

# Multi-path Transmission, Selection and Handover Mechanism for High-Quality VoIP

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## 1. Introduction

With the development of audio encoding standards and IP technology, voice over IP (VoIP) is becoming quite popular. However, high-quality voice data over current networks without QoS Support, such as Internet and UMTS, still poses several challenging problems because of the adverse effects caused by network bandwidth restrictions and complex dynamics. One approach to provide QoS for VoIP applications over the wireless networks is to use multiple paths to deliver VoIP data destined for a particular receiver, i.e., this data is fragmented into packets and the different packets take alternate routes to the receiver. One advantage of this approach is that the complexity of QoS provision can be pushed to the network edge and hence improve the scalability and deployment characteristics while at the same time provide a certain level of QoS guarantees.

The common view among researchers of the next generation mobile communication is that it will be a heterogeneous network environment, offering seamless services such as VoIP across multiple wireless access technologies. In the future there will be more multimode devices which can access multiple radio access networks. Moreover in the future we will see greater overlap between the coverage provided by the differing access technologies as Fig. 1. A host is multi-homed if it can be addressed by multiple IP addresses, as is the common case when the host has multiple network interfaces. Multi-homing is increasingly economically feasible and can be expected to be the rule rather than the exception in the near future.

This chapter proposed a novel transport layer solution cmpSCTP that aims at exploiting SCTP's multi-homing capability by selecting several paths among multiple available network interfaces to improve data transfer rate to the same multi-homed device. As such, it is naturally leads to another two new issues: (1) How to select most appropriate paths for CMT. As different paths are likely to overlap each other and even share bottleneck which lurks behind the IP/network layer topology, it is necessary to fall back on end-to-end probes to estimate this correlation by analyzing path characteristics so that we can select multiple independent paths as much as possible; (2) How to seamless handover paths for mobility.

Using cmpSCTP's flexible path management capability, we may switch the flow between multiple paths automatically to realize the seamless handover called Latent Handover, which is flow-oriented and switches the traffic to the new path progressively to make the handover process unconscious to users or upper layer applications, especially for real-time

VoIP application. The theoretical analysis evaluated the multipath transmission model and verified that the Latent Handover can efficiently optimize the handover process and enhance transmission efficiency during handover. Extensive simulations under different scenarios verified that the multipath mechanism can effectively enhance VoIP transmission and mobility efficiency.

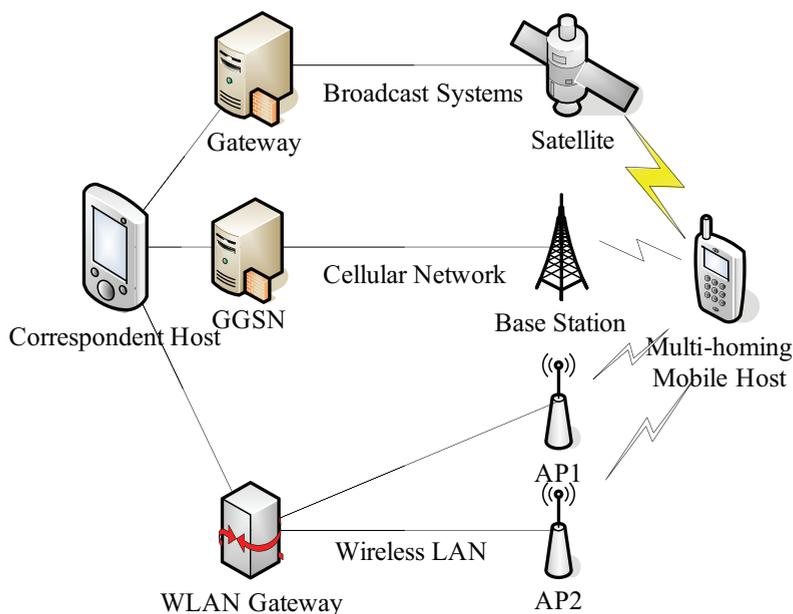


Fig. 1. Heterogeneous overlapping radio environment

## 2. Extension of SCTP to support multi-path transmission

### 2.1 Advance of multi-path transmission

Stream Control Transmission Protocol (SCTP) is the third transport layer protocol to be ratified by the Internet Engineering Task Force (IETF). SCTP provides reliable, connection oriented communication to endpoints that may have multiple IP addresses. Allowing a connection to span across multiple IP addresses is known as multi-homing, and it is just one of the features of SCTP which has researchers interested in using it as more than a signalling transport protocol. Yet, the multi-homing feature of SCTP can only exploit at most one of the available paths at any given time.

The work (Iyengar et al., 2006), by the original SCTP proposers, suggests to change the SCTP sender operation to compensate for the problems introduced by using a unique sequence-number space for tracking packets sent over multiple paths. The sender maintains a set of per-destination virtual queues and spreads the packets across all available paths as soon as the congestion window allows it. Retransmissions are triggered only when several Selective ACKnowledgments (SACKs) report missing chunks (SCTP protocol data units) from the same virtual queue.

(Al et al., 2004) proposes Load-Sharing SCTP (LS-SCTP), a mechanism to aggregate the bandwidth of all the paths connecting the endpoints and dynamically add new paths as they become available. (Hsieh & Sivakumar, 2002) proposes pTCP (parallel TCP) based on the Transmission Control Protocol (TCP). pTCP has two components - Striped connection Manager (SM) and TCP-virtual (TCP-v). This decoupling of functionality allows for intelligent scheduling of transmissions and retransmissions.

However, none of the previous proposals fully addresses the case in which the paths comprised in the SCTP association exhibit widely-different bandwidths and round trip times (RTTs). In such scenario, the packets reach the destination out of order, which is bound to trigger a lot of unnecessary retransmissions.

## 2.2 cmpSCTP design

Similar to LS-SCTP, cmpSCTP is also based on the idea of separating the association flow control from congestion control. In cmpSCTP the flow control is on an association basis; thus both the sender and receiver endpoints use their association buffer to hold the data chunks regardless of the path on which these data chunks were sent or received. On the other hand, congestion control is performed on a per path basis; thus the sender has separate congestion control for each path.

To support the decoupling of functionalities, cmpSCTP uses several novel mechanisms including multi-buffer structure, multi-state management, two-level sequence number, and cooperative SACK strategy to realize effective bandwidth aggregation. Also cmpSCTP includes an overall retransmission technique that prevents the side effects of simultaneous transmission of data on paths with different characteristics, including unnecessary fast retransmissions, which ensures fast delivery of lost data chunks to prevent stalling the association.

Through extending dynamic address reconfiguration, cmpSCTP keeps ongoing end-to-end paths alive and provides adaptive load sharing on multiple paths. In addition, cmpSCTP extends the SCTP path-monitoring feature, through regular transmission of actual effective data chunks to update the list of unstable paths suitable for load sharing. The detailed design of cmpSCTP may be found in [Liao et al., 2008].

## 3. Correlation-aware multi-path selection

The most researches about CMT have the assumption that multiple paths are independent (Iyengar et al., 2006), but this assumption is rarely warranted at real network. For example, two different paths are likely to overlap one or more joint links somewhere in the network, even share similar bottleneck. So it is necessary to diminish this assumption and take into account the correlation between paths (Apostolopoulos & Trott 2004). Furthermore, the benefits of path diversity do not just depend on whether paths are absolutely independent or dependent, but rather on their correlated degrees in actual networks. Evaluating correlation degrees of available paths and selecting relative independent paths if possible is an important element in effective use of path diversity, which is partly motivated by the observation that packets sent over dependent paths are likely to suffer simultaneously from large packet delays, and otherwise not. Therefore, we can conclude that if the delay patterns on different paths are strongly (or weakly) correlated, the internal shared congestions are

more (or less) likely to occur. It is reasonable to model the path correlation based on the path delay patterns, and what we need to do is to collect a history of delay values of each path through external end-to-end measurements, without cooperation from the network routers. Intuitively, we can view the selection of a highly reliable set of end-to-end paths as the problem of maximizing the effect of path diversity for a parallel-series network. Path bottleneck points are the most critical to impact the performance of the entire path, and their relative locations directly affect the degree of path correlation. Therefore it is crucial to identify bottlenecks in the large-scale network so as to evaluate path correlation.

### 3.1 Effect of path diversity

The exploitation of path diversity has attracted much attention recently, and a broad overview of the general area is provided by (Apostolopoulos & Trott 2004). We note that the existence of multiple disjoint paths can result in many benefits including: (1) increased bandwidth, and (2) improved loss characteristics. There are a number of approaches [3-5] to accomplishing multipath data delivery, the path diversity-based approach is considered in this paper.

There are other similar works in interface (Casetti et al., 2008), access network (Alkhawani & Ayes, 2008) and IP address (Iyengar et al., 2006) selection for multihomed wireless host. Historically, this was good, as the first link was usually the bottleneck which had the least bandwidth. Often now, however, it is a "backhaul" rather than the access link that has the most constrained bandwidth - an example of this could be a satellite or 3G link which connects a train WLAN to the internet. Therefore, the target should be how to select end-to-end complete paths instead of merely part of them. Another work in (Fracchia et al., 2007) aims at selecting the best path among several available end-to-end paths through the use of bandwidth estimation techniques, which is more suited to the single path selection.

Multipath selection needs to take advantage of the benefits of path diversity, so discovering the correlation characteristics of multiple paths is the most key problem. It can be done either by internal nodes or by end systems. The aforementioned approaches attempt to learn about single path characteristics, but do not address directly the problem of identifying the correlations between multiple paths. Unlike others, the work (Rubenstein et al., 2002) attempt to detect whether two flows share the same bottleneck through end-to-end measurement. However, their goal is to exploit the relation between the flows rather than the paths.

### 3.2 Problem statement

Consider the multihomed networks are constituted by the multihomed end-devices (see Fig. 2). The source and the destination are connected via a network of communication links. An end-to-end path is a virtual link directly connecting two IP addresses which come from source and destination device respectively. It can be mapped to the IP path. For example, the Path  $P_{12}$  started from  $IP_s^1$  and ended with  $IP_d^2$  consists of the nodes  $N_s$ ,  $N_m$ ,  $N_k$ , and  $N_D$ . Characteristics of two end-to-end paths may be correlated because they may share some IP links or nodes. For example, the  $P_{12}$  and  $P_{13}$  share the IP links ( $N_s$ ,  $N_m$ ) and ( $N_m$ ,  $N_k$ ).

An  $M$ -by- $N$  multihomed network topology can be abstracted as a directed acyclic graph  $G=(V,E)$  between  $M$  source addresses in the source device and  $N$  destination addresses in the destination device, along with a given single-path routing policy that maps each source-destination pair to a single route from the source to the destination. Ignoring the topology

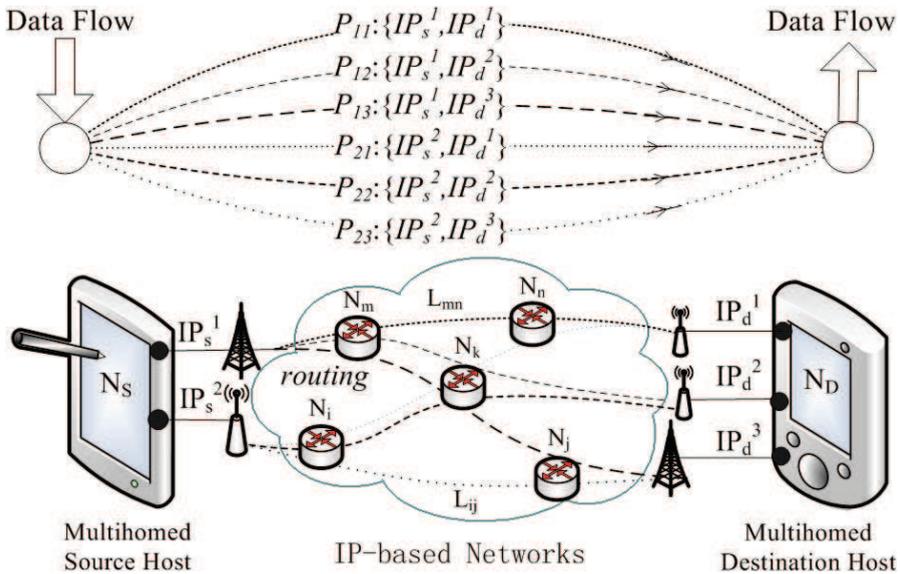


Fig. 2. An example path graph mapping to connectivity graph

and physical links of the network, we let  $P_{ij}$  simply denote any one path connecting source address  $IP_s^i$  and destination addresses  $IP_d^j$ . We assume that drops at congestion points are burst due to the Drop-tail nature of most routers, and the packets are dropped in an i.i.d. fashion. Moreover the packet drop processes in different links are independent of each other. We ignore quantization issues, data corruption or random delays.

Our goal is to select the number of paths required by the upper application and at the same time to minimize the correlation of selected path set. Nevertheless, the attempt to select correlation-minimization path set directly is an *Integer Quadratic Programming* problem (Garey & Johnson, 1979), which is an exponential exhaustive search to select paths. In addition, we observe that path bottleneck is the most critical congestion to impact the performance of the entire path, and their location relationship affect the degree of path correlation directly. Thus, we introduce a pre-grouping process according to whether they exist shared bottleneck or not, and then perform multipath selection among groups which is solvable in a reasonable amount of time. The proposed GMS solution consists of the following three steps: (1) grouping based on whether these paths exist shared bottleneck or not; (3) simple selection of the best path from each group; (4) precise selection of the required number of paths based on the paths obtained in step 3, if necessary. In GMS, we get rid of the strongly correlated paths and carry out the multipath selection on a smaller number of candidate paths, since the benefit of path diversity is never gained from the paths with shared bottleneck.

**3.3. Grouping process**

When sufficient samples are usable, path correlation computation can be performed for any two paths to determine whether exists shared bottleneck or not. This information is used to classify paths and produce a series of groups with each containing a set of highly correlated paths. The group list is the final output of the classification process.

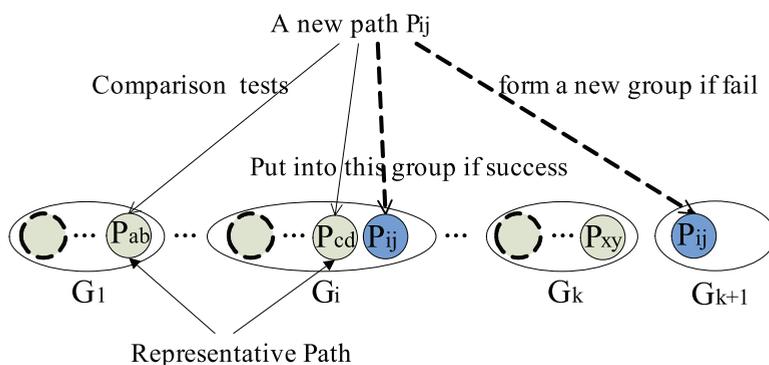


Fig. 3. The grouping method for a new path

The grouping process starts with empty group lists and a set of target paths (with sufficient samples) to be grouped. It first selects the first path  $P_{11}$  in a group. Then the second path  $P_{12}$  is compared with  $P_{11}$  to determine whether it should join the group or create a new group. Next for a new path  $P_{ij}$  to be grouped, we propose a “representative” path which is the first path in a group. The grouping method for a new path is shown in Fig. 3. A new path is only compared with the representative path to determine whether it should join the group or create a new group. This ensures that all paths that are grouped together are highly correlated with the same shared bottleneck.

### 3.4 Selection process

In the second step, it is necessary to find the best paths (Fracchia et al., 2007) within each group firstly. The best path is the path which yields minimum expected transmission time for the requested data given the concurrent transmissions. This path selection just need consider the observable performance of the path, not involving the complex routing mechanism. Different from the correlation between paths used for multi-path selection, the intrinsic performance of path is more important for the single path selection within each group. The motivation behind this is to give preference to high-bandwidth low-latency path, for instance we can simply choose it on their bandwidth whose complexity is linear. This kind of selection, no restricted by the number of paths, upper-layer application and so on, is called *free selection*.

Additionally, it may happen that the upper layer application or end system may impose specific requirements on the number of paths. In this case, we need to select the required number of paths among groups as the selection output. To differentiate from *free selection*, this additional selection is called *restrained selection*. The candidate paths are the within-group optimal paths selected in *free selection*. In fact, these paths have *weak* correlation among individuals, and may use for multipath transmission straightly to provide the maximum flow as much as possible.

For the number of paths required  $s$  is greater than the number of candidate paths (or groups)  $k$ , i.e.  $s \geq k$ , more paths are needed to be selected as transmission paths. The actual strategy can depend on the specific scenarios, and the final results can still use the output results of *free selection*, or append several other paths by random selection. For the other cases of  $s < k$ , further selection is needed to find fewer paths as required. These candidate

paths do not have shared bottleneck, but they are likely to share some ordinary congestion events which still present a certain correlation. In *restrained selection*, we adopt the *cross-measure* value of  $M_x = \rho(P_{ij}, P_{xy})$  to quantify path correlation and select several paths with minimum correlation, which can be formulated as an optimization problem.

### 3.5 Evaluation results

In this section, we evaluate the effectiveness of our scheme in selecting optimal multiple paths, and also compare several strategies related to path selection. We construct a topology that the source is provided with 2 addresses and the destination with 3, so there will be 6 parallel paths. Six concurrent TCP-like flows are generated as foreground traffic, accompanied by the same number of multiplexed self-similar flows generated as background traffic. Here, to interpret the paths more easily, we express a path on its order as  $pk$  to identify the path from  $IP_s^i$  to  $IP_d^j$  rather than the form of  $P_{ij}$  on the interface. The transform rule is:  $k=(i-1)*N+j$ .

In the simulation results presented next, SPS denotes the original single best path selection scheme; RMS denotes the random multiple better paths selection scheme without the consideration of path correlation, which selects paths according to the priority of their Bandwidth-Delay Product; GMS-Free denotes *free selection* scheme in order to achieve the maximum flow based on GMS algorithm; GMS-Restrained denotes *restrained selection* scheme subject to some restrictions, here only considering the number of paths.

As different selection schemes can affect the performance, we compare the effect of aggregating throughput between GMS and other schemes. In this experiment, we demonstrate the effect of aggregating throughput based on four schemes separately in Fig. 4. We use FTP applications as our foreground traffic along with probing packets through all available paths. All six paths are all used to send data to collect the path delay, evaluate the path correlation, and consequently, select suitable path sets with different selection schemes. For GMS-Restrained, the number of paths required  $s$  is all set to 3, i.e.  $s=3$ . The possible selected path sets are  $\{p4\}$  of SPS,  $\{p2, p3, p6\}$  of RMS,  $\{p1, p3, p4\}$  of GMS-Restrained, and  $\{p1, p3, p4, p5\}$  of GMS-Free.

After finding suitable path set, the sender transmits the application data over the selected paths. The simulation results, shown in Fig. 4, demonstrate that aggregating throughput of

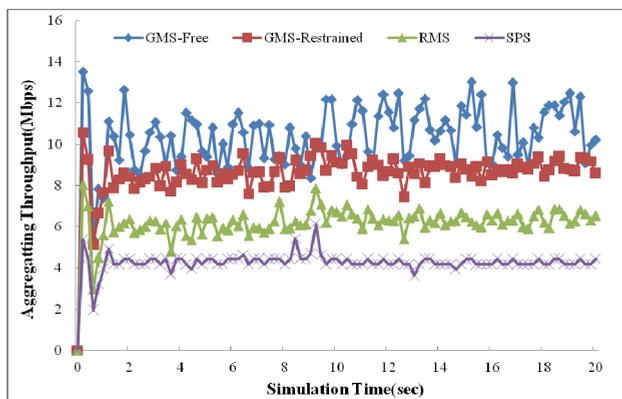


Fig. 4. Effect of different selection schemes

GMS-Free attained is the highest achieved by fully independent multiple paths, which is attributed to the exploitation of path correlation. Moreover, comparing the curves for GMS-Restrained and RMS, we observe that the aggregating throughput based on RMS is significant lower than GMS-Restrained, though both of them have the same number of selected paths. This is because RMS is a *correlation blind* scheme that cannot exploit path-diversity.

#### 4. Flow-oriented latent handover

Handover management in wireless overlapping networks that have fully overlapping coverage should be paid more attention. Handover management techniques should allow mobile users to roam among multiple wireless networks in a manner that is completely transparent to applications and keep service continuity as much as possible. A number of handover management techniques have been proposed in the literatures (Nasser et al., 2006), (Ma et al., 2004), but the existing handover schemes all possess three inherent characteristics. One is that these handover schemes are connection-oriented, where exist connection intervals unavoidably even if they have already been cut down to a very low level. As such, it is difficult to realize seamless handover indeed; the second one is that their flow-control mechanisms are not aware of handover process, which causes the traffic flow to fluctuate remarkably and inevitable packet loss; the third one is that these schemes don't take into consideration the differences in the paths characteristics, which can lead to a situation where a slow path can drag down the performance of the handover.

In this paper, we proposed and designed a new handover scheme called Latent Handover, which is flow-oriented and switches the traffic to the new path progressively to hidden the handover process unconscious by user and upper layer application especially for real-time service. The basic idea of Latent Handover is to exploit IP diversity to keep the multiple paths alive during the process of setting up the new path to achieve a seamless handover. At the same time, flow-control is integrated with the process of handover to switch traffic progressively during the process of falling off the old path to achieve a smooth handover.

In order to avoid drastic performance degradation, the proposed Latent Handover greatly reduces the packet loss during handover by implementing the redundant transmission through old and new paths to maintaining former traffic, and by monitoring the available bandwidth of the new path and then selecting the qualified paths to concurrent transfer different packets.

##### 4.1 Latent handover description

In this section, the architecture of Latent Handover in heterogeneous overlapping network is described, and how to use cmpSCTP for Latent Handover in the transport layer with the help of the concurrent multihoming feature is also described.

###### 4.1.1 Architecture

The proposed Latent Handover need to acquire multiple paths from the sender to the receiver during handover, estimate the available bandwidth on each path through an end-to-end congestion control algorithm, calculate the number of flows and the target rate of each fragment, and assign different flows to different paths for transmission. Fig. 5 illustrates the overall system architecture of the proposed Latent Handover.

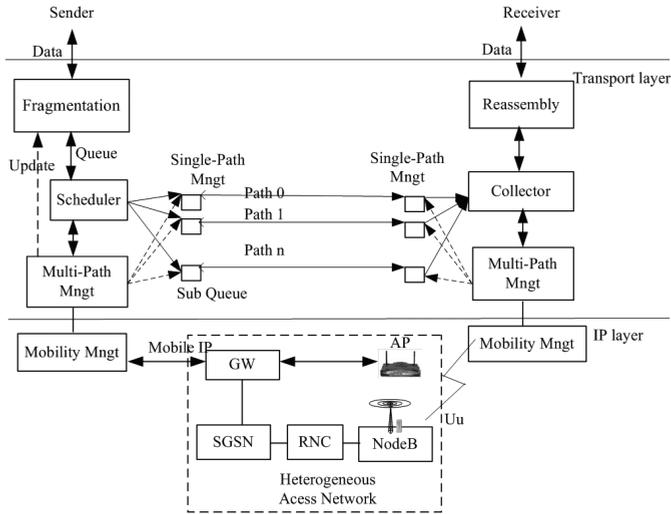


Fig. 5. System architecture of Latent Handover

The Multi-Path Management module at each end of the transport protocol manages the currently available paths, using CoA (Care of Address) binding update messages in the mobile IP protocol. The Multi-Path Management modules report the existence of multiple paths to the Scheduler and the Collector. The Multi-Path Management module also assigns a Single-Path module to a new path and removes a Single-Path module from an old path during handover. The Scheduler module calculates and reports the number of flows and the flow rate for each flow to the Fragmentation at the sender. The Collector module at the receiver accepts incoming packets from multiple paths, the out-of-order chunks is filtered and reordered by the Reassembly module before delivering to the application.

#### 4.1.2 Handover process

The simple handover process of Latent Handover between two cells can be described by the following four steps using the cmpSCTP protocol, which is shown in Fig. 6.

- Step 1.** Obtain new IP address : The handover preparation procedure begins when MH moves into the overlapping wireless coverage area of two adjacent cells. Once the MH receives the router advertisement from the new Access Point (AR2), it should begin to obtain a new IP address generated by a DHCP server , The cmpSCTP association get the new IP address to maintain two paths simultaneously through two methods: standard IP and Mobile IP. The main difference lies in cmpSCTP over Mobile IP allows both MH and CH to simultaneous binding multiple addresses in network layer, So cmpSCTP over Mobile IP is a preferred method for Latent Handover to obtain a new address since it might reduce the required signalling time in cmpSCTP layer.
- Step 2.** Add new path to association: When the cmpSCTP association is initially setup, only the CH's IP address and the MH's first IP address (Path1) are exchanged between CH and MH. After the MH obtains another IP address (Path2 in STEP 1), MH should bind Path2 into the association (in addition to Path1) and notify CH about the availability of the new path.

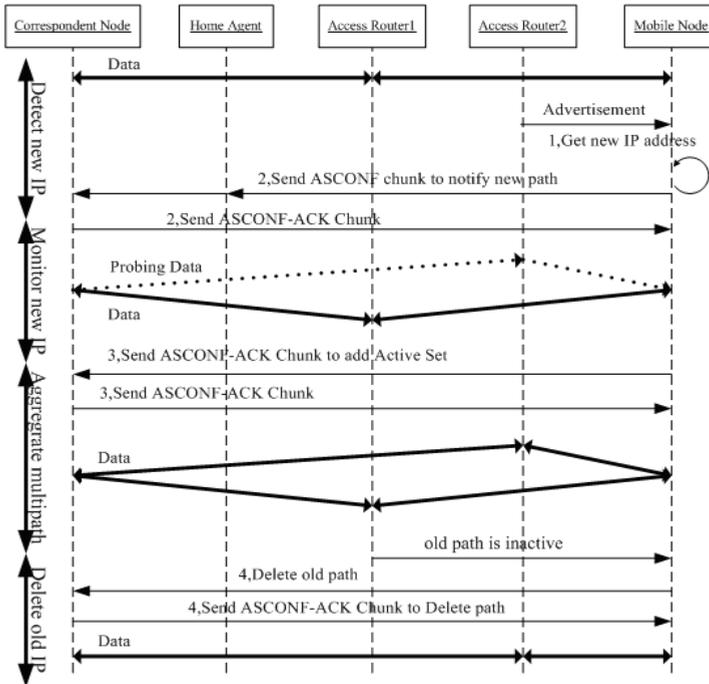


Fig. 6. Timing diagram of Latent Handover

In Latent Handover, cmpSCTP provides a graceful method to modify an existing association when the MH wishes to notify the CH that a new Path will be added to the association and this has no impact on existing active Path1.. MH notifies CH that Path2 is available for data transmission by sending an ASCONF chunk to CH. On receipt of this chunk, CH will add Path2 to its local control block for the association and reply to MH with an ASCONF-ACK chunk indicating the success of the IP addition. At this time, Path1 and Path2 are both ready for receiving data transmitted from CH to MH, but transmission strategy is a little different.

Due to Path2 likely presents instable in a period of time, which needs go through a probing stage. In this stage, Path2 are monitored utilizing the amount of actually significant data originally ready to be transmitted in path1 as probing packet. This kind of redundant transmission guarantees the smoothness of handover and increases the possibility of data being delivered successfully to the MH.

**Step 3.** Add monitored path to *Active\_Set*: When MH moves further into the coverage area of wireless access network2, Path2 becomes increasingly so as reliable to take on the task of transmission data of its own. This task can be accomplished by the MH sending an ASCONF chunk with the ActivePath parameter, which results in CH adding Path into the *Active\_Set*.

Then CH can partition data traffic into the Path1 and Path2 to increase the association throughput of data. During Latent Handover, CH will update the fragmentation and schedule strategy according real-time status of each path to optimize the total transmission efficiency. Once MH detects the quality of any path

drops down below the threshold of *Active\_Set*, the path will put into the *Monitored\_Set*. By deactivating instead of deleting the path, Latent Handover can adapt more gracefully to MH's zigzag (often referred to as ping pong) movement patterns and reuse the previously obtained Path1, as long as the lifetime of Path1 has not expired. This will reduce the latency and signalling traffic that would have otherwise been caused by obtaining a new IP address.

**Step 4.** Delete obsolete Path: When MH moves out of the coverage of wireless access network1, no new or retransmitted data packets should be directed to Path1. In Latent Handover, MH can notify CH that IP1 is out of service for data transmission by sending an ASCONF chunk to CH (Delete Path). Once received, CH will delete Path1 from its local association control block and reply to MH with an ASCONF-ACK chunk indicating the success of the Path deletion.

#### 4.1.3 Multi-path management

During handover, to allow the multi-path management module at the sender to maintain multiple paths simultaneously, the mobile IP (Johnson et al., 2004) simultaneous binding and route optimization options are used. The simultaneous binding option allows the receiver to simultaneously register multiple CoAs, and the route optimization option allows the sender to be informed of the current CoA registrations. When a new CoA is reported, the Multi-Path Management module assigns a flow control module to the new path and notifies the local multi-path transmitter/receiver of the new path; when a loss of a CoA is reported, the Multi-Path Management module removes a flow control module and notifies the local multi-path transmitter/receiver of a loss of a path.

Based on the cmpSCTP, the new paths are put into the *Monitored\_Set* to detect their available network conditions. These paths are periodically checked against the so called "triggering conditions". If a triggering condition is fulfilled, the MH decides if a path should be added to the *Active\_Set*. Then, MH creates a report which is sent to the CH. The rest of the candidate paths are kept in a *Monitored\_Set*, from which replacement paths will substitute failed or degraded paths from the *Active\_Set*.

The Multi-Path Management is responsible for updating the active paths list, which includes all the paths that can be used for load sharing, as well as for monitoring the status of the active paths. The Multi-Path Management updates the active paths list as it gets a feedback from the network regarding the failure of an exiting path or the availability of a new path. For example, when mobile IP protocol reports a new Care Of Address (CoA), with a PATH-ADD message, the Path Monitor performs the following actions: 1) It adds the new path to the existing association, using the Address Configuration Change (ASCONF) chunk [28]; 2) It creates a logical buffer for the new path; 3) Finally, it adds the new path to the active paths list. On the other hand, when the Multi-Path Management receives a PATH-LOSS message from the mobile IP, it performs the following: 1) It removes the path from the active paths list; 2) It deletes the logical buffer that corresponds to the path; 3) Finally, it removes the path from the association using the ASCONF chunk.

In addition, the Multi-Path Management removes a path from the active paths list when the number of consecutive retransmission time-outs on the path exceeds Path.Max.Retrans, which is set to 5, or when the path quality deteriorate to a limit that could affect the performance of the whole association. Currently, we are using a reasonable default threshold for the average loss rate on each path, and basing the path membership in the active paths list on that specified value. Inactive paths remain as a part of the association,

and the sender keeps monitoring them through special copy of one of the data chunks for probing the path, on the contrary the standard SCTP, that through Heartbeat control chunks, as will be described in the next section. As soon as a path recovers, the Multi-Path Management adds it again to the active paths list.

#### 4.2 Simulation model

In this section, we describe the simulation topology and parameters applied for evaluating the performance of the Latent Handover scheme. The purpose of the extensive simulations is two-fold: first to investigate the performance of the proposed scheme with various network parameters, and second to compare the proposed scheme with other existing handover schemes.

In our simulation, we created the network topology consisting two hosts as shown in Fig. 7. We assumed that an cmpSCTP association is already initiated between the two multihomed cmpSCTP hosts: cmpSCTP source and destination, and the association is unidirectional, which means that data chunks will only be sent from the Corresponding Host (CH) to Mobile Host (MH). Our simulation experiments concentrate on analyzing a single handover instance shown in Fig. 7 since a more general scenario with a sequence of handovers consists of individual handovers with different parameter settings. The mobile The following network configurations is used in the simulations. The coverage radius of each WLAN AP or UMTS base station is 300 meters, and the distance between two neighboring UMTS base stations is 400 meters. In each cell, a host is placed to simulate the background traffic. Wireless links are 802.11b WLAN 2Mbps links, while UMTS links are 1Mbps with  $RTT = 60\text{ms}$ . The bit error rate on a link dynamically changes within the range between  $1 \times 10^{-3}$  to  $1 \times 10^{-5}$  (with the average of  $2 \times 10^{-5}$ ), and all wireless links have the same bit error rate characteristics. All wired links are 155Mbps with  $RTT = 100\text{ms}$ , with  $1 \times 10^{-12}$  bit error rate, and  $10\mu\text{s}$  propagation delay, unless otherwise noted. The path MTU at each path is 1 Kbytes, and each data chunk also has size of 1 Kbytes. We set the application packets inter-arrival time so as to insure that the application will always have packets for transmission.

Existing schemes chosen to compare against the proposed Latent Handover scheme use a single path from the sender to the mobile host (i.e., the receiver). In order to evaluate the performance of Latent Handover to perform vertical handover, we have performed three simulation scenarios and derived various performance measures, the goodput especially. The first one, the sender would send over all networks by concurrent multi-streaming the packets using Latent Handover, in the second scenario, the sender will achieve its sending with performing multi-path based on mSCTP, the last one, we utilize the original handover mechanism without performing multi-path. In our performance study we used the association throughput as a performance metrics, which is defined as the amount of data delivered to the receiver's application layer per second.

Available bandwidth in the new cell (i.e., the cell that the mobile host is entering) is varied by changing the average of the Poisson distribution used to generate background traffic in the new cell. Available bandwidth of the old cell (i.e., the cell that the mobile host is leaving) is assumed to be 2Mbps. In some simulations, a mobile host leaves an old cell (2Mbps) and enters a new cell which has a large amount of available bandwidth (5Mbps). In other simulations, a mobile Host enters a new cell with a lesser amount of available bandwidth (1Mbps). In this case, congestion occurs in the new cell. RTT from the sender to the mobile host is varied by changing the transmission delay from the mobile host to the backbone router.

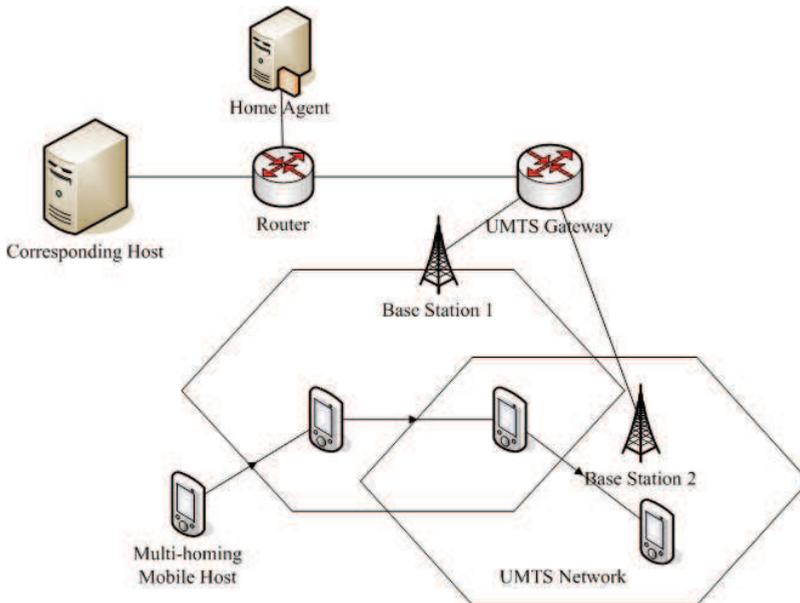


Fig. 7. Simulation scenario

### 4.3 Numerical results

In this section, simulation results are presented to evaluate the performance of the Latent Handover scheme. All the figures will be presented in this section, SP denotes the single-path handover scheme; MP\_mSCTP denotes the multi-path handover scheme based on mSCTP. MP\_cmpSCTP denotes the proposed multi-path Latent Handover scheme. Each result is an average of multiple simulation runs under the same set of parameters.

#### 4.3.1 Throughput

In this experiment we assumed that we have two paths, namely path 1 and path 2 in order to examine the performance of cmpSCTP under the condition of paths with diverse capacities. The speed of mobile host movement is assumed to be 15 m/s (meters per second) and the RTT is assumed to be 60 ms. Fig. 8 shows the throughput during handoff. The x-axis in Fig. 8 represents the time, while the y-axis represents the effective throughput excluding the duplicate packets. In Fig. 8(a), the mobile host moves from a cell with a larger amount of available bandwidth (2Mbps) to a cell with a smaller amount of available bandwidth (1Mbps). In Fig. 8(b), a mobile host moves between two homogeneous cells with the same amount of available bandwidth (2Mbps). In Fig. 8(c), a mobile host moves from a cell with a smaller amount of available bandwidth (2Mbps) to a cell with a larger amount of available bandwidth (5Mbps).

As can be seen from Fig. 8, that despite the difference in the bandwidths of the paths, the throughput achieved by cmpSCTP is close to the ideal throughput. The high throughput achieved by cmpSCTP is due to its striping mechanism that is based on the rate of the bandwidth of the paths. This is because the Latent Handover scheme allows utilization of all

available paths as soon as a mobile Host enters an overlapping area, making it possible to utilize the maximum available bandwidth throughout the duration of handover. The single path scheme and the multiple path scheme based on mSCTP switch to a path in a new cell in the middle of the handover period, making it not possible to use the path with the maximum available bandwidth throughout the duration of handover.

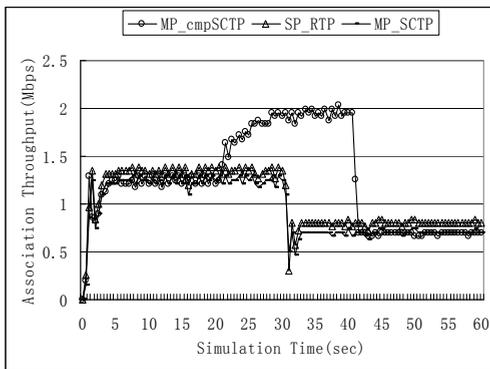
In Fig. 8 (b), no congestion occurs in the new cell since it has the same amount of available bandwidth with the old cell. As a result, all three schemes show relatively small fluctuations in the throughput. In Fig. 8(a), on the other hand, the other two schemes show a drastic drop in the throughput due to congestion loss in the new cell. This is because the rate control at the source is not aware of the handoff and continues sending data packets at a high rate that matches the available bandwidth in the old cell, resulting in congestion loss. The proposed Latent Handover scheme in Fig. 8(c) shows smooth changes in the throughput due to the TFRC rate control in the new cell and redundant transmission of the partial packets.

From Figures 8 (a) through (c), it is shown that the Latent Handover scheme achieves the highest throughput in almost all cases that have been simulated.

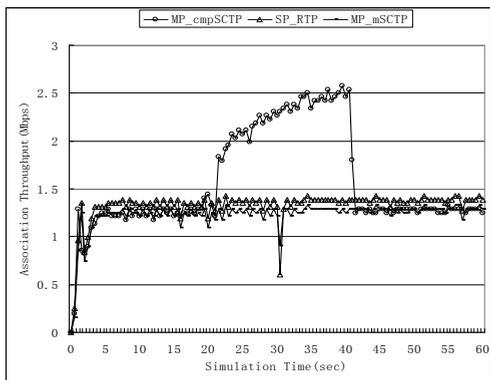
### 4.3.2 Handover latency

In this section, we simulation the latency of handover for MH. The handover latency is defined as the gap between 'the time that the MH has received the last DATA chunk over the old IP address', and 'the time that the MH has received the first DATA chunk over the new IP address'. For handover analysis, we consider the handover latency is the length of time interval between new path acquisition time and the receiving time of the last packet from the old path. For the single-homing MH, the new path acquisition time can be calculated by summing up the time TDHCP (for the configuration of a new IP address from a DHCP server), the handover delay of the underlying link layer  $T_{link\_handover}$  (for the processing time of the link-down and link-up in the underlying link layer), and the other signal negotiation latency. For the multihoming MH based on mSCTP, the new path acquisition time will be more affected by the signal negotiation latency, the primary factor is TASCNF (for the Add-IP and Primary-Change and Delete-IP operations in the mSCTP handover). TASCNF corresponds to the Round Trip Time (RTT) for exchange of ASCNF and ASCNF-ACK chunks between MH and CH. It is noted that the RTT is proportional to the distance between two endpoints and also inversely proportional to the bandwidth of the link. We also note that the mSCTP handover requires three times of exchanges of ASCNF and ASCNF-ACK chunks for ADD-IP, Primary-Change, Delete-IP, respectively. Accordingly, for Latent Handover scheme, the above operations are performed in advance before MH cuts off the old path, therefore the handover latency of cmpSCTP is much lower so much as close to zero. Fig. 9 show the handover latency for different moving speed of MH. For this experiment, all of the handover approaches are applied in order to compare and investigate the impact of MH moving speed to the performance of the different handover schemes.

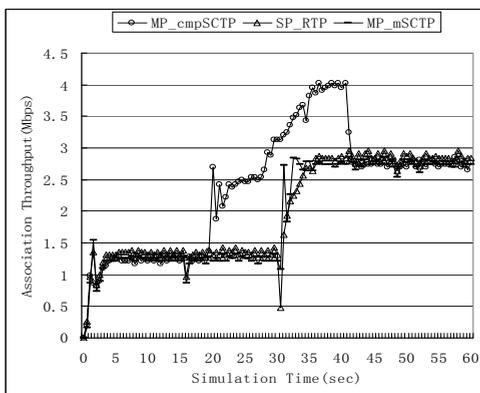
As the moving speed of MH becomes faster, handover latency increases in all the handover schemes. If two MHs with different moving speed start transiting the cell overlapping area at the same time, the faster MH should escape from the overlapping area earlier, i.e., the faster MH stops receiving packets from the previous path earlier. Since the path acquisition time is not affected by the moving speed of MH, the time to start receiving packets through the new



(a) The new cell has smaller available bandwidth



(b) The new cell has the same available bandwidth



(c) The new cell has larger available bandwidth

Fig. 8. Association throughput during handover

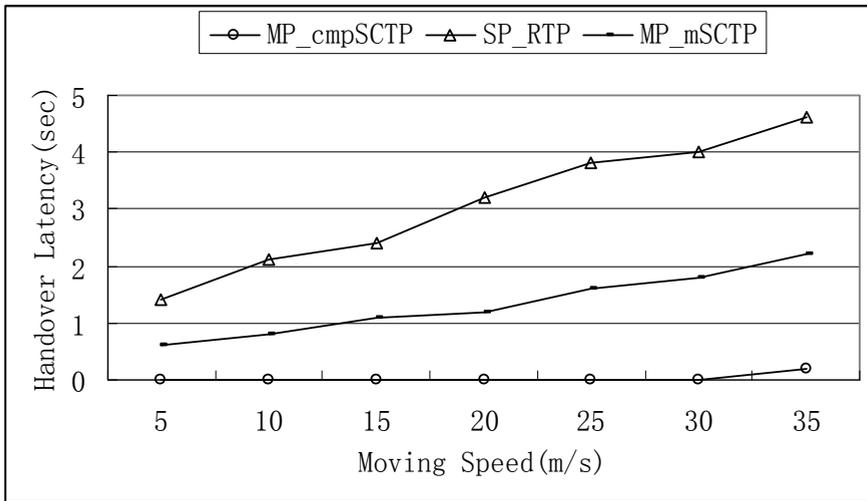


Fig. 9. Impact of moving speed on handover latency.

path is almost the same regardless of the moving speed. Therefore, handover latency becomes larger as the moving speed becomes faster, and the Latent Handover scheme always has the handover latency close to zero for all moving speeds, which explained for Fig. 9. Until the speed of MH movement increases to the degree that MH's overlapping area transiting time is smaller than the new path acquisition time, cmpSCTP will cause some amount of handover latency.

## 5. Conclusion

In future wireless access networks, CMT can enhance aggregating throughput and enable the network resource to be utilized efficiently. In this chapter, we proposed a new cmpSCTP protocol to better support high-quality VoIP applications over heterogeneous wireless networks. The cmpSCTP keeps two or more end-to-end paths concurrent, transferring new data from a source to a destination host.

More sophisticated network deployments mean that there may be some topologically shared or joint links between different transport paths. Thus, we propose a multipath selection strategy to exploit the path diversity by taking into account the potential path correlation. The probing and grouping mechanism can select the path set with minimum correlations, thus enabling the subsequent selection to avoid underlying shared bottleneck.

There is another demand for mobility between networks with maintained connectivity which requires the ability to switch the transmission path. Thus, we discuss the issue of handover in heterogeneous wireless networks. Our simulation results demonstrate that the Latent Handover leads to satisfactory performance due to appropriate treatment with the flow switch.

Further investigation is planned to address some of the issues associated with the media coding of VoIP applications, forward error correction (FEC) and hybrid strategies on CMT. The analysis and evaluation of these issues are our future work.

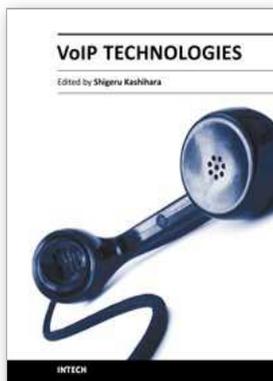
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