RELIABLE RSVP PATH RESERVATION FOR MULTIMEDIA COMMUNICATIONS UNDER AN IP MICROMOBILITY SCENARIO

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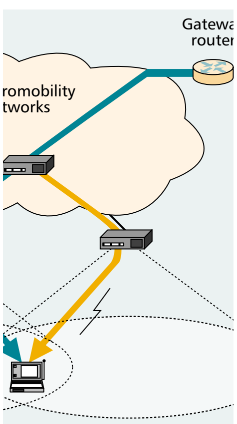

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ABSTRACT

In this article we focus on how quality of service) guarantees can be provided for RSVP flows during handoff events in an IP micromobility network. For this purpose, RSVP message delays and signaling overheads should be minimized, and handoff service disruption should also be minimized. By rerouting the RSVP branch path at a crossover router at every handoff event, and establishing the new RSVP path between the CR and new BS in advance while the existing reservation path is maintained, ongoing RSVP flows can be kept with the guaranteed QoS. In this article we propose the seamless switching of an RSVP branch path for soft handoff, and also show that this scheme could provide QoS guarantee with simulation and examples.

INTRODUCTION

Typically a handoff event can cause packet losses when the processing of a flow request via a new base station (BS) is delayed. In this situation, some packets might be discarded, and thereby overall quality of the ongoing flow might be degraded significantly. In the worst case, a delay in handoff may cause the connection to be dropped. Hence, handoff quality of service (QoS) signaling should be carried out very quickly. If the time required to restore the flow of traffic, after a mobile node (MN) receives the beacon that triggers a handoff, is very short, it might be possible to provide QoS guarantees to some real-time applications to aid in proper retransmission buffer size and well-measured beacon period. Under Resource Reservation Protocol (RSVP) [1], however, it may not possible to get short enough total handoff time to provide QoS guarantee due to reservation delay and signaling overhead during RSVP branch path reestablishment at every handoff. For example, when the amount of link bandwidth to be reserved for a real-time application is rather large, even short handoff time for RSVP message processing can cause a significant amount of packet loss. Thus, ongoing RSVP flow may be disrupted until the new reservation is installed along the path via a new BS after handoff. Using retransmission buffers in BSs and MNs to recover from packet losses incurred during the transition between cells would violate the semantics of guaranteed QoS for interactive services such as Internet telephony and teleconferencing, since it would introduce additional delay.

In this article we first investigate how RSVP is applied in an IP micromobility network. We then carefully develop the mechanisms to determine the location of crossover router in tree topology and reserve an RSVP branch path in advance. We also propose a seamless switching scheme for the RSVP branch path for soft handoff. We finally show that this scheme can provide QoS guarantee through simulation and examples.

IP MICROMOBILITY PROTOCOL

Mobile IP was optimized for macromobility and relatively slow-moving MNs. Due to frequent notification to the MN's home agent (HA), it gives service disruption during handoff and high signaling overhead. However, micromobility protocols aim to handle local movement of MNs without interaction with the Mobile IP enabled Internet. In other words, micromobility has the ability for an MN to move without notifying its HA. This has the benefit of reducing delay and packet loss during handoff, and eliminating registration between MNs and possibly distant HAs when MNs remain inside their micromobility regions. Eliminating registration to HAs reduces the signaling load experienced by the core network in support of mobility.

Micromobility networks with hierarchical topology such as Cellular IP [2] or HAWAII [3] are normally organized as a tree, and a single gateway node (GW) becomes the root of this tree. These protocols reduce the performance impact of mobility by hiding local migrations from HAs. That is, an MN's care-of address known by a HA represents the address of a GW that is common to potentially large numbers of network access points [2, 3]. Therefore, a correspondent node (CN) regards the GW's address

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as an MN's care-of address. In order to ensure that packets arriving at the GW are forwarded to the appropriate access point and thus delivered to the MN's actual point of attachment, the nodes within a micromobility network maintain a routing database that maps host identifiers (e.g., IP addresses) to location information (e.g., interface numbers). Each entry in a routing database contains a pointer to the next node toward the MN's actual point of attachment. Thus, for forwarding a downlink packet, intermediate nodes must read the original destination address, find the corresponding entry, and forward the packet to the next node.

In Cellular IP [2], an MN sets up a routing path by sending a route update message toward the GW. The route update message is then received by the BS (in this article, we use access router, AR, and BS interchangeably) and forwarded hop by hop toward the GW. Whenever a route update message passes an intermediate routing node, a routing entry, which is a mapping of an MN's IP address to the interface from which the packet arrived at the node, is updated in the routing cache. In HAWAII [3], each node also maintains a routing cache to manage mobility, and special packets are transmitted hop by hop on the network to update the caches.

RSVP UNDER IP MICROMOBILITY

In RSVP path setup, a sender in the Internet will typically send an RSVP PATH message to the GW because it regards the GW's address as an MN's care-of address in a micromobility access network. The GW will then forward a PATH message to an MN, and send an RESV message back to the sender node after the MN replies with it. Since RSVP generally uses an MN's destination address to identify a session, the resource reservation should be newly made along the entire path from the sender node to an MN on every MN's handoff. Under IP micromobility, however, the GW will hide the mobility of the end node, and therefore there will be no RSVP signaling messages between the sender node in the Internet and the GW in the micromobility access network. That is, an RSVP resource reservation path needs to be repaired locally between the GW and an MN whenever an MN changes its access point within a domain.

An IP micromobility network with hierarchical topology is normally organized in a tree with a single GW as a root [2, 3]. Whenever a large number of mobile users with RSVP sessions move frequently between small cells in a micromobility access network, RSVP path setup should be performed very frequently. This situation causes longer reservation restoration delay and more control traffic overhead. HAWAII [3] includes interactions with RSVP in the domain root router (e.g., GW) while an MN remains within a domain. That is, the RSVP path between the GW and an MN is newly restored whenever an MN changes its access point within a domain. However, this may cause unnecessary control traffic overhead and rather long reservation delay. HMRSVP [4] integrates RSVP with Mobile IP regional registration and makes advance resource reservations only when interregion movement may happen. The Pointer Forwarding scheme makes advance resource reservations only on a forward one-step path from an MN along the forwarding pointer chains. This scheme can thus reduce the length of links to reserve newly at each handoff, but may cause an excessively long RSVP path due to triangle or loop routing during several handoffs. Hence, the RSVP resource reservation process needs to be managed efficiently in the branch part of the tree, instead of traveling the rather long path between the GW and an MN. That is, RSVP signaling messages need to be exchanged between the closest network node common to the former RSVP path and an MN.

During the lifetime of an RSVP connection under an IP micromobility network, several links are utilized to support ongoing real-time flows. When more multiple hops for a connection are utilized, the probability of network congestion and resource reservation failure will also be higher [5]. In particular, for flows with excessive capacity demands such as streaming audio and video, fewer hops can improve the overall link utilizations. Hence, shorter hops and circuit reuse should be taken into account during RSVP path rerouting due to handoff: not only should the shortest RSVP reservation path be discovered, but also the remaining RSVP circuits should be reused because only the branch part of the entire path is changed. When an MN performs a handoff, the overall RSVP path setup time mainly depends on the number of hops required to reroute the RSVP partial branch path, which is crossover router (CR)-dependent. Hence, this necessitates that the mechanism discovers a CR. On the other hand, even though path rerouting typically has the potential to create an optimal path, the time taken to determine the location of a CR and reroute the RSVP branch path may exceed the delay bounds for QoS provisioning. However, due to the characteristics of tree topology, the time taken to discover a CR is very short compared to the time taken to process route update messages on the intermediate nodes in a micromobility network.

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CROSSOVER ROUTER DISCOVERY SCHEME

Typically, an RSVP-enabled router sends its RSVP daemon a path change notification (PCN) message using the Routing Support for Resource Reservations (RSRR) interface, which is a specification for communication between RSVP and routing daemons [6]. RSVP resource reservation is accomplished by using this routing interface that allows RSVP to access forwarding database entries whenever entries change in an IP micromobility network. The RSVP daemon on the router should be able to identify the flows from information on the RSVP states (*Reservation State* and *Path State*); hence, RSVP needs to include a flow label in a PATH message of an IP/UDP packet [7]. Basically, an RSVP flow can be defined by combination of the session (*destination address*, *IP protocol Id*, *destination port*) and filter (*source address*, *source port*) in IPv4 or the combination of the *source address* and *flow Id* in IPv6. The IPv6 flow label allows routing to be based on the flow label as well as source and destination addresses. Under IP micromobility, however, the RSVP state information needs to be modified because the forwarding mechanism is dependent not on normal IP routing but on the particular micromobility protocol. Figure 1 shows a diagram of an RSVP-enabled router in an IP micromobility network.

The crossover switch discovery algorithms for path rerouting in wireless asynchronous transfer mode (ATM) LANs [5] have also been evaluated on different network topologies. The work in [5] concludes that the network topology can affect the performance of the crossover node discovery algorithm. There has been much research on RSVP supporting Mobile IP, which is well summarized in [8], in which the CR finding scheme proposed by Q. Shen *et al.* in Mobile IP-enabled Internet with mesh topology is explained. This scheme depends only on the RSVP message itself to find the location of the CR. However, for efficient path rerouting, we here develop a discovery scheme of the CR that depends on the tree topology and the interaction between micromobility protocol and RSVP daemon through an RSRR interface. When an MN performs a handoff and sends a route update message toward the GW, the intermediate nodes along the new path toward the GW are notified of the change in forwarding entries. One of the intermediate nodes on the new path then realizes that it becomes a CR by seeing the same IP address (of the source or destination) in the new forwarding entry with an interface number different from that stored in the old forwarding entry. The CR then sends its RSVP daemon a PCN message in order for RSVP to recognize the existence of the CR. In an IP micromobility network, when an MN moves into a new cell, the rerouting of an RSVP branch path at the CR can guarantee minimal path change and the shortest path from the GW to the MN: in the worst case, the CR is the GW itself.

Soft Handoff

There are three types of handoffs in cellular systems: intrafrequency handoff, interfrequency handoff, and intersystem handoff. Intrafrequency handoff is a movement event between BSs using the same carrier frequency like soft handoff in code-division multiple access (CDMA) systems. Interfrequency handoff is a movement event between BSs using different carrier frequencies like hard handoff in time-division multiple access (TDMA) and frequency-division multiple access (FDMA) systems. Intersystem handoff is a movement event between BSs employing different air interfaces like vertical handoff or interface switching; for example, handoff between Global System for Mobile Communications (GSM)and wideband CDMA (W-CDMA) systems or between IS-95 and AMPS systems.

Basically, soft handoff can be considered not only for CDMA systems but also for TDMA/FDMA systems. However, it is not easy to implement soft handoff in TDMA/FDMA due to problems such as synchronization of time slots and multiple receptions, and transmissions at different frequencies [9]. TDMA/FDMA systems typically execute hard handoff, which restricts their utilization of macrodiversity by implementing hysteresis. The major advantage of soft handoff is macroscopic diversity, where a mobile station can be in contact with more than one base station at a time. That is, soft handoff allows a mobile station to communicate with multiple BSs. The soft handoff mechanisms in the main CDMA proposals such as W-CDMA and CDMA2000 for third-generation (3G) services are very similar to those supported in IS-95, even though a substantial change is required for CDMA2000 1x EV-DV (data/voice) and W-CDMA High Speed Downlink Packet Access (HSDPA) because they do not employ symmetric soft handoff [10, 11]. In IS-95-based soft handoff, the frequency signal strength measurement is based on the pilot E_c/I_0, which is the ratio of the pilot chip energy E_c to the total received in-band power I_0. Mobile-assisted handoff (MAHO) [9] can also be considered, where the mobile station takes the signal strength measurements and the BS makes decisions.

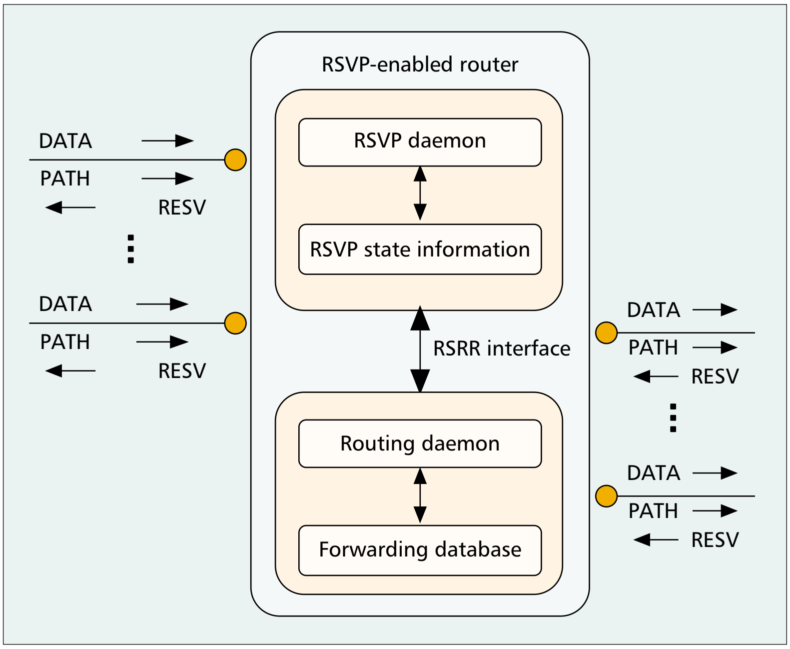
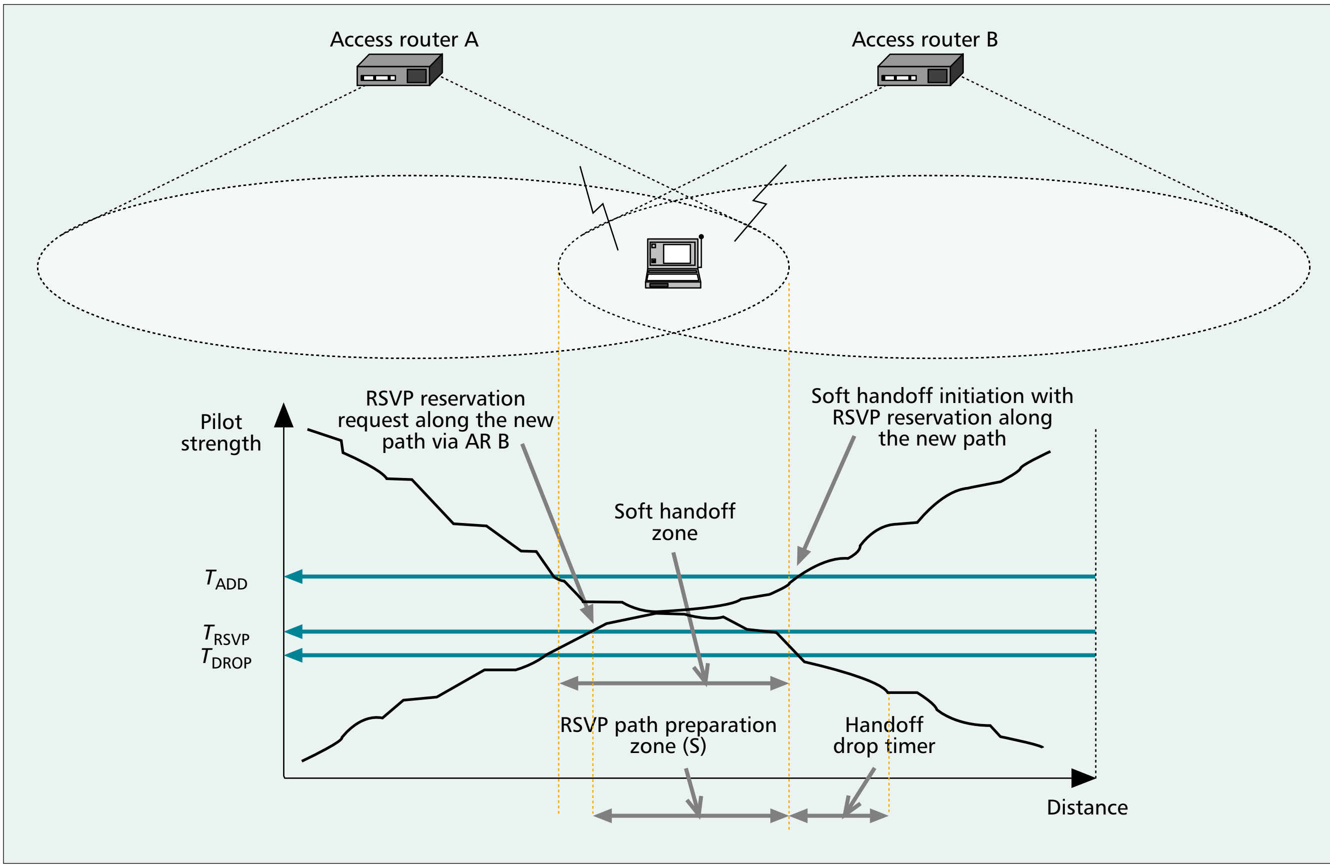


Figure 1. *An RSVP-enabled router in an IP micromobility network.*

The concept of CDMA soft handoff entails the use of pilot sets, which are grouped according to their functionality in the handoff process. The different pilot sets, which can be modified or added according to IS-95-based systems, are basically *Active Set*, *Candidate Set*, and *Neighbor Set* [10]. These pilot sets are updated by the network through a Handoff Direction Message (HDM) sent by the BS to the mobile station. The mobile station confirms successful reception of the HDM through the Handoff Completion Message (HCM). The mobile station reports pilot E_c/I_0 values through the Pilot Strength Measurement Message (PSMM) so that the base station may update the pilot sets for the mobile station [10]. In other words, a mobile station must make a conditional decision that depends on the changes in signal



■ Figure 2. *RSVP path reservation by a threshold of pilot strength.*

strength from the two or more BSs involved. Actual handoff is performed after making sure that the signal from one BS is considerably stronger than those from the others. Thus, an MN eventually communicates with only one BS. In the interim period, a mobile station communicates with all the BSs in the *Active Set* at the same time. Thus, soft handoff can guarantee that a mobile station is indeed linked at all times to the BS from which it receives the strongest signal, whereas hard handoff cannot guarantee this.

Advance Reservation of an RSVP Branch Path

In the hard handoff event, the QoS of an RSVP flow may be typically disrupted until the new reservation is installed along all the intermediate nodes on the fresh path toward the CR via a new AR. Moreover, the old reservation cannot be explicitly removed, and thus the utilization of network resources will decrease. However, soft handoff can provide reliable RSVP reservations; from the changes in pilot signal strength, the receiver can select one candidate (for handoff) of all the possible ARs involved. Thus, new RSVP reservations along the new path via the candidate AR can be established while the existing reservation path is maintained.

Figure 2 illustrates typical pilot strength variation as an MN moves from one BS area to another in the proposed scheme. We assume that an MN moves from a BS coverage area to an adjacent BS area. If an MN finds a neighboring BS with a pilot signal higher than a predetermined threshold (T_{ADD}), a new link to the BS is established while the existing link is maintained. If the pilot signal from either the old BS or the new BS drops below a predetermined threshold T_{DROP}, the corresponding link is released. In [12], the authors proposed a mechanism for resource reservation on a wireless link by a predetermined threshold in a BS coverage area. However, we here extend this reservation mechanism to all the links within an IP micromobility network to aid RSVP and the CR discovery scheme. Thus, we define a new parameter, T_{RSVP}, which is a threshold of RSVP reservation requests. This value is less than T_{ADD}. If an MN finds any neighboring BS with pilot strength exceeding T_{RSVP}, it sends a RSVP reservation request message to the RSVP daemon on the associated BS. Afterwards, if the pilot strength drops and stays below T_{RSVP} during a predetermined period, an MN asks the RSVP daemon on the associated BS to release the RSVP branch path. On the other hand, if the pilot strength reaches T_{ADD}, an MN with an RSVP session switches from the old branch path to the newly reserved branch path by initiating soft handoff and keeps the flow with the guaranteed QoS. In Fig. 2, the threshold T_{RSVP} is not an absolute value but rather a relative value to T_{ADD}. When T_{ADD} is dynamically determined according to the current wireless link status and network load condition, T_{RSVP} can also be adaptively modified.

Seamless Switching of an RSVP Branch Path for Soft Handoff

When intermediate RSVP-capable routers intercept PATH messages sent by an MN, they update their path state entries for it. If no *path state* exists, the RSVP-capable routers create it. Typically, *path state* includes the TSPEC (which defines the QoS parameters of the sender's data traffic stream), the PHOP (which is the address of the previous hop router), and optionally an ADSPEC (which is used to gather end-to-end characteristics of the path) [1]. The PHOP address needs to be stored in path state entries in order to route RESV messages in the reverse direction. We now describe an RSVP branch-path rerouting at CR during handoff. In this scheme, only the RSVP reservation path between the CR and an MN is reestablished. If an MN is a sender, an RSVP PATH message is sent by an MN after the route update is completed (or it can be implicitly sent as a route update message in order to reduce the RSVP PATH signaling overhead). When the RSVP daemon on the CR, which is determined by the route update message, receives an RSVP PATH message after a mobility event, it immediately sends an RSVP RESV message to an MN without delivering to the original receiver.

If an MN is a receiver, the RSVP daemon on the CR can trigger an RSVP PATH message immediately when detecting any changes to the stored PATH state or receiving a PCN message from the underlying routing daemon. This PATH message can be generated based on the *path state* stored for the flow during previous RSVP message exchanges. That is, after making sure that the ADSPEC and PHOP objects for each outgoing interface are updated accordingly, the RSVP daemon on the CR then sends a PATH message along the forwarding path established freshly by a route update message from an MN. When the MN receives this PATH message, it generates an RSVP RESV message after some receiver processing delay on the RSVP daemon.

We now propose seamless switching of an RSVP branch path for soft handoff. In Fig. 3, when an MN is a sender, it sends an RSVP PATH message (or the route update message including a PATH message) via the new AR before an MN performs actual handoff. In order to minimize RSVP resource reservation delay, the new path reservation must be made between a CR and a new AR. Thus, an RSVP branch path can be successfully established after an MN receives an RESV message sent by the intended receiver (CR). When an MN is a receiver, it responds with an RSVP RESV after receiving a PATH message (via the new AR) sent by the CR. During this resource reservation phase, the packets are still delivered through the path reserved via the old AR (or BS). After starting to receive the packets through the path reserved freshly via the new AR, an MN can explicitly remove the reservation along the old path, and finally tunes its radio to the new AR. During this RSVP branch path rerouting period, the amount of bandwidth consumed through both the old and new reservation paths becomes double. However, this period becomes very short because the old path is released soon.

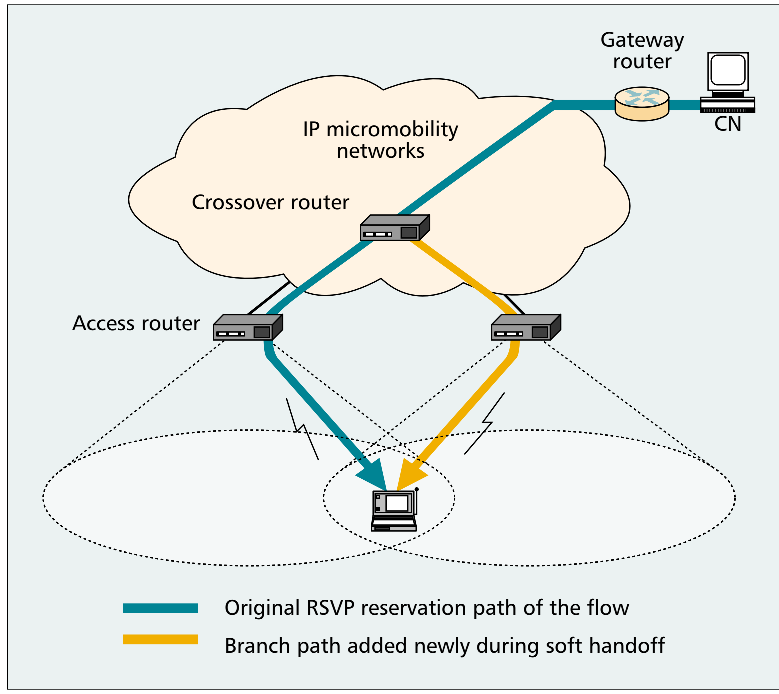


Figure 3. *Switching of an RSVP branch path using soft handoff.*

Performance Measures

In our simulation, a handoff is required if the signal level received from the current BS drops below that of the neighboring BS. We assume that the threshold values of T_{ADD}, T_{DROP}, and T_{RSVP} are given within the range of –31.5 to 0 dB. Furthermore, we assume that an MN's velocity V is a constant and the power strength of each BS is identical. Thus, the distance an MN moves within a cell boundary area becomes proportional to the difference between two pilot signal strengths. Hence, from the formula given in [9], the RSVP path preparation zone denoted by S in Fig. 2 is equal to

$$\left(10^{\frac{K_{1-T_{RSVP}}}{K_2}} - 10^{\frac{K_{1-T_{ADD}}}{K_2}} \right)$$

where K_1 depends on the transmitted power in the BS, and K_2 is typically a constant due to path loss. As the MN moves to the neighboring BS, the time it takes for a pilot signal to be changed from T_{RSVP} to T_{ADD}, ΔT, can thus be calculated by S/V. ΔT can actually be adjusted dynamically by changing T_{RSVP}, but a too low T_{RSVP} value can cause excessive unnecessary RSVP reservations.

On the other hand, a significant portion of the overall handoff time under RSVP depends on the partial path connection setup time. RSVP connection setup latency is a function of the signaling protocol overhead, the number of hops, the signal propagation delay, and the number of connection requests. Since it is undesirable to limit the number of connection requests made by

Type of load	ΔP	ΔR	ΔPR
Low load	2.00 (0.20)	3.07 (0.30)	1.72 (0.17)
Medium load	3.90 (0.40)	5.41 (0.54)	2.14 (0.20)
High load	5.44 (0.54)	6.40 (0.64)	2.98 (0.30)

Table 1. *Average control packet latency (in ms) under three types of loads in the network.*

real-time applications, the signaling protocol overhead and the number of hops required to set up the partial path during handoff become the target for reducing the connection setup time [5]. Now we need to define the terminology for the signaling protocol overhead and the number of hops. The RSVP packet processing delays, which are ΔP and ΔR for PATH and RESV messages, respectively, on a router are defined as the difference between the timestamps at which the packet appears on the input and output links [7]. The setup time for RSVP branch path rerouting, $\Delta RSVP$, is defined as the delay between the time when the first PATH message appears on the MN's (or CR's) interface and the time when the first RESV message is detected on the same interface. The receiver processing delay, ΔPR, during this setup is the latency between the time the first PATH message is seen on the CR's (or MN's) interface and the time at which the first RESV message is seen on the same interface.

These delays depend on the load of routers and the number of existing RSVP connections; we can assume that they go by normal distributions with the parameters in Table 1, obtained from the results in [7]. It shows the mean latency of RSVP control packets in the three types of loads when a certain number of real-time sessions already exist. The numbers in parentheses show the standard deviations. The setup time, $\Delta RSVP$, is thus given as $L \times \Delta P + L \times \Delta R + \Delta PR$ where L is the number of links (routers) between the CR and an MN. Total handoff delay ΔT_RSVP of a flow with RSVP resource reservation is the time it takes for an MN to receive (or send) the first packet through the new RSVP reservation path when performing an actual handoff. Therefore, the time difference between ΔT and ΔT_RSVP becomes an important parameter for measuring the QoS of a flow with RSVP reservation. When an MN moves into a new AR area under RSVP, the packets transmitted on the RSVP path reserved freshly via the new AR may be lost if ΔT_RSVP is greater than ΔT. Hence, the total handoff signaling process via the new AR should be completed during the period ΔT.

When an MN is a sender, ΔT_RSVP is $\Delta RSVP$ if a PATH message is sent inserted in a route update message in order to reduce the signaling overhead. When an MN is a receiver, it has to wait for DU to send the route update packet to the CR, and then also wait for $\Delta RSVP$ for RSVP branch path rerouting. In order to keep the flow with the same QoS after a handoff, it has to wait for the additional propagation delay ΔG from the CR to an MN. That is, an MN has to perform an actual soft handoff after receiving the first packet through the new RSVP branch path. However, the propagation delay ΔG can be ignored under a micromobility network. Thus, for a mobile receiver, the total handoff delay ΔT_RSVP is $\Delta U + \Delta RSVP$. Hence, the total number of lost packets of a flow with RSVP resource reservation at soft handoff is B ($\Delta T\_RSVP - \Delta T$) where B is the amount of link bandwidth reserved for the flow. Consequently, if the value of $\Delta T\_RSVP - \Delta T \leq 0$, service disruption does not occur. This means that this scheme can provide the QoS guarantee by dynamically adjusting ΔT through threshold T_{RSVP}.

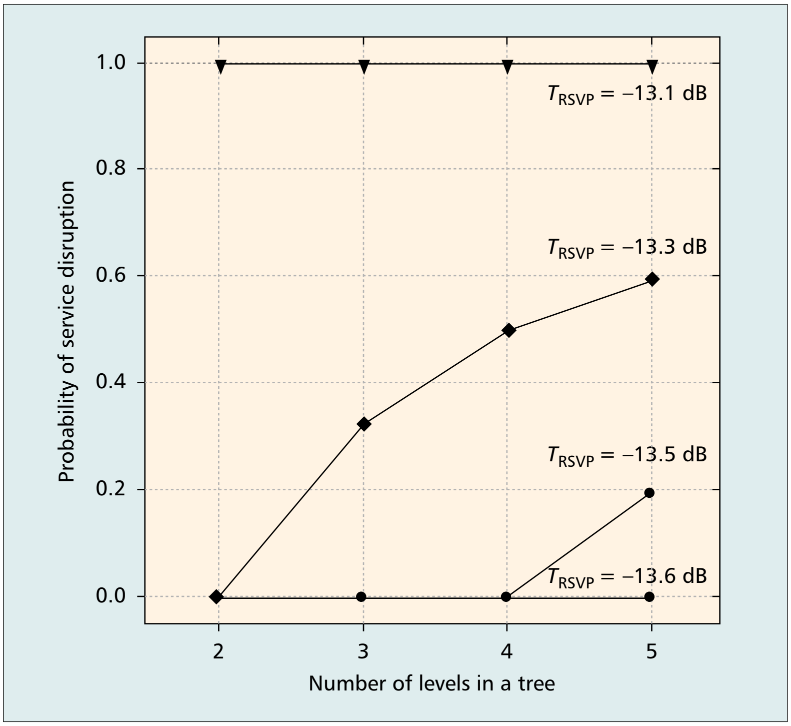


Figure 4. *Probability of service disruption with various* T_{RSVP} *under* $V = 9.0$ *m/s and high load.*

Examples and Discussions

In an example of simulation, we consider an IP micromobility network where the network has a tree hierarchy structure. For simplicity of the simulation, we also assume a full binary tree with a GW as a root. The depth k of a full binary tree with N nodes is $\lfloor \log_2 N \rfloor + 1$. Hence, a full binary tree of depth k has 2^{k-1} nodes, $k \geq 1$, and the number of nodes (BSs) at level k is 2^{k-1}. We take the mean latencies of RSVP control packets from Table 1. We also fixed the threshold value, T_{ADD}, as –13.0 dB, and constants K_1 and K_2 in received signal level as 35.3 and 40.9, respectively.

Figure 4 shows the probability of service disruption with various threshold values of T_{RSVP}. RSVP control packet latency values are taken when the load of routers is high. Here, an MN's velocity V is 9.0 m/s. In this figure, service disruption always occurs with T_{RSVP} = –13.1 dB, but there is no service disruption after T_{RSVP} = –13.6 dB. That is, as the pilot signal difference between T_{ADD} and T_{RSVP} gets bigger, the time an MN spends in the RSVP path preparation zone in the cell boundary area becomes longer. On the other hand, the mean number of links required to set up a branch path at every handoff depends on the number of levels in a tree. Hence, the smaller the number of levels in a tree, the shorter the RSVP branch path setup time. In this figure the reasonable number of levels in a tree is within 5. Also, a well-defined T_{RSVP} value results in enough time to set up a new RSVP branch path when an MN moves to the neighboring BS.

Figure 5 shows the probability of service disruption with various load conditions (in Table 1) under V = 10.0 m/s and T_{RSVP} = –13.3 dB. In this situation, under only low load of the routers in the network, packet loss can be minimized and QoS guarantee achieved. Hence, according to the current wireless link status and network load condition, T_{RSVP} should also be adaptively modified. For this kind of purpose, a mechanism is needed to measure the network condition and link status.

Conclusions

In this article, we considered rerouting of the RSVP branch path at a crossover router in order to minimize resource reservation delay and the packet loss resulting from handoffs under RSVP. We proposed a seamless rerouting scheme of an RSVP branch path for soft handoff in order to guarantee the QoS of ongoing RSVP flows during a handoff event. We also showed that this scheme could provide QoS guarantee in an IP micromobility network through simulation analysis and examples. For the dynamic and adaptive modification of threshold value, we conclude that a mechanism is needed to measure the network condition and link status.

Acknowledgments

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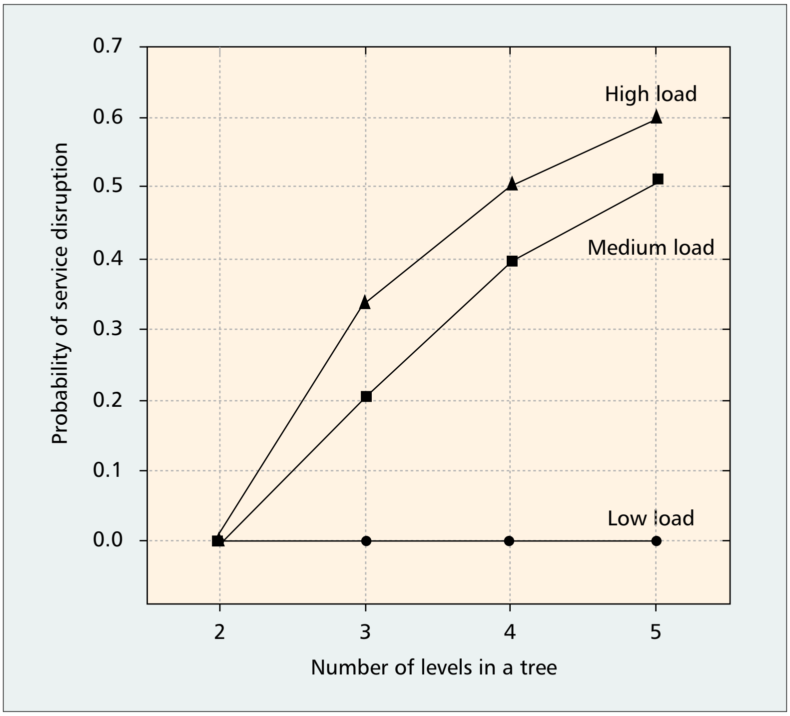

Figure 5. *Probability of service disruption with various load conditions under* V = *10.0 m/s and* T_{RSVP} = *–13.3 dB.*

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Biographies

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HAMID AGHVAMI [SM] (hamid.aghvami@kcl.ac.uk) obtained his M.Sc. and Ph.D. degrees from King's College, University of London, in 1978 and 1981, respectively. He joined the academic staff at King's in 1984. In 1989 he was promoted to reader, and to professor in telecommunications engineering in 1992. He is presently the director of the Centre for Telecommunications Research at King's. He carries out consulting work on digital radio communications systems for both British and international companies. He has published over 200 technical papers and given invited talks all over the world on various aspects of personal and mobile radio communications, and has taught courses on the subject worldwide. He was a visiting professor at NTT Radio Communication Systems Laboratories in 1990 and a senior research fellow at BT Laboratories in 1998–1999. He is currently an executive advisor to Wireless Facilities Inc., United States, and managing director of Wireless Multimedia Communications LTD. He leads an active research team working on numerous mobile and personal communications projects for third-generation systems; these projects are supported by both government and industry. He was a distinguished lecturer of the IEEE Communications Society in 1993. He has been a member, chair, and vice-chair of the technical program and organizing committees of a large number of international conferences. He is also the founder of the International Conference on Personal Indoor and Mobile Radio Communications (PIMRC). He is a fellow of the IEE.