Q-MEHROM: Mobility support and resource reservations for mobile senders and receivers

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Abstract

The increasing use of wireless networks and the popularity of multimedia applications, lead to the need for Quality of Service support in a Mobile IP-based environment. This paper investigates the reservation of resources for mobile receivers as well as senders in combination with micromobility support. We present Q-MEHROM, which is the close coupling between the micromobility protocol MEHROM and a resource reservation mechanism. In case of handoff, Q-MEHROM updates the routing information and allocates the resources for a sending or receiving mobile host simultaneously. Invalid routing information and reservations along the old path are explicitly deleted. Resource reservations along the part of the old path that overlaps with the new path are reused. Q-MEHROM uses access network topology and link state information calculated by QOSPF. Simulation results show that the control load is limited. Moreover, it consists mainly of QOSPF traffic and it is influenced by the handoff rate in the network. Q-MEHROM makes real use of the mesh links and extra uplinks, which are present in the access network to increase the robustness against link failures, to reduce handoff packet loss and to improve the performance for highly asymmetric network loads. Also, attention is paid to the differences between the mobile sender and the mobile receiver scenario.

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1. Introduction

Today, wireless networks evolve towards IP-based infrastructures to allow a seamless integration between wired and wireless technologies. Most routing protocols that support IP mobility, assume that

the network consists of an IP-based core network and several IP domains (also referred to as access networks), each connected to the core network via a domain gateway. This is illustrated in Fig. 1.

In contrast to wired networks, the user's point of attachment to the network changes frequently due to mobility. Since an IP address indicates the location of the user in the network as well as the end point of its connections, user mobility leads to several challenges. Mobile IP (IPv4 [1], IPv6 [2]), which is standardized by the IETF, is the best known routing protocol that supports host mobility.

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Fig. 1. General structure of an all IP-based network.

While Mobile IP is used to support macromobility, i.e., the movements from one IP domain to another, much research is done to support the local movements within one IP domain, called micromobility. Examples of micromobility protocols are per-host forwarding schemes like Cellular IP [3] and Hawaii [4], and tunnel-based schemes like MIPv4 Regional Registration [5] and Hierarchical MIPv6 [6], proposed within the IETF, and the BCMP protocol [7], developed within the IST BRAIN Project. These protocols try to solve the weaknesses of Mobile IP with respect to micromobility support, by aiming to reduce the handoff latency, the handoff packet loss and the load of control messages in the core network. Low Latency Handoff protocols, like Low Latency MIPv4 [8] and Fast MIPv6 [9], were developed by the IETF to reduce the amount of configuration time in a new subnet by using link layer triggers in order to anticipate the movement of the mobile host. However, most research in the area of micromobility assumes that the links of the access network form a tree topology or hierarchical structure. Nevertheless, for reasons of robustness against link failures and load balancing, a much more meshed topology is preferred. In our previous work [10,11], MEHROM (Micromobility support with Efficient Handoff and Route Optimization Mechanisms) was developed, resulting in good performance, irrespective of the topology, for frequent handoffs within an IP domain.

In a mobile IP-based environment, users want to receive real-time applications with the same QoS (Quality of Service) as in a fixed environment [12]. Several extensions to RSVP (Resource Reservation Protocol) under macro- and micromobility are proposed in [13,14]. However, the rerouting of the RSVP branch path at the cross-over node under micromobility again assumes an access network with tree

topology. Moreover, the cross-over node triggers a PATH or RESV message after a Route Update message is received, introducing a substantial amount of delay. Current work within the IETF NSIS (Next Steps in Signaling) working group includes the analysis of some of the existing QoS signaling protocols for an IP network [15], the listing of Mobile IP specific requirements of a QoS solution [16] and the development of an architectural framework for protocols that signal information about a data flow along its path in the network [17]. The applicability of the proposed NSIS protocols in mobile environments [18] is also investigated; however, only macro-mobility scenarios are considered until now.

In this paper, we investigate the reservation of resources for data flows from mobile receivers and senders in the micromobility scenario. We present Q-MEHROM, which is the close coupling between the micromobility protocol MEHROM and a resource reservation mechanism. At the time of handoff, the updating of routing information and the allocation of resources for a mobile receiver or sender are performed simultaneously, irrespective of the topology. Information gathered by QOSPF (Open Shortest Path First protocol with QoS extensions [19,20]) is used.

The rest of this paper is structured as follows. Section 2 presents the framework used. In Section 3, a short overview of the goals and operation of the micromobility protocol MEHROM is given. Section 4 describes which information, obtained by the QOSPF protocol, is used by Q-MEHROM. In Section 5, the operation of Q-MEHROM is explained for mobile senders and receivers. Simulation results are presented in Section 6. The final Section 7 contains our concluding remarks.

2. Framework for micromobility support and resource reservations

In Fig. 2, the framework, used for a close interaction between micromobility support and resource reservations, is presented. The grey blocks are the focus of this paper and are explained in more detail in the following subsections.

2.1. Micromobility protocol and resource reservations

The central block in Fig. 2 is responsible for the propagation of information through the access network about the location of the mobile hosts and

Fig. 2. Framework for micromobility routing and QoS support in an IP-based access network.

about the requested resources for the data flows sent or received by those mobile hosts. Frequent handoffs within one IP domain are supported by the micromobility protocol MEHROM [11], as explained in Section 3. By defining the resource reservation mechanism as an extension of MEHROM, resources can be allocated or re-allocated at the same time that the routing tables are updated at power up or after handoff. The combination of MEHROM and its resource reservation extensions is referred to as Q-MEHROM and is further explained in Section 5.

Although a micromobility protocol is only required to update the routing tables to support data traffic towards a mobile host, in this paper we consider the reservation of resources for both data flows towards as well as from a mobile host.

2.2. Routing agent

In order to obtain information about the topology of the access network and the state of the links, we use the routing agent QOSPF, as described in [20]. This is represented by the upper left block of the framework in Fig. 2.

The interaction between both grey blocks is as follows: QOSPF computes paths in the access network that satisfy given QoS requirements and provides this information to Q-MEHROM in the form of QoS tables, which are presented in Section 4. Every time Q-MEHROM reserves or releases resources on a link, QOSPF is informed so that the updated link states can be advertised through the access network.

2.3. Admission control

The upper right block in Fig. 2 represents the admission control policy. Although a variety of

mechanisms is possible, we have chosen for a simple admission control priority mechanism: priority is given to handoff requests over new requests. When a new request for resources is made by a mobile host, its access router decides whether the access network has sufficient resources to deliver the required QoS. If not, the request is rejected. At the time of handoff, the mobile host sends a handoff request for its existing connection. If the required resources cannot be delivered via the new access router, the handoff request is not rejected, but the delivered service is reduced to best-effort. This means that for a mobile receiver, a best-effort path is installed between the domain gateway and the access router, while for a mobile sender, standard IP routing is used.

If the availability of resources for an existing connection is only checked at the time of handoff, this mechanism would have an important drawback: as long as a mobile host, receiving best-effort service, does not perform handoff, its service remains best-effort, even if enough resources became available due to the handoff of other mobile hosts. Therefore, the mobile host itself can trigger a new check at the access router, by sending an additional request. The mobile host sends this trigger when it receives a new beacon from its current access router, as long as it receives best-effort service and as long as it is not performing handoff soon. To make an estimation about the next time of handoff, cross-layer information can be used, e.g., link layer (L2) triggers or location information.

The admission control mechanism gives the routing agent information about the resources that were reserved by the mobile host before handoff, as these resources can be reused. The routing agent in turn provides information about paths with sufficient resources in the access network by its QoS tables.

It is obvious that during admission control, an access router must also take into account the availability of resources on the wireless link. This is, however, out of the scope of this paper.

2.4. Packet classifier and scheduler

The lower blocks in Fig. 2 are the packet classifier and scheduler. When Q-MEHROM updates the routing tables, these routes are installed in the packet classifier so that data packets are mapped towards the correct outgoing link. For the scheduler, a variant of CBQ (Class Based Queueing) is used [21].

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When resources are reserved for a mobile host, Q-MEHROM inserts a class for that mobile host. When these resources are released after handoff, the class is removed again. The different classes for the mobile hosts have the same priority. Within those classes, the scheduler uses weighted round-robin, with weights proportional to the amount of reserved resources. One class, that is never removed and that has a higher priority, is the class for all control traffic. To reduce complexity, we assume that the routing decision is only based on the mobile host's care-of address, irrespective of the amount of flows. For simplicity, we consider one class for all flows to a specific mobile host and one class for all flows from a specific mobile host. Extensions to path setups and resource reservations for individual data flows are however straightforward.

3. Micromobility support by MEHROM

3.1. Requirements for micromobility support

Based on our study of Cellular IP, Hawaii and MIPv4 Regional Registration [22,23], we concluded that it is necessary to cope with the following requirements for the handoff process to achieve a micromobility protocol that is able to support frequent handoffs:

1. During the handoff process, the load of the control messages should be concentrated near the involved access routers at the edge of the access network. If possible, the messages should not traverse the whole access network nor overload the domain gateway.
2. The handoff control messages should update the necessary routers as fast as possible, trying to limit packet loss and handoff latency.
3. The handoff process should result in an optimal new path between the current access router and the domain gateway. The term 'optimal path' may refer to a path with minimum hop count, lowest cost, highest available bandwidth,...
4. The mobile host should be informed whether the handoff process succeeded or failed, so that it can react in case of a handoff failure.
5. The use of a micromobility protocol should be transparent to the mobile terminal, as this can ease the integration with Mobile IP. Doing so enables the mobile host to travel to domains that support Mobile IP but no micromobility protocol.

Table 1

Performance of Cellular IP (CIP), Hawaii (HAW) and MIPv4 Regional Registration (MIPv4-RR) concerning the protocol requirements

	CIP	HAW	MIPv4-RR
Control load near access routers	±	Yes	No
Low latency and low packet loss	±	Yes	No
Optimal paths (minimum hop count)	Yes	No	Yes
Handoff acknowledgements	No	Yes	Yes
Transparent to mobile host	No	Yes	±

Although the above mentioned micromobility protocols work correctly in a meshed access network, the topology has an important influence on their performance [22,23]. For example, Cellular IP and MIPv4 Regional Registration do not use the mesh links, while Hawaii takes advantage of the mesh links to reduce the handoff latency and packet loss. However, the use of Hawaii in a meshed topology results in suboptimal routes and high end-to-end delays after several handoffs. To what extent the requirements are fulfilled by the studied existing micromobility protocols, when used in a meshed access network topology, is summarized in Table 1.

3.2. MEHROM handoff scheme

Our developed micromobility scheme MEHROM aims to satisfy the requirements previously described for frequent handoffs within an IP domain and irrespective of the topology. This is realized by splitting the handoff scheme into two phases. During the first phase, a fast handoff is made, by sending a Route Update message from the new access router to the old one. As a result, MEHROM can use mesh links to limit the handoff latency and packet loss, in contrast to Cellular IP and MIPv4 Regional Registration. Only if the new path is not optimal, is the second phase executed by sending a new Route Update message from the new access router towards the domain gateway. This guarantees the setup of an optimal new path between the domain gateway and the current access router in meshed topologies, in contrast to Hawaii. A more detailed description of MEHROM and a comparison with Cellular IP, Hawaii and MIPv4 Regional Registration, is given in [10,11].

MEHROM is a per-host scheme and every router along the path between the domain gateway and the current access router has an entry in its routing table indicating the next hop to the mobile host. To perform handoff, MEHROM updates the

routing tables of the routers in the access network to set up an optimal path between the domain gateway and the currently used access router. Here, an optimal path is defined as the path with minimum hop count. Data packets are routed towards the mobile host by the use of the entries installed by MEHROM. For the routing of data packets from the mobile host towards the core network, thus via the domain gateway, standard IP routing is used.

The handoff scheme has the following characteristics: at the time of handoff, the necessary signaling to update the routing tables is kept locally as much as possible. New entries are added by Route Update messages and obsolete entries are explicitly deleted by Route Delete messages, resulting in a single installed path for each mobile host. A successful setup of a new path is reported to the new access router by an Acknowledgment message. This micromobility scheme is very suitable to be closely coupled with a resource reservation mechanism. When a mobile host performs a handoff, we want to propagate the necessary QoS information as fast as possible to limit the degradation of the delivered QoS. In addition, we want to restrict the signaling to the part of the new path that does not overlap with the old path and explicitly release reserved resources along the unused part of the old path. In what follows, we assume that the requested resource is a certain amount of bandwidth.

4. Information calculated by QOSPF

In order to develop a resource reservation mechanism, information about the state of the access network must be provided. QOSPF advertises link metrics, like link available bandwidth and link delay, across the access network by Link State Adver-

Fig. 3. Example of a simple access network [x] = [available bandwidth (Mbps)].

tisements (LSAs). As a result, the domain gateway (GW), all routers and all access routers (ARs) have an updated link-state database that reflects the access network state and topology. To provide useful information to Q-MEHROM, QOSPF calculates, in each node of the access network, several QoS routing tables from the database. Fig. 3 shows a simple access network, which is used to illustrate the structure of the different QoS routing tables. One bidirectional link is indicated by two directed edges, each with its available bandwidth.

4.1. Delay table

The Delay table is only used during the setup of a path towards a mobile host, after handoff. In this case, the first phase of the Q-MEHROM handoff algorithm uses the Delay table to send as fast as possible a Route Update message from the new access router towards the old one. The Delay table of a router has this router as source and an entry for every access router as destination. Therefore, the router calculates the path with smallest delay to a specific AR, using a single objective path optimization. The next hop to that AR is then put in the Delay table, as illustrated in Table 2. As the delay characteristics are not expected to change frequently, the Delay table needs no frequent recalculation.

4.2. Bandwidth table

A Bandwidth table is used when resources are reserved for a new traffic flow. Here, the available bandwidth on the links of the access network is taken into account. A double objective path optimization is used, also taking the hop count into account. For a certain value of the hop count, the path with at most this number of hops and with maximum bandwidth (BW) is calculated between source and destination. If more than one path with maximum bandwidth is available, the shortest path is chosen. To make reservations for data traffic towards a mobile host (MH), a router calculates a

Table 2
Delay table for router R2 of Fig. 3, if all links have the same link delay

Delay table	
Destination	Next hop
AR1	R1
AR2	AR2

Table 3
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Table 3
Bandwidth tables for router R2 of Fig. 3

Max. hops	BWtable_to_MH		BWtable_from_MH	
	Last hop	Max. bw	Next hop	Max. bw
1	—	—	—	—
2	R3	2 Mbps	R3	4 Mbps
3	R1	3 Mbps	R3	4 Mbps

BWtable_to_MH with the domain gateway as source and itself as destination. The BWtable_to_MH gives the last node on the path before reaching the destination. To make reservations for data traffic from a mobile host, the router calculates a BWtable_from_MH with itself as source and the domain gateway as destination. In this case, the next hop on the path to the domain gateway is put in the BWtable_from_MH. When the amount of available bandwidth in the access network changes, the Bandwidth tables should be recalculated. An example is given in Table 3.

4.3. Reuse-Bandwidth table

A Reuse-Bandwidth table is used for handoff reservations. When a mobile host performs handoff, a new path must be set up. It is possible that the new path partly overlaps the old path. Resources along this common part should be reused and not be allocated twice. Therefore, QOSPF must consider the resources reserved for the mobile host before handoff, also as available resources and calculate the Reuse-Bandwidth tables, called the RBWtable_to_MH for the data path towards the mobile host and the RBWtable_from_MH for the data path from the mobile host. Note that it is not our intention that the new path overlaps as much as possible with the old path. These tables can only be calculated at the time of handoff and they need the old path and the amount of reserved bandwidth for the mobile host as input. The Reuse-Bandwidth tables have the same structure as the Bandwidth tables. For the values in Table 4, it is assumed that a mobile host performs handoff from AR1 to AR2, with an old

reservation of 2 Mbps on the downlink path [GW,R3,R1,AR1] and of 1 Mbps on the uplink path [AR1,R1,R3,GW].

5. Q-MEHROM mechanism

In this section, we explain the basic operation of Q-MEHROM in three cases. First, the situation where the mobile host is the receiver is considered. Secondly, the mechanisms in the case where the mobile host is the sender are presented. Thirdly, the situation where the mobile host is both sender and receiver is discussed.

The update of the routing tables and the reservation of resources at the time of handoff is initiated by the mobile host. This results in a receiver-initiated path setup for data traffic towards the mobile host and a sender-initiated setup of the path for data traffic from the mobile host. By initiating the setup by the mobile host when performing handoff, the new path and reservations are set up as fast as possible and the reduction in the delivered QoS is minimized.

Fig. 4 illustrates the packet formats, specific to Q-MEHROM (Version = 2), that are used in the following subsections. The fields in bold are extensions to the basic MEHROM protocol (Version = 1).

5.1. Mobile host is receiver

The same phases of MEHROM are adopted to reduce the handoff packet loss (thanks to phase 1) and to guarantee the setup of an optimal path (thanks to phase 2). In Q-MEHROM, these phases are extended with a reservation mechanism. An optimal path is now defined as a path with minimum hop count that can deliver the requested amount of bandwidth. Like basic MEHROM, Q-MEHROM is capable detecting whether the new path will be optimal, using an *optimal_path* parameter in the Route Update messages. The basic operation of Q-MEHROM is explained using the three successive situations in Fig. 5. These three situations are elaborated below.

5.1.1. Bandwidth reservations (Fig. 5(1))

When a mobile host (MH) powers up in the access network, only MEHROM is used to set up a (best-effort) path for the MH in the access network. This path is a path with minimum hop count between the domain gateway (GW) and the current access router.

Table 4
Reuse-Bandwidth tables for router R2 of Fig. 3

Max. hops	RBWtable_to_MH		RBWtable_from_MH	
	Last hop	Max. bw	Next hop	Max. bw
1	—	—	—	—
2	R3	2 Mbps	R3	5 Mbps
3	R1	5 Mbps	R3	5 Mbps

Fig. 4. Packet formats specific to Q-MEHROM. 'Optimal' is the optimal_path parameter. 'O' is a flag indicating whether the new path is optimal. 'S' is a flag indicating whether the mobile host is sender.

When a traffic flow is set up towards a MH, this MH requests an amount of bandwidth (information obtained from the application layer) for that flow at its current access router. After a positive admission control, the access router starts the resource reservation mechanism, using its BWtable_to_MH. If the MH is the receiver of multiple flows, the requested bandwidth is the sum of the individual amounts of bandwidth requested by the applications.

5.1.2. Handoff phase 1—fast handoff (Fig. 5(2))

After the receipt of a Mobile IP registration request, the new access router (nAR) (we assume a positive admission control) adds a new entry for the MH in its routing table and sends a Route Update message towards the old access router (oAR) in a hop-by-hop fashion.

When R2 processes the Route Update message, it checks the optimal_path parameter in this message. As the node is part of the optimal path between the GW and the nAR, the value of the optimal_path parameter was set to 1. Therefore, the necessary resources are reserved on the link between R2 and the nAR. As a next step, it looks up the next hop on the path with smallest delay towards the oAR in the Delay table (i.e., R1). Furthermore, it retrieves in the RBWtable_to_MH the last node before reaching R2 on the optimal path between the GW and R2 (i.e., R3). As both nodes are different, the optimal_path parameter is set to 0, indicating the path will be suboptimal. Once this parameter contains the value 0, it remains 0 and only the Delay table must be consulted. The Route Update message is forwarded using the next hop from the Delay table.

R1 has an old entry for the MH. Therefore R1 is considered as the cross-over node (CN), and the Route Update message is not forwarded further. The CN sends a suboptimal handoff Acknowledgment (ACK) back to the nAR. The CN also deletes the reservation on the link from R1 to oAR and sends a Route Delete message to the oAR, to delete the invalid entry in its routing table.

The nAR is informed through a suboptimal handoff ACK that a suboptimal path was found during phase 1. As data packets can reach the MH via this suboptimal path, the nAR first sends a Mobile IP registration reply to the MH. Next, the nAR starts the route optimization phase.

5.1.3. Handoff phase 2—route optimization (Fig. 5(3))

The nAR sends a new Route Update message towards the GW, also in a hop-by-hop fashion, to establish an optimal path. During phase 2, the optimal_path parameter is set to value 2, indicating that the Route Update message must be forwarded towards the node retrieved in the RBWtable_to_MH (the Delay table is not consulted). Since R2 already has a new entry in its routing table, the entry is refreshed and the message is simply forwarded. The Route Update message finds a new CN, i.e., R3, which updates its routing table, allocates resources on the link from R3 to R2 and deletes the reservation on the link from R3 to R1. At that time, an optimal path is set up: an optimal handoff ACK is sent back to the nAR and a Route Delete message is sent to R1.

Fig. 5. Example of handoff phase 1 (ms), available

5.2. Mobile host

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Fig. 5. Example of bandwidth reservation for a mobile receiver. (1) the MH requests resources to receive its traffic flows. The MH performs handoff which consists of phase 1 (see 2) and phase 2 (see 3). The arrows indicate entries for the mobile receiver and point to the next hop towards the mobile host. A dashed arrow indicates an entry without resource reservations on the next link. $[x, y] = [\text{link delay (ms), available bandwidth (Mbps)}]$; $[z] = [\text{requested bandwidth (Mbps)}]$.

5.2. Mobile host is sender

At the time of handoff, only the second phase of Q-MEHROM is required as the mobile host always sends the data packets to its current access router.

This results in two successive situations, which are illustrated in Fig. 6. The setup of a best-effort path after handoff towards the mobile host is realized by basic MEHROM and is not considered in the section, as this is very similar to Section 5.1.

Fig. 6. Example of bandwidth reservation for a mobile sender. (1) the MH requests resources to send its traffic flows, (2) the MH performs handoff which consists of a single phase. The arrows indicate entries for the mobile sender and point to the next hop towards the domain gateway. $[x, y] = [\text{link delay (ms)}, \text{available bandwidth (Mbps)}]$; $[z] = [\text{requested bandwidth (Mbps)}]$.

5.2.1. Bandwidth reservations (Fig. 6(1))

When a MH powers up in the access network, standard IP routing is used to route the data packets on a (best-effort) path towards the domain gateway.

When a traffic flow from a MH is set up, this MH requests an amount of bandwidth (information obtained from the application layer) for that flow at its current access router. After a positive admission control, the access router starts the resource reservation mechanism, using its *BWtable_from_MH*. If the MH is the sender of multiple flows, the requested bandwidth is the sum of the individual amounts of bandwidth requested by the applications.

5.2.2. Handoff (Fig. 6(2))

After the receipt of a Mobile IP registration request, the nAR (again we assume a positive admis-

sion control) adds a new entry for the MH in its routing table and reserves the necessary resources on the link between the nAR and R2.

The optimal path parameter is set to value 2, indicating that the Route Update message must be forwarded towards the GW, in a hop-by-hop fashion. Therefore, the next hop retrieved in the *RBWtable_from_MH* (no Delay table is consulted) is used. Thus, the nAR forwards the Route Update message to R2, which updates its routing table, makes reservations on the link between R2 and R3 and forwards the Route Update message further to R3.

R3 has an old entry for the MH. Therefore R3 is considered as the CN, and the Route Update message is not forwarded further. The CN sends an optimal handoff ACK back to the nAR. Upon receipt of this ACK, the nAR sends a Mobile IP

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Table 6
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Table 5
Cross-over node detection by router R3 for a receiving mobile host in Fig. 5(3)

	Destination	Next hop	Reserved bandwidth (Mbps)
Before handoff	MH	R1	3
After handoff	MH	R2	3

Table 6
Cross-over node detection by router R3 for a sending mobile host in Fig. 6(2)

	Source	Next hop	Previous hop	Reserved bandwidth (Mbps)
Before handoff	MH	GW	R1	3
After handoff	MH	GW	R2	3

registration reply to the MH. The CN also sends a Route Delete message to R1, in order to delete the reservation on the link from R1 to R3. Finally this Route Delete message arrives in the oAR and the reservations on the link from oAR to R1 are released.

5.3. Mobile host is receiver and sender

When the mobile host is both sender and receiver, the Q-MEHROM handoff mechanisms for the path from the mobile host and for the path towards the mobile host can be performed independently from each other. The Q-MEHROM control messages must indicate to which handoff mechanism they belong. As a result, both paths do not necessarily contain the same nodes and the cross-over nodes can be different. Tables 5 and 6 illustrate how a router can detect whether it has the function of cross-over node during handoff. In the case of the path for data flowing towards the mobile host, this is based on a changing next hop in the router's routing table, illustrated in Table 5. When the path for data flowing from the mobile host towards the domain gateway is considered, a changing previous hop in the routing table indicates that the router is the cross-over node, as shown in Table 6.

6. Evaluation

The evaluation is done by examining the control traffic load and the handoff packet loss. Also the case of a highly loaded network is investigated.

In order to evaluate the performance of Q-MEHROM, the protocol is implemented in the network simulator ns-2 [24]. QOSPF is simulated with extensions for the calculation of the different QoS routing tables, added to the implementation of [25]. Unless otherwise mentioned, the following parameter values are chosen:

Wired and wireless links. The wired links of the access network have a delay of 2 ms and a capacity of 2.5 Mbps. This rather low value for the link capacity is chosen to investigate highly loaded networks with a limited number of mobile hosts. For the wireless link, IEEE 802.11 is used with a physical bitrate of 11 Mbps (ns-2 does not take scanning and authentication delays on the link layer (L2) into account).

Access routers and mobile hosts. Every access router broadcasts beacons at fixed time intervals T_b of 1.0 s. The distance between two adjacent access routers is 200 m, with a cell overlap d_o of 30 m. All access routers are placed on a straight line. Mobile hosts move at a speed v_{MH} of 20 m/s and travel from one access router to another, maximizing the overlap time of d_o/v_{MH} .

Traffic. CBR (constant bit rate) data traffic patterns are used, with a bitrate of 0.5 Mbps. For every mobile node (receiver or sender), one UDP connection is set up between a fixed host in the core network directly connected to the domain gateway and the mobile terminal itself.

Access network topology. Tree, mesh and random topologies are investigated. The topologies that are used for the simulations, are given in Fig. 7. Every

Fig. 7. Tree, mesh and random topology of the access network, used during the simulations. The mesh topology consists of the tree structure (full lines) with the indicated additional mesh links (dashed lines), while the random topology is formed by adding extra uplinks (dotted lines) to the mesh topology.

change in link available bandwidth triggers QOSPF LSAs, and the information in the QoS routing tables is calculated on demand.

6.1. Load of control traffic in the access network

For the different topologies of Fig. 7, the average amount of control traffic on a wired link in the access network is investigated. The results for an increasing number of mobile hosts are shown in Fig. 8, where in the left figure mobile receivers and in the right figure mobile senders are considered. Fig. 9 investigates the influence of the velocity of a single mobile host, where the figure on the left shows the results for a mobile receiver and the figure on the right the results for a mobile sender. During one simulation, the mobile hosts move randomly from one access router to another during 300 s, requesting 0.5 Mbps. Randomly means that a mo-

bile node moves towards a randomly chosen access router. When arriving at its destination, the mobile host moves towards another (again randomly) chosen access router. Using this movement pattern, a mobile host never stops and stays in a single cell.

There are two contributors to the control load: Q-MEHROM and QOSPF. Both are shown in the figures. The Q-MEHROM control load is formed by the Route Update, Route Delete, Acknowledgment and Power Up messages. The QOSPF control traffic, formed by Link State Advertisements and Acknowledgements, consists of two parts. The first part is formed by the QOSPF messages at the start of the simulation, advertising the initial link state information through the network. The second part is the QOSPF traffic caused by resource reservations and resource releases as these change the amount of available bandwidth on the involved links.

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Fig. 8. Average control load on a wired link of the access network as a function of the number of mobile receivers (left figure) or senders (right figure).

Fig. 9. Average control load on a wired link of the access network as a function of the speed of a single mobile receiver (left figure) or sender (right figure).

20
15
10
5
Average number of lost packets

Fig. 10. Average number of lost packets as a function of the speed of a single mobile receiver (left figure) or sender (right figure).

The load of Q-MEHROM messages is very low compared to the load of QOSPF traffic. The QOSPF traffic in the absence of mobile hosts contains only the first part, with messages to advertise the initial link state information. This part depends purely on the topology and the number of links. The second part of the QOSPF load, with messages triggered by resource reservations and releases, is also determined by the number of handoffs and their location in the topology.

The required amount of bandwidth for QOSPF and Q-MEHROM control traffic increases for higher handoff rates, i.e., the number of handoffs in the network per time unit. This handoff rate increases for higher number of mobile hosts, illustrated in Fig. 8 and for higher speeds as shown in Fig. 9.

The load caused by Q-MEHROM messages is a little higher for mobile senders compared to the situation with mobile receivers. Although a mobile sender only requests reservations along a path towards the domain gateway, the micromobility protocol must also set up a best-effort path from the domain gateway towards the current access router. In contrast, no best-effort path to the domain gateway is set up for a mobile receiver, as standard IP routing can be used.

Also the QOSPF load is higher for mobile senders, but for a different reason. When a mobile receiver performs handoff, the cross-over node makes reservations on the new link, releases the reservations on the old link and triggers a single link state update. For a mobile sender, the node that is indicated as the previous hop before handoff in the routing table of the cross-over node releases the resources and triggers a link state update. In addition, the new previous hop makes resource reservations and again triggers a link state update.

Note that we have investigated the worst case, where every change in available bandwidth triggers QOSPF LSAs. Periodically triggering of LSAs or triggering only after a significant change in available bandwidth can reduce the control load, at the cost of the accuracy of link state information. Even in the considered worst case, the required amount of bandwidth for control traffic remains low compared to the link capacities ($\pm 0.053\%$ for 8 mobile receivers with a speed of 20 m/s and $\pm 0.075\%$ for 8 mobile senders with a speed of 20 m/s). Therefore, we reserved 1% of the given link capacity for the control traffic class of CBQ. This is sufficient to support more than 100 mobile hosts with a speed of 20 m/s.

6.2. Handoff performance

To investigate the handoff performance, the following scenario is considered: during 1 simulation, a single mobile host moves from the leftmost to the rightmost access router of Fig. 7, performing 7 handoffs. The results in Figs. 10 and 11 are average values of a set of 200 independent simulations, i.e., there is no correlation between the sending of beacons by the access routers, the movements of the mobile host and the sending of the data packets.

Fig. 10 shows the loss of data packets as a function of the speed of the mobile host. The data flow has a packet size of 500 bytes and a rate of 1 Mbps. Results are given for beacons sent at time intervals $T_b = 1.0$ s, 0.75 s and 0.50 s. The packet loss is independent of the velocity, as long as the mobile host resides long enough in the overlap region to receive at least one beacon from a new access router while it is still connected to its previous access router. Otherwise, packet loss increases rapidly. In the

Fig. 10. Average packet loss as a function of the mobile receiver's (left figure) or sender's (right figure) speed, for several beacon time intervals.

Fig. 11. Average packet loss as a function of the data rate sent to (left figure) or from (right figure) the mobile host, for several packet sizes.

considered situation, where the mobile host moves on a straight line through the center of the overlap regions, this requirement is fulfilled when

$$v_{MH} \leq d_o / T_b. \quad (1)$$

When we compare the results for a mobile receiver (left figure of Fig. 10) with the results for a mobile sender (right figure of Fig. 10), some important differences can be noticed. As long as the mobile sender resides long enough in the overlap region, the packet loss is much lower (almost zero) compared to the case of the mobile receiver. As soon as the mobile sender receives a beacon from a new access router, it sends its new data packets towards this new access router, while the mobile receiver must wait until a new path towards the new access router is set up and new data packets are routed towards this new access router. If requirement (1) is not fulfilled, the packet loss for a mobile sender is much higher. When the mobile sender moves out of the area of the old access router, all data packets, generated before the receipt of a new beacon, are routed towards the old access router and wait in the buffer of the mobile host to be sent. Even if the mobile sender receives a beacon from a new access router, it still tries to send those data packets to the old access router. This results in an extra delay before the first data packet is sent to the new access router. This extra delay leads to higher packet loss due to buffer overflow in the mobile sender. For the mobile receiver, the packet loss only increases because the time to set up a new path in the access network is longer when requirement (1) is not fulfilled. In the latter case of the mobile receiver, Q-MEHROM takes advantage of mesh links and extra uplinks to reduce the packet loss compared to the tree topology. For the mobile sender, the results

are almost the same for the three considered topologies.

Fig. 11 gives the results for the data packet loss as a function of the data rate. The mobile host moves at a speed of 20 m/s and the access routers send beacons at time intervals of 1.0 s. The packet sizes used are 500 bytes, 1000 bytes and 1500 bytes. The use of IEEE 802.11 and collisions on the wireless link limit the achievable throughput. For the simulations in this subsection, the RTS/CTS scheme was used. For a wireless bitrate of 11 Mbps and a data packet size of x bytes, the TMT (Theoretical Maximum Throughput) is given by [26]

$$TMT(x) = \frac{8x}{ax + b} \cdot 10^6 \text{ bps with} \quad (2)$$

$$\times \begin{cases} a = 0.72727, & b = 890.73 & \text{for CSMA/CA,} \\ a = 0.72727, & b = 1566.73 & \text{for RTS/CTS.} \end{cases}$$

This explains the rapid increase of packet loss for a packet size of 500 bytes and data rates higher than 1.85 Mbps ($TMT = 2.072$ Mbps). In the case of a mobile receiver (left figure of Fig. 11), while after handoff the attempts of the old access router to send a data packet to the mobile host are useless, the next beacon of this access router can be delayed. This delay is higher for increasing data rates and can result in a ping-pong handoff and thus higher packet loss. In the case of the mobile sender (right figure of Fig. 11), handoffs in combination with high data rates can result in a buffer overflow in the mobile host. Furthermore, the mobile sender can fail to successfully receive a beacon from the new access router because it was sending a data packet to the old access router at the same time.

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In the case of a mobile receiver, for a given packet size, the packet loss increases for higher data rates. Furthermore, it is higher for the tree topology compared to the other topologies. The reason is that for a mobile receiver, the handoff packet loss depends on the time needed to set up a new path. For the mobile sender, the packet loss is much less influenced by the data rate and is not influenced by the access topology.

6.3. Highly loaded access networks

In order to investigate how well Q-MEHROM can handle mismatch in traffic load and network capacity, we consider the following scenario: at the start of the simulation, the network is symmetrically loaded by a single mobile host in each of the eight cells of Fig. 7. During the simulation, these mobile hosts move randomly from one access router to another during 300 s with a velocity of 20 m/s. Each

mobile host is the receiver or sender of a CBR data flow with a packet size of 1500 bytes and a bitrate of 0.5 Mbps. These values correspond to a situation where the wireless channel is not the bottleneck for the received or sent bandwidth (TMT = 6.056 Mbps for the CSMA/CA scheme and TMT = 4.515 Mbps for the RTS/CTS scheme), even if all mobile hosts move into the same cell. For each of 8 mobile hosts, the average received or sent bandwidth, calculated as a sliding average with a window of 3 s, as a function of the simulation time is given in Figs. 12 and 13 for the tree topology and in Figs. 14 and 15 for the random topology. For the presented results, the CSMA/CA scheme was used.

For the tree topology, see Figs. 12 and 13, only one possible path between the domain gateway and a specific access router exists. So both in the best-effort case where basic MEHROM and standard IP routing are used (left figures) as in the case of resource reservations by the use of Q-MEHROM

Fig. 12. Received bandwidth by the mobile hosts in highly loaded networks for the tree topology.

Fig. 13. Sent bandwidth by the mobile hosts in highly loaded networks for the tree topology.

Fig. 14. Received bandwidth by the mobile hosts in highly loaded networks for the random topology.

Fig. 15. Sent bandwidth by the mobile hosts in highly loaded networks for the random topology.

(right figures), the data packets of the data flows of mobile hosts residing in the same cell are routed via the same path. The capacity of the links closest to the domain gateway limits the amount of bandwidth that can be allocated for mobile hosts residing in the underlying cells. As a small part of the total link bandwidth of 2.5 Mbps is reserved for control traffic, only four reservations of 0.5 Mbps can be made on a single link. For the best-effort situation, the available bandwidth is shared between all mobile hosts using the same link. When Q-MEHROM is used, the mobile hosts that made a reservation, receive their requested bandwidth irrespective of newly arriving mobile hosts. As a result, more mobile hosts receive 0.5 Mbps compared to best-effort.

For the random topology, the difference between the best-effort situation and the use of Q-MEHROM is much more significant, as illustrated in Figs. 14 and 15. Due to the presence of extra uplinks, more than one path with minimum hop count

may be found between the domain gateway and a specific access router. In the case of best-effort, one of these possible paths is chosen without taking into account the available bandwidth. Only for the mobile hosts in cell 15 of Fig. 7, does ns-2 use the path via the right link closest to the domain gateway. All the other mobile hosts share the bandwidth of the left link closest to the domain gateway. In contrast, Q-MEHROM chooses a path with enough resources, if available. Due to the mesh links and extra uplinks, the capacity of the links closest to the domain gateway no longer forms a bottleneck. The right figures of Figs. 14 and 15 clearly show how the proposed Q-MEHROM handoff scheme efficiently makes use of the extra links to support asymmetric network loads to spread the data load over the network.

The results for mobile senders are very similar compared to the results for mobile receivers. However, when several mobile hosts are sending to the

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same access router, many more collisions on the wireless link occur than when an access router has data packets for several mobile receivers. This explains the higher amount of smaller bandwidth variations in the case of mobile senders compared to the case of mobile receivers.

7. Conclusions

In this paper we presented Q-MEHROM, which is the close coupling between the micromobility protocol MEHROM and a resource reservation mechanism. While a micromobility protocol updates the routing tables to support data traffic towards a mobile host, Q-MEHROM supports resource reservations for both mobile receivers and senders. In addition, Q-MEHROM makes no assumptions about the access network topology. A router can detect itself that it has the function of cross-over node and whether the new path is optimal. Q-MEHROM uses topology and link state information, which is gathered and calculated by QOSPF and provided to Q-MEHROM in the form of QoS tables.

At the time of handoff, the Q-MEHROM handoff scheme is initiated by the mobile host, sender or receiver (or both). The updating of the routing information and the resource reservations for the data flows of the mobile host are performed at the same time. In addition, invalid routing information and reservations along the old path are explicitly deleted. Resource reservations along the part of the old path that overlaps with the new path are reused.

Simulation results showed that the amount of control overhead caused by Q-MEHROM and QOSPF is mainly QOSPF traffic. The control load increases for higher handoff rates in the network, which is influenced by the number of mobile hosts and their velocity. For the studied topologies and scenarios, this load remains very low compared to the link capacities. The first phase of Q-MEHROM efficiently uses the extra links, which are present in the topology to increase the robustness against link failures, to reduce the handoff packet loss compared to a pure tree topology. This handoff packet loss is independent of the speed of the mobile hosts and increases with the data rate. For high network loads, the use of Q-MEHROM allows mobile hosts to make reservations and protect their received bandwidth against newly arriving mobile hosts. Furthermore, Q-MEHROM takes the available bandwidth into account while choosing a path and is able to

use mesh links and extra uplinks to improve the balancing of data load in the access network.

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