QoS multicast routing with uncertain link state information

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1. Introduction and related works

Next generation networks will extend the set of QoS aware applications. The QoS management should cover the admission control procedures, the handover between access segments, the dynamic allocation of network resources in different (backbone and access) networks [4] [10]. A dominant part of the QoS aware, new network applications as video on demand or television relies several users at the same time: the application needs multicast routing. In this paper we focus on routing optimization for QoS aware multicast applications. A way to manage the QoS and find the route corresponding to the end-to-end QoS requirements is to use a feedback control loop based management (cf. [7]). In other propositions negotiation procedures are called to ensure the overall QoS requirement using network components/agents [9]. Generally, the communication request and the associated end-to-end QoS requirement affect several routing domains. For scalability purposes in large networks the routing should use aggregated topology information and the end-to-end QoS constraint must be decomposed to local QoS constraints. In our paper we suppose that the QoS criterion is expressed for a given homogeneous routing domain. This can be due to an aggregation, a decomposition or a negotiation procedure. Our goal corresponds to finding the best multicast tree in the domain which can satisfy the QoS requirements with maximal probability. In QoS aware routing methods, when a route request is presented, a route selection is executed to find an admissible or the better route (path or tree) from among the available routes. Different routing strategies can be applied in order to satisfy the conditions of the QoS aware communications. A good overview of the QoS routing for the next generation networks can be found in [11]. In the case of dynamic routing the information in the routing tables is revised regularly. 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 due to off-line computation or prepared on demand when changes are needed. In any case the route computation (the path/tree selection) requires efficient combinatorial optimization algorithms.

To perform routing in a given domain, the exact values of link descriptors (available bandwidth, delay, jitter, etc.) should be known. 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 network capacity, 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 different from the routes 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 [5]. The simplest way to compute sub-optimal routes is executing traditional methods (e.g. Dijkstra or Bellmann-Ford algorithms to find shortest paths, Kou or Takahashi-Matsuyama algorithms to find partial spanning trees) on the last advertised link values. This is the manner how the currently used routing protocols can work [1, 2]. To handle uncertainties on link state information randomized on-demand QoS routing algorithm was proposed in [6]. The algorithm is based on pre computation of the maximum safety rate and the minimum delay of each node in the network. The routing process is dynamically directed by the safety rate and delay of the partial routing path developed so far and by the maximum safety rate and the minimum delay of the next node. The effectiveness of the routing algorithm can be increased by using the knowledge about the mechanism of link descriptor advertisement (e.g. which thresholds are used during the operation). Probabilistic models can be set up to provide more appropriate routes for QoS flows [5, 3]. These referenced works propose path selection algorithms based on the probabilistic description of the routing problem only for unicast communications. Obviously, the objective of the route selection based on different types of probabilistic methods corresponds to determine the paths, which can fulfill the QoS requirement with maximum probability. Multicast routing algorithms handling the uncertainties of the link state information are needed. The main focus of this paper is to introduce this kind of algorithms which are able to perform route selection based on probabilistic link measures in the case of the most typical types of QoS requirements and analyze theirs performances against the currently standardized algorithms (which work on "stale" deterministic link measures). The results are tested by extensive simulations. These topics will be treated in the following way: 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 typical QoS objectives and the appropriate metrics; in Section 4 extensive numerical analysis of the methods are given before to conclude.

2. Multicast routing with QoS

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 [11]. These analyses are based based on deterministic link values and can help to classify the multicast routing cases. In the following discussion, the network is represented by a graph $G\left(E, V, \delta_{u,v}, (u,v) \in E\right)$, where V denote the set of vertices, E is the set of edges, and $\delta_{u,v}$ represent the link state descriptors which can either be delay or bandwidth or any other parameter of interest. Our concern is to find proper routes R on the graph which satisfy given QoS requirements.

Assuming bottleneck type of link metrics (e.g. bandwidth)

The goal of the multicast routing algorithm is to finding a feasible tree in which the critical link value exceeds a given value required by the application. If α corresponds to the asked value (e.g. the needed bandwidth), the criterion can be written as

$$\min_{(u,v)\in T} \delta_{(u,v)} > \alpha \tag{1}$$

Case of additive type of unicast link metrics

Two typical cases of multicast objectives should be distinguished.

A) QoS requirement concerning the end-to-end quality
For delay, jitter, negative logarithm of the packet loss the goal of the tree construction is to finding a tree in which the required end-to-end quality is satisfied on the used set of paths of the tree. The criterion can be written as

$$\max_{R_{(r_i,r_j)}\in\mathcal{R}_T} \sum_{(u,v)\in R_{(r_i,r_j)}} \delta_{(u,v)} < \beta \tag{2}$$

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 leaves r_i and r_j of the tree T. If there is a Single Source Multicast model then $r_i = s$ a given source node and $r_j \in V_m \backslash \{s\}, j = 1, ..., M)$ are the receivers. In the case of an Any Source Multicast application $\mathcal{R}_T$ denotes the paths between every leaf pair in T. Originated from the frequently used source based applications and the algorithmic complexity the paper is concentrated to the Single Source Multicast model.

B) Requirements concerning the overall cost of the spanning tree
In these cases the sum of the link values in the tree should be limited. If γ is the total cost tolerated by the demand, the QoS criterion corresponds to

$$\sum_{(u,v)\in T} \delta_{(u,v)} < \gamma \tag{3}$$

Note: a third type of link metrics corresponds to *multiplicative* link metrics. Since the logarithm of this kind of metrics is an additive metric we do not discuss here this case.

3. Muticast routing with incomplete information

With determined link values the multicast routing algorithm can be confined to find a feasible solution: a tree corresponding to the given criterion. In our case (when the known link descriptors correspond to stale and uncertain values) a better objective can be to find trees which maximize the probability that the required QoS constraint is satisfied. The proposed objective of the multicast routing is to find an optimal tree T^* which spans the multicast nodes and most likely fulfills the QoS criterion as follows.

Considering bottleneck type of link metrics

The optimal solution is the tree T_1^* which maximize the probability of satisfying the demand:

$$T_1^* : \arg\max_{T\in\mathcal{T}} P(\min_{(u,v)\in T} \delta_{(u,v)} > \alpha) \tag{4}$$

In [5] the authors embark on solving the unicast routing problem with incomplete information for the bandwidth requirement. Similar considerations can be used for the multicast routing problem and the (4) problem can easily be transformed to a Steiner problem. Assuming link independence the solution of (4) is equivalent to solving a partial minimal spanning tree (PMST) problem with the deterministic measures assigned to link (u,v) being $\kappa_{(u,v)} = -\log\ P\left(\delta_{(u,v)} > \alpha\right)$:

$$T_1^* : \arg\min_{T\in\mathcal{T}} \sum_{(u,v)\in T} -\log P(\delta_{(u,v)} > \alpha) \tag{5}$$

For more details cf. [13]. Unfortunately problem (5) is NP hard and so can only be approximated in polynomial time. We will show that the newly obtained solutions are more efficient than the solutions based on the stale, determined values. Heuristic methods as Kou and Takahashi-Matsuyama heuristics can approximate the optimal solution or meta-heuristic can be used.

Considering additive type of link metrics

As can be seen from (6) and (9), the selection of the optimal partial spanning tree (PST) based on additive type of link metrics depends on the quality criterion. End-to-end and overall cost models must be distinguished.

A) End-to-end quality requirement
In this case the optimal solution T_2^* maximize the probability that the "longest" path in the tree is shortest than the asked value β:

$$T_2^* : \arg\max_{T\in\mathcal{T}} P(\max_{R_{(s,r_j)}\in\mathcal{R}_T} \sum_{(u,v)\in R_{(s,r_j)}} \delta_{(u,v)} < \beta) \tag{6}$$

To simplify, let us introduce random variables ξ_i as the path metric $\xi_i = \sum_{(u,v)\in R_{(s,r_i)}} \delta_{(u,v)}$:

$$T_2^* : \arg\max_{T\in\mathcal{T}} P(\bigcap_{i=1}^{M} \{\xi_i < \beta\}) \tag{7}$$

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. 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). By applying the central limit theorem T_2^* can be formulated as

$$T_2^* : \arg\min_{T\in\mathcal{T}} \int_\beta^\infty ... \int_\beta^\infty \frac{exp\{-\frac{1}{2}(\bar{x}-\bar{m})^T \bar{\bar{K}}^{-1}(\bar{x}-\bar{m})\}}{\sqrt{(2\pi)^M det\bar{\bar{K}}}} d\bar{x} \tag{8}$$

where $\bar{m}$ contains the expected values and $\bar{\bar{K}}$ corresponds to the covariance matrix.

So, the quality of T_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 (8). In [13] a heuristic greedy algorithm was proposed to find approximated solutions. The proposed heuristic works as the Takahashi and Matsuyama partial spanning tree construction: the destinations are added to the tree one after the other. The algorithm tries to avoid solutions having large end-to-end delay and common links with large variance. The complete description of the heuristic is given in [13].

B) Overall cost function
In this case, the probability that the overall cost of the tree is limited should be maximal:

$$T_3^* : \arg\max_{T\in\mathcal{T}} P(\sum_{(u,v)\in T} \delta_{(u,v)} < \gamma) \tag{9}$$

Unfortunately, it is a very hard task to find the optimal solution of (9), 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 problem (9) to be tractable is to reduce it to the task of finding the PMST based on deterministic link measures and try to find suboptimal solution for the original problem. Assuming link independence, the solution of (9) can be approached by solving a PMST problem with the deterministic measures assigned to link (u,v) being $\kappa_{(u,v)} = \mu_{(u,v)}(s) = lnE\{e^{s\delta_{(u,v)}}\}$ (cf. details in [13]):

$$T_3^* : \min_T exp(\sum_{(u,v)\in T} \mu_{(u,v)}(s) - s\gamma) \tag{10}$$

So the three mentioned and frequently raised multicast rooting problems in the case of incomplete information become approximatively solvable with the help of greedy heuristics. The quality of the approximated solution compared to the deterministic routing algorithm is proved by simulations and presented in the next section.

4. Performance analysis

Three kinds of multicast trees are introduced and calculated for comparison at the moment of the routing requests. *1) The solution T_{QOSPF} with QOSPF.* To obtain this performance the QOSPF like link state advertisement strategy should be implemented. In this strategy the value t_i is advertised, if the real link value at the moment of the measurement is in the interval $[t_i, t_{i+1}[$. Appropriate algorithms based on the last advertised link measures should determine the corresponding partial spanning trees. *2) The instantaneous optimal solution T_{opt}.* Optimal solutions corresponding to the network state at the time instant of the routing request can be determined using the exact link values. These values are known only via simulation and generally cannot be available in a real networking environment. *3) The proposed solution T_P.* As it is proposed in Section 3., different approximated solutions can be used for the three QoS criterion taking into account the uncertainty of the link values. 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. Two measures: the measures η_{QOSPF} and η_P are introduced by calculating the ratios of $v(T_{QOSPF})$ and $v(T_{opt})$ or $v(T_P)$ and $v(T_{opt})$ (dividing the smaller value with the larger one). These performance measures show the real qualities of the spanning trees T_{QOSPF}

and T_P at the moment of the routing request. Finally, the average values $\bar{\eta}_{QOSPF}$ and $\bar{\eta}_P$ are calculated over a set of randomly generated multicast groups and QoS requirements. To perform the simulation over real network dimensions the ANSNET backbone topology was used [8, 11]. Its connectivity was improved for ensuring the existence of multiple paths between each node pair (see [12]). In order to illustrate the impact of the granularity of QOSPF measurement technology, three different grids (three different values of Δt) were used for each environment. For each routing method 500 routing requests were generated and repeated for each value of $\Delta t = t_{i+1} - t_i$. The multicast group members were selected randomly (10 - 25 members per group). The link values were determined randomly using uniform distribution.

In the case of bottleneck type of QoS requirements, in Figure 1 the first column of each group shows the value of the performance measure $\bar{\eta}_{QOSPF}$, while the second and third ones show the value of $\bar{\eta}_P$ depending on whether the optimal solution (5) were approximated using the Kou or the Takahashi-Matsuyama heuristics. It can be seen that solutions with higher throughput can be obtained by using the new probabilistic methods.

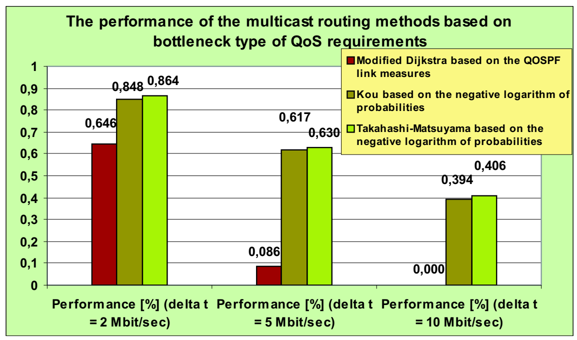

Figure 1: *The performance metrics $\bar{\eta}_{QOSPF}$ and $\bar{\eta}_P$ in the case of bottleneck type of link values*

In additive type of end-to-end QoS requirements cases the first column of Figure 2 shows also the value of the performance measures $\bar{\eta}_{QOSPF}$, while the second one shows the value of $\bar{\eta}_P$. Approximately the same performance can be obtained by QOSPF and by the proposed method when Δt takes small values. When this value increases our proposed heuristic results solutions with higher quality. In additive type of overall QoS

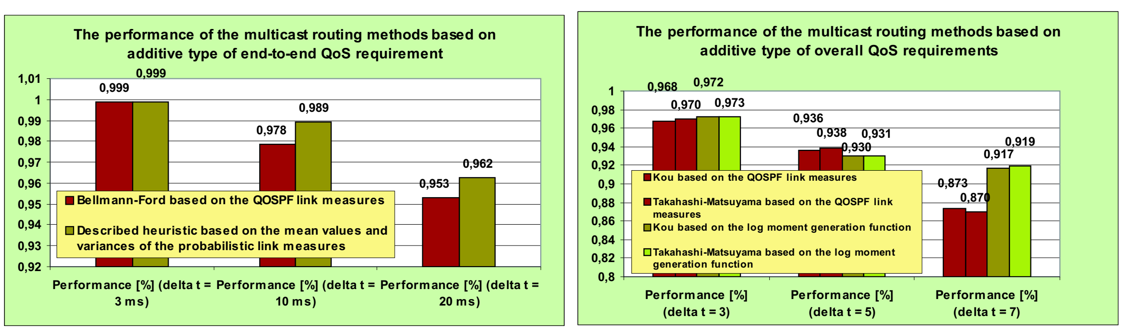

Figure 2: *The performance metrics $\bar{\eta}_{QOSPF}$ and $\bar{\eta}_P$ in the case of end-to-end and overall cost requirements*

requirements cases, the optimal tree T_{opt} is calculated by exhaustive search, but the multicast trees T_{QOSPF} and T_P are approximated solutions of the corresponding Steiner problems. In the right side of Figure 2 the first and second columns show the value of the performance measure $\bar{\eta}_{QOSPF}$, while the third and fourth ones show the value of $\bar{\eta}_{subopt}$ - 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 Δt takes small value. When increasing this uncertainty the new approximation techniques have higher performance.

5. Conclusions

Often in QoS aware routing cases the link values required for routing decisions are incomplete. In heterogeneous network the uncertainties arise from network topology aggregation. Dynamic traffic results also important doubtfulness. 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 bottleneck, additive end-to-end and overall cost type metrics of QoS requirements in the case of incomplete information. The computation of the proposed multicast trees is based on equivalent deterministic link values which can determined in the routers locally. Then spanning trees fulfilling the asked QoS criterion with high probability 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 routing algorithms result solutions having high quality. In some cases the ratio of the first order errors can be large but it can significantly be decreased, while the ratio of the second order errors is slightly increased. Moreover, in the case of bottleneck 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. For this a simple parameter (the goodness threshold of the accepted solutions) can be changed.

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