025 \pm 4.6 \times 10^{-3}}$	$\mathbf{0.051 \pm 7.6 \times 10^{-3}}$	$0.054 \pm 7.4 \times 10^{-3}$	$0.094 \pm 2.0 \times 10^{-2}$
10%	0.044	0.103	$\mathbf{0.043 \pm 4.4 \times 10^{-3}}$	$\mathbf{0.082 \pm 7.4 \times 10^{-3}}$	$0.089 \pm 1.1 \times 10^{-2}$	$0.157 \pm 3.0 \times 10^{-2}$
20%	0.038	0.106	$\mathbf{0.062 \pm 4.4 \times 10^{-3}}$	$\mathbf{0.111 \pm 1.0 \times 10^{-2}}$	$0.117 \pm 6.7 \times 10^{-3}$	$0.215 \pm 2.3 \times 10^{-2}$
30%	0.048	0.121	$\mathbf{0.080 \pm 6.3 \times 10^{-3}}$	$\mathbf{0.152 \pm 1.1 \times 10^{-2}}$	$0.132 \pm 8.0 \times 10^{-3}$	$0.251 \pm 1.0 \times 10^{-2}$
40%	0.067	0.177	$\mathbf{0.101 \pm 6.9 \times 10^{-3}}$	$\mathbf{0.184 \pm 2.2 \times 10^{-2}}$	$0.145 \pm 9.0 \times 10^{-3}$	$0.255 \pm 3.5 \times 10^{-2}$
Serviço $s = 3$						
-20%	0.003	0.005	$\mathbf{0.004 \pm 1.8 \times 10^{-3}}$	$\mathbf{0.017 \pm 8.5 \times 10^{-3}}$	$0.006 \pm 4.5 \times 10^{-3}$	$0.023 \pm 1.5 \times 10^{-2}$
-10%	0.011	0.019	$\mathbf{0.011 \pm 2.9 \times 10^{-3}}$	$\mathbf{0.031 \pm 6.8 \times 10^{-3}}$	$0.036 \pm 7.4 \times 10^{-3}$	$0.078 \pm 1.3 \times 10^{-2}$
0%	0.022	0.032	$\mathbf{0.026 \pm 3.6 \times 10^{-3}}$	$\mathbf{0.062 \pm 1.5 \times 10^{-2}}$	$0.077 \pm 1.5 \times 10^{-2}$	$0.153 \pm 2.7 \times 10^{-2}$
10%	0.044	0.136	$\mathbf{0.046 \pm 4.3 \times 10^{-3}}$	$\mathbf{0.103 \pm 2.8 \times 10^{-2}}$	$0.115 \pm 1.1 \times 10^{-2}$	$0.209 \pm 2.1 \times 10^{-2}$
20%	0.087	0.180	$\mathbf{0.068 \pm 4.8 \times 10^{-3}}$	$\mathbf{0.129 \pm 1.6 \times 10^{-2}}$	$0.138 \pm 4.6 \times 10^{-3}$	$0.265 \pm 2.2 \times 10^{-2}$
30%	0.117	0.203	$\mathbf{0.090 \pm 7.2 \times 10^{-3}}$	$\mathbf{0.161 \pm 2.2 \times 10^{-2}}$	$0.145 \pm 4.3 \times 10^{-3}$	$0.272 \pm 2.7 \times 10^{-2}$
40%	0.139	0.285	$\mathbf{0.114 \pm 1.0 \times 10^{-2}}$	$\mathbf{0.195 \pm 2.3 \times 10^{-2}}$	$0.149 \pm 4.4 \times 10^{-3}$	$0.265 \pm 1.7 \times 10^{-2}$

Table 3: Service Performance: comparison with analytical results and with RTNR

MODR-S Network Performance (cont.)

Factor Sobrec.	MODR–S Modelo Simulacional		DAR Modelo Simulacional	
	$B_{ms} \pm \Delta$	$B_{Ms} \pm \Delta$	$B_{ms} \pm \Delta$	$B_{Ms} \pm \Delta$
Serviço $s = 1$				
0.8%	$0.002 \pm 2.6 \times 10^{-4}$	$0.009 \pm 2.8 \times 10^{-3}$	$\mathbf{< 10^{-3}}$	$\mathbf{< 10^{-3}}$
0.9%	$0.003 \pm 6.3 \times 10^{-4}$	$0.009 \pm 1.6 \times 10^{-3}$	$\mathbf{< 10^{-3}}$	$\mathbf{< 10^{-3}}$
0%	$0.004 \pm 6.1 \times 10^{-4}$	$0.014 \pm 2.6 \times 10^{-3}$	$\mathbf{0.001 \pm 1.8 \times 10^{-4}}$	$\mathbf{0.002 \pm 1.3 \times 10^{-4}}$
10%	$0.005 \pm 9.5 \times 10^{-4}$	$0.017 \pm 3.6 \times 10^{-3}$	$\mathbf{0.002 \pm 1.5 \times 10^{-4}}$	$\mathbf{0.004 \pm 2.4 \times 10^{-4}}$
20%	$0.006 \pm 4.0 \times 10^{-4}$	$0.017 \pm 2.6 \times 10^{-3}$	$\mathbf{0.003 \pm 3.2 \times 10^{-4}}$	$\mathbf{0.006 \pm 5.8 \times 10^{-4}}$
30%	$0.008 \pm 9.3 \times 10^{-4}$	$0.021 \pm 6.4 \times 10^{-3}$	$\mathbf{0.004 \pm 4.7 \times 10^{-4}}$	$\mathbf{0.008 \pm 1.4 \times 10^{-3}}$
40%	$0.009 \pm 1.2 \times 10^{-3}$	$0.022 \pm 3.3 \times 10^{-3}$	$\mathbf{0.005 \pm 5.1 \times 10^{-4}}$	$\mathbf{0.010 \pm 7.8 \times 10^{-4}}$
Serviço $s = 2$				
0.8%	$0.003 \pm 1.2 \times 10^{-3}$	$\mathbf{0.011 \pm 3.5 \times 10^{-3}}$	$\mathbf{0.003 \pm 9.0 \times 10^{-4}}$	$0.013 \pm 5.0 \times 10^{-3}$
0.9%	$0.012 \pm 2.7 \times 10^{-3}$	$0.032 \pm 9.7 \times 10^{-3}$	$\mathbf{0.009 \pm 1.9 \times 10^{-3}}$	$\mathbf{0.029 \pm 3.2 \times 10^{-3}}$
0%	$0.025 \pm 4.6 \times 10^{-3}$	$\mathbf{0.051 \pm 7.6 \times 10^{-3}}$	$\mathbf{0.023 \pm 4.5 \times 10^{-3}}$	$0.053 \pm 1.0 \times 10^{-2}$
10%	$0.043 \pm 4.4 \times 10^{-3}$	$\mathbf{0.082 \pm 7.4 \times 10^{-3}}$	$\mathbf{0.040 \pm 2.6 \times 10^{-3}}$	$0.084 \pm 1.1 \times 10^{-2}$
20%	$0.062 \pm 4.4 \times 10^{-3}$	$\mathbf{0.111 \pm 1.0 \times 10^{-2}}$	$\mathbf{0.061 \pm 5.6 \times 10^{-3}}$	$0.120 \pm 1.0 \times 10^{-2}$
30%	$\mathbf{0.080 \pm 6.3 \times 10^{-3}}$	$\mathbf{0.152 \pm 1.1 \times 10^{-2}}$	$0.084 \pm 7.4 \times 10^{-3}$	$0.155 \pm 6.3 \times 10^{-3}$
40%	$\mathbf{0.101 \pm 6.9 \times 10^{-3}}$	$\mathbf{0.184 \pm 2.2 \times 10^{-2}}$	$0.108 \pm 7.6 \times 10^{-3}$	$0.191 \pm 1.4 \times 10^{-2}$
Serviço $s = 3$				
0.8%	$\mathbf{0.004 \pm 1.8 \times 10^{-3}}$	$\mathbf{0.017 \pm 8.5 \times 10^{-3}}$	$0.009 \pm 3.6 \times 10^{-3}$	$0.035 \pm 7.7 \times 10^{-3}$
0.9%	$\mathbf{0.011 \pm 2.9 \times 10^{-3}}$	$\mathbf{0.031 \pm 6.8 \times 10^{-3}}$	$0.023 \pm 4.8 \times 10^{-3}$	$0.055 \pm 7.8 \times 10^{-3}$
0%	$\mathbf{0.026 \pm 3.6 \times 10^{-3}}$	$\mathbf{0.062 \pm 1.5 \times 10^{-2}}$	$0.051 \pm 7.8 \times 10^{-3}$	$0.122 \pm 7.9 \times 10^{-3}$
10%	$\mathbf{0.046 \pm 4.3 \times 10^{-3}}$	$\mathbf{0.103 \pm 2.8 \times 10^{-2}}$	$0.088 \pm 6.6 \times 10^{-3}$	$0.201 \pm 3.3 \times 10^{-2}$
20%	$\mathbf{0.068 \pm 4.8 \times 10^{-3}}$	$\mathbf{0.129 \pm 1.6 \times 10^{-2}}$	$0.132 \pm 1.0 \times 10^{-2}$	$0.258 \pm 4.5 \times 10^{-2}$
30%	$\mathbf{0.090 \pm 7.2 \times 10^{-3}}$	$\mathbf{0.161 \pm 2.2 \times 10^{-2}}$	$0.177 \pm 1.2 \times 10^{-2}$	$0.312 \pm 3.2 \times 10^{-2}$
40%	$\mathbf{0.114 \pm 1.0 \times 10^{-2}}$	$\mathbf{0.195 \pm 2.3 \times 10^{-2}}$	$0.219 \pm 1.4 \times 10^{-2}$	$0.361 \pm 3.6 \times 10^{-2}$

Table 4: Service Performance: comparison with DAR

Performance of the MODR-S Heuristic:

• Extensive experimental study in multirate-loss fully meshed networks with the MODR-S heuristic using a discrete event simulation platform [L. Martins *et al*. 03, 06] revealed that it outperformed reference dynamic routing methods (RTNR, Real Time Network Routing, developed by AT&T and DAR-S, Dynamic Alternative Routing) in most situations and for most metrics

• MODR-S routing solutions **dominate** solutions of the reference dynamic routing methods in most **overload situations**.

MODR-S: A Multiobjective Dynamic Routing Model for Multiservice Networks (cont.)

CONCLUSIONS

- In this hierarchical multiobjective dynamic routing model, with stochastic inputs *complexity, imprecision and uncertainty issues are closely inter-related*.

- These difficulties result from the *interdependencies among basic mathematical entities of the model, the stochastic nature of the objective function coefficients, reflecting a stochastic environment, and the imprecision of the representation of the system of preferences.*

- The necessity of calculating and selecting network routing solutions *in short time periods in an automated manner* is an inherent limitation to the multicriteria resolution approaches in this or similar contexts.

MODR-S: A Multiobjective Dynamic Routing Model for Multiservice Networks (cont.)

CONCLUSIONS

- **A heuristic approach, using as ‘core’ algorithm an exact bi-objective shortest path procedure incorporating a preference threshold mechanism, was proposed**.

- This approach had to deal with the various instances of complexity, imprecision and uncertainty of the model in an effective manner.

- **Development of effective approaches for this type of difficult routing problems requires the use of various methodological tools of an interdisciplinary nature and an in-depth knowledge of the underlying teletraffic engineering problem.**

MODR-S: A Multiobjective Dynamic Routing Model for Multiservice Networks (cont.)

CONCLUSIONS

- The proposed MODR method enables to treat in a consistent manner eventually conflicting QoS/economic criteria while seeking to take advantage of the dynamic alternative routing principle
- It enables the explicit representation of fairness QoS objectives at network and service levels
- It uses a very efficient constrained bi-objective shortest path algorithm
- It recurs, in the selection of candidate solutions obtained from this algorithm, to dynamically changing preference regions in the objective functions space

MODR-S: A Multiobjective Dynamic Routing Model for Multiservice Networks (cont.)

CONCLUSIONS

- Application to a classical single-channel circuit-switched network showed that implied cost and blocking probability may be conflicting criteria namely in global or local overload conditions

- MODR-S was shown to give very good results, concerning the most relevant network performance metrics as compared with reference dynamic routing methods, in the case of strongly meshed multirate loss networks, specially in overload conditions.

MODR-S: A Multiobjective Dynamic Routing Model for Multiservice Networks (cont.)

CURRENT DEVELOPMENTS OF THIS WORK AND FURTHER WORK

CURRENT DEVELOPMENTS

[J. Craveirinha *et al.*, 05][L.Martins *et al.*, 05]

- Generalisation of the base model leading to the formulation of a general hierarchical multiobjective routing framework for multiservice networks, based on virtual paths or explicit routes and effective bandwidths (as in ATM or in MPLS connection-oriented services)

- Development of a method of network dimensioning suitable to MODR-S, based on the use of implied costs.

MODR-S: A Multiobjective Dynamic Routing Model for Multiservice Networks (cont.)

FURTHER WORK

- Another important *issue* related to the appllication scope of a network-wide optimisation model such as MODR-S which deserves attention refers to **the development of distributed computation models corresponding to decentralized routing control schemes,** where the route calculation procedures are assigned to the nodes assuming the required information is available to each of them.

  This is particular important to enhance the tractability of MODR-S in practical networks.

REFERENCES-1

-Aboellela, E., C. Douligeris (1999). Fuzzy generalyzed network approach for solving an optimization model for routing in B-ISDN. Telecommunication Systems, vol. 12, 237-263.

- Akkanen J. and J. Nurminen (2001), Case study on the evolution of routing algorithms in an etwork planning tool, The Journal of Systems and Software, 58(3): 181-198.

-Anandalingam, G., K. Nam (1997). Conflict and cooperation in designing international telecommunication networks. Journal of the Operational Research Society, vol. 48, 600-611.

-Antunes, C.H., J. Clímaco, J. Craveirinha, C. Barrico (1999). Multiple objective routing in integrated communication networks. In D. Smith and P. Key (Eds.), "Teletraffic Engineering in a Competitive World", Proceedings of the 16th International Teletraffic Congress - ITC 16, Volume 3b Teletraffic Science and Engineering, 1291-1300, Elsevier.

-Antunes, C.H., J. Craveirinha and J. Clímaco (1998). Planning the evolution to broadband access networks - a multicriteria approach. European Journal of Operational Research, vol. 109, nº 2, 530-540.

- Antunes, C.H.; J. Craveirinha; J. Clímaco (1994), A flexible MOLP approach to the modernization of telecommunication networks incorporating sensitivity analysis". In "Teletraffic Science and Engineering", J. Labetoulle and J. W. Roberts (Eds.), vol. 1b, Proceedings of the International Teletraffic Congress - ITC 14, 1425-1434, Elsevier.

REFERENCES-1

- Antunes, C.H.; J. Craveirinha J.; Clímaco (1993). A multiple criteria model for new telecommunication service planning. European Journal of Operational Research **71** (3), 341-352.
- Assi, C.; Shami, A.; Ali, M., (2001) Optical networkingand real –time provisioning:an integrated vision of the next generation Iternet, IEEE Networks, pp 36-45, July/August 2001.
- Clímaco, J.; Craveirinha, J.; Pascoal, M. (1982); A bicriterion shortest path algorithm , European Journal of Operational Research 11 (1982), 399-404.
- Clímaco, J.; and E. Martins. (2003); A bicriterion approach for routing problems in multimedia networks, Networks, Vol. 41(4): 206-220, 2003.
- Clímaco, J.; Craveirinha,J.; Pascoal,M. (2004); Routing Calculation in Multimedia: A Procedure Based on a Biciteria Model, in electr. Proc of ECCOMAS 2004, 4th Europ. Congr. on Computational Methods in Applied Sciences and Enginering, Voll II.-Mini-Symposyum on Multiobjective Optimisation and its Applications., p. 442 do Vol II of Book of Abstracts, Jyvaskyla, July 2004.
- Clímaco, J.and Craveirinha, J, Multicriteria Analysis in Telecommunication Network Planning and Design-problems and issues, Chap. 22 in MCDA - State of the Art Surveys, ed. by J. Figueira, S. Greco and M. Ehrgott, Sringers Int. Series, 2005

REFERENCES-1

- Craveirinha,J.;Martins, L.;Gomes, T.;Antunes, C.;Clímaco,J. (2001), A new multiple objective dynamic routing method using implied costs, in Journal of Telecommunications and Information Technology (special issue), Vol 3 /2003: 50-59. Pub. Tel. Inst., Warsaw.
- Craveirinha,J.; Martins, L.;Antunes, C.;Clímaco,J. (2004), Dealing with complexity in a multiobjective dynamic routing model for multiservice networks- a heuristic approach, in elect. Proc of the Mini Euro Conf, Managing Uncertainty in Decision Support Models, Coimbra, sept. 2004.
- Craveirinha,J.; Girão, R..and Clímaco, J. (2005), A meta-model for multiobjective routing in MPLS, Proc. of the 5th. Int Conference on Decision Support for Telecommunicatoions and Information Society, 2005, 11-34.
- Douligeris, C., I. Pereira (1994). A telecommunications quality study using the analytic hierarchy process", IEEE Journal on Selected Areas in Communications, vol 12, no. 2, 241-250.
- Kelly, F. (1988). Routing in circuit-switched networks: optimisation, shadow prices and decentralisation, Adv. Applied Probability, vol. 20, 112-144.
- Kuipers, F., Van Mieghem, P., An overview of constrained-based path selection algorithms for QoS routing, in IEEE Communications Magazine, Dec 2002, p. 50-55
- Lee, W.C., M.G. Hluchyj and P.A. Humblet (1995) Routing subject to quality of service constraints in integrated communication networks. IEEE Network, July/Aug. 1995, 46-55.

REFERENCES-1

- Martins, E.; Pascoal, M., Santos, J. (1999) Deviation algorithms for ranking shortest paths, International Journal of Foundations of Computer Science, 10, pp. 247-263.
- Martins, L.; Craveirinha, J.; Clímaco, J.; Gomes,T;(2005), On a bi-dimensional alternative routing method, Eur. Jour of Operational Research 166 (2005) 828-842.
- Martins, L., Craveirinha, J., Clímaco, J.,(2003) A new multiple objective dynamic routing method for multiservice networks-modelling and performance evaluation, Technical Report INESC-Coimbra.
- Martins, L., Craveirinha, J., Clímaco, J.,(2006) A new multiple objective dynamic routing method for multiservice networks-modelling and performance, to appear in issue 10287 (art. 14) of Computational and Management Science.
- Pornavalai, C., G. Chakraborty, N. Shiratori (1998). Routing with multiple QoS requirements for supporting multimedia applications. Telecommunication Systems, vol. 9, 357-373.
- Resende, M. and Ribeiro, C., A GRASP with path relinkingfor private virtual circuit routing. Networks, 41(3):104-114, 2003.

REFERENCES-1

-Thirumamlasetty, S., and Medhi, D., (2001) MPLS traffic engineering for survivable look-ahead guaranteed services, Technical report Univ of Missourin www.estp.umkc.edu/public/papers/dmedhi/tm-mag-te.pdf.

- El-Sayed, M.; Jaffe, J.,A View of Telecommunications Evolution, in IEEE Communications Magazine, Dec 2002, p. 74-81.

-Wang, Z. and J. Crowcroft (1996) Quality-of-Service routing for supporting multimedia applications. IEEE Journal on Selected Areas in Communications, vol. 14-7, 1228-1234.

- Vogel, R., R. G. Herrtwich, W. Kalfa, H. Wittig and L. C. Wolf (1996) QoS-Based routing of multimedia streams in computer networks. IEEE Journal on Selected Areas in Communications, vol. 14-7, 1235-1244.

- Zang, H.; Jue, J.; Mukherjee, B.(2000); A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks, Optical Networks Magazine, pp 47-60, January 2000.

- Zhu, B. (2000) Routing and Wavelength assignment in all optical networks by multiobjective genetic algorithms, Technical Report, Univ of California, 2000.

REFERENCES-2

H. Akimaru and K. Kawashima. *Teletraffic: Theory and Applications*. Telecommunication Networks and Computer Systems. Springer-Verlag, 1993.

D. Awduche, A. Chiu, A. Elwalid, I. Widjaja, and X. Xiao. Overview and principles of Internet traffic engineering. RFC 3272, Network Working Group, May 2002.

D. Awduche, J. Malcolm, J. Agogbua, M. O'Dell, and J. McManus. Requirements for traffic engineering over MPLS. RFC 2702, Network Working Group, Sep. 1999.

N. Bourquia, W. B. Ameur, E. Gourdin, and P. Tolla. Optimal shortest path routing for Internet networks. In *Proceedings of the International Network Optimization Conference (INOC 2003)*, pp. 119-125, Evry/Paris, France, Oct. 27-29 2003.

J. C. N. Clímaco, J. M. F. Craveirinha, and M. M. B. Pascoal. A bicriterion approach for routing problems in multimedia networks. *Networks*, 41(4):206-220, 2003.

REFERENCES-2

J. Craveirinha, R. Girão-Silva, and J. Clímaco. A meta-model for multiobjective routing in MPLS. In *Proceedings of the V International Conference on Decision Support for Telecommunications and Information Society (DSTIS'05)*, Warsaw, Poland, Sep. 1-3 2005.

A. Elwalid, C. Jin, S. Low, and I. Widjaja. MATE: MPLS adaptive traffic engineering. In *Proceedings of IEEE Infocom 2001*, Anchorage, Alaska, Apr. 2001.

A. Elwalid, D. Mitra, I. Saniee, and I. Widjaja. Routing and protection in GMPLS networks: From shortest paths to optimized designs. *Journal of Lightwave Technology*, 21(11):2828-2838, Nov. 2003.

S. C. Erbas. Utilizing evolutionary algorithms for multiobjective problems in traffic engineering. In W. Ben-Amur and A. Petrowski, editors, *Proceedings of the International Networks Optimization Conference (INOC 2003)*, pp. 207-212, Evry/Paris, France, Oct. 27-29 2003. Institut National des Télécommunications.

REFERENCES-2

S. C. Erbas and C. Erbas. A multiobjective off-line routing model for MPLS networks. In J. Charzinski, R. Lehnert, and P. Tran-Gia, editors, *Proceedings of the 18th International Teletraffic Congress (ITC-18)*, pp. 471-480, Berlin, Germany, 2003. Elsevier, Amsterdam.

S. C. Erbas and R. Mathar. An off-line traffic engineering model for MPLS networks. In B. Bakshi and B. Stiller, editors, *Proceedings of the 27th Annual IEEE Conference on Local Computer Networks (27th LCN)*, pp. 166-174, Tampa, Florida, Nov. 2002. IEEE Computer Society.

M. Franzke and A. Pönitz. Global shortest path solutions for the traffic engineering problem. In *Proceedings of NETWORKS 2002 - 10th International Telecommunication Network Strategy and Planning Symposium*, pp. 275-278, München, Germany, Jun. 23-27 2002.

E. Gelenbe, R. Lent, A. Montuori, and Z. Xu. Cognitive packet networks: QoS and performance. In *MASCOTS Symposium*. IEEE Computer Society, Oct. 2002.

REFERENCES-2

E. Gelenbe, R. Lent, and A. Nunez. Self-aware networks and QoS. In *Proceedings of the IEEE*, vol. 92, pp. 1478-1489, Sep. 2004.

G. Hasslinger and S. Schnitter. Algorithms for traffic engineering. In *Proceedings of 6th INFORMS Telecommunications Conference*, Boca Raton, Florida, Mar. 10-13 2002.

G. Hasslinger and S. Schnitter. *Telecommunications Network Design and Management*, chap. 7 - Optimized Traffic Load Distribution in MPLS Networks, pp. 125-141. Kluwer Academic Publishers, 2003.

J. S. Kaufman. Blocking in a shared resource environment. *IEEE Transactions on Communications*, COM-29(10):1474-1481, Oct. 1981.

F. Kelly. Notes on effective bandwidths. In F. P. Kelly, S. Zachary, and I. Ziedins, editors, *Stochastic Networks: Theory and Applications*, vol. 4 of *Royal Statistical Society Lecture Notes Series*, pp. 141-168. Oxford University Press, 1996.

REFERENCES-2

F. P. Kelly. Routing in circuit-switched networks: Optimization, shadow prices and decentralization. *Advances in Applied Probability*, 20(1):112-144, Mar. 1988.

F. P. Kelly. Routing and capacity allocation in networks with trunk reservation. *Mathematics of Operations Research*, 15(4):771-793, Nov. 1990.

J. Knowles, M. Oates, and D. Corne. Advanced multi-objective evolutionary algorithms applied to two problems in telecommunications. *BT Technology Journal*, 18(4):51-65, Oct. 2000.

H. Kochkar, T. Ikenaga, Y. Hori, and Y. Oie. Multi-class QoS routing with multiple routing tables. In *Proceedings of IEEE PACRIM'03*, pp. 388-391, Victoria, B.C., Canada, Aug. 2003.

H. Kochkar, T. Ikenaga, and Y. Oie. QoS routing algorithm based on multiclasses traffic load. In *Proceedings of Global Telecommunications Conference - GLOBECOM'01*, pp. 2193-2198, San Antonio, TX, 2001.

REFERENCES-2

F. Kuipers, P. Van Mieghem, T. Korkmaz, and M. Krunz. An overview of constraint-based path selection algorithms for QoS routing. *IEEE Communications Magazine*, pp. 50-55, Dec. 2002.

F. A. Kuipers, T. Korkmaz, M. Krunz, and P. Van Mieghem. A review of constraint-based routing algorithms. Technical report, Technical University Delft, Jun. 2002.

Q. Ma and P. Steenkiste. Supporting dynamic inter-class resource sharing: A multi-class QoS routing algorithm. In *Proceedings of IEEE Infocom'99*, pp. 649-660, New York, Mar. 1999.

L. Martins. *Um Método de Encaminhamento Dinâmico Multiobjectivo em Redes de Telecomunicações - Modelação e Desempenho*. PhD thesis, Faculdade de Ciências e Tecnologia da Universidade de Coimbra, Coimbra, 2004.

REFERENCES-2

L. Martins, J. Craveirinha, and J. Clímaco. A new multiobjective dynamic routing method for multiservice networks - modelling and performance. In W. Ben-Amur and A. Petrowski, editors, *Proceedings of the International Networks Optimization Conference (INOC 2003)*, pp. 404-409, Evry/Paris, France, Oct. 27-29 2003. Institut National des Télécommunications.

L. Martins, J. Craveirinha, and J. Clímaco. A new multiobjective dynamic routing method for multiservice networks - modelling, resolution and performance. Research Report 2/2005, INESC-Coimbra (www.inescc.pt), Feb. 2005.

D. Medhi and I. Sukiman. Multi-service dynamic QoS routing schemes with call admission control: A comparative study. *Journal of Network and Systems Management*, 8(2):157-190, 2000.

D. Mitra and J. A. Morrison. Erlang capacity and uniform approximations for shared unbuffered resources. *IEEE/ACM Transactions on Networking*, 2(6):558-570, Dec. 1994.

REFERENCES-2

D. Mitra, J. A. Morrison, and K. G. Ramakrishnan. Optimization and design of network routing using refined asymptotic approximations. *Performance Evaluation*, 36-37:267-288, 1999.

D. Mitra and K. G. Ramakrishnan. Techniques for traffic engineering of multiservice, multipriority networks. *Bell Labs Technical Journal*, 6(1):139-151, Jan. 2001.

C. Pornavalai, G. Chakraborty, and N. Shiratori. Routing with multiple QoS requirements for supporting multimedia applications. *Telecommunication Systems*, 9(3,4):357-373, Sep. 1998.

J. W. Roberts. Teletraffic models for the Telecom 1 integrated services network. In *Proceedings of 10th International Teletraffic Congress*, Montreal, Canada, 1983.

M. Rombaut, G. Hébuterne, and M. Priem. The limited version of the mille feuilles: A routing algorithm for packet networks and circuit switched networks with a constraint number of paths. In *Proceedings of NETWORKS 2002 - 10th International Telecommunication Network Strategy and Planning Symposium*, pp. 365-372, München, Germany, Jun. 23-27 2002.

REFERENCES-2

E. Rosen, A. Viswanathan, and R. Callon. Multiprotocol label switching architecture. RFC 3031, Network Working Group, Jan. 2001.

S. Schnitter and G. Hasslinger. Heuristic solutions to the LSP-design for MPLS traffic engineering. In *Proceedings of NETWORKS 2002 - 10th International Telecommunication Network Strategy and Planning Symposium*, pp. 269-273, München, Germany, Jun. 23-27 2002.

L. Tralhão, J. Craveirinha, and J. Paixão. A study on a stochastic system with multiple MMPP inputs subject to access functions. In *New Progress in Probability and Statistics - 4th International Symposium on Statistics of the Base Country*, pp. 415-428. VSP - International Publishers, 1994.

R. Widyono. The design and evaluation of routing algorithms for real-time channels. Technical Report TR-94-024, Tenet Group - University of California at Berkeley & International Computer Science Institute, Jun. 1994.

A. P. Wierzbicki, M. Makowski, and J. Wessels (Eds.). *Model-Based Decision Support Methodology with Environmental Applications*. Kluwer Academic Publishers, Dordrecht, Netherlands, June 2000.

MTPT 2006

Leiria, September 2006

A multiobjective routing optimisation framework for multiservice networks- a heuristic approach

(part - II)

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Summary

- **1. Overview of explosive evolution of network technologies - new challenges and issues for OR**

- **2. Why multicriteria modelling is an actual issue in telecommunication network routing**

- **3. A multiobjective routing optimisation framework for multiservice networks :**
  - ***3.1 Why multicriteria routing models***
  - ***3.2 Overview of multicriteria routing approaches***
  - ***3.3 MODR-S - a multiobjective dynamic routing method for muliservice networks***
  - ***3.4 A general multiobjective routing framework for MPLS networks***

- **Future trends and issues**

3.4 (Part-II): *A general multiobjective routing framework for MPLS networks*

Summary:

- **Introduction - Routing in MPLS**
- **Conceptual issues in multiobjective routing models for MPLS**
- **Proposal of a multiobjective routing framework for MPLS**
  - *Base Model*
  - *Model for two classes of traffic (QoS and Best Effort)*
  - *Traffic modelling approach*
- **Conclusions and Further Work**

Introduction - Routing in MPLS

Review of some basic concepts in MPLS

- When packets enter the network they are grouped in different FECs (Forward Equivalent Classes) according to specific criteria (e.g originating/terminating node, grade of service to be provided to the packet stream) and labelled accordingly.

- The packet routing mechanism is based on the establishment of LSPs (Label Switched Paths): at each intermediate node (Label Switching Routers) the packets are forwarded according to a specific label switching technique

- MPLS enables the establishment of ***explicit routes*** (corresponding to “LSP tunnels”) where the route follwed by each traffic stream is entirely determined by the ingress router as well as other advanced routing mechanisms (traffic engineering mechanisms) in multiservice packet networks.

Routing in MPLS

Review of some basic concepts in MPLS (cont.)

- A *micro-flow* can be defined as a specific stream of packets with the same source and destination addresses, source and destination ports and protocol identifier .

- A *traffic trunk* is an aggregation of traffic flows of the same class which are forwarded through a given path and may be characterized by the incoming/outgoing nodes and a set of treaffic engineering attributes, associated with its dynamics and corresponding requirements from the network, namely QoS related requirements.

Review of some basic concepts in MPLS (cont.)

- The necessity arises for MPLS routing models dealing with multiple, heterogeneous QoS requirements**.**
- **Therefore, there are potential advantages in using multiobjective formulations for the routing calculation problems in this MPLS networks**.

Conceptual and Methodological Issues in Multiobjective Routing Models in MPLS

- A significant number of routing models have been proposed for MPLS networks seeking to explore the features and capabilities of MPLS.
- In [Craveirinha *et al.*, *05*] an overview of multiobjective routing models proposed for MPLS networks, is presented.
- Those proposals often differ in *key instances of the routing framework* and those differences are not discussed in most cases…

Conceptual and Methodological Issues in Multiobjective Routing Models in MPLS (cont.)

- Those remarkable differences refer to fundamental aspects of the model:
  - Optimisation frameworks: Two major types of optimisation frameworks can be identified:
    - Network-wide
    - Flow-oriented
  - Nature of the model, concerning several instances.

Conceptual and Methodological Issues in Multiobjective Routing Models in MPLS (cont.)

Nature of the model concerning:

- Key features of the underlying routing system (eg.: on-line/off-line; static/dynamic; ...)
- Specified objective functions and constraints and their technical-economic meaning
- Representation of the traffic to be routed, concerning:
  - Level (granularity) of the representation (traffic trunk / packet stream)
  - Nature of the representation:
    - Deterministic (typical in classical multicommodity network flow formulations)
    - Stochastic

Proposal of a Framework for Routing Optimisation in MPLS

It is based on a **network-wide optimisation routing model** of new type:

- **Hierarchical multiobjective optimisation model**
  - First level: objective functions formulated at network level (considering the combined effect of all traffic flows)
  - Second level: average performance metrics associated with different types of services
  - Third level: average performance metrics associated with the μ-flows of packet streams

- Explicit consideration of **fairness objectives** at the three levels of optimisation.

Proposal of a Framework for Routing Optimisation in MPLS (cont.)

- It includes an *explicit and 'direct' representation* of the most relevant technical-economic objectives, namely total expected revenue and packet total average delay (rather than the corresponding 'indirect' or 'refracted' objective functions).

- It considers a *bi-level stochastic representation* of the traffic in the network

    - <u>Macro-level</u>: ***traffic flows*** that correspond to a stochastic representation of the connection demands in the traffic trunks associated with explicit routes

    - <u>Micro-level</u>: stochastic representation of **μ-flows of packet streams** inside any given traffic flow

Base-model

- Formulation of a hierarchical multiobjective routing optimisation problem:

Network objectives: $\min_{\overline{R}_t}\{-W_T\}$

$\min_{\overline{R}_t}\{B_{Mm}\}$

Service objectives: $\min_{\overline{R}_t}\{B_{ms}\},\ s \in S$

$\min_{\overline{R}_t}\{B_{Ms}\},\ s \in S$

μ-flow network objectives: $\min_{\overline{R}_t}\{D'_T\}$

$\min_{\overline{R}_t}\{D_{Mm}\}$

Base-model (cont.)

- **Network objectives**
  - Total expected network revenue

$$W_T = \sum_{s \in S} A_s^c w_s$$

S: set of service types

A_s^c: total traffic carried for service s

w_s: expected revenue per μ-flow of type s

  - Maximal average blocking probability among all service types (*network-level fairness objective*)

$$B_{Mm} = \max_{s \in S} \{B_{ms}\}$$

- **Service objectives**
  - Maximal blocking probability among all traffic flows of type s (*fairness objective at service level*)

$$B_{Ms} = \max_{f_s \in F_s} \{B(f_s)\}$$

Base-model (cont.)

- **Service objectives** (cont.)
  - –Average blocking probability for all traffic flows of type s (the set of which is F_s)

$$B_{ms} = \frac{1}{A_s^o} \sum_{f_s \in F_s} A_t(f_s) B(f_s)$$

A_s^o: total traffic offered for service s

$A_t(f_s)$: traffic offered for traffic flow f_s

$B(f_s)$: the corresponding end-to-end blocking probability

- **μ-flow network objectives**
  - –Average packet delay for all types of services, weighted by the relative bandwidths

$$D_T^{'} = \frac{1}{\gamma_T^{'}} \sum_{s \in S} D_{ms}^{'} \gamma_s^{'}$$

Base-model (cont.)

•µ-flow network objectives (cont.)

$$D_T' = \frac{1}{\gamma_T'} \sum_{s \in S} D_{ms}' \gamma_s'$$

D_{ms}' = average delay experienced by packets from an arbitrary flow of type s weighted with bandwidths

γ_s' = average bandwidth offered to the network by flows of type s

γ_T' = total average bandwidth offered to the network by all flows

–Maximal average packet delay experienced by all types of packet streams (*fairness objective at µ-flow network level*)

$$D_{Mm} = \max_{s \in S} \{D_{ms}\}$$

D_{ms} = average delay experienced by packets from an arbitrary flow of type s

Base-model (cont.)

- **This generic model should be envisaged as a multiobjective routing optimisation framework with a significant degree of <u>flexibility</u> and <u>adaptability</u>.**

- **The proposed *meta-model* i.e. the model underlying concepts and logical relations may be configured for other specifications of objective functions and /or constraints as far as the basic structure of the meta-model is preserved.**

Base-model (cont.)

- ✓ **The MODR-S model previously described may be considered as a particular application of the proposed meta-model to a modelling situation whith one service class only (QoS) and just a macro-level traffic representation.**

Model for QoS and Best Effort service classes

QoS <> class of services S_Q, with guaranteed specific QoS levels (higher 'priority')

Best Effort <> class of services S_B, the traffic flows of which are carried on a 'best effort' basis, concerning QoS, but seeking not to jeopardise the QoS of the QoS traffic flows (lower 'priority')

- The treatment in terms of routing of two (or more) classes of traffic flows is a 'complex' issue and different approaches have been proposed (ex.: bandwidth reservation techniques, virtual networks).

Model for QoS and Best Effort service classes (cont.)

- In the framework of the meta-model, this issue can be tackled in terms of the following hierarchical optimisation problem for two service classes:

1st level

QoS network objectives: $\min_{\overline{R}_t}\{-W_{T|Q}\}$

$\min_{\overline{R}_t}\{B_{Mm|Q}\}$

2nd level

QoS service objectives: $\min_{\overline{R}_t}\{B_{ms|Q}\},\ s \in S_Q$

$\min_{\overline{R}_t}\{B_{Ms|Q}\},\ s \in S_Q$

BE network objective: $\min_{\overline{R}_t}\{-W_{T|B}\}$

3rd level

µ-flow network objectives: $\min_{\overline{R}_t}\{D'_T\}$

$\min_{\overline{R}_t}\{D_{Mm}\}$

Model for QoS and Best Effort service classes (cont.)

- The functions $W_{T|Q}$, $W_{T|B}$, $B_{Mm|Q}$, $B_{ms|Q}$, $B_{Ms|Q}$ have the meaning described before, but with the index Q (B) indicating that their calculation is reported to traffic flows of class QoS (Best Effort) alone.

- While QoS and BE traffic flows are treated separately in terms of upper level objective functions, the interactions among all traffic flows remain represented in the model (via the teletraffic model underlying the routing optimisation model).

  – In fact, the *link traffic model* must integrate the contributions of all the traffic flows which may use every link.

Traffic modelling approach

- **Traffic flows** (macro level) are represented through *marked point processes of multirate Poisson* type
  - The concept of *effective bandwidth* (d_{ks}) required by traffic flows f_s on link l_k, is used.
  - *This is a stochastic measure of the utilization of network transmission resources capable of representing the variability of the rates of different traffic sources, as well as effects of statistical multiplexing in the network.*

- This and other parameters are included as 'attributes' contained in the traffic engineering descriptors of traffic flow $f_s = (v_i, v_j, \bar{y}_s, \eta(f_s))$ from node v_i to v_j.

Traffic modelling approach - macro level

- The traffic model of a link for calculating the blocking probabilities B_{ks} experienced by flows f_s on link l_k is a multidimensional Erlang system $M_1+M_2+\ldots+M_n/M/C_k/0$.

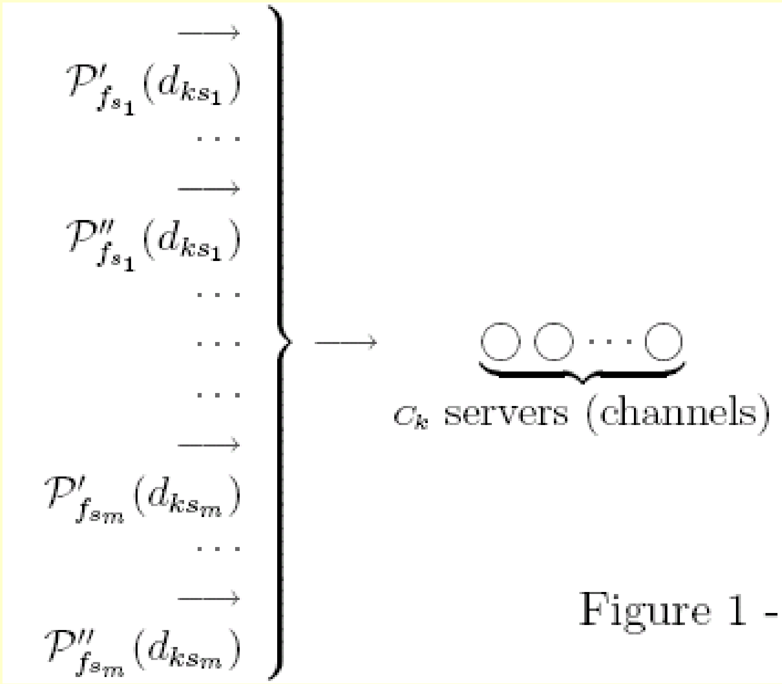

Figure 1 - Traffic model for a link at the traffic flow level.

Traffic modelling approach - macro level (cont.)

$$B_{ks} = L_s(\bar{d}_k, \bar{\rho}_k, C_k)$$

$$\bar{d}_k \equiv [d_{ks}] = \text{vector of effective bandwidths of flows of type } s \text{ in } l_k$$

$$\bar{\rho}_k \equiv [\rho_{ks}] = \text{vector of reduced traffic loads offered by flows of type } l_k$$

L_s is a loss function implicit in the analytical model.

- Its values can be calculated by adequate efficient and robust algorithms (as the Kaufman/ Roberts algorithm or the UAA - Uniform Asymptotic Approximation- for large C_k) as in MODR-S.

Traffic modelling approach - micro level

- **Traffic modelling at packet μ-flow level (micro level)** uses marked point processes characterised by their intensities $I'_t(f_s)$ [packet/s] and $h^k(f_s)$ (mean service time in l_k of a packet from μ-flows in f_s).

  - The mean [Erl] of each of these processes defines the *potential traffic offered* to l_k by f_s, at time period t.
  - The *loss* and *control access mechanisms* may be represented by a multidimensional access function for each link.

Traffic modelling approach - micro level (cont.)

- This access function enables the calculation of *reduced offered loads* $\rho_t^{k*}(f_s)$ and of the fictitious <u>equivalent total offered traffic</u>

$$\rho_t^{k*} = \sum_{s \in S} \sum_{f_s \in F_s} \rho_t^{k*}(f_s)$$

M* is an equivalent (fictitious) total Poisson offered traffic with mean ρ_t^{k*}

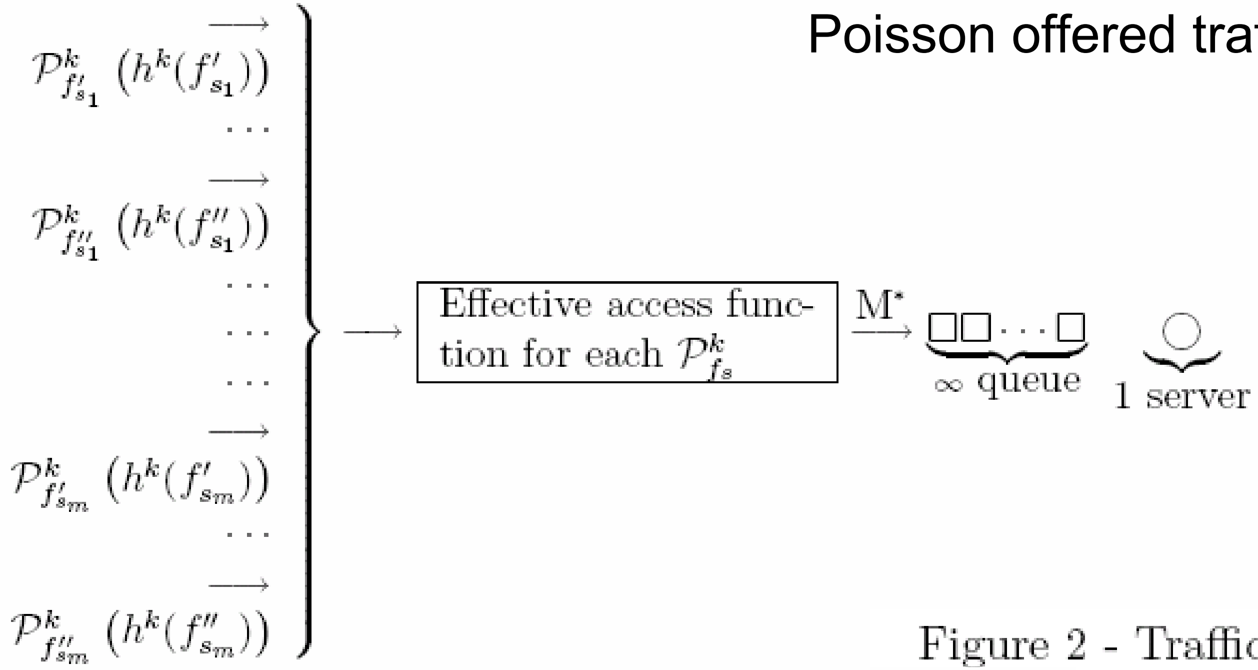

Figure 2 - Traffic model for a link at the packet μ-flow level.

Traffic modelling approach - micro level (cont.)

- The *average expected delay* $D_k(f_s)$ experienced in l_k by packets in μ-flows from f_s may be estimated, in a first, rough aproximation, from a M/GI/1/∞ queue model.
  - A first approximation to the service time distribution is a hyper-exponential distribution, the weights of which represent the probability of an arbitrary packet offered to l_k being originated from each f_s.

- A detailed description of the meta-model and of the underlying traffic model are in [Craveirinha *et al.*,*05*]

Conclusions and Further Work

- A discussion of conceptual and methodological issues raised by routing optimisation models for MPLS networks, was outlined.

- A **framework for multiobjective routing optimisation in MPLS** has been described

  - ❖ It is based on a *hierarchical multiobjective formulation of a network-wide optimisation problem* with innovative features including *fairness objectives at network and service levels*.

Conclusions and Further Work (cont.)

- It is **adaptable** to various routing principles and situations.
- A model resulting from the application of this framework to multiobjective routing with **QoS** and **Best Effort** service classes was presented

- A teletraffic modelling stochastic approach to be used in the context of the meta-model, for calculating traffic related parameters, was described.

Conclusions and Further Work (cont.)

- The proposed modelling framework raises a number of open issues and difficulties:
  - The complexity of the associated routing optimisation problems requires the development of resolution approaches of heuristic or meta-heuristic type.
  - Consideration in the model of load sharing or traffic splitting routing mechanisms having in mind to enhance its trafic carrying flexibility
  - Representation of the system of preferences in an automatic decision environment taking into account the great complexity of the hierarchical multiobjective optimisation model.
  - Treatment of inaccuracy and uncertainty associated with many parameters.

4

Future trends and issues

FUTURE TRENDS AND ISSUES

- The development of **multicriteria models** for routing problems seems to be an area where there is still a significant amount of work to be done.

  The following **trend**s and **issues** can be identified in this area:

- **Routing of continuous media streams** (such as audio and video in packet-switched networks) where the basic problem is to find, for each flow, a path satisfying multiple, conflicting objectives and constraints.

FUTURE TRENDS AND ISSUES (cont.)

- **The search for new multicriteria models devoted to routing problems in distributed multimedia applications which require multiple QoS performance constraints**; this is a challenging problem associated with the integrated /differentiated service models in the Internet and MPLS.

  Examples of bi-objective flow-oriented models of this type are described in [Pornavalai *et al.*,98]] and [Clímaco *et al.*,03, 06]. While the first one uses a rule-based heuristic based on the Dijkstra algorithm, in the second approach the complete set of efficient paths, is generated.

FUTURE TRENDS AND ISSUES (cont.)

- In this context the modelling of multiple constraints (bandwidth, delay, jitter and blocking probabilities) in terms of possible simplifications and interdependencies is a relevant issue.

- **The need of incorporating approximate stochastic models for representing certain criteria and/or constraints**, having in mind the nature of the nodes of the network, that may represent switches, routers or servers depending on the type of problem and the application environment (e.g. WDM optical networks, MPLS-Internet).

FUTURE TRENDS AND ISSUES (cont.)

- **Investigation of models and OR techniques for dealing with uncertain or imprecise parameters of the routing models.**

  For instance, in a dynamic routing model, where routing paths are updated as a function of the measurement of the traffic loads and/or the state of occupations, the cost of routing calls on each link must reflects the stochastic nature of the network . Such "cost" to be incorporated in the definition of cost functions of multiobjective dynamic routing models have an inherent imprecise and uncertain nature that has to be modelled in some manner.

FUTURE TRENDS AND ISSUES (cont.)

- Recent optical network technologies, namely WDM (Wavelength Division Multiplexing), DWDM (Dense WDM), optical cross-connects and optical multiplexers and Internet technologies (namely GMPLS-Generalised Multiprotocol Label Switching) pave the way towards the creation of a broadband Internet over “all-optical” network [Assi *et al., 01*].

  In this context of wavelength-routed networks a new type of routing problems arises, designated as **route wavelength assignment problems** (RWA).

FUTURE TRENDS AND ISSUES (cont.)

- These problems involve the determination and selection of two or more *lightpaths* (a lightpath is a fixed bandwidth connection between two network elements) between a given source-destination pair and involve two types of problems: the "routing problem" (this involves the determination of a path along which a connection can be established) and the "wavelength assignment problem" (this involves to assign a wavelength or a set of wavelengths on each link along the selected path). Various types of formulations and algorithmic approaches have been proposed for these problems [Zan *et al.,00*].

◈ This is an area where the possible introduction of multicriteria analysis approaches deserves investigation.

FUTURE TRENDS AND ISSUES (cont.)

- Other areas where the existence of conflicting criteria and multifaceted constraints requires that complex and difficult trade-offs have to be made in order to obtain satisfactory compromise solutions have been identified in the literature, namely the **dimensioning of international telecommunication networks** [Anandalingam &Nam, 97].

Several actors must be considered in the decision process. So, group decision and negotiation are together with multicriteria decision support very important issues.

FUTURE TRENDS AND ISSUES (cont.)

An interesting *open methodological issue* that deserves attention refers to **the specification of the system of preferences in hierarchical multiobjective optimisation models**:

- The search for non-dominated solutions is fundamentally determined by the set of non-dominated solutions of the first level optimisation functions.

FUTURE TRENDS AND ISSUES (cont.)

• In the selection of solutions in this set, the second, third,…level objective functions will play some form of *"filtering" role*. The way in which this task should be approached is not trivial in many models, and is also dependent on the model characteristics

• In the case of very complex models (e.g. MODR-S) where an algorithm for generating the whole non-dominated solution set of the first optimisation level is not available, this issue is further complicated…

FUTURE TRENDS AND ISSUES (cont.)

• Another important *issue* related to the appllication scope of network-wide optimisation models which deserves attention refers to **the development of distributed computation models corresponding to decentralized routing control schemes,** where the route calculation procedures are assigned to the nodes assuming the rquired information is available to each of them.

This is particular important to enhance the tractability of this models in practical networks.

CONCLUSIONS

- A multiple objective paradigm to approach routing problems in multiservice communication networks, was presented.

- This enables to grasp in a rationalised manner the trade-offs among distinct QoS requirements and conflicting objectives in different types of multiservice networks and raises a number of challenging methodological and application issues.