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Multicast routing with QoS based on incomplete link state information

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Abstract: This paper is concerned with developing novel algorithms for multicast routing in packet switched communication networks when there is no available exact information about the link states in the network. In these cases probabilistic models can be used and the goal of the route selection procedure is to find an admissible route with maximal probability. The multicast probabilistic routing model with bandwidth and cost requirement in the case of incomplete information is reduced to a deterministic Steiner tree problem. The multicast routing concerning the end-to-end delay requirement can be transformed in some cases to finding shortest paths between the multicast nodes based on equivalent deterministic link measures.

Key-words: Network, multicast routing, Quality of Service, Steiner problem

(Résumé : tsvp)

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Routage multicast avec QoS basé sur des informations incomplètes des liens

Résumé : Dans cet article, nous développons de nouveaux algorithmes pour le routage multicast dans les réseaux de communication. Plus précisemment, nous proposons des algorithmes pour les cas où les informations sur l'état des liens ne sont pas fiables. Pour le problème du routage multicast avec contrainte de bande passante ou d'un coût généralisé, nous proposons la transformation du problème lorsque l'information est incomplète en un problème de Steiner déterministe équivalent. Lorsque la QoS de la communication multicast est donnée sous la forme d'une limitation du délai de bout en bout, nous proposons de transformer le problème en un problème similaire utilisant des valeurs déterministes sur les liens. Nous en donnons unw solution approchée pour le routage.

Mots-clé : Réseaux, routage multicast, qualité de service, problème de Steiner

1 Introduction

In routing methods, when a connection allocation request is presented, a path selection is executed to find an admissible (or the better) path or tree from among the available routes that satisfies the request. Different routing strategies can be applied in order to satisfy the requested conditions of the QoS aware communications. QoS goals can be achieved with the help of fixed or dynamic routing strategies. In the case of dynamic routing the routing procedure (mainly the routing table) is revised. Routing tables can be altered at a fixed point in time or according to the state of the network. In certain dynamic routing solutions some events implicate the modification of routing tables and so the routing becomes event dependent. The used routing tables can be pre-planned with the help of an off-line computation or prepared on demand when changes are needed. The computation can be centralized or distributed [14]. In any case the route computation (the path/tree selection) requires efficient path or tree computation algorithms.

To perform routing which can really be called QoS routing, the exact values of link descriptors (available bandwidth, delay, jitter, etc.) should be known at the proper nodes where the route selection should be fulfilled in the network while calculating routes. Unfortunately, this is not a possible way originated from the required amount of capacity should be used to distribute these exact values in the network. To avoid using the significant fraction of network capacity for transmitting link state information, the values of link descriptors can be advertised periodically or only at the time instants when predefined thresholds are exceeded. In this way the routing algorithms can select routes based on the last advertised values of link descriptors and can obtain solutions which can be quite different from the solutions could be found knowing the exact values. So, the routing methods can only work on "incomplete information" and can find only sub-optimal routes for flows requiring QoS. The simplest way to calculate sub-optimal routes is simply executing traditional methods (e.g. Dijkstra or Bellmann-Ford algorithms to find shortest paths, Kou or Takahashi-Matsuyama algorithms [5, 6] to find partial spanning trees) on the last advertised link values. This is the manner how the currently used routing protocols can work [3, 4].

The effectiveness can be increased by using the knowledge about the mechanism of the advertisement of link descriptors (e.g. which thresholds are used during the operation). Based on this and some a priori information about the behavior of the values of the link descriptors, probabilistic models can be set up to provide more appropriate routes for QoS flows [8, 9]. Obviously, the objective of the route selection based on different types of probabilistic methods corresponds to determine the optimal routes, which can fulfill the QoS requirement with maximum probability.

There are other reasons why the routing methods can only work on incomplete information. Such a reason comes from the OSPF and PNNI protocols, which works in hierarchical manner, where the values of the link descriptors on higher hierarchical levels are calculated as average values over the lower ones. So, routing in these levels are also based on incomplete link values (the exact values from the lower levels are not known) [8]. Determining the thresholds, which are used to be advertised, is an interesting task because it means drawing a balance between the network capacity used for distributing the link state information and the incompleteness of the information stored in the routing tables. Increasing the distance between the thresholds decreases the necessary capacity for advertisement while increases the incompleteness of information about link values. On the other hand when the distances are decreased advertisement events will occur more frequently (much more bandwidth may be needed for link state messages), but more precise link state information will be stored in the routers (the probability of fulfilling the QoS requirement along the selected route will be increased).

The main focus of this paper is to introduce new multicast routing algorithms which are able to perform route selection based on probabilistic link measures in the case of the most typical types of QoS requirements (overall cost, end-to-end delay or jitter, minimal bandwidth) and analyze theirs performances against the currently standardized algorithms (which work on "imprecise" deterministic link measures). The results are tested by extensive simulations.

These topics will be treated in the following structure:

- in *Section 2* the model and the notation is introduced to tackle the problem;
- in *Section 3* we propose solutions for the multicast routing problem in the case of incomplete information using the typical QoS objectives and the appropriate metrics;
- in *Section 4* extensive numerical analysis of the methods are given before the conclusions.

2 Network model and technology

Let $G = (V, E)$ be the graph representing the network topology and let us suppose that the network is able to perform QoS routing mechanisms. For this reason the state of the network is monitored and link values corresponding to the selected QoS goals are known with a given doubtfulness. The link value measurement and the propagation of the values are insured with the help of a QOSP like mechanism [3, 4].

Let us suppose that routers advertise the values of the link descriptors over the network, in the following fashion:

- The parameter axis (the set of possible values of the link descriptor) is covered with a grid $D = \{t_i, i = 1, ..., N\}$.
- At each time instant the value t_i is advertised from the link (u, v), if the value of the link descriptor on link (u, v) steps into the interval (t_i, t_{i+1}).

In this way each link $(u, v) \in E$ has a QoS descriptor $\delta_{(u,v)}$ which is assumed to be random variable subject to the conditional probability distribution function

$$F^{(i)}_{\delta_{(u,v)}}(x) = P(\delta_{(u,v)} < x | t_i < \delta_{(u,v)} < t_{i+1})$$

In certain cases the random variables corresponding to the different links can be considered as independent random variables (cf. Section 3).

The set of multicast group members is given and denoted by $V_m \subset V$.

The goal of the multicast routing is to find a partial spanning tree T which spans for all u in V_m and which corresponds to the required QoS criterion with the maximal probability:

$$T_{opt} : \arg\max_{T \in \mathcal{T}} P(\text{ QoS criterion is true}) \tag{1}$$

where $\mathcal{T}$ is the set of trees spanning V_m.

The most frequently used QoS criterions for multicast tree selection are analysed in the next section of this paper.

3 Routing with incomplete information

The QoS aware routing problems vary in the used objective function and in the used link metrics. A few papers analyze the QoS routing problem with determined link metrics and with appropriate objective functions. A large overview and classification of routing problems and solutions can be found in [2]. These analyzes are out of scope of our paper. Our analyze aims the routing problem when the link values are measured with uncertainty. In our case the QoS routing models based on determined values can not be applied.

Generally, the QoS criterion formulation depends on the type of the used link metrics. If the link values are known with uncertainty, the objective functions for multicast tree selection can be formulates as follows.

1. Assuming *bottleneck type* of link metrics (e.g. bandwidth) the criterion can be written as

   $$\min_{(u,v) \in T} \delta_{(u,v)} > \alpha$$

   where α corresponds to the asked value (e.g. the needed bandwidth);

2. In the case of *additive type* of unicast link metrics two typical cases of multicast objectives should be distinguished.

   (a) For QoS requirement concerning *the end-to-end quality* (e.g. delay, jitter, negative logarithm of the packet loss) the criterion can be written as

   $$\max_{R_{(s,r_i)} \in \mathcal{R}_T} \sum_{(u,v) \in R_{(s,r_i)}} \delta_{(u,v)} < \beta$$

   Here β corresponds to the value tolerated by the QoS requirement (e.g. tolerated end-to-end delay) and $\mathcal{R}_T$ denotes the set of paths between the sender ($s \in V_m$) and the receiver ($r_i \in V_m \backslash \{s\}, i = 1, ..., M$) nodes (Single Source Multicast model) or the paths between every node pair of V_m (Any Source Multicast model). Originated from the frequently used source based applications and the algorithmic complexity the paper is concentrated to the Single Source Multicast model.

(b) For requirements concerning the *overall cost* of the spanning tree the QoS criterion corresponds to

$$\sum_{(u,v)\in T} \delta_{(u,v)} < \gamma$$

where γ is the cost tolerated by the demand.

The objective of the multicast routing is to find an optimal tree T_{opt} which spans the multicast nodes and most likely fulfills the QoS criterion, namely:

1. considering bottleneck type of link metrics

$$T_{opt1} : \arg\max_{T\in\mathcal{T}} P(\min_{(u,v)\in T} \delta_{(u,v)} > \alpha) \tag{2}$$

2. considering additive type of link metrics

   (a) in the case of end-to-end quality requirement

$$T_{opt2} : \arg\max_{T\in\mathcal{T}} P(\max_{R_{(s,r_i)}\in\mathcal{R}_T} \sum_{(u,v)\in R_{(s,r_i)}} \delta_{(u,v)} < \beta) \tag{3}$$

   (b) in the case of an overall cost function

$$T_{opt3} : \arg\max_{T\in\mathcal{T}} P(\sum_{(u,v)\in T} \delta_{(u,v)} < \gamma) \tag{4}$$

The following discussion analyzes the optimization tasks (2)-(4).

3.1 Bottleneck type of link metrics

The following lemma states that (2) can easily be transformed to a Steiner tree problem and so can only be approximated in polynomial time.

Lemma 1 *Assuming link independence the solution of (2) is equivalent to solving a partial minimal spanning tree (PMST) problem with the deterministic measures assigned to link* (u,v) *being* $\kappa_{(u,v)} = -\log P\left(\delta_{(u,v)} > \alpha\right)$.

Proof: We seek the multicast tree

$$T_{opt1} : \arg\max_{T\in\mathcal{T}} P(\min_{(u,v)\in T} \delta_{(u,v)} > \alpha)$$

which is equivalent to

$$T_{opt1} : \arg\max_{T\in\mathcal{T}} P(\bigcap_{(u,v)\in T} \delta_{(u,v)} > \alpha)$$

Assuming independent random variables (*i.e.* link independency)

$$P(\bigcap_{(u,v)\in T} \delta_{(u,v)} > \alpha) = \prod_{(u,v)\in T} P(\delta_{(u,v)} > \alpha)$$

and the optimum can be defined by

$$T_{opt1} : \arg\min_{T\in\mathcal{T}} \sum_{(u,v)\in T} -\log P(\delta_{(u,v)} > \alpha) \tag{5}$$

Therefore assigning measure $\kappa_{(u,v)}$ to link (u,v) as $\kappa_{(u,v)} := -\log P(\delta_{(u,v)} > \alpha)$. Q.E.D.

Heuristic methods (Kou, Takahashi-Matsuyama, etc.) can approximate the optimal solution [7].

3.2 Additive type of link metrics

As can be seen from (3) and (4), the selection of the optimal PST based on additive type of link metrics depends on the quality criterion.

3.2.1 End-to-end QoS requirement

Generally, the paths between the sender node and the receiver ones contain common links in a multicast tree. So, the random measures over these paths statistically depend on each other. Taking into account the events of including the same link(s) in different paths results an optimization task having high complexity, since the joint distribution of the paths should be known.

$$T_{opt2} : \arg\max_{T\in\mathcal{T}} P(\bigcap_{R_{(s,r_i)}\in\mathcal{R}_T} \{\sum_{(u,v)\in R_{(s,r_i)}} \delta_{(u,v)} < \beta\}) \tag{6}$$

Originated from the fact that there is no available method to solve (6) directly, the following discussion is concentrated on a special case when the joint distribution of the paths included in the PSTs takes a relatively simply form and it is determined by the first two moments (by the expected value and the variance).

Let us introduce random variables ξ_i as

$$\xi_i = \sum_{(u,v)\in R_{(s,r_i)}} \delta_{(u,v)}$$

and rewrite (6) as

$$T_{opt2} : \arg\max_{T\in\mathcal{T}} P(\bigcap_{i=1}^{M}\{\xi_i < \beta\})$$

Applying the central limit theorem T_{opt2} can be formulated as

$$T_{opt2} : \arg\min_{T \in \mathcal{T}} \int_{\beta}^{\infty} ... \int_{\beta}^{\infty} \frac{exp\{-\frac{1}{2}(\bar{x}-\bar{m})^T \bar{\bar{K}}^{-1}(\bar{x}-\bar{m})\}}{\sqrt{(2\pi)^M det\bar{\bar{K}}}} dx, \tag{7}$$

where $m_i = E\{\xi_i\}$ is the expected value of ξ_i, $K_{ij} = E\{(\xi_i - m_i)(\xi_j - m_j)\}$, $i, j = 1, ..., M$ and M corresponds to the cardinality of the set of paths. The matrix $\bar{\bar{K}}$ can easily be calculated when assuming the link independency (of course the path independency is not true)

$$K_{ij} = \sum_{(u,v) \in R_{(s,r_i)} \bigcap R_{(s,r_j)}} \sigma^2_{(u,v)}. \tag{8}$$

So, the quality of T_{opt_2} is determined by the mean values and variances of link descriptors along the paths and the sum of the variances of the common links included in the tree. As can be seen finding the optimal solution means a complex discrete optimization task, still when the joint distribution takes a simply form like (7).

In the following, a heuristic greedy algorithm is proposed to find approximated solutions. Denote V_r the set of the destinations which are still not connected to the spanning tree $T = (V_t, E_t)$ being under construction. In order to register the end-to-end delay, a weight v_z is associated to each node $z \in V_t$. This weight is calculated as the sum of the mean values and variances along the path connecting the node z to the source node s in $T = (V_t, E_t)$:

$$v_z = \sum_{(u,v) \in R_{(s,z)}} m_{(u,v)} + \sigma^2_{(u,v)}$$

The algorithm works as follows:

1. Calculate the link measures as $\kappa_{(u,v)} = m_{(u,v)} = E\{\delta_{(u,v)}\}$, $\forall (u,v) \in E$;
2. Set $V_r = \{r_i, i = 1, ..., M\}$ and $V_t = \{s\}$, where s is the sender node and $v_s = 0$;
3. Find shortest paths from each multicast node $r_i \in V_r$ to each node $w \in V_t$ of the currently constructed tree

$$R_{(r_i,w)} : \arg\min_{R} \sum_{(u,v) \in R} \kappa_{(u,v)}; \tag{9}$$

4. Select the shortest one $R_{(r_{i^*},w^*)} : \arg\min_{r_i \in V_r, w \in V_t}\{v_w + \sum_{(u,v) \in R_{(r_i,w)}} \kappa_{(u,v)}\}$;
5. Add each node z included in $R_{(r_{i^*},w^*)}$ to V_t ($V_t = V_t \bigcup \{z\}$) with the calculated weight $v_z = v_{w^*} + \sum_{(u,v) \in R_{(z,w^*)}} (m_{(u,v)} + \sigma^2_{(u,v)})$, where $R_{(r_{i^*},w^*)} = R_{(r_{i^*},z)} \bigcup R_{(z,w^*)}$. Add the edges of the path $R_{(r_{i^*},w^*)}$ to E_t;
6. Set $V_r := V_r \backslash \{r_{i^*}\}$;

7. If $|V_r| \neq 0$ then go to step 3;

As can be seen, the heuristic tries to avoid solutions having large end-to-end delays and common links with large variances. Applying the Bellman-Ford algorithm the heuristic has $(M^2 + M)|E|(|V|-1)/2$ complexity.

3.2.2 Overall QoS requirement

Unfortunately, it is a very hard task to find the optimal solution of (4), because the task of finding PMSTs is a NP hard problem already in the case of deterministic link measures. The most attractive way to make the original NP hard problem (4) to be tractable is to reduce it to the task of finding PMST based on deterministic link measures and try to find suboptimal solution for the original problem.

Lemma 2 *Assuming link independence, the solution of (4) can be approached by solving a PMST problem with the deterministic measures assigned to link* (u, v) *being*

$$\kappa_{(u,v)} = \mu_{(u,v)}(s) = lnE\{e^{s\delta_{(u,v)}}\}$$

Proof: The original routing task can be transformed to a tail estimation problem by rewriting into

$$T_{opt3} : \arg\min_{T} P\Big(\sum_{(u,v)\in T} \delta_{(u,v)} > \gamma\Big)$$

which allows us to use well known statistical inequalities. By applying the Chernoff inequality the latter probability can be upper-bounded

$$P\Big(\sum_{(u,v)\in T} \delta_{(u,v)} > \gamma\Big) \leq e^{\mu_T(s)-s\gamma} \tag{10}$$

where $\mu_T(s)$ $(\forall s > 0)$ is the log-moment generating function of the sum of the probabilities given by

$$\mu_T(s) = \sum_{(u,v)\in T} \mu_{(u,v)}(s)$$

Therefore, minimizing the bound as

$$T_{opt3} : \min_{T} exp\Big(\sum_{(u,v)\in T} \mu_{(u,v)}(s) - s\gamma\Big) \tag{11}$$

the original problem is reduced to find the PMST with link measures $\kappa_{(u,v)} = \mu_{(u,v)}(s)$. Q.E.D.

Since the upper bound in (10) depends on the value of s, optimizing this value a good upper bound and solutions closer to the optimum can be obtained. We consider the optimal value of s as follows:

$$s_{opt} : \sum_{(u,v)\in T} \frac{d\mu_{(u,v)}(s)}{ds} = \gamma$$

4 Simulation results

To analyze the qualities of the solutions can be achieved by using traditional and the new multicast routing methods it is necessary to make some notation.

4.1 Calculated partial spanning trees

To generate performance measures three kinds of multicast trees are introduced and calculated for comparison.

1. ***The solution*** T_{QOSPF}

   The selection of the methods used to find the QOSPF conform solutions were motivated by analyzing the performance could be obtained in a currently available real QOSPF environment. To obtain this performance the link state advertisement strategy described in the previous section should be implemented and appropriate algorithms with low complexities and based on deterministic link values should determine the partial spanning trees. In our simulation this kind of multicast trees are built using one of the regular PST computation algorithms based on the last advertised $t_i^{(u,v)}$ or $t_{i+1}^{(u,v)}$ link measures. The computation of the PST depends on the type of the QoS requirement and the following computational considerations are proposed.

   - Bottleneck type of QoS requirements with QOSPF correspond to find

     $$T_{QOSPF_1} : \min_{(u,v)\in T} t_i^{(u,v)} > \alpha$$

     If there are solutions fulfilling this condition, then the optimum (the tree with maximal capacity) corresponds to one of them. The optimal tree can be computed by using Bellman-Ford or Dijkstra algorithms with max-min algebra and can be proposed as T_{QOSPF_1}

     $$T_{QOSPF_1} : \arg\max_{T\in\mathcal{T}} \min_{(u,v)\in T} t_i^{(u,v)}$$

   - Additive type of end-to-end QoS requirements correspond to find a tree

     $$T_{QOSPF_2} : \max_{R_{(s,r_i)}\in\mathcal{R}_T} \sum_{(u,v)\in R_{(s,r_i)}} t_{i+1}^{(u,v)} < \beta$$

where $\mathcal{R}_T$ indicates the set of paths from the source to the destinations in T. If there are solutions, then the shortest paths tree is a solution fulfilling the condition and can easily be determined by the superposition of shortest paths. This shortest path tree can be proposed as the solution of a QOSPF like computation:

$$T_{QOSPF_2} : \bigcup_{r_i \in V_m \backslash s} \arg \min_{R_i \in \mathcal{R}_{(s,r_i)}} \sum_{(u,v) \in \mathcal{R}_i} t_{i+1}^{(u,v)}$$

where $\mathcal{R}_{(s,r_i)}$ is the set of possible paths from s to r_i. (We suppose that T_{QOSPF_2} is the union of shortest paths between s and the different destinations r_i.)

- Additive type of overall QoS requirements using a real QOSPF environment correspond to the objective

$$T_{QOSPF_3} : \sum_{(u,v) \in T} t_{i+1}^{(u,v)} < \gamma$$

The computation of the best solution (the minimal cost tree) is NP-hard, but heuristics can be used to find approximated solutions. A good approximation can be found for example by using the Kou and Takahashi-Matsuyama heuristics. Finally in our simulation T_{QOSPF_3} is an approximate solution of the corresponding Steiner problem:

$$T_{Steiner} : \arg \min_{T \in \mathcal{T}} \sum_{(u,v) \in T} t_{i+1}^{(u,v)}$$

The proposed algorithms having low complexities compute the spanning trees based on the advertised link measures $t_i^{(u,v)}$ (bottleneck type) or $t_{i+1}^{(u,v)}$ (additive type).

2. ***The instantaneous optimal solution*** T^*_{opt}

Optimal solutions at the time instant of the routing request can be determined using the exact $\hat{\delta}_{(u,v)}$ link values. These values are known only via simulation and cannot be available in a real networking environment. Using the simulation method we avoid the necessity of using exhaustive search to determine the optimal solutions, which can fulfill the conditions (2), (3) and (4). If there are solutions at the time instant of the request, then the optimal solutions are candidates to fulfill the QoS conditions. These optimal solutions are used in our analyze to compare with the QOSPF based solutions and with the solutions proposed in this paper. The computation of the instantaneous optimal solutions depends on the QoS requirement.

- Bottleneck type of QoS requirement:

$$T^*_{opt_1} : \arg \max_{T \in \mathcal{T}} \min_{(u,v) \in T} \hat{\delta}_{(u,v)}$$

- Additive type of end-to-end QoS requirement:

$$T^*_{opt_2} : \bigcup_{r_i \in V_m \setminus s} \arg \min_{R_i \in \mathcal{R}_{(s,r_i)}} \sum_{(u,v) \in \mathcal{R}_i} \hat{\delta}_{(u,v)}$$

- Additive type of overall QoS requirement:

$$T^*_{opt_3} : \arg \min_{T \in \mathcal{T}} \sum_{(u,v) \in T} \hat{\delta}_{(u,v)}$$

  This optimal solution is tried to be found by using exhaustive search (by one of the Steiner Tree Enumeration Algorithms).

3. ***The suboptimal solution*** T_{subopt}

For the three QoS criterions analyzed here different approximated solutions are proposed in Section 3 taking into account the uncertainty of the link values. Finally the selection of the proposed algorithms were motivated by analyzing the performance and the complexity of the algorithms. In real routing environment only algorithms having low complexity can be used.

- For bottleneck type of QoS requirements the tree allowing the maximal probability of the asked QoS value corresponds to the solution of the Steiner problem with deterministic link measures $\kappa_{(u,v)} = -\log P(\delta_{(u,v)} > \alpha)$.
  In real cases an approximated solution T_{subopt_1} can be computed by using the Kou (cf. [5]) and the Takahashi-Matsuyama (cf. [6]) heuristic algorithms.
- For additive type of end-to-end QoS requirements an approximated solution T_{subopt_2} is built with the help of the greedy method described in Section 3.2.1 using link values $\kappa_{(u,v)} = m_{(u,v)} + \sigma^2_{(u,v)}$.
- For additive type of overall QoS requirement an upper-bound can be obtained by finding the solution of the Steiner problem with link measures $\kappa_{(u,v)} = \mu_{(u,v)}(s)$. In real routing environment an approximated solution T_{subopt_3} can be computed by using the Kou and the Takahashi-Matsuyama algorithms.

Note : Since the routing problems in incomplete link state environment are reduced to optimization tasks based on $\kappa_{(u,v)}$ deterministic link values using the proposed solutions, the probabilistic link measure $\delta_{(u,v)}$ can be handled locally (only in the router advertising $\kappa_{(u,v)}$ if it is possible).

4.2 Performance measures

The performance analysis is focused on the comparison of the qualities of the spanning trees T_{QOSPF_i} and T_{subopt_i} with the qualities of the optimal spanning trees T_{opt_i} at the moment of the routing request. To each tree T a "cost value" $v(T)$ has been assigned corresponding to the critical value from the point of view of the QoS criterion. To compare, this cost values are based on real link values at the moment of the routing request and are computed as follows. In the case of

- bottleneck type of metrics:
$$v(T) = \min_{(u,v)\in T} \hat{\delta}_{(u,v)}$$
- additive type of metrics in end-to-end QoS requirement:
$$v(T) = \max_{r_i\in V_m\setminus s} \arg \min_{R_i\in \mathcal{R}_{(s,r_i)}} \sum_{(u,v)\in \mathcal{R}_i} \hat{\delta}_{(u,v)}$$
- additive type of metrics in overall QoS requirement:
$$v(T) = \sum_{(u,v)\in T} \hat{\delta}_{(u,v)}$$

Two measures: the measures η_{QOSPF_i} and η_{subopt_i} are introduced by calculating the ratios of $v(T_{QOSPF_i})$ and $v(T_{opt_i})$ or $v(T_{subopt_i})$ and $v(T_{opt_i})$ (dividing the smaller value with the larger one). These performance measures show the real qualities of the spanning trees T_{QOSPF_i} and T_{subopt_i}, since theirs costs are also calculated based on the $\hat{\delta}_{(u,v)}$ values. The better the solutions T_{QOSPF_i} and T_{subopt_i} are, the closer the performance measures get to 1. Finally, the average values $\bar{\eta}_{QOSPF_i}$ and $\bar{\eta}_{subopt_i}$ are calculated over an ensemble of randomly generated sets of multicast nodes and QoS requirements as described in the next subsection.

The performance measures are calculated under the assumption that the QoS requirement is satisfied by the spanning tree presented in the numerator and the denominator at the same time. Therefore, two types of errors should be distinguished.

1. ***F**irst **O**rder **E**rror*: the solution T_{QOSPF_i} (based on $t_i^{(u,v)}$ measures) and / or T_{subopt_i} (based on $\kappa_{(u,v)}$ measures) seems not to satisfy the QoS requirement, while the corresponding T_{opt_i} satisfies that. In this case there is at least one tree where the traffic flow could be routed but the traffic is not transmitted (low network utilization).
2. ***S**econd **O**rder **E**rror*: the solution T_{QOSPF_i} (based on $t_i^{(u,v)}$ measures) and / or T_{subopt_i} (based on $\kappa_{(u,v)}$ measures) seems to satisfy the QoS requirement, while the requirement actually is not satisfied along this spanning tree (based on $\hat{\delta}^{(u,v)}$ measures). In this case the traffic flow is routed over a spanning tree which violates the QoS requirement.

Since the second order errors are more crucial in QoS communication it should be eliminated if its ratio cannot be controlled.

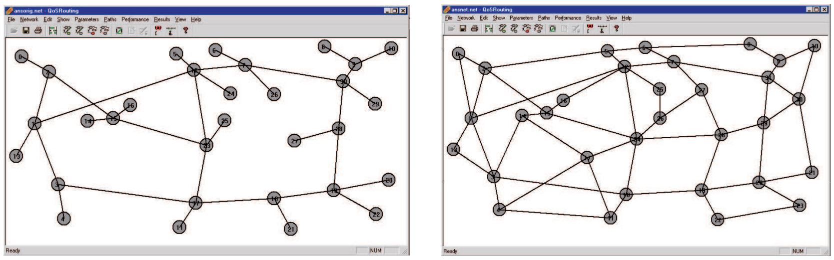

Figure 1: *The network topology of ANSNET and its modification*

4.3 Network topologies and simulation parameters

To perform the simulation over real network dimensions the ANSNET backbone topology was used [1, 2]. Its connectivity was improved for ensuring the existence of multiple paths between each node pair (see [10]). To get a realistic view about the operation of the multicast routing methods, the following considerations were taken into account.

In order to illustrate the impact of the granularity of QOSPF measurement technology, three different grids (three different values of $t_{i+1} - t_i$) were used for each environment. For each routing method $K = 500$ routing requests were generated and repeated for each value of $t_{i+1} - t_i$. The multicast group members were selected randomly (10 - 25 members per group). The link values were determined randomly in two steps: at a fist time the $[t_i^{(u,v)}, t_{i+1}^{(u,v)}]$ interval of the QOSPF grid was selected using uniform distribution, and at a second time the value of the link descriptor was generated randomly in $[t_i^{(u,v)}, t_{i+1}^{(u,v)}]$ according to the conditional distributions $F_{(u,v)}^{(i)}(x)$ of Table 1. In the case of end-to-end QoS requirement we consider normal distribution, with

$$m_{(u,v)}^{i} : \frac{t_i^{(u,v)} + t_{i+1}^{(u,v)}}{2}$$

and

$$\sigma_{(u,v)}^{i} : \int_{t_i^{(u,v)}}^{t_{i+1}^{(u,v)}} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x - m_{(u,v)}^{i})^2}{2\sigma^2}} dx = 1 - \epsilon$$

where $\epsilon = 0.05$ is rpopsoed for the simulation.

The simulation parameters were generated as listed in Table 1.

Name	Parameter	Type	Value
QoS	α	bandwidth	u. d. in [0.1 Mbit/s, 13 Mbit/s]
	β	delay	u. d. in [30 ms, 160 ms]
	γ	cost	u. d. in [30, 200]
Link value	$\delta_{u,v}$	bandwidth	u. d. in [0 Mbit/s, 15 Mbit/s]
		delay	u. d. in [0 ms, 50 ms]
		cost	u.d. in [0, 10]
Distribution	$F^{(i)}_{(u,v)}(x)$	bandwidth	u. d. in $[t_i^{(u,v)}, t_{i+1}^{(u,v)}]$
		delay	normal d. in $[t_i^{(u,v)}, t_{i+1}^{(u,v)}]$
		cost	u.d. in $[t_i^{(u,v)}, t_{i+1}^{(u,v)}]$
Grid	$t_{i+1}^{(u,v)} - t_i^{(u,v)}$	bandwidth	2, 5, 10 Mbit/s
		delay	3, 10, 20 ms
		cost	3, 5, 7

Table 1: *Simulation parameters (u.d. refers to uniform distribution)*

4.4 Simulation results

The following results show the performance and describe the first and second order error of each routing method after 500 routing requests.

4.4.1 Bottleneck type of QoS requirements case

In Figure 2 the first column shows the value of the performance measure $\bar{\eta}_{QOSPF_1}$, while the second and third ones show the value of $\bar{\eta}_{subopt_1}$ depending on whether the optimal solution (5) were approximated using the Kou or the Takahashi-Matsuyama algorithms.

It can be seen that solutions with higher throughput can be obtained by using the new approximation method. Each measure decreases when $t_{i+1} - t_i$ increases, but the performance measures of $\bar{\eta}_{subopt_1}$ tends to zero slowly than $\bar{\eta}_{QOSPF_1}$ and the relative difference between them increases. It is originated from the fact that increasing $t_{i+1} - t_i$ the QOSPF link measure $t_i^{(u,v)}$ can be more far from the actual value of the available bandwidth of the link (u, v), so the spanning tree calculated based on this imprecise link measure (which underestimates the available bandwidth) may yild results having low quality. The reason why the link measures $t_i^{(u,v)}$ (and not $t_{i+1}^{(u,v)}$) are selected to calculate T_{QOSPF_1} is to avoid the second order errors. Since $t_i^{(u,v)}$ underestimates the available link bandwidth no second order errors are occurred, but the ratio of the first order errors is very high (e.g. 18% when $t_{i+1} - t_i = 5Mbit/sec$). Therefore, the network cannot be used effectively when no second order errors are tolerated. The high ratio of the first order errors can be eliminated by

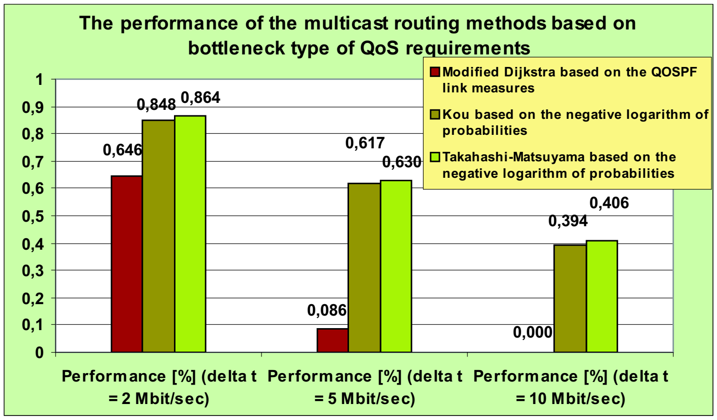

Figure 2: *The value of* $\bar{\eta}_{QOSPF_1}$, $\bar{\eta}_{subopt_1}$ *using the Kou or the Takahashi-Matsuyama algorithm at different values of* $t_{i+1} - t_i$

solving (5) (0% when $t_{i+1} - t_i = 5Mbit/sec$).

$Method$	$2Mbit/s$	$5Mbit/s$	$10Mbit/s$
T_{QOSPF_1}	0.056/0	0.18/0	0.18/0
$T_{subopt_1} - Kou$	0/0.114	0/0.236	0/0.6
$T_{subopt_1} - Takahashi - Matsuyama$	0/0.084	0/0.208	0/0.6

Table 2: *First / Second Order Error Ratios of the methods working on bottleneck type of QoS requirement at different values of* $t_{i+1} - t_i$

But, simply solving (5) results high ratio of the second order errors (e.g. 23.6% when using Kou, 20.8% when using Takahashi-Matsuyama and $t_{i+1} - t_i = 5Mbit/sec$), since it determines the spanning tree having the maximum probability of fulfilling the QoS requirement α. This solution may have significant probability to violate this requirement and may result second order errors with this probability. Taking into account the probability of fulfilling the QoS requirement and only accepting the solution T if it fulfills this criterion at least with probability $p = 1 - \varepsilon$:

$$exp\{-\sum_{(u,v)\in T} \kappa_{(u,v)}\} = \prod_{(u,v)\in T} P(\delta_{(u,v)} > \alpha) \geq p$$

Using this condition and repeating the simulation with $\varepsilon = 0.2$ the ratio of the second order errors can significantly be decreased (e.g. 4% using Kou, 6% using Takahashi-Matsuyama in the worst case when $t_{i+1} - t_i = 10Mbit/sec$) while the ratio of the first order errors slightly increased (e.g. 9.4% using Kou or Takahashi-Matsuyama in the worst case when

$t_{i+1} - t_i = 10 Mbit/sec$).

$Method$	$2Mbit/s$	$5Mbit/s$	$10Mbit/s$
T_{QOSPF_1}	0.056/0	0.18/0	0.18/0
$T_{subopt_1} - Kou$	0.034/0	0.056/0	0.094/0.04
$T_{subopt_1} - Takahashi - Matsuyama$	0.038/0	0.058/0	0.094/0.06

Table 3: *First / Second Order Error Ratios of the methods working on bottleneck type of QoS requirement at different values of* $t_{i+1} - t_i$ *when accepting only solution which fulfills the QoS criterion at least with 0.8 probability*

As a special case, using $\varepsilon = 0$ (cf. the criterion (5)) results solutions having zero second order error. Decreasing the value of ε the algorithm provides solutions fulfilling the QoS requirement with larger probability, however the network utilization will significantly be decreased (larger probability of first order errors). Increasing this value more effective network utilization can be achieved, however the probability of the second order error will be increased.

4.4.2 Additive type of end-to-end QoS requirements case

In Figure 3 the first column shows the value of the performance measures $\bar{\eta}_{QOSPF_2}$, while the second one shows the value of $\bar{\eta}_{subopt_2}$. It can be seen that approximately the same performance can be obtained when $t_{i+1} - t_i$ takes small values. When this value increases our proposed heuristic results solutions with higher quality. Using this new heuristic much lower ratio of first order errors can be achieved (5.4% instead of 19% when $t_{i+1} - t_i = 20ms$).

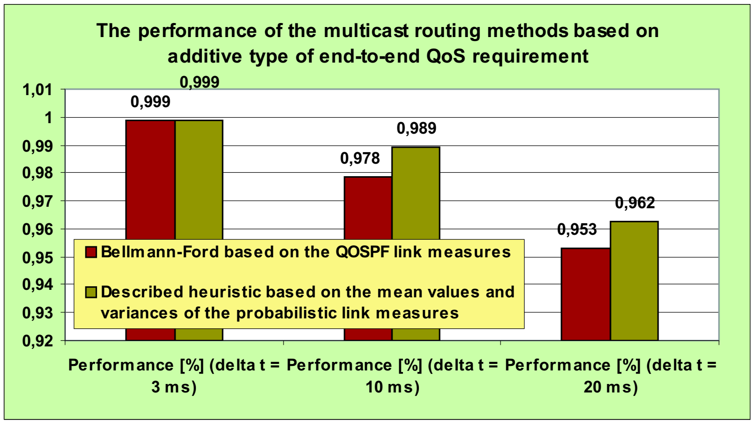

Figure 3: *The value of* $\bar{\eta}_{QOSPF_2}$ *and* $\bar{\eta}_{subopt_2}$ *at different values of* $t_{i+1} - t_i$

Since the Bellman-Ford algorithm based on the $t_{i+1}^{(u,v)}$ overestimates the delays along the paths, it results no second order ratio (this is the reason why T_{QOSPF_2} is calculated using the link measures $t_{i+1}^{(u,v)}$ instead of $t_i^{(u,v)}$) and high first order ratio (which increases hardly when $t_{i+1} - t_i$ increases). The new heuristic is able to keep the ratio of the second order errors low (1.6% in the worst case when $t_{i+1} - t_i = 20ms$), while allows utilizing the network much more effective (5.4% when $t_{i+1} - t_i = 20ms$).

$Method$	$3ms$	$10ms$	$20ms$
T_{QOSPF_2}	0.04/0	0.112/0	0.19/0
$T_{subopt_2} - Kou$	0.006/0.006	0.016/0.01	0.054/0.016

Table 4: *First / Second Order Error Ratios of the methods working on additive type of end-to-end QoS requirement at different values of* $t_{i+1} - t_i$

4.4.3 Additive type of overall QoS requirements case

As mentioned in Section 4.1 the optimal tree T_{opt_3} is calculated by exhaustive search, but the multicast trees T_{QOSPF_3} and T_{subopt_3} are approximated solutions of the corresponding Steiner problem. In Figure 4 the first and second columns show the value of the performance measure $\bar{\eta}_{QOSPF_3}$, while the third and fourth ones show the value of $\bar{\eta}_{subopt_3}$ - depending on whether the solutions were approximated using the Kou or the Takahashi-Matsuyama heuristics. It can be seen that approximately the same performance can be obtained when $t_{i+1} - t_i$ takes small value. When increasing this distance the new approximation techniques

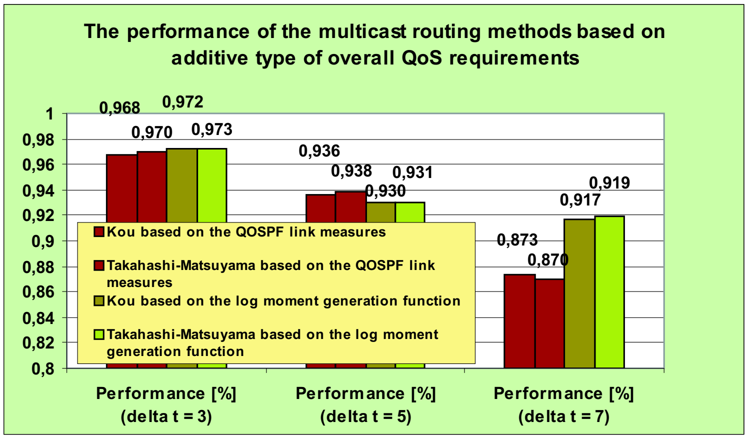

Figure 4: *The value of* $\bar{\eta}_{QOSPF_3}$ *and* $\bar{\eta}_{subopt_2}$ *depending on the use of the Kou or the Takahashi-Matsuyama algorithms at different values of* $t_{i+1} - t_i$

solving (11) have higher performance. Higher performance of T_{subopt_3} could be obtained by implementing more complex techniques which approximate the optimal Steiner tree more precisely than the Kou or Takahashi-Matsuyama do (these latters offer a ratio 2).

$Method$	$3(costs)$	$5(costs)$	$7(costs)$
$T_{QOSPF_3} - Kou$	0.24/0	0.476/0	0.51/0
$T_{QOSPF_3} - Takahashi - Matsuyama$	0.232/0	0.472/0	0.51/0
$T_{subopt_3} - Kou$	0/0.482	0/0.438	0/0.486
$T_{subopt_3} - Takahashi - Matsuyama$	0/0.482	0/0.438	0/0.486

Table 5: *First / Second Order Error Ratios of the methods working on additive type of overall QoS requirement at different values of* $t_{i+1} - t_i$

T_{QOSPF_3} is calculated using the link measure $t_{i+1}^{(u,v)}$ in order to avoid second order errors. Unfortunately, significant fraction of the network capacity cannot be used in this case (e.g. 51% when $t_{i+1} - t_i = 7$ cost units). The high ratio of the second order errors of the new method is not surprising, since the solution of (11) reduces to

$$T_{opt3} : \min_{T} \sum_{(u,v)\in T} \mu_{(u,v)}(s)$$

which is independent from the QoS requirement γ. We approximated the solution which has the maximal probability of fulfilling the QoS requirement and this optimal solution can have high probability of not fulfilling this requirement. Originated from this fact the ratio of the second order errors can significantly be decreased accepting only solutions which fulfill the QoS requirement at least with probability $p = 1 - \varepsilon$:

$$P(\sum_{(u,v)\in T} \delta_{(u,v)} > \gamma) \leq exp\{\sum_{(u,v)\in T} \kappa_{(u,v)} - s\gamma\} \leq \varepsilon$$

Using this strategy with $\varepsilon = 0.01$ and repeating again the simulation no second order errors were occurred while the ratio of first order errors are significantly increased (e.g. using the Kou method: 39.6% when $t_{i+1} - t_i = 7$, but remained lower than at T_{QOSF_3} which was 51%).

$Method$	$3(costs)$	$5(costs)$	$7(costs)$
$T_{QOSPF_3} - Kou$	0.24/0	0.476/0	0.51/0
$T_{QOSPF_3} - Takahashi - Matsuyama$	0.232/0	0.472/0	0.51/0
$T_{subopt_3} - Kou$	0.1/0	0.244/0	0.396/0
$T_{subopt_3} - Takahashi - Matsuyama$	0.1/0	0.244/0	0.394/0

Table 6: *First / Second Order Error Ratios of the methods working on additive type of overall QoS requirement at different values of* $t_{i+1} - t_i$ *when accepting only solution, which fulfills the QoS criterion at least with 0.9 probability*

So, the parameter ε can be used again to balance between the network utilization and the probability of satisfying the QoS requirement. As a limit, when (11) is used with $\varepsilon = 0$ than it results solutions T_{subopt_3} which satisfy the QoS requirement with probability 1.

5 Conclusions

Novel multicast routing algorithms were introduced in the paper taking into account the random behavior of the link descriptors. The new methods are able to meet bandwidth, end-to-end delay and overall cost type of QoS requirements in the case of incomplete information. The computation of the proposed multicast trees is based on approximated solutions but can be realized with low complexity algorithms.

The simulation results presented that more appropriate multicast trees can be found by taking into account the probabilistic nature of the routing problem. In the case of bottleneck and additive type of QoS requirements the new approximation technics results solutions having high quality. The large ratio of the first order errors can significantly be decreased, while the ratio of the second order errors is slightly increased. Moreover, in the case of bandwidth and overall cost type of QoS requirements the new routing methods are able to balance between the network utilization and the probability of the second order errors by changing the value of a computational parameter ε.

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