Multi-source Multipath HTTP (mHTTP): A Proposal

Juhoon Kim, Ramin Khalili, Anja Feldmann
{jkim,ramin,anja}@net.t-labs.tu-berlin.de, Telekom Innovation Laboratories / TU Berlin, Germany.

Yung-Chih Chen, Don Towsley
{yungchih,towsley}@cs.umass.edu, University of Massachusetts, Amherst, USA.

1. ABSTRACT
Today, most devices have multiple network interfaces. Coupled with wide-spread replication of popular content at multiple locations, this provides substantial path diversity in the Internet. We propose Multi-source Multipath HTTP, mHTTP, which takes advantage of all existing types of path diversity in the Internet. mHTTP needs only client-side but not server-side or network modifications as it is a receiver-oriented mechanism. Moreover, the modifications are restricted to the socket interface. Thus, no changes are needed to the applications or to the kernel.

As mHTTP relies on HTTP range requests, it is specific to HTTP which accounts for more than 60% of the Internet traffic [20]. We implement mHTTP and study its performance by conducting measurements over a testbed and in the wild. Our results show that mHTTP indeed takes advantage of all types of path diversity in the Internet, and that it is a viable alternative to Multipath TCP [1] for HTTP traffic. mHTTP decreases download times for large objects up to 50%, whereas it does no harm to small object downloads.

2. INTRODUCTION
In today’s Internet, one of the main deterrents in user experience is completion times of data transfers that for large objects is limited by network capacity. However, recent developments have opened new opportunities for reducing end-to-end latencies. First, most end-user devices have multiple network interfaces (e.g., 3G/LTE and WiFi interfaces for smart-phones). Second, popular contents are often available at multiple locations in the network. When combined, these provide substantial path diversity within the Internet that can be used by users to improve their quality of experience.

Previous work has taken partial advantage of this path diversity in the Internet. Multipath TCP (MPTCP) uses the path diversity available between a single server and a single client [13, 28]. Application specific download managers are other examples of related work that benefits from the path diversity between a single server and a single client [36, 37]. Content Distribution Networks (CDNs) provide replication of content and smart matching of users to appropriate CDN server, e.g., via PaDIS [23] or ALTO [32] services, which takes advantage of this replication. Moreover, there are application specific video streaming protocols that try to take advantage of the replication of streaming contents provided by CDNs [12, 21, 33]. Bittorrent is another sophisticated application which takes advantage of content replication among its users [10]. The drawback of each of the above approaches is that they do not utilize all of different types of path diversity in the Internet or if they do, they are application specific.

We propose Multi-source Multipath HTTP, mHTTP, which enables users to establish simultaneous connections with multiple servers to fetch a single content. mHTTP is designed to combine the advantage obtained from distributed network infrastructures provided by CDNs with the advantage of multiple interfaces at end-users. Unlike existing proposals: a) mHTTP is a purely receiver-oriented mechanism that requires no modification either at the server or at the network, b) the modifications are restricted to the socket interface; hence, no changes are needed to the applications or to the kernel, and c) it takes advantage of all existing types of path diversity in the Internet.

mHTTP is proposed for HTTP traffic, which accounts for more than 60% of the total traffic in today’s Internet [20]. As stated in Popa et al. [25], HTTP has become the de-facto protocol for deploying new services and applications. This is due to the explosive growth of video traffic and HTTP infrastructure in the Internet in recent years. mHTTP is primarily designed to improve download times of large file transfers (such as streaming contents). Measurements results have shown that connections with large file transfers are responsible for the bulk of the total volume of traffic in the Internet [21]. Furthermore, while mHTTP decreases download times for large objects by up to 50%, it does no harm to small object downloads as shown in Section 7.

The key insight behind mHTTP is that HTTP allows chunking a file via byte range requests and that these chunks can be downloaded from different servers as long as these servers offer the identical copies of the object. mHTTP learns about the different servers that host the same content by either using multiple IP addresses returned by a regular DNS query, sending multiple queries to multiple DNS servers, or utilizing the eDNS feature [11]. It also works with a single server when multiple paths are available between the receiver

1 Multipath TCP is an extension to regular TCP that allows a user to simultaneously use multiple interfaces for a data transfer [13].
2 The extra header added by the application might be different from server to server. mHTTP parser, refer to Section 5, deals with the application headers.
and the server. Hence, mHTTP can also be used as an alternative to MPTCP for HTTP traffic.

The mHTTP design consists of: (i) multiHTTP: a set of modified socket APIs which splits a content into multiple chunks, requests each chunk via individual HTTP range requests from the available servers, reassembles the chunks and delivers the content to the application. (ii) multiDNS: a modified DNS resolver that obtains IP addresses for a server name by harvesting the DNS replies and/or by performing multiple lookups of the same server name by contacting different domain name servers.

Our key contribution is the concept of mHTTP along with a prototype implementation and evaluation. We evaluate the performance of mHTTP through measurements over a testbed and in the wild. We compare the performance of mHTTP with regular HTTP operating over single-path TCP and MPTCP. We observe that

- mHTTP indeed takes advantage of all types of path diversity in the Internet.
- For large object downloads, it decreases download times up to 50% compared to the single-path HTTP transmission. Moreover, it does no harm to small object downloads.
- mHTTP performs similar to MPTCP while only requiring receiver-side modifications. As MPTCP requires changes to the kernel, both at the sender and receiver, we consider mHTTP to be a viable alternative when running HTTP.

The comparison with MPTCP is performed in a single-server scenario as MPTCP is restricted to the use of a single server. mHTTP, on the other hand, can be used both in single-server and in multi-server scenarios.

This paper is structured as follows. In the next section, we provide an overview of mHTTP from a system viewpoint. We give a detailed description of our prototype implementation in Sections 4-6. In Section 7 we study the performance of mHTTP through measurements. Related work is presented in Section 8. Section 9 provides a summary of our results and discusses next steps.

3. Multi-source Multipath HTTP

Content Distribution Network (CDN) provide wide-spread replication of popular content at multiple locations in the Internet. Multi-source Multipath HTTP (mHTTP) is designed to combine the advantage obtained from such a diversity with the advantage of diverse network connectivity at end-users. In this section, we describe the high-level concept of mHTTP.

3.1 Regular HTTP over TCP

Before we discuss the design of mHTTP, we review various components of HTTP communication over TCP. As illustrated in Figure 1(a), when an HTTP application tries to download an object from a web server, it first requests to the local DNS resolver to translate the human-friendly URL to a set of IP addresses. And then it sends an HTTP request to establish a connection to one of these addresses. TCP Socket API is the interface to the underlying transport protocol (TCP). The TCP stack in the kernel ensures reliable data transmission and congestion control. Note that (i) one domain name may be associated with multiple IP addresses. Moreover, (ii) different DNS servers may return different IP addresses. This is often observed in server infrastructures which serve popular contents. (i) occurs when the load is spread across multiple servers [23]. (ii) occurs in Content Delivery Networks (CDNs). However, even though the content is in principle available at multiple locations, traditional HTTP/TCP cannot take advantage of this. To overcome this limitation, we propose a novel protocol, mHTTP, built on the regular HTTP-over-TCP architecture.

3.2 mHTTP

mHTTP is designed with the following three key features in mind:

- mHTTP must take advantage of multiple built-in interfaces, multiple paths, and multiple data sources, by establishing simultaneous connections via multiple interfaces to multiple data servers where the identical content is stored.
- mHTTP must not make any modifications on the server-side infrastructure or the protocol stack.
- The client-side implementation must be transparent to the application, i.e., modifications must be limited to only socket APIs.

The key idea of mHTTP is to use the HTTP range request feature to fetch different content chunks from different servers. We define a chunk as a block of content delivered within one HTTP response message. mHTTP includes two components, multiHTTP
Figure 2: An mHTTP, with two connections over two available interfaces, operation in a CDN. Servers S1, S2, and S3 host replicas of content of A.com.

and multiDNS as shown in Figure 1(b). These components extend the functionality of HTTP and the DNS resolver. The main purpose of multiHTTP is to handle chunked data delivery between the application and multiple servers; and that of multiDNS is to collect IP addresses of available content sources. Figure 2 illustrates the process for a 2-connection mHTTP session in a CDN.

multiHTTP is the core component of mHTTP. It is responsible for the management of data chunks; taking advantage of multiple content servers and therefore of path and network diversity; and scheduling chunk requests. multiHTTP intercepts all messages sent from the application to the remote end-host (e.g., server). When a TCP connection is identified as an HTTP connection, on reception of an HTTP request from the application, the multiHTTP module modifies the header of the HTTP request by adding a range field. The HTTP response header includes the file size. Thus mHTTP can issue multiple range requests to multiple servers that serve the same object and their IP addresses are known via multiDNS.

If the connection is not an HTTP connection, mHTTP falls back to regular socket APIs. Also, for an HTTP connection, if the server does not reply with a partial data response to the HTTP request, or if multiDNS only returns a single IP address and the client is single homed mHTTP may still decide to fall back to regular HTTP.

multiDNS obtains different IP addresses by performing multiple lookups of the same server name by contacting different DNS servers (i.e., the local DNS servers of the upstream ISPs for each of its interfaces, a Google DNS server, an OpenDNS server, etc.). Additionally, it can use the eDNS extension to uncover many more servers in a CDN infrastructure.

4. IMPLEMENTATION OF multiDNS

In this section, we describe multiDNS the core element designed for discovering IP addresses of servers that hold replicas of a content. Note that mHTTP also works with a single server when multiple paths are available between the receiver and the server (refer to Section 7.3 for an example).

4.1 Data Source Diversity

Before we discuss details of the multiDNS implementation, we analyze how many IP addresses we receive from a single query for a hostname. We choose the top-1000 hostnames provided by Alexa.com and request the resolution of these hostnames by sending DNS queries to the local DNS server of a client residing in a university campus. As illustrated in Figure 3(a), even with a single query to the local DNS server, approximately 30% of the total hostnames are associated to more than one IP address and respectively 10% and 5% of the total hostnames are in different network prefixes and reside in different ASes (Autonomous Systems). When performing two lookups, one query to the local DNS and another to the Google DNS (not shown as a figure), these numbers increase to 35% (IP addresses), 17% (prefixes), and 7% (ASes). This can be seen as an evidence that CDNs may provide a different set of IP addresses to a user depending on the choice of a DNS server. More evidence of the content diversity can be found in the work of Poese et al. [24].

In Figure 3(b), we narrow down the scope to the top 300 hostnames and our result shows that almost all hostnames are associated with at least two IP addresses. Given the fact that the major fraction of the total traffic originates from a small number of popular content providers [3, 8] and the fact that the top 15 domains account for 43% of the total HTTP traffic in a large European ISP [20], the fraction of the traffic contributed by providers through multiple servers should be significant.

4.2 Getting an IP address by a Hostname

When an application needs to obtain an IP address from a human-readable URL, it invokes name resolvers such as gethostbyname() or getaddrinfo(). The resolver, then, creates a request message and sends it to the local DNS server usually provided by the local ISP. Depending on the content sources, if content is only available at a single server, the DNS returns the IP address of that particular server so that the request can be routed to the server. However, if content is available at multiple places (e.g., a server farm or CDNs), DNS returns a list of IP addresses. In the case of multiple IP addresses, a typical behavior of an application is to choose the first IP address.
address in order to establish the connection and to discard the rest. multiDNS, however, keeps the rest of the IP addresses for later use.

4.3 Getting more IP addresses
As mentioned above, different DNS servers may provide different sets of IP addresses. Therefore, it is worthwhile querying multiple DNS servers in order to obtain more IP addresses. multiDNS plays the role of managing the identities of different resolver of different access networks, whenever an interface is activated and the IP address is assigned. It also handles the DNS query by validating the availability of a local DNS server in each access network for each interface. If local DNS is still available at the point of a name translation, a query to that content is made to the local DNS of that particular access network. For each interface, multiDNS receives a list of IP addresses from each access network, and chooses desired number of IP addresses from every list. Hence, if the desired contents are available at CDNs, mHTTP does not only retrieve them from the CDNs accessible to the public, but from the CDN nodes in the CDN server farm known to the local DNS resolvers.

5. IMPLEMENTATION OF multiHTTP
The main task of multiHTTP is to interpret mHTTP for regular HTTP speakers such as web servers and client-side applications.

5.1 HTTP Byte Range Request
RFC2616 [12] specifies the use of a byte range request which enables the partial delivery of content. A client initiates such a request by adding a range field within the header of an HTTP request message including offsets of the first byte and the last byte of the partial content. If the server supports this operation, it replies with 206 as the status code (on acceptance of the request message) followed by sequences of bytes. Otherwise, the server replies with a different status code (e.g., 200 OK on success). Note that a block of partial content is referred to as a chunk in this paper. Although [12] defines this operation as an optional feature, our tests on well-known web servers during the development of mHTTP show that almost all web servers accept range requests.

Partial content delivery is widely employed by HTTP-based downloaders in order to continuously resume fetching a transferred file. Another common usage of this feature is multi-threaded downloading implemented in some software, i.e., [36] and [37]. Such software boosts download speed by fetching different parts of the content over different connections using the partial content delivery. At first sight, mHTTP is similar to those software; however mHTTP operates in the Socket API thus helps existing HTTP software to utilize the bandwidth more effectively. As mHTTP is designed to communicate with multiple servers containing identical copies of the content, it is clearly distinguished from multi-thread and downloader approaches.

5.2 mHTTP Buffer
multiHTTP initializes mHTTP buffer and creates a file descriptor associated with the buffer when socket() is called by the application. The buffer consists of a queue and a pool of content blocks (chunks). The queue is a large memory block that is continuously read by the application. Thus, the file descriptor plays the role of a communication channel between the application and the mHTTP buffer (Figure 4). The pool maintains multiple content blocks in which chunked data collected from individual TCP

buffers is stored. A content block can be indexed by the combination of the socket descriptor and the starting byte of the chunk. Data within content blocks is moved to the queue as soon as it is continuous from the last byte that is stored in the queue. The size of the queue does not grow greatly since it is continually drained by the application. However, the size of the pool needs to be sufficient to store out-of-order received chunks. We study the required size of the mHTTP buffer through measurements in Section 6. If mHTTP decides to fall back to the regular HTTP, or if the connection is not an HTTP connection, one of the socket descriptors replaces the file descriptor and the mHTTP buffer is discarded.

5.3 Manipulating HTTP Headers
Once the connection is identified as an HTTP connection, multiHTTP enables an HTTP parser, which examines HTTP messages during the content delivery period. The tasks of the HTTP parser are mainly three-fold:

- **HTTP request manipulation** The HTTP parser adds the range field to the end of the header with the specified chunk size when the initial HTTP request is sent by the application. When the response message to the initial request arrives back to the application, multiHTTP knows the size of the file and whether or not the server accepts a byte range request.

- **Parsing HTTP headers** The HTTP parser extracts and stores important information from the request and response headers such as availability of content, support for the partial content delivery, content size, and the byte range of the content block.

- **Response header management** In order to allow applications to use mHTTP without modification, the behavior of mHTTP must be the same as that of a regular HTTP communication from an application’s point of view. To this end, the HTTP parser replaces the initial response header (206) with a header that indicates the acceptance of the request (200). All subsequent headers are discarded by the HTTP parser.

5.4 Connections
Upon confirmation of the complete delivery of the initial response message, multiHTTP establishes additional TCP connections using different IP addresses provided by multiDNS. In order to obtain another IP address, multiHTTP invokes get_ip() from multiDNS (see 6 and 7 in Figure 1). The mechanism used by multiDNS to select IP addresses is independent of the operation of multiHTTP.
The current version of multiDNS hands IP addresses over to multiHTTP in the order that they are retrieved. Similarly, the number of connections to be used is configurable.

multiHTTP operates collector, a background process that collects data from individual TCP connection buffers. Each new connection must be attached to the collector as soon as it is successfully established. Likewise, a connection can be detached from the collector.

Determining what content chunk to request over each connection is another important task of multiHTTP. It keeps track of the requested chunks and decides which chunk to ask on the next request message after the previous chunk on the same connection is completely fetched. A scheduler is needed to better allocate chunks across different connections.

6. SCHEDULING

Different connections may have different qualities, in terms of latency, capacity, and loss rate. This may cause reordering of the chunks received at the mHTTP buffer. Figure 5 illustrates an example of such reordering. We have two connections: one slow and one fast (in terms of download time). The 4th chunk is downloaded over the slow connection and the 5th, 6th, 7th, and 8th chunks are downloaded over the fast connection. As the download of the 4th chunk is not finished yet, these later chunks cannot be moved to the queue. Hence, a mechanism that allocates chunks to different connections plays a critical role in multiHTTP. In this section, we explore mHTTP’s design choice with regard to chunk scheduling.

For simplicity, we assume a client with two interfaces (e.g., e0 and e1). Let \( S_0 = \{ s_{01}, s_{02}, \ldots, s_{0,N_0} \} \) and \( S_1 = \{ s_{11}, s_{12}, \ldots, s_{1,N_1} \} \) be respectively sets of servers available to the client through \( e_0 \) and \( e_1 \). Note that \( S_0 \) and \( S_1 \) are not necessarily disjoint sets. \( N_0 \) and \( N_1 \) are numbers of discovered servers over \( e_0 \) and \( e_1 \). Let \( P_0 \) and \( P_1 \) denote the connections established through \( e_0 \) and \( e_1 \) to servers in \( S_0 \) and \( S_1 \). In this paper, we limit the number of established connections over each interface to one and the total number of connections to two. However, our implementation can accept an arbitrary number of connections per interface.

We measure the instantaneous throughput of each connection by measuring the number of bytes received at the mHTTP every 20 ms. We use a moving average to estimate the average throughput of each connection:

\[
THR_{\text{new}} = 0.8 \times THR + 0.2 \times THR_{\text{old}}
\]

where \( THR \) is the instantaneous throughput measured every 20 ms and \( THR_{\text{old}} \) is the estimated average throughput. We denote by \( THR_0 \) and \( THR_1 \) the estimated average throughput measured over connections \( P_0 \) and \( P_1 \).

Let \( L \) denote the size of the object and \( C \) the chunk size, both measured in bytes. We denote by \( N = \lceil L/C \rceil + 1 \) the number of chunks to be fetched by the client and by \( 1, 2, 3, \ldots, N \) the chunk numbers. Here, \( \lceil x \rceil \) is the largest integer not greater than \( x \). Also, let \( D \) be the set of chunks that have not yet been requested for download. \( D \) is a sorted set based on the chunk numbers.

The scheduling algorithm decides what chunk to request over each connection. For example, if a chunk is successfully fetched over connection \( P_0 \), the next chunk over this connection must be carefully chosen in order to avoid a bottleneck situation such as presented in Figure 5. mHTTP decides the next chunk over \( P_0 \) uses the following mechanism:

1. calculate \( T_0 = \max (THR_0, THR_1)/THR_0 \);
2. ask for the \( T_0 \)th chunk from the set \( D \). If \( T_0 > |D| \), no chunk is requested. \( |D| \) is the size of set \( D \).
3. Remove the requested chunk from the set \( D \).

\( T_0 \) predicts the number of chunks that can be delivered over the best connection among \( P_0 \) and \( P_1 \) while one chunk is transmitted over \( P_0 \). If \( P_0 \) is the best connection, then \( T_0 = 1 \). When mHTTP needs to issue a new request over \( P_0 \), it does not request the next chunk but skips to the \( T_0 \)th chunk from the set \( D \).

mHTTP uses similar mechanism to decide the next chunk to be requested over connection \( P_1 \), with the modification that \( T_0 \) is replaced with \( T_0 = \max (THR_0, THR_1)/THR_1 \)

In Section 7, we compare the performance of our scheduler with a baseline that multiHTTP simply requests the next chunk in \( D \), whenever it needs to issue a new chunk request over a connection. We show that our scheduler can efficiently reduce the the size of the mHTTP buffer without affecting the performance of mHTTP.

7. PERFORMANCE EVALUATION

In this section, we study the potential benefit of using mHTTP in different indoor and outdoor scenarios through measurements. We study how mHTTP takes advantage of different types of diversity in the Internet and compare its performance to that of regular HTTP operating over single-path TCP and MPTCP.

We use the download completion time as the performance metric in our evaluation. It is defined as the duration between the first SYN packet from the client and the last data packet from the servers. The download completion times are measured for different file sizes, i.e., 4MB, 16MB, and 64MB. We run each measurement 30 times and show the median, 25%–75% percentiles (boxes), and dispersion (lines, 5%–95% percentiles). In each round of measurement, we randomize the configuration sequence to account for traffic dependencies and/or correlation from time to time and from size to size. Specifically, we randomize the order of file sizes, the choice of protocol (e.g., single-path, mHTTP, and MPTCP), and the choice of chunk sizes for mHTTP.

The servers run an Apache2 web server on port 80 and hold copies of the same files. The client uses wget in order to retrieve the files.
Figure 6: Scenario 1: 2 interfaces at the client; 2 servers; 2 paths (dashed lines). In our indoor testbed, AN1 and AN2 are Ethernet routers with a nominal rate of 100Mbps. In our outdoor testbed, the client is a mobile device (laptop) with one WiFi and one LTE interface.

from the servers and runs on the Linux operating system with the kernel version 3.5.7. We use 10 MSS as the initial size of the congestion window. Furthermore, TCP Cubic [14] is used as the default congestion control at the server. It is the default congestion control used in the current version of the Linux kernel.

Our measurements are performed on two testbeds: an easily configurable indoor testbed that emulates different topologies with different characteristics; and an outdoor testbed using one commercial Internet service provider and a major cellular carrier in the US. Our outdoor testbed represents real world scenarios.

For the scenarios in which we enable MPTCP, we use the stable release (version v0.86) downloaded from [35]. To provide a fair comparison between MPTCP and mHTTP, we also use uncoupled congestion control with Cubic for MPTCP. Uncoupled Cubic represents the case where regular TCP Cubic is used on the subflows. It increases the size of the congestion window of each subflow regardless of the congestion state of the other subflows that are part of the MPTCP session. We set the maximum receive buffer to 6MB to avoid potential performance degradation to MPTCP [28]. Our testbed configuration is optimized for MPTCP. Hence, we observe the best performance we can achieve using MPTCP. Our results show that mHTTP performs very close to this baseline.

We first analyze the overhead of mHTTP and study its effect on the performance of downloading small objects; we then show the benefits of mHTTP when downloading large objects.

7.1 Overhead analysis for small objects

mHTTP suffers a performance degradation each time that a connection performs a range request. We evaluate this degradation by measuring the download completion time of a file over a single path connection using HTTP and mHTTP. The client is connected via an Ethernet interface to an Ethernet router with a nominal rate of 100Mbps. The server is also connected to the Ethernet router via an Ethernet interface. A round trip time of 50ms of the round-trip time is generated on the link using a built-in traffic control module of the Linux kernel (qdisc [4]). We evaluate the overhead of mHTTP with different chunk sizes assuming the transfer over regular HTTP as the baseline. We show the results in Figure 7. We observe that the overhead is around 5 – 10%. The poor performance of mHTTP with small chunk sizes is puzzling and a topic for future investigation.

We now study the performance of mHTTP for downloading small objects. We evaluate the download completion time of downloading files of various sizes (from 8KB to 2MB) over mHTTP using 512KB as the chunk size. We consider a scenario where the client has two interfaces and downloads an object from two servers as illustrated in Figure 6. We emulate AN1 and AN2 with Ethernet routers with a nominal rate of 100Mbps. The servers and the client are connected via Ethernet interfaces to the routers. The round-trip times over the connections are set to 50ms. The measurement results are depicted in Figure 8. We observe that mHTTP does not provide any performance gain for small object downloads but does no harm either. For object downloads larger than the chunk size (512KB in this measurement), mHTTP provides good performance by utilizing the diversity in the network.

Our results in this section show that mHTTP with large chunk sizes, such as 512KB and 1024KB, provides good performance for small file downloads and introduces negligible overhead when used over a single-path connection. In the rest of the paper, we focus our analysis on the performance of mHTTP for large object downloads.

7.2 mHTTP vs regular HTTP

Now, we consider a scenario where the client has multiple interfaces and downloads a file from multiple servers. We assume a 2-server case in this scenario. As illustrated in Figure 6, the client is equipped with two interfaces connected to different access networks (ANs). Thus, the client can establish two different connections to two different servers that contain identical copies of the file.
Figure 9: Scenario 1 (indoor testbed): download completion time of regular HTTP vs. mHTTP for different file and chunk sizes. mHTTP can efficiently use the bandwidth available to the client and outperforms the best performing connection among regular HTTP connections. 1024KB of the chunk shows the optimal performance in all file sizes.

Figure 10: Scenario 1 (outdoor testbed): download completion time of regular HTTP vs. mHTTP for different file and chunk sizes. mHTTP can efficiently take advantage of the diversity exists in the network. We observe that mHTTP shows a relatively low performance when using small chunk sizes compared to the measurements with large chunk sizes which is due to the fact that our server configuration is not optimized for mHTTP.

same content. Note that MPTCP cannot be used in this scenario as it is a single-server-oriented protocol.

As the first step, we emulate the above scenario in our indoor testbed where AN1 and AN2 are Ethernet routers with nominal rates of 100Mbps each. Each server is connected via an Ethernet interface to a corresponding router. The client has two Ethernet interfaces that connect to the routers. In order to emulate different link latencies in the scenario, we set round-trip times to 10ms and 50ms on the first link and the second link, respectively. The measurement results are depicted in Figure 9. We show download completion times of file sizes 4MB, 16MB, and 64MB. Each figure compares the performance of regular HTTP over a single-path connection with that of mHTTP that uses both connections. The results are presented for different mHTTP chunk sizes. We observe that (1) the connection over the eth0 interface has a much better performance than the one over the eth1 connection; (2) mHTTP greatly benefits from the existing diversity in the network, the performance gain from us-
In Section 6, we proposed a scheduler that decides what chunk to request over each connection to avoid a bottleneck situation such as presented in Figure 5. Here, we compare the performance of this scheduler with a baseline that mHTTP simply requests for the next chunk in $D$, whenever it needs to issue a new chunk request over a connection. Recall that $D$ is the set of chunks that have not yet been requested for download. The experiment is done in our indoor testbed and for file size of 16MB.

Measurements show that (1) mHTTP with and without scheduler exhibit similar performance (in term of download completion time). Hence our scheduler does not affect the performance of mHTTP. As the results for mHTTP without scheduling are similar to Figure 9 we do not show them in this paper. (2) Our scheduler efficiently reduces the mHTTP buffer size. Figure 11 depicts the CCDF (Complementary Cumulative Distribution Function) of mHTTP buffer sizes for both cases. We observe that mHTTP without scheduling requires larger buffer sizes. The results for 2048 chunk size are identical. As in this case we have 8 chunks to be requested over the connections, the scheduler would not have any impact. (3) Furthermore, we observe that the mHTTP buffer size is smaller than 1MB in more than 50% of the cases. The maximum buffer occupancy is 7 MB. Note that mHTTP buffer uses user level memory and not the kernel space memory.

Now, we move our measurements to a more realistic network using our outdoor testbed. We configure two servers in a university campus and a mobile device (laptop) as the client. The servers are connected to the Internet via 1Gbps Ethernet cables (i.e., the bottleneck is not at the server). The client device is equipped with two wireless interfaces (WiFi and LTE) that respectively connect to a WiFi network and a cellular network. We show the results of our measurements in Figure 10 for file sizes of 4MB, 16MB, and 64MB and for different chunk sizes. We observe from the results that (1) LTE and WiFi exhibit very similar performance; and (2) mHTTP can efficiently use the available bandwidth, especially when the chunk size is 1024KB. In this case, we observe that mHTTP’s throughput equals the sum of the throughput of LTE and WiFi. Hence, mHTTP fully utilizes the available capacity and shows a substantial performance by reducing the completion time by 50%. For smaller chunk sizes, we observe a lower performance than that for large chunk sizes. This is mainly due to the overhead of range requests as analyzed in Section 7.1. Improving the performance of mHTTP for small chunk sizes is a future research topic.

Figure 11 depicts the fraction of traffic carried over the LTE interface using mHTTP. We show the results for different chunk sizes and for a file size of 16MB. We observe from Figure 10 that LTE exhibits a slightly higher throughput than WiFi. Hence, we expect mHTTP to send more or less the same amount of traffic over LTE and WiFi. Our results in Figure 12 confirm our expectation specifically for large chunk sizes.

### 7.3 mHTTP vs MPTCP for a single server case

Our second scenario focuses on comparing the performance of mHTTP and MPTCP in the multi-homed and single data source environment as illustrated in Figure 13.

As in the previous section, we first report measurements on our indoor testbed. The topology of the testbed is slightly changed in this scenario: there is only one server, and thus no data source diversity. The server and the client are booted with the MPTCP-enabled kernel when we measure the performance of MPTCP. The results are
Figure 14: Scenario 2 (indoor testbed): download completion time of mHTTP vs. MPTCP and regular HTTP. Our testbed configuration is optimized for MPTCP. Hence, MPTCP is able to fully utilize the available capacity and provide a good performance. We observe that mHTTP perform very close to MPTCP and always outperforms regular HTTP over the best path.

Figure 15: Scenario 2 (outdoor testbed): download completion time of mHTTP vs. MPTCP and regular HTTP. We observe that MPTCP is able to fully use the available bandwidth and mHTTP performs close to MPTCP.

shown in Figure [14]. As stated before, we configure our testbed in such a way that it is optimal for MPTCP. Hence, we expect MPTCP with independent cubic be able to fully utilize the available capacity and provide good performance. The results confirm this: the MPTCP throughput equals to the sum of the throughput of two connections. Moreover, we observe that mHTTP performs closely to MPTCP when the chunk size is 1024KB.

Furthermore, we observe for 64MB file size, and for large chunk sizes, that mHTTP outperforms MPTCP. This is due to the fact that MPTCP uses a shared TCP receive buffer which can limit its performance when paths have different characteristics [28]. However, mHTTP uses a separated TCP receive buffer for different established connections and hence can perform well in such a situation.

Now, we show measurement results from our outdoor testbed: a server residing at a university campus and a client equipped with LTE and WiFi network interfaces. The results are depicted in Figure[14]. Again, we observe that MPTCP fully uses available capacity and mHTTP performs close to MPTCP, especially for large file sizes and 1024KB as the chunk size.
Figure 16: Scenario 2 (outdoor testbed): fraction of traffic carried over a LTE connection for 16MB file using mHTTP as well as MPTCP. We show the results for 16MB file.

Figure [16] depicts the fraction of traffic transmitted over the LTE connection for both mHTTP and MPTCP. We show the results for 16MB file size. As WiFi and LTE connections exhibit similar performance, we expect that MPTCP and mHTTP transmit more and less the same amount of traffic over each of these connections as observed in the results. Moreover, we observe some differences between using different chunk sizes for mHTTP.

7.4 mHTTP in a multi-source CDN
Finally, we conduct performance measurements on an existing CDN infrastructure. We choose a 16MB file from a well known site on Alexa.com’s top-50 list, where the content is hosted in a CDN. We evaluate the performance of mHTTP when multiDNS uses the following two approaches: to simply use Google’s public DNS or to leverage separate local DNS resolvers. For the first approach, multiDNS queries Google’s DNS over each interface separately, and uses the set of IP addresses returned for each interface. For the second approach, multiDNS sends a DNS query over each interface to the local DNS of that access network to obtain IP addresses.

We depict the download times of the file using single-path or mHTTP with different chunk sizes in Figure [7]. Note that for single-path TCP, each interface by default queries its local DNS resolver. We observe that mHTTP reduces download times by up to 50% when compared to the single-path case and performs very well across a wide range of chunk sizes. Moreover, no significant differences are observed for both approaches that multiDNS uses. Our results in Figure [7] confirms that mHTTP can benefit from the path diversity in the Internet and can fully utilize the available bandwidth.

7.5 mHTTP is robust to the changes
Finally, we show an example how mHTTP performs when one of its connections experiences performance drops (due to the congestion either on the path or at the server). We use a scenario similar to what is depicted in Figure 6. We emulate this scenario in our indoor testbed. AN1 and AN2 are Ethernet routers with nominal rates of 100Mbps. Each server is connected via an Ethernet interface to a corresponding router. The RTTs of both connections are initially set to 50 ms. The RTT of the second connection is configured to be changed to 100ms 3 seconds after the transfer begins. We investigate how mHTTP reacts to this change. We show the results for 64MB file downloads when 1024KB chunk size is used.

Figure [18(a)] depicts the throughput on each of the connection of mHTTP and the overall throughput of mHTTP. We show the results for one experiment run. We observe that upon the RTT change of the second connection, the throughput over this connection decreases. However, mHTTP is robust to such a change and takes advantage of the diversity in the network.

Figure [18(b)] depicts the download completion time of mHTTP and compares its performance with when we use single-path HTTP over each of these connections (recall that the performance of the second connection drop after 3 second). We show the results from 30 rounds of measurement. We observe that mHTTP provides a significant performance gain, especially when we compare it with single-path HTTP over the second connection.

8. RELATED WORK
The goal of our study is to boost the speed of the HTTP-based content delivery. Indeed, the need for such a latency reduction in the Internet has already been acknowledged by network communities.

Multipath Approaches One of the closest siblings of mHTTP is MPTCP [13,28] which is an extension of the regular TCP that enables a user to spread its traffic across disjoint paths. Although MPTCP focuses on the path diversity between a single server and a single receiver and requires the modification at both end-hosts, the fundamental idea behind these two protocols is the same. Furthermore, mHTTP sheds light on solving a middlebox conundrum [7] that MPTCP currently struggles with. Kaspar [17] thoroughly studies the path diversity in the Internet and discusses use cases on the transport layer as well as on the application layer. His work and mHTTP have many features in common except that his work is limited on a single client/server scenario and it does not take scheduling into the design consideration.

Multi-source Approaches Content Distribution Network (CDN) is a key technology for reducing the delivery latency in today’s Internet and the performance of CDN has been evaluated by many studies [15,16,19,30]. CDNs provide widely distributed servers with multiple copies of the content available at different locations. CDN typically selects the content server based on the IP address of client’s DNS server and it often makes an incorrect suggestion due to the use of a public DNS [2] or the malfunction of the IP ge-
Single Path Approaches

used for any HTTP-type traffic, including streaming contents. on specific features of DASH. mHTTP, on the other hand, can be
extension of DASH [1] video streaming protocol, but heavily relies
the Internet. Tian et al. [33] has proposed a mechanism that is an
multiple content servers for utilizing path and server diversity of
communication to a single server. Instead, mHTTP connects to
distribution infrastructures. However, mHTTP does not limit the
discussed in the community. Our goal is to leverage such content
selection, mechanisms such as PaDIS [23] or ALTO [32] have been
implemented in our current mHTTP implementation, we do not allow a user to
in our implementation to better deal with small flows.

Single Path Approaches

Google has proposed a new protocol, SPDY [6][38], which shares the ultimate goal with mHTTP, i.e., re-
ducing the user latency. These two protocols (mHTTP and SPDY) have a similar architecture that does not need any modifications in
existing applications. SPDY uses only one server and one interface
at a time and utilizes a single TCP connections as if there are multi-
ple connections in it. To achieve this, server-side socket APIs must
be used for any HTTP-type traffic, including streaming contents.

Application Specific Approaches

Bittorrent implements a sophisticated mechanism which enables users to download the same con-
tent from multiple sources [10]. However, Bittorrent is an applica-
tion specific protocol and it needs modification both at the sender's
and at the receiver's side. Download managers, often run as add-on
software in a web browser or as stand-alone software, can be other
examples of application specific approaches, e.g., [36][37].

9. SUMMARY

Advantages of simultaneously utilizing multiple paths over a net-
work communication are widely evaluated and understood [5][9]
[22][26]. Given the fact that HTTP accounts for more than 60% [20]
of today's Internet traffic and that the major fraction of the total web
servers are operated on content distribution infrastructures [19][34],
it is meaningful to broaden the benefit via globally replicated con-
tent sources. However, convincing application developers and con-
tent providers to modify/update their software is practically infeasible
within a reasonable amount of time. mHTTP's key contribution
is to bring significant benefits to the end-to-end content delivery by
utilizing the path diversity in the Internet without any changes on
existing applications and the server-side network stack.

Our results show that the performance gain of mHTTP is relatively
lower when small chunk sizes are used. Part of the problem is
due to our testbed configuration. Additionally, our implementa-
tion is still in the testing phase. Optimizing the HTTP parser and
 restructuring mHTTP further will provide substantial performance
increase. This is a topic for future investigation.

For small object downloads, we observed that mHTTP does not
provide a high performance gain, but does not harm either. More-
ever, we can modify mHTTP such that it does not establish multi-
ple paths if the object size is relatively small. Hence, for the small
flows, mHTTP will fall back to regular HTTP. Furthermore, we
can integrate ideas like socket intense proposed in [31] in our im-
plementation to better deal with small flows.

In regard to the comparison with MPTCP in single server scenarios,
we observe that mHTTP exhibits similar performance as MPTCP
for large chunk sizes, e.g., 1024KB, and for downloading large ob-
jects. Moreover, previous studies show that MPTCP, similarly to
mHTTP, does not provide a high performance gain for small object
downloads [9]. Hence, we consider mHTTP to be a viable alternative
when running HTTP. Note that MPTCP requires changes to the
kernel, both at the sender and receiver. mHTTP, on the other hand,
requires only receiver-side modifications which are restricted to the
socket interface.

In our current mHTTP implementation, we do not allow a user to
establish more than two connections and, in particular, not more
than one connection over an interface. However, we let the user
leverage his possible resources, that is decided by regular TCP, over
each of these connections. Hence, an mHTTP user will not be more
aggressive than a TCP user over each interface and will not use the
network bandwidth more than twice than a regular single-path user.
This provides some level of fairness in the network.

We can use similar mechanisms as MPTCP, coupled-control [27]
or OLIA [13], to provide load balancing across multiple connections
of a content download. As our design goal is not to modify servers,
this can be implemented by modifying the TCP kernel of the re-
ceiver. The idea is that we can limit/regulate the transmission rate
over a connection by adjusting the receive window size advertised
by the receiver. This is a topic for future research.

Finally, We plan to extend our study to other use cases such as a
streaming content delivery (e.g., YouTube and/or Netflix) from
multiple data sources. Specifically, we are interested in studying if using mHTTP can reduce the start-up latency of streaming contents.\textsuperscript{29} The performance study of mHTTP in high Bandwidth-Delay-Product environments is another future research topic.

10. ACKNOWLEDGEMENTS
This work was supported by the EU project CHANGE (FP7-ICT-257422) and by the EIT KIC project MONC. This material is also based upon work supported by the US Army Research laboratory and the UK Ministry of Defense under AgreementNumber W911NF-06-3-0001 and by the National Science Foundation under Grants IIS-0916726 and CNS-1040781.

11. REFERENCES
[1] Adhikari, V. K., Guo, Y., Hao, F., Varvello, M., Hilt, Y., Steiner, M., and Zhang, Z.-L. Unraveling netflix: Understanding and improving multi-cdn movie delivery. In IEEE INFOCOM 2012.
[2] Ager, B., Muhlbaier, W., Smaragdakis, G., and Uhlig, S. Revisiting dns resolvers in the wild. In ACM IMC 2010.
[3] Ager, B., Schneider, F., Kim, J., and Feldmann, A. Multipath tcp: from theory to practice. In NETWORKING 2011. Springer.
[4] Almesberger, W., et al. Linux network traffic control - implementation overview, 1999.
[5] Barre, S., Paasch, C., and Bonaventure, O. Multipath tcp tutorial at iee cloudnet 2012.
[6] Belshe, M., and Peon, R. Spdy protocol.
[7] Bonaventure, O. Multipath tcp tutorial at iee cloudnet 2012.
[8] Breslau, L., Cao, P., Fani, L., Phillips, G., and Shenker, S. Web caching and zip-like distributions: Evidence and implications. In IEEE INFOCOM 1999.
[9] Chen, Y.-C., Lim, Y.-S., Gibbens, R. J., Nahum, E. M., Khalili, R., and Towsley, D. A measurement-based study of multipath tcp performance over wireless networks. In ACM IMC 2013.
[10] Cohen, B. Incentives build robustness in bittorrent. In Workshop on Economics of Peer-to-Peer systems 2003.
[11] Damas, J., Graff, M., and Vixie, P. Extension mechanisms for dns (edns (0)). In RFC 6891.
[12] Fielding, R., Gettys, J., Mogul, J., Frystyk, H., Masinter, L., Leach, P., and Berners-Lee, T. Hypertext transfer protocol – http/1.1. In RFC 2616.
[13] Ford, A., Raiciu, C., Handle, M., Barre, S., and Iyengar, J. Architectural guidelines for multipath tcp development. In RFC 6182.
[14] Ha, S., Rhee, I., and Xu, L. Cubic: A new tcp-friendly high-speed tcp variant. ACM SIGOPS Operating Systems Review 42 (2008).
[15] Huang, C., Wang, A., Li, J., and Ross, K. W. Measuring and evaluating large-scale cdns. In ACM IMC 2008.
[16] Karagiannis, T., Rodriguez, P., and Papagiannaki, K. Should internet service providers fear peer-assisted content distribution? In ACM IMC 2005.
[17] Kasper, D. Multipath Aggregation of Heterogeneous Access Networks. PhD thesis, University of Oslo, 2012.
[18] Khalili, R., Gast, N., Popovic, M., Upadhyay, U., and Boudec, J.-Y. L. Mptcp is not pareto-optimal: performance issues and a possible solution. In ACM CoNEXT 2012.
[19] Krishnamurthy, B., Wills, C., and Zhang, Y. On the use and performance of content distribution networks. In ACM SIGCOMM Workshop on Internet Measurement, 2001.
[20] Maier, G., Feldmann, A., Paxson, V., and Allman, M. On dominant characteristics of residential broadband internet traffic. In ACM IMC 2009.
[21] Maier, G., Sommer, R., Dreger, H., Feldmann, A., Paxson, V., and Schneider, F. Enriching network security analysis with time travel. In ACM SIGCOMM Computer Communication Review, 2008.
[22] Nguyen, S. C., and Nguyen, T. M. T. Evaluation of multipath tcp load sharing with coupled congestion control option in heterogeneous networks. In IEEE Global Information Infrastructure Symposium, 2011.
[23] Poese, I., Frank, B., Ager, B., Smaragdakis, G., and Feldmann, A. Improving content delivery using provider-aided distance information. In ACM IMC 2010.
[24] Poese, I., Uhlig, S., Kaaafar, M. A., Donnet, B., and Gueye, B. Ip geolocation databases: unreliable? ACM SIGCOMM Computer Communication Review 2011.
[25] Popa, L., Ghodsi, A., and Stoica, I. Http as the narrow waist of the future internet. In ACM HotNets 2010.
[26] Raiciu, C., Barre, S., Pluntke, C., Greenhalgh, A., Wischik, D., and Handle, M. Improving datacenter performance and robustness with multipath tcp. In ACM SIGCOMM 2011.
[27] Raiciu, C., Handly, M., and Wischik, D. Coupled congestion control for multipath transport protocols. RFC 6356 (Experimental) (2011).
[28] Raiciu, C., Paasch, C., Barre, S., Ford, A., Honda, M., Duchene, F., Bonaventure, O., and Handle, M. How hard can it be? designing and implementing a deployable multipath tcp. In USENIX NSDI 2012.
[29] Rao, A., Legout, A., Lim, Y.-S., Towsley, D., Barakat, C., and Dabbous, W. Network characteristics of video streaming traffic. In ACM CoNEXT 2011.
[30] Ratnasamy, S., Handle, M., Karp, R., and Shenker, S. Tolerance-aware overlay construction and server selection. In IEEE INFOCOM 2002.
[31] Schmidt, P. S., Enghardt, T., Khalili, R., and Feldmann, A. Socket intents: Leveraging application awareness for multi-access connectivity. ACM CoNEXT (2013).
[32] Seedorf, J., and Burger, E. Application-layer traffic optimization (alto) problem statement. In RFC 5693.
[33] Tian, G., and Liu, Y. Towards agile and smooth video adaptation in dynamic http streaming. In ACM CoNEXT 2012.
[34] Triukose, S., Al-Qudah, Z., and Rabinovich, M. Content delivery networks: protection or threat? In Computer Security–ESORICS 2009. Springer.
[35] Multipath tcp - linux kernel implementation. http://mptcp.info.ucl.ac.be/
[36] Flashget. http://www.flashget.com/
[37] Jdownloader. http://jdownloader.org/
[38] Spdy: An experimental protocol for a faster web. http://www.chromium.org/spdy/spdy-whitepaper