Comparative Analysis of Quality of Service Routing in Wireless Metropolitan Area Networks

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Abstract — **Currently we see the evolution of large scale community and metropolitan area networks based on inexpensive wireless local area network technology. We present the results of an experimental analysis which investigates the potential of quality of service routing mechanisms within this challenging environment. Our investigation is based on a model of a radio access network designed to cover a large city center. The workload is modeled to reflect the estimated usage patterns based on statistical data collection of user mobility and combined with synthetic traffic matrices. We present results for various routing strategies including shortest path routing, delay constrained routing as well as various multipath quality of service routing variants. Moreover, we investigate different traffic distributions. Our findings are, that multipath routing is able to enhance the utility of the network significantly.**[*]

Keywords — **Experimental Analysis, Metropolitan Area Network, Radio Access Network, Quality of Service Routing, Load Balancing, Mobility**

I. INTRODUCTION

The concepts of 4G networks and the Wireless Internet embrace a heterogeneous set of access technologies, ranging from UMTS over wireless local area networks to small scale personal area networks. Currently, we see the evolution of large scale community and metropolitan area networks based on inexpensive wireless local area network technology. The resulting radio access networks give rise to several interesting research challenges.

The main directions of research in this area are not related to routing but for example to performance optimizations on the link layer. Recently authentication, authorization and accounting related security issues have also drawn attention. Despite the fact that a huge amount of work is performed in this area, the implications of quality of service mechanisms within the context of large scale metropolitan area networks are not well known. Induced from user and device mobility - while tightly coupled to usage and application-specific traffic patterns - these networks will experience heavily varying loads on different timescales. Quality of service (QoS) issues are not sufficiently discussed in the context of upcoming real-time applications as for example IP-telephony. We believe that today's mainly hierarchical radio access network topologies as well as static resource management approaches need reconsideration.

Within this paper, we evaluate and analyze the potential of QoS routing strategies for load balancing within the challenging environment envisioned above. We regard the investigation of these problems as crucial to allow for efficient network planning and control of large scale wireless communication networks.

The chosen scenario for this study is a model of a radio access network covering Darmstadt, Germany, a city with around 140.000 inhabitants. Since analytical tractability is out of scope due to the given complexity of the scenario, an experimental analysis is performed. We give a brief description of the employed workload model as well as of the investigated topology.

The major contributions of our investigation are:

(I) The analysis of various routing strategies in wireless metropolitan area networks with respect to load balancing. We include shortest path routing, delay constrained routing as well as various multipath QoS routing strategies.
(II) The evaluation of the influence induced by different traffic distributions. This includes centralized traffic only to/from an edge gateway as well as different ratios of external/internal traffic.

The remainder of the paper is organized as follows. In the next section, previous and related work is surveyed. In Section III we describe the overall system as well as the goals and services therein. We present the selection of metrics and parameters to study. Section IV contains the concise description of the experimental design based on the selection of factors and workload. The analysis and interpretation of the results is presented in Section V. The paper is concluded summarizing the major results and discussing further aspects of future research in Section VI.

II. RELATED WORK

The area of QoS routing has recently attracted a lot of research. Traditionally, QoS routing is applied to find constrained paths within the context of fine-grained resource reservation. Constraints may be of additive, concave or multi-

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plicative type [1]. The complexity of finding a feasible path through the network depends on the number of constraints and their type as well as on the nature of the algorithm (centralized, decentralized, hierarchical). Constraints may be for example delay, bandwidth, jitter and loss-ratio. [1] showed that the problem to find feasible paths with two independent types of constraints is NP-complete (note that delay and bandwidth are not independent and allow for algorithms and heuristics with lower complexity).

Current QoS routing strategies can be divided into source-routing, distributed-routing and hierarchical routing. A good overview to the field of constraint based routing and QoS routing can be found in [2] and [3]. For an excellent algorithmic treatment of constraint based routing algorithms see [4], where the authors simulated several algorithms in order to determine their worst case complexity. Last, [5] gives an algebra for QoS path computation and concisely describes hop-by-hop QoS routing mechanisms including multipath algorithms as well.

The use of QoS routing mechanisms for load balancing has been discussed for multiple protocols. However most of the work was done for source routing algorithms like the Q-OSPF protocol [6]. Since Q-OSPF was designed for QoS routing in the sense of finding hard-QoS constrained paths the “abuse” for resource management / traffic engineering inherits some restrictive assumptions. This includes the operation on the granularity of flows and the need for a surrounding framework for admission and reservation of resources. There are other algorithms as for example shortest path first algorithms optimized for computation of minimum congestion paths [7] which are also limited by the source routing paradigm. Summarized, source routing strategies are well suited within reservation-based or connection-oriented systems. However, they impose unnecessary and unwanted complexity in connectionless systems which rely on hop-by-hop operation.

If we regard connection oriented networks, it is quite natural to use multiple paths between source-destination pairs and thus follow a multipath paradigm. The class of multipath routing algorithms is often overlooked, however. The use of multiple paths at the same time allows for dispersion of the traffic on different granularity and thus alternate paths can help improving network performance significantly. Work in the area of traffic dispersion on packet or sub-packet level range from early work [8] to more recent approaches. Examples for multipath routing algorithms include [9], [10], [11] and [12]. Hereby the first three are based on a link state protocol and thus operate on global imprecise network state. The last algorithm is a distance vector based algorithm operating on information provided from neighboring nodes.

The OSPF variants ECMP (Equal-Cost Multipath) [9] and OMP (Optimized Multipath) [10] are heuristics which are targeted to better distribute load over multiple paths. OSPF-ECMP for example distributes the load over multiple equal-cost paths using simple round robin mechanisms and thus limits the possible load-balancing to this restricted set of paths. The equal distribution among these paths may result in suboptimal performance, too. OSPF-OMP optimizes this distribution using heuristics to predict which path to use. The necessary load information of the network is hereby distributed using OSPF opaque link state advertisements.

In contrast to the more intuitive heuristics given in [9] and [10] the recent work from Vutukury and Garcia-Luna-Aceves approaches the problem from a more theoretical perspective. Based on optimal routing [13] they formulate the properties a distributed multipath routing protocol must follow. The application for traffic engineering is described, too [14].

For multipath algorithms it is crucial to efficiently deal with routing loops, because the number of feasible paths largely depends on the strategy chosen to handle loops [5]. However, it is not necessary for the paths to be disjoint if the algorithm is carefully designed. The promising analysis of the performance properties of multipath algorithms in [5] and the robustness of such algorithms are of high interest.

What currently misses for all of the above mentioned QoS routing protocols are investigations of their performance within our target scenario: wireless metropolitan area networks. Most of the protocols have been designed and evaluated for use in backbone topologies. However, in our scenario, we expect heavily varying loads on different timescales induced by user and device mobility. The network structure is likely to be more regular than in backbone networks while the degree of interconnection will be higher.

We are not aware of comparative investigations of QoS routing algorithms within metropolitan radio access networks. This is not surprising, because so far, these have not been routing networks. There exist on the other hand some recent work which investigates large scale wireless LAN topologies. In particular, the work of Tang and Baker [15] is able to provide deep insights of user behavior for a metropolitan area wireless network. The work of Kotz and Essien [16] claims to be the largest and most comprehensive real world trace of a production wireless LAN. The results however do account for a special campus style network and mainly focus on traffic analysis - the mobility aspect is restricted by the campus setup and thus cannot be transferred to public networks. While these works address the area of wireless metropolitan area networks, they are only able to survey the current usage patterns within these networks. The investigation of underlying network characteristics or specialized routing strategies are beyond the scope of these works.

Our work addresses the combination of the above outlined research areas: the comparative analysis of QoS routing strategies for use in wireless metropolitan area networks.

III. SCENARIO

Why do we want to analyze the performance of QoS routing algorithms within wireless metropolitan area networks? We believe that the challenges of mobility should be addresses using novel paradigms in network control and design. We expect access network infrastructures to become more and more heterogeneous, for example by incorporating wireless local area

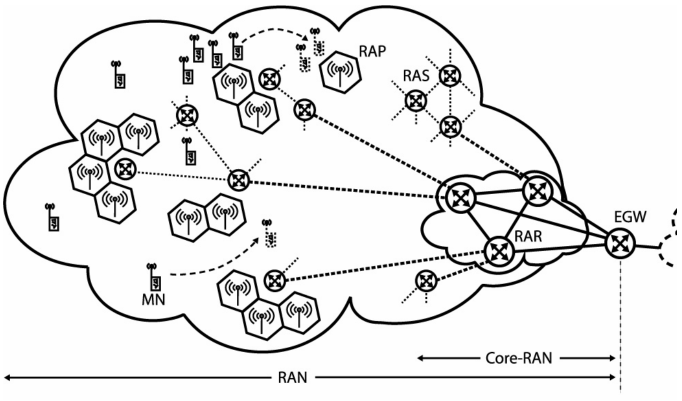


Figure 1: Schematic overview of radio access network topology

network technology into traditional cellular network infrastructures. With the increasingly important role of Internet technology, there are also new opportunities for optimization of traditional mechanisms. We are particularly interested in the investigation of resource management and load balancing issues within future metropolitan radio access networks.

The system boundaries for our analysis are defined by the MobQoS scenario [17]. The topology we investigate is a tightly meshed metropolitan radio access network infrastructure which is instantiated for the case of Darmstadt. Hereby, we follow a three-tier architecture depicted in Fig. 1. The architecture is derived from existing concepts of the IETF, here especially Mobile IPv4 [18] and IPv6 [19] respectively, QoS architectures [20] as well as traffic engineering work [21], and the concepts of telecommunication, here especially UMTS technology [22]. A crucial point is the distributed and decentralized nature of the topology instead of traditional hierarchical ones in telecommunication networks like GSM.

The mobile nodes or terminals (MN) of the customers are associated to wireless base stations, the so called Radio Access Points (RAP) representing the last hop of the provision network. The function of the first tier thus can be described as radio access.

The second tier, the core Radio Access Network (RAN) comprises so called Radio Access Server (RAS), which are used to attach multiple RAPs. Within the radio range covered by all RAPs attached at one RAS mobility is supported by appropriate link layer mechanisms, like e.g. handover. Each RAS has built-in IP-Router functionality. The RAS are meshed with neighboring systems and thus allow the start of resource management starting at this level. The core of the second tier is built by Radio Access Router (RAR). Between selected RAS and RAR are uplinks, the RAR are fully meshed.

The transition to the third tier of the architecture, the core provider network respectively the Internet, is performed by one or multiple edge gateways (EGW). At this point the technology may be mapped to the according mechanisms and strategies of the core provider network or the Internet and vice versa.

We model the presence of a large number of radio access points deployed in decentralized fashion. However, current approaches towards traffic engineering mainly rely on centralized components and build upon explicit mechanisms for signalling and resource admission. Within our investigation we decided to preserve the connectionless nature of the Internet by employing decentralized hop-by-hop QoS routing strategies. The approach should be able to work without explicit signaling and without a need to operate on flow level. Goals and services include a resource management to ensure resource-efficient network operation in decentralized fashion while supporting mobile users.

The radio access network for Darmstadt resulting from the above introduced assumptions consists of a large number of micro cells and 83 macro cells (see [17] for a map of darmstadt and the corresponding macro cells). Hereby not all macro cells are equal in size, because the area chosen for investigation cuts through some of them. Each of these macro cells is maintained by a RAS. Since a core idea behind MobQoS is a decentralized RAS structure which allows for Resource Management starting at RAS level, the RAS are modeled as routers which are interconnected to provide for alternate links. We have chosen a tightly meshed infrastructure as a starting point. See Fig. 2 for the resulting topology.

IV. EXPERIMENT

Since analytical tractability is out of scope for the given complexity of the problem, we use the methodology of experimental analysis for our investigation [23]. This section comprises the concise description of the experimental design based on the selection of factors and workload.

The experiment was implemented using ns-2 [24]. We incorporated major changes to the ns-2 simulation framework. This includes the implementation of a flexible multipath QoS algorithm which can be parameterized to reflect different variants of routing strategies. Moreover, we needed to implement methods

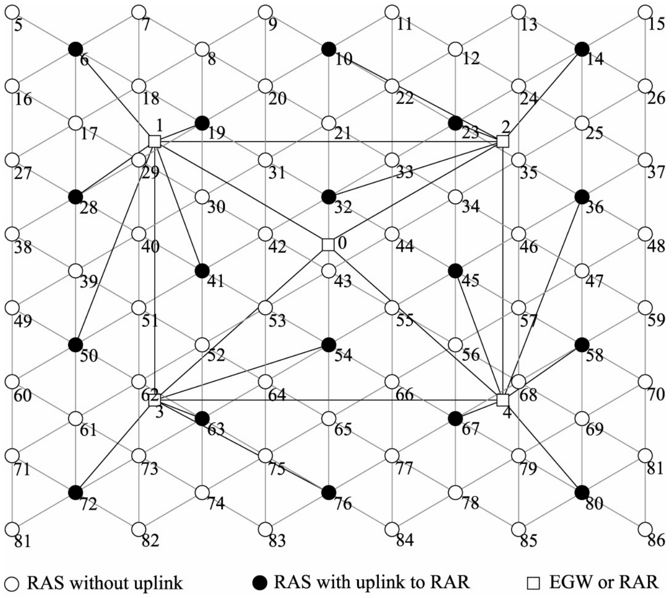


Figure 2: Topology of radio access network

to transfer the results of our traffic model into the simulation environment.

A. Factors

The parameter of utmost importance is the routing strategy. Other parameters include the influence of user mobility and the influence of the traffic distribution. The routing strategies investigated include combinations out of the sets {static, dynamic}, {singlepath, multipath} and {distance, delay}. In particular we include the following routing algorithms in our investigation:

- Static shortest-distance singlepath algorithm: *dst*.
- Static minimum-delay singlepath algorithm: *dly*.
- Static equal-shortest-distance multipath algorithm: *smp*.
- Dynamic minimum-delay multipath algorithm, multipath scheduling is done using round robin on packet level: *dmp*.
- Dynamic minimum-delay multipath algorithm, multipath scheduling is done using weighted round robin on packet level: *wmp*.

Due to oscillating behavior of the original *dmp* and *wmp* algorithm we also included the damped versions *dmp1*, *dmp2*, *wmp1* and *wmp2* in our investigation.

We also investigate the influence of different traffic distributions. The starting point is derived from current radio access network structures, which are strictly hierarchical. This corresponds to only external traffic for the end-systems to/from a single edge gateway. Moreover, we use different ratios of external to internal traffic (e/i-ratio) within our investigation. This reflects the amount of local traffic which may arise for future services. We use the four traffic classes {conversational, streaming, transactional, background} introduced in [22] since they should reflect a good guess of the intended usage of the network in question. The e/i-ratio is set for each class independently. See Table 1 for the predictor variables and their corresponding levels.

TABLE 1: PREDICTOR VARIABLES, LEVELS AND CORRESPONDING DESCRIPTION

Variable /Factors	***Description***			
Routing Algorithm				
	Dynamic	*Metric*	*Type*	*Multipath Scheduling*[1]
dst	No	Distance	Singlepath	-
dly	No	Delay	Singlepath	-
smp	No	Distance	Multipath	RR
dmp	Yes	Delay	Multipath	RR
wmp	Yes	Delay	Multipath	WRR
Traffic Distribution[2] *(external/internal)*				
Class[3]	*Conv.*	*Stream.*	*Interact.*	*Back.*
Dist. (0)	100/0	100/0	100/0	100/0
Dist. (1)	75/25	90/10	80/20	85/15
Dist. (2)	50/50	80/20	60/40	70/30
Dist. (3)	25/75	70/30	40/60	55/45
Dist. (4)	0/100	60/40	20/80	40/60

[1] RR: Round Robin, WRR: Weighted Round Robin

[2] The traffic distribution is given as external/internal traffic ratio (*e/i-ratio)*. For example 80/20 means: 80% of total traffic to/from the edge gateway, 20% of total traffic internal.

[3] *Conv.*: Conversational, *Stream.*: Streaming, *Interact.*: Interactive, *Back.*: Background

B. Workload

We use a workload model which is a hybrid between purely synthetical and statistical models for our investigation. The analytical foundations of the model are described in [25]. An instantiation based on extensive collection of statistical data for the scenario of Darmstadt can be found in [26]. In short, the model combines a statistical mobility part with a synthetic traffic part to allow for flexible but realistic workload generation. The resulting workload for the ns-2 simulation can be summarized as follows. We see low user activity in the early morning. Starting from 4:00h in the morning, the number of active users increases as people get ready to work and on their way to work (including pupils and students as well). From 8:00h on most people are up and active. It is important to keep in mind that the geographical distribution of user density changes significantly over day, due to the different activities pursued by the different species of users. This shift in density can be seen especially from residential areas to workplaces. Special places like the university attract large numbers of user during daytime. The decrease in the evening is not as abrupt as the increase seen in the morning. Nevertheless, the focus is changed from work to residential areas. Fig. 3 illustrates the summarized number of active users over a day for all user groups.

The overall traffic estimate over day is given in Fig. 4. Because users in different classes produce different load, the peak traffic value does not correspond directly with the peak value of user activity. As we noticed earlier, our traffic distribution is dependent on the geographical location which cannot be seen in Fig. 4.

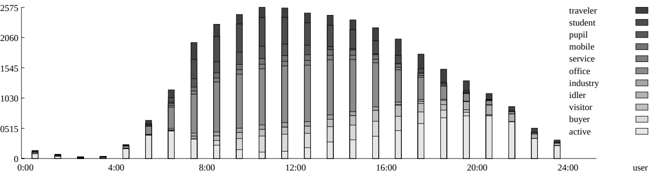


Figure 3: Summarized number of active users over day

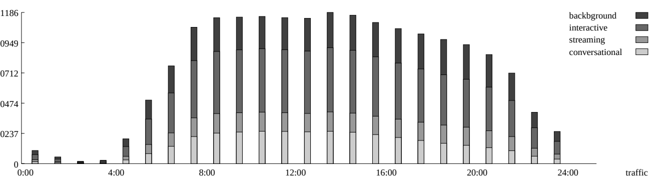


Figure 4: Summarized traffic rate over day in kbit/s

The summarized traffic density for the modeled day is given in Fig. 5. The snapshots presented cannot show the geographical fluctuation of traffic. To do so, an animation of the traffic density over day can be found at [17]

C. Experimental Design

We have chosen to implement a full factorial experiment, since we regard only two predictor variables with five levels each [23]. The routing algorithm and the traffic distribution act as predictor variables. There are several factors which where kept constant for all experiments.

The scaling of the experiment to a different timescale is inevitable due to the size and complexity of the modeled scenario. We choose the simulation time to be 960 seconds to match the real time of 24 hours. Thus one second in simulation equals 90 seconds in real time. The amount of traffic is given by our workload model and used to parametrize the traffic agents at regular intervals. The updates of the workload were performed every 2 minutes (real time). The routing updates were performed every 6 minutes (real time). The mobility of users is inherently included within the mobility model and thus reflected in the workload model.

The runtime of each experiment is approximately one week while memory usage approaches nearly 800MB of RAM (we used four simulation machines each equipped with Pentium4 2,2GHz, 1GB of RAM in parallel).

V. RESULTS

The main goal of our analysis was the investigation of the feasibility of QoS routing mechanisms to support load balancing within future wireless metropolitan area network topologies. Efficient load balancing translates into maximizing the overall utility of the network, which cannot easily be measured. We investigate various response variables, which are tightly related to the overall utility of the network. Moreover, we analyze the results on different aggregation levels of the obtained data which are *link level*, *flow level* and *packet level*.

Besides measuring the exact numbers, we give various visualizations to allow for better interpretation of the results. For most parts, we provide results which cover the complete 24 hour simulation period. If necessary, we give the results for the busy hour. Since we obtained a large set of results, we will only give the most important ones within this document due to space limitations. We use the following notation in the figures: `algorithm-0.distribution-varianta`, thus the suffix `wmp-0.3-2a` denotes the *wmp* algorithm variant *2*, traffic distribution *dist. (3)*.

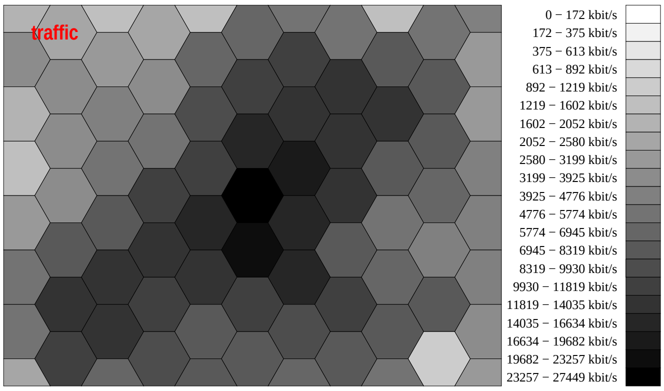


Figure 5: Summarized traffic density over day

The results are structured as follows. Results on link level are given in Section V.1. This includes figures to illustrate *load* and *loss* for RAS-RAS, RAS-RAR and RAR-Backbone level for selected algorithms and traffic distributions as well as a summary of *load* and *loss* on link level for selected algorithms. The results obtained on *flow level* are given in Section V.2. This includes results for various metrics on flow level including *load*, *loss* and *path length* as well as *delay* and *delay variation*. The results on *packet level*, namely *delay* and *reordering* of individual packets are presented in Section V.3. Finally, we give a *summary* of all *application* and *routing* related response variables in Section V.4.

1) Results on Link Level

The results on link-level include the mean load and loss for the various levels of the network topology. This accounts for multiple aspects of the algorithms studied:

- Does the algorithm use the interconnections on RAS-RAS level efficiently.
- Which levels of the infrastructure are dimensioned too wide or too narrow.
- Is the performance of the algorithm acceptable under normal conditions (investigated over 24 hours) and under heavy load (investigated over the busy hour).

We give some graphs which allow for comparison of the different algorithms for an e/i-ratio of 100/0 for all traffic classes as well as for selected other distributions. Moreover, we provide some selected visualizations of individual algorithms for all traffic distributions investigated.

Load on Link-Level

The load on link-level clearly favors the shortest path algorithms including the shortest multipath as well (see Fig. 6 and Fig. 7). The more advanced algorithms try to use unused links at the expense of longer routes. This increases the overall load per level. Though, the absolute load cannot be used as indicator

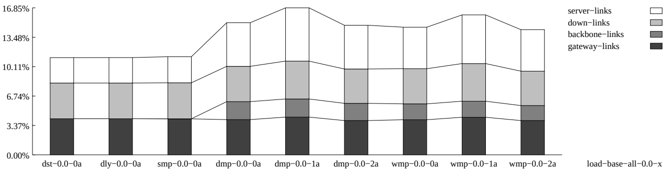


Figure 6: Average load over 24 hours for all algorithms, dist (0)

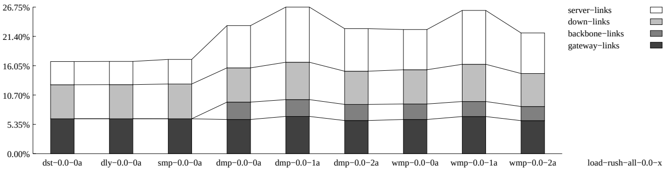
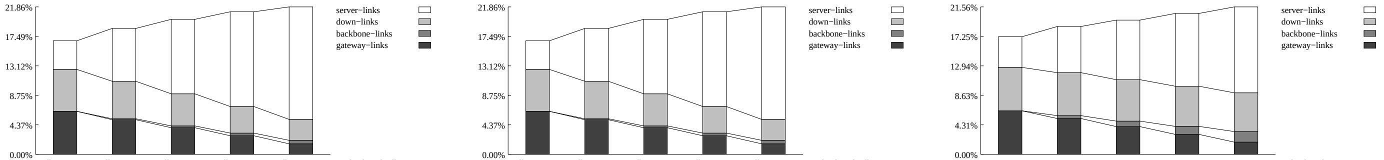
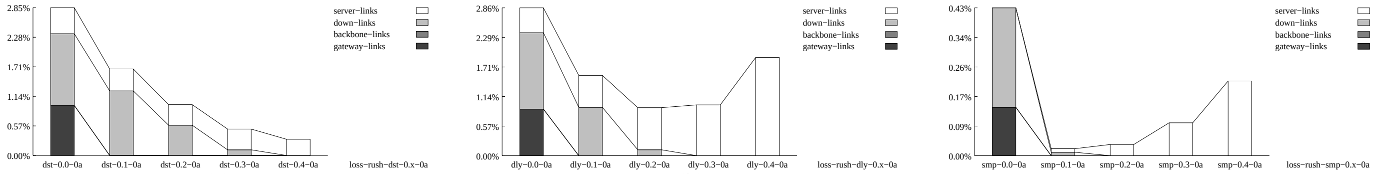


Figure 7: Average load in the busy hour for all algorithms, dist. (0)



(a) (b) (c)

Figure 8: Average load over 24 hours for (a) *dst*, (b) *dly* and (c) *smp* for all traffic distributions



(a) (b) (c)

Figure 9: Average loss over 24 hours for (a) *dst*, (b) *dly* and (c) *smp* for all traffic distributions

for the quality of the load balancing. It allows however to see at which levels the algorithms act differently. In our example the increased use of server links is visible for the *dmp* and *wmp* variants. The results also exhibit the possible gain within the modeled network if we assume alternate paths in combination with multipath routing to distribute the load.

The differences between the algorithms remain visible if we introduce local traffic. However the individual algorithms show different tendencies under these conditions. While the *dst* algorithm improves due to the shift of load from the uplinks, the *dly* algorithm suffers under the same conditions. The *smp* algorithm performs well under all traffic distributions outperforming all single path algorithms. Fig. 8 illustrates this for (a) *dst*, (b) *dly* and (c) *smp* for all investigated traffic distributions.

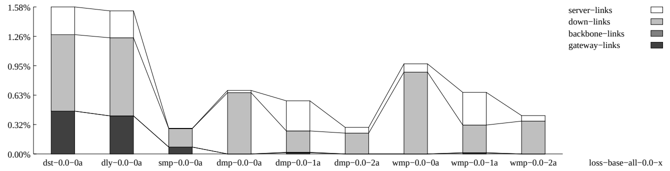


Figure 10: Average loss over 24 hours for all algorithms, dist (0)

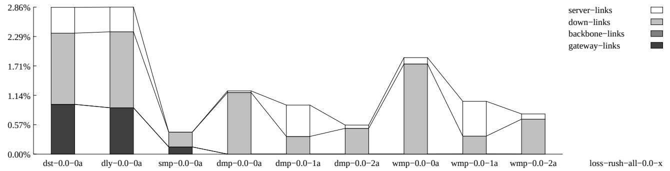


Figure 11: Average loss in the busy hour for all algorithms, dist. (0)

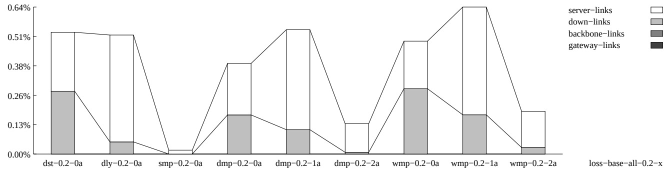


Figure 12: Average loss in the busy hour for all algorithms, dist. (2)

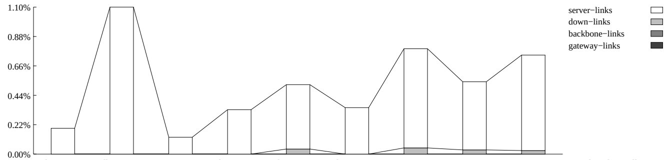


Figure 13: Average loss in the busy hour for all algorithms, dist. (4)

Loss on Link-Level

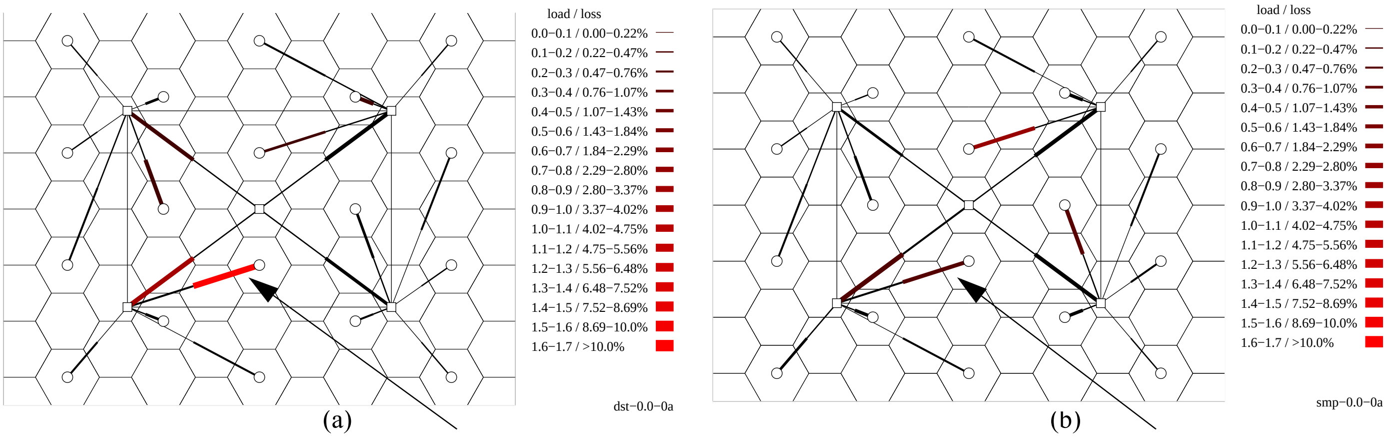
The loss on link-level is an indicator for congested links and areas within the network. Moreover, the hierarchy level at which loss occurs is closely related to the fundamental principles of the underlying algorithms. Our results for the best algorithm *smp* show minor losses on the downlinks (RAS-RAR) and on the gateway links (RAR-EGW). These losses occur because the links are not capable of carrying all traffic to/from the EGW to the source or destination even using multiple paths. The single path algorithms are clearly limited by the bandwidth of the links (see Fig. 10 and Fig. 11). The results for *dmp* and *wmp* cannot easily be analyzed without additional data. It seems that the load balancing achieved comes at the expense of overloading individual levels unnecessarily.

The loss behavior of the algorithms changes significantly if the traffic distribution includes more internal traffic. Fig. 12, and Fig. 13 show a comparison of the average loss for all algorithms for the traffic distributions dist. (2) and dist. (4) during the busy hour. Fig. 9 gives the average loss over 24 hours for the algorithms (a) *dst,* (b) *dly* and (c) *smp* to illustrate the loss characteristics for all investigated traffic distributions.

Visualizations of Load and Loss

Besides the above mentioned values, we are interested in finding the “problem zones” of our network. It is obvious, that the hot spots of our workload model are correlated to these areas. However we observed interesting effects on how the different routing algorithms deal with these hot spots. The following visualizations have to be interpreted as follows: The width of the edges entering a node depicts the mean percentage of load (in relation to link capacity) entering this node (the traffic direction is important to model asymmetry, because we estimate more gateway - host traffic than vice versa). The brighter edges mark links where loss occurs. The brighter the gray, the more loss is measured. We give results for the RAR-Backbone level.

The busy hour plot shows different degrees of loss for both algorithms. The hot spots during the busy hour are clearly



(a) (b)

Figure 14: Load / loss visualization, busy hour, (a) *dst* RAR-EGW, (b) *smp* RAR-EGW, all for dist. (0)

visible. The losses for the single path *dst* algorithm are induced from traffic which flows from the gateway to the center of the city (see Fig. 14 (a)). In addition to the large losses on RAR-EGW level and RAS-RAR level there are minor losses at the RAS-RAS level. The *smp* algorithm is able to split the traffic and thus only a small fraction of packets is lost (see Fig. 14 (b)). Moreover the link utilization (load) is distributed more equally. We can conclude that even simple multipath algorithms are able to achieve a better load distribution than standard Internet routing.

2) Results on Flow Level

Some response variables including delay and path length can only be measured for individual flows, thus we give these results on flow-level. Delay acts as a response variable describing the ability of the algorithm to balance the network load (the delay decreases or remains low even under heavy load) while path length is of special interest for the quality of the multipath algorithms. Moreover we include results for loss and delay. These results account directly for the treatment individual flows get throughout the entire network while load and loss on link-level (see above) accounts for the treatment of all flows in the corresponding hierarchy level.

Load, Loss, Delay and Path Length on Flow-Level

The loss on flow level gives the fraction of data which was dropped inside the network. The results show, that the single path algorithms perform worse than the multipath algorithms. The *smp* algorithm shows the best performance of all algorithms investigated. The increased delay and hop count of the *dmp* and *wmp* are due to the usage of longer routes for load balancing. The results during the busy hour are much worse than the results over 24 hours. Especially the single path algorithms have to drop a significant amount of data. The multipath algorithms perform better under these conditions. In Fig. 15 and Fig. 16 we give the results for 100% EGW traffic.

The delay variation gives a measure for the quality of the load balancing. In a perfect balanced network, the variance should be near zero. An algorithm, which only loads some links while leaving others unused will increase the variance. The single path algorithms have no choice of load distribution and thus the variance is significantly larger than the variance of the multipath algorithms. This behavior is even more evident for the busy hour. See Fig. 17 and Fig. 18 for the delay and delay variation on flow level for the traffic distribution dist. (1).

3) Results on Packet Level

The trace of the treatment of individual packets allows to give results on packet-level. We injected some measurement flows into the network, which were closely monitored. The flows were injected in both directions between measurement points to account for asymmetric behavior. From a total of eight

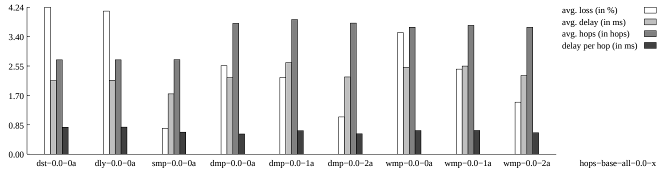


Figure 15: various metrics on flow level, 24 hours, 100% EGW

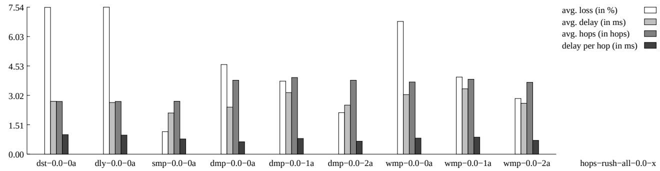


Figure 16: various metrics on flow level, rush hour, 100% EGW

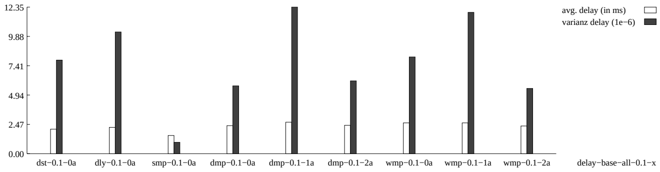


Figure 17: Average delay in ms and delay variation, 24h, dist. (1)

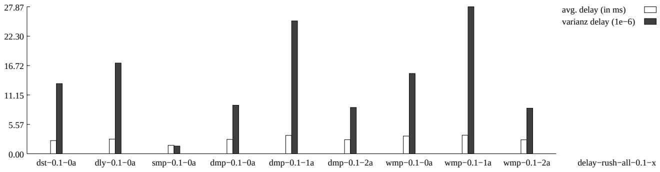


Figure 18: Average delay in ms and delay variation, busy hour, dist. (1)

measurement flows, which were present in each run of the experiment, we only provide the most interesting insights. The individual measurement flows have been set up as constant bitrate over UDP, 128kBit/s each.

In the following, we present the comparison of some algorithms using selected measurement flows. We selected a trace from the gateway to a RAS located in the center of the network (EGW-RAS53, see Fig. 2). We expect the results to be of interest, because during the rush hour this area of the network is under heavy load. The second trace selected starts from RAS 83 and is destined to RAS 43. This trace crosses the backbone (shortest path) or tries to find a way around if the backbone is under heavy load conditions (for delay sensitive algorithms). We present these traces for *dst*, *smp*, *dmp* and *wmp2.*

The scatter-plots give the delays for individual packets. If packets are dropped due to congestion, the time delay until their drop is counted. Please note that the scale on the y-axis may vary and thus cannot easily be compared between algorithms.

Delay of Packets, EGW to RAS53

The figures Fig. 19 to Fig. 23 show a measurement flow from the edge gateway to the city center. All scatterplots show an increasing delay for the time period between 8:00 and 18:00h. The *dst* algorithm shows some dramatic increases in delay if the path chosen is congested. Please notice the different scale on the y-axis: The delay for the *dst* algorithm rises as high as 19ms while the *smp* algorithm constantly remains below 8ms. The *dmp* and *wmp* variants show a good performance most of the time, the maximum delay being around 8ms. However, there are some short periods where the algorithm fails and as a result dramatic losses and an increasing delay up to around 20ms can be observed.

We provide the results for the *smp* algorithm to show the behavior for traffic distribution (4). Fig. 23 clearly shows the smaller delay (reduced load) compared to Fig. 20 due to the shift from Edge Gateway traffic to localized traffic.

The oscillating behavior of the *dmp* and *wmp* algorithms will be investigated below. Periods of good delay / loss ratio are followed by periods where loss occurs and the achieved delay increases significantly. With the current parametrization of the routing algorithms these variants do not provide a stable performance.

Delay of Packets, RAS83 to RAS43

The result for the measurement flow between RAS83 and RAS43 are very interesting. The single path algorithm *dst* “fails” if the backbone is under heavy load. The loss increases and the delay is as high as 21ms. The rise is relatively abrupt and the decline is more smooth. This is due to the traffic load which is similarly shaped. The *smp* algorithm has only short periods of time where the increase in delay and loss is heightened. The increase in delay starts approximately 2 hours later in time and the decrease around 3 hours earlier in time as observed with the *dst* algorithm. This shows the much better handling of congestion using multipath algorithms which are able to split the traffic.

The *dmp* and *wmp* algorithms do not perform as good as intended. We see the influence of multiple paths with different visible steps in the delay. *Dmp* as depicted in Fig. 26 shows heavy oscillations, while the damped version of *wmp* (*wmp2*) works much better. The increase in delay and loss occurs later than for the *dst* algorithm though earlier than for the *smp* algorithm. The delay of the majority of packets for all multipath variants remains low (<10ms) even under heavy load.

To further illustrate the oscillating behavior observed for the dynamic multipath algorithms Fig. 28 shows the busy hour for the *wmp2* algorithm. The oscillations are clearly visible: periods of good performance (no loss, low delay) alternate with periods of bad performance (high loss, higher delay). The boundaries between these periods are determined by our rerouting interval of 6 minutes.

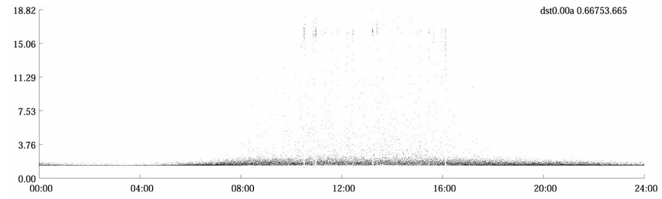


Figure 19: Packet delay, *dst* algorithm, 24h, dist. (0), EGW-RAS53

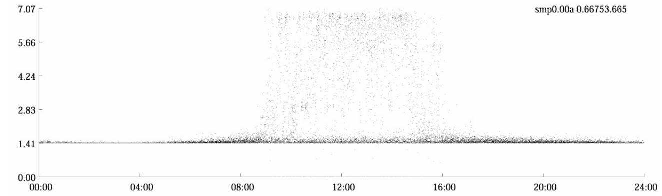


Figure 20: Packet delay, *smp* algorithm, 24h, dist. (0), EGW-RAS53

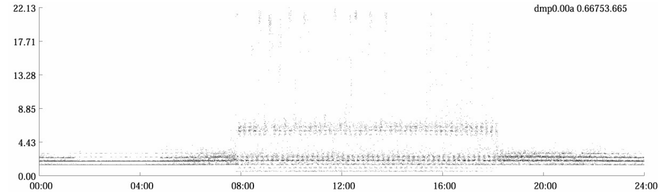


Figure 21: Packet delay, *dmp* algorithm, 24h, dist. (0), EGW-RAS53

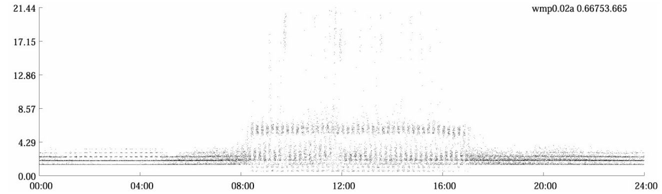


Figure 22: Packet delay, *wmp2* algorithm, 24h, dist. (0), EGW-RAS53

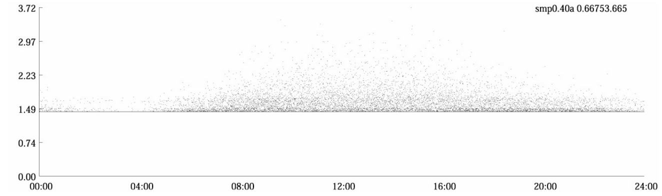


Figure 23: Packet delay, *smp* algorithm, 24h, dist. (4), EGW-RAS53

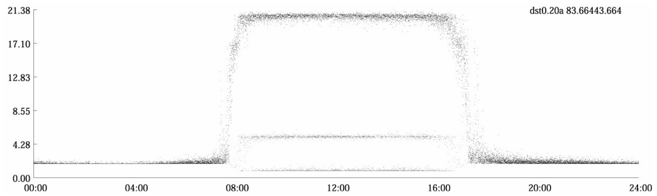


Figure 24: Packet delay, *dst* algorithm, 24h, dist. (2), RAS83-RAS43

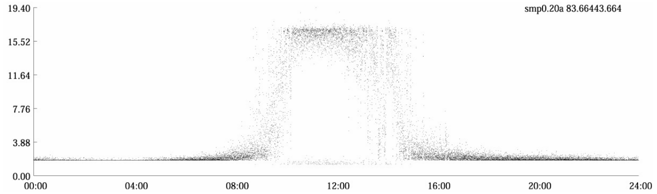


Figure 25: Packet delay, *smp* algorithm, 24h, dist. (2), RAS83-RAS43

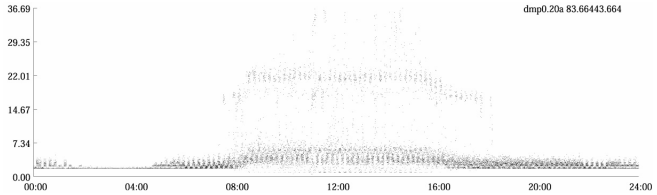


Figure 26: Packet delay, *dmp* algorithm, 24h, dist. (2), RAS83-RAS43

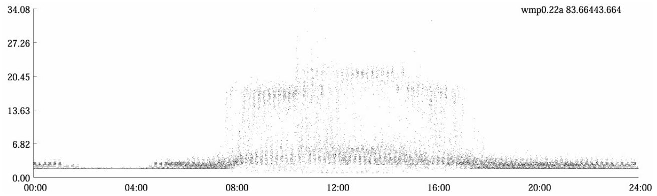


Figure 27: Packet delay, *wmp2* algorithm, 24h, dist. (2), RAS83-RAS43

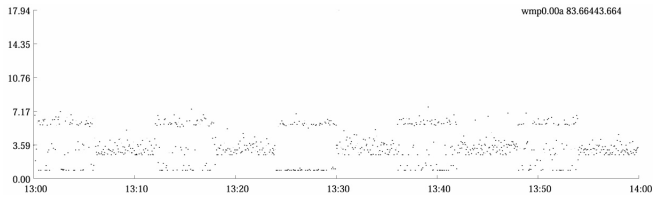


Figure 28: Packet delay, *wmp2* algorithm, busy hour, dist. (0), RAS83-RAS43

Reordering of Packets

We used sequence numbers to trace the order of the packet arrival to account for the reordering which may occur using multipath algorithms. To describe these effects, we used two metrics:.

- The percentage of packets received to late in order (fraction of reordered packets) is given by the number of reordered packets divided by the total of all packets.
- A reorder index. The relative lateness of late packets to the packet with the highest sequence number received so far is summed and divided by the number of reordered packets. This gives the average “lateness” per reordered packet. Fig. 29 illustrates the metrics. Using our definition, three packet are late and the summed lateness equals six. The reorder index is 6/3=2.

Table 2 gives the results for our investigation. As expected, the single path algorithms do not reorder any flows. The multipath algorithms exhibit different behavior: the *smp* algorithm reorders an average of 3.37% of all packets, each of these packets is 3.65 steps late on average. The reordering imposed by the *dmp* and *wmp* variants is significantly higher: 7.28% and 7.93%. The steps the reordered packets are too late are higher, too. This may be explained by the oscillations which we observed for the *dmp* and *wmp* algorithms. The reordering can only be observed for high bandwidth flows. Depending on the variant of TCP used, the degree of reordering may be prohibitive.

TABLE 2: REORDERING OF PACKETS

	dst	***dly***	***smp***	***dmp***	***wmp***
Reordering					
Fraction of Reordered Packets	0%	0%	3.37%	7.28%	7.93%
Reorder Index (in steps per packet)	0	0	3.65	4.64	7.11

```
source:     1---2---3---4---5---6---7---8---9
             \   \       \       \      \   \
destination:  1---2-------4-3-----6-------8-7-9-5
                            ^               ^   ^
reordered/lateness:         1               1   4
```

Figure 29: Reordering example

4) Summary of Results

Table 3 gives a summary of the overall results obtained for the 100% to/from Edge Gateway traffic distribution. The overall performance of the network can be judged using the application related parameters of average loss and average end-to-end delay. The routing related values include the mean path length which is of particular interest for the multipath algorithms. Moreover, the load in combination with the load variation is given for different hierarchy levels. The smaller the variance, the more effective the load balancing achieved.

VI. CONCLUSIONS

We have discussed the influence of QoS routing algorithms within wireless metropolitan area networks with respect to load balancing. As a first step, we defined the requirements for use within the investigated environments and modeled a corresponding topology.

We have chosen a set of routing strategies to compare. Moreover, we gave a concise description of the experimental design. This included the definition of predictor variables as well as a brief description of the workload model employed. The models served as a basis for the second part of our investigation: the quest for efficient load balancing within wireless metropolitan area networks. The impact of the different algorithms as well as of various traffic distributions on the overall routing performance was traced by means of simulation.

Efficient resource management increases the overall network utility - which cannot be measured easily, however. Thus, a detailed analysis of the results has been performed. We used the loss and load of individual link classes as well as of the entire network to represent this overall utility. Moreover we investigated the delay and delay variation of individual streams and packets. Our findings are, that multipath algorithms exhibit very promising results compared to single path algorithms. However, we have not been able to tap the full potential of dynamic multipath routing algorithms based on the minimum delay metric.

The insights presented aid network designers in developing new paradigms in the area of wireless metropolitan area networks. This specially includes resource management scenarios. As future work, we perceive the analysis of the oscillating behavior of the delay based multipath algorithms.

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TABLE 3: SUMMARY OF RESULTS

	dst	***dly***	***smp***	***dmp***	***dmp1***	***dmp2***	***wmp***	***wmp1***	***wmp-2a***
Application related									
Average E2E Delay (standard deviation)	2.15ms (0.00273)	2.14ms (0.00279)	1.74ms (0.00122)	2.21ms (0.00173)	2.65ms (0.00265)	2.23ms (0.00348)	2.51ms (0.00259)	2.55ms (0.00327)	2.27ms (0.00202)
Loss	4.24%	4.13%	0.75%	2.56%	2.22%	1.08%	3.51%	2.46%	1.50%
Routing related									
Mean Path Length [hops]	2.73	2.73	2.73	3.78	3.89	3.79	3.67	3.72	3.66
RAS-RAS Level Load (variance) from 0:00-23:59	4.65% (3.9)	4.68% (3.9)	4.79% (1.94)	8.01% (1.48)	9.78% (2.1)	8.03% (1.49)	7.62 (1.48)	8.93% (1.91)	7.63% (1.47)
RAS-RAR Level Load (variance) from 0:00-23:59	20.59% (0.96)	20.60% (0.97)	20.76% (0.83)	20.34% (0.70)	21.81% (0.72)	19.80% (0.58)	20.29% (0.97)	21.71% (0.68)	19.81% (0.56)