Internet Engineering Task Force (IETF)
Request for Comments: 8041
Category: Informational
ISSN: 2070-1721

O. Bonaventure
UCLouvain
C. Paasch
Apple, Inc.
G. Detal
Tessares

January 2017

Use Cases and Operational Experience with Multipath TCP

Abstract

This document discusses both use cases and operational experience with Multipath TCP (MPTCP) in real networks. It lists several prominent use cases where Multipath TCP has been considered and is being used. It also gives insight to some heuristics and decisions that have helped to realize these use cases and suggests possible improvements.

Status of This Memo

This document is not an Internet Standards Track specification; it is published for informational purposes.

This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Not all documents approved by the IESG are a candidate for any level of Internet Standard; see Section 2 of RFC 7841.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at http://www.rfc-editor.org/info/rfc8041.

Table of Contents

1. Introduction

Multipath TCP was specified in [RFC6824] and five independent implementations have been developed. As of November 2016, Multipath TCP has been or is being implemented on the following platforms:

- Linux kernel [MultipathTCP-Linux]
- Apple iOS and macOS
- Citrix load balancers
- FreeBSD [FreeBSD-MPTCP]
- Oracle Solaris

The first three implementations are known to interoperate. Three of these implementations are open source (Linux kernel, FreeBSD and Apple's iOS and macOS). Apple's implementation is widely deployed.

Since the publication of [RFC6824] as an Experimental RFC, experience has been gathered by various network researchers and users about the operational issues that arise when Multipath TCP is used in today's Internet.

When the MPTCP working group was created, several use cases for Multipath TCP were identified [RFC6182]. Since then, other use cases have been proposed and some have been tested and even deployed. We describe these use cases in Section 2.

Section 3 focuses on the operational experience with Multipath TCP. Most of this experience comes from the utilization of the Multipath TCP implementation in the Linux kernel [MultipathTCP-Linux]. This open-source implementation has been downloaded and implemented by thousands of users all over the world. Many of these users have provided direct or indirect feedback by writing documents (scientific articles or blog messages) or posting to the mptcp-dev mailing list (see https://listes-2.sipr.ucl.ac.be/sympa/arc/mptcp-dev). This Multipath TCP implementation is actively maintained and continuously improved. It is used on various types of hosts, ranging from smartphones or embedded routers to high-end servers.

The Multipath TCP implementation in the Linux kernel is not, by far, the most widespread deployment of Multipath TCP. Since September 2013, Multipath TCP is also supported on smartphones and tablets beginning with iOS7 [IETFJ]. There are likely hundreds of millions of MPTCP-enabled devices. This Multipath TCP implementation is

currently only used to support the Siri voice recognition/control application. Some lessons learned from this deployment are described in [IETFJ].

Section 3 is organized as follows. Supporting the middleboxes was one of the difficult issues in designing the Multipath TCP protocol. We explain in Section 3.1 which types of middleboxes the Linux Kernel implementation of Multipath TCP supports and how it reacts upon encountering these. Section 3.2 summarizes the MPTCP-specific congestion controls that have been implemented. Sections 3.3 to 3.7 discuss heuristics and issues with respect to subflow management as well as the scheduling across the subflows. Section 3.8 explains some problems that occurred with subflows having different Maximum Segment Size (MSS) values. Section 3.9 presents issues with respect to content delivery networks and suggests a solution to this issue. Finally, Section 3.10 documents an issue with captive portals where MPTCP will behave suboptimally.

2. Use Cases

Multipath TCP has been tested in several use cases. There is already an abundant amount of scientific literature on Multipath TCP [MPTCPBIB]. Several of the papers published in the scientific literature have identified possible improvements that are worth being discussed here.

2.1. Datacenters

A first, although initially unexpected, documented use case for Multipath TCP has been in datacenters [HotNets][SIGCOMM11]. Today's datacenters are designed to provide several paths between single-homed servers. The multiplicity of these paths comes from the utilization of Equal-Cost Multipath (ECMP) and other load-balancing techniques inside the datacenter. Most of the deployed load-balancing techniques in datacenters rely on hashes computed over the five tuple. Thus, all packets from the same TCP connection follow the same path: so they are not reordered. The results in [HotNets] demonstrate by simulations that Multipath TCP can achieve a better utilization of the available network by using multiple subflows for each Multipath TCP session. Although [RFC6182] assumes that at least one of the communicating hosts has several IP addresses, [HotNets] demonstrates that Multipath TCP is beneficial when both hosts are single-homed. This idea is analyzed in more details in [SIGCOMM11], where the Multipath TCP implementation in the Linux kernel is modified to be able to use several subflows from the same IP address. Measurements in a public datacenter show the quantitative benefits of Multipath TCP [SIGCOMM11] in this environment.

Although ECMP is widely used inside datacenters, this is not the only environment where there are different paths between a pair of hosts. ECMP and other load-balancing techniques such as Link Aggregation Groups (LAGs) are widely used in today's networks; having multiple paths between a pair of single-homed hosts is becoming the norm instead of the exception. Although these multiple paths often have the same cost (from an IGP metrics viewpoint), they do not necessarily have the same performance. For example, [IMC13c] reports the results of a long measurement study showing that load-balanced Internet paths between that same pair of hosts can have huge delay differences.

2.2. Cellular/WiFi Offload

A second use case that has been explored by several network researchers is the cellular/WiFi offload use case. Smartphones or other mobile devices equipped with two wireless interfaces are a very common use case for Multipath TCP. In September 2015, this is also the largest deployment of MPTCP-enabled devices [IETFJ]. It has been briefly discussed during IETF 88 [IETF88], but there is no published paper or report that analyses this deployment. For this reason, we only discuss published papers that have mainly used the Multipath TCP implementation in the Linux kernel for their experiments.

The performance of Multipath TCP in wireless networks was briefly evaluated in [NSDI12]. One experiment analyzes the performance of Multipath TCP on a client with two wireless interfaces. This evaluation shows that when the receive window is large, Multipath TCP can efficiently use the two available links. However, if the window becomes smaller, then packets sent on a slow path can block the transmission of packets on a faster path. In some cases, the performance of Multipath TCP over two paths can become lower than the performance of regular TCP over the best performing path. Two heuristics, reinjection and penalization, are proposed in [NSDI12] to solve this identified performance problem. These two heuristics have since been used in the Multipath TCP implementation in the Linux kernel. [CONEXT13] explored the problem in more detail and revealed some other scenarios where Multipath TCP can have difficulties in efficiently pooling the available paths. Improvements to the Multipath TCP implementation in the Linux kernel are proposed in [CONEXT13] to cope with some of these problems.

The first experimental analysis of Multipath TCP in a public wireless environment was presented in [Cellnet12]. These measurements explore the ability of Multipath TCP to use two wireless networks (real WiFi and 3G networks). Three modes of operation are compared. The first mode of operation is the simultaneous use of the two wireless networks. In this mode, Multipath TCP pools the available resources

and uses both wireless interfaces. This mode provides fast handover from WiFi to cellular or the opposite when the user moves. Measurements presented in [CACM14] show that the handover from one wireless network to another is not an abrupt process. When a host moves, there are regions where the quality of one of the wireless networks is weaker than the other, but the host considers this wireless network to still be up. When a mobile host enters such regions, its ability to send packets over another wireless network is important to ensure a smooth handover. This is clearly illustrated from the packet trace discussed in [CACM14].

Many cellular networks use volume-based pricing; users often prefer to use unmetered WiFi networks when available instead of metered cellular networks. [Cellnet12] implements support for the MP_PRIO option to explore two other modes of operation.

In the backup mode, Multipath TCP opens a TCP subflow over each interface, but the cellular interface is configured in backup mode. This implies that data flows only over the WiFi interface when both interfaces are considered to be active. If the WiFi interface fails, then the traffic switches quickly to the cellular interface, ensuring a smooth handover from the user's viewpoint [Cellnet12]. The cost of this approach is that the WiFi and cellular interfaces are likely to remain active all the time since all subflows are established over the two interfaces.

The single-path mode is slightly different. This mode benefits from the break-before-make capability of Multipath TCP. When an MPTCP session is established, a subflow is created over the WiFi interface. No packet is sent over the cellular interface as long as the WiFi interface remains up [Cellnet12]. This implies that the cellular interface can remain idle and battery capacity is preserved. When the WiFi interface fails, a new subflow is established over the cellular interface in order to preserve the established Multipath TCP sessions. Compared to the backup mode described earlier, measurements reported in [Cellnet12] indicate that this mode of operation is characterized by a throughput drop while the cellular interface is brought up and the subflows are reestablished.

From a protocol viewpoint, [Cellnet12] discusses the problem posed by the unreliability of the REMOVE_ADDR option and proposes a small protocol extension to allow hosts to reliably exchange this option. It would be useful to analyze packet traces to understand whether the unreliability of the REMOVE_ADDR option poses an operational problem in real deployments.

Another study of the performance of Multipath TCP in wireless networks was reported in [IMC13b]. This study uses laptops connected to various cellular ISPs and WiFi hotspots. It compares various file transfer scenarios. [IMC13b] observes that 4-path MPTCP outperforms 2-path MPTCP, especially for larger files. However, for three congestion-control algorithms (LIA, OLIA, and Reno -- see Section 3.2), there is no significant performance difference for file sizes smaller than 4 MB.

A different study of the performance of Multipath TCP with two wireless networks is presented in [INFOCOM14]. In this study the two networks had different qualities: a good network and a lossy network. When using two paths with different packet-loss ratios, the Multipath TCP congestion-control scheme moves traffic away from the lossy link that is considered to be congested. However, [INFOCOM14] documents an interesting scenario that is summarized hereafter.

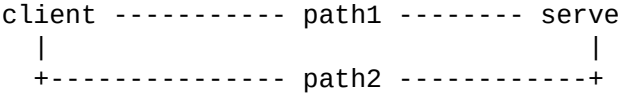

Figure 1: Simple network topology

Initially, the two paths in Figure 1 have the same quality and Multipath TCP distributes the load over both of them. During the transfer, the path2 becomes lossy, e.g., because the client moves. Multipath TCP detects the packet losses and they are retransmitted over path1. This enables the data transfer to continue over this path. However, the subflow over path2 is still up and transmits one packet from time to time. Although the N packets have been acknowledged over the first subflow (at the MPTCP level), they have not been acknowledged at the TCP level over the second subflow. To preserve the continuity of the sequence numbers over the second subflow, TCP will continue to retransmit these segments until either they are acknowledged or the maximum number of retransmissions is reached. This behavior is clearly inefficient and may lead to blocking since the second subflow will consume window space to be able to retransmit these packets. [INFOCOM14] proposes a new Multipath TCP option to solve this problem. In practice, a new TCP option is probably not required. When the client detects that the data transmitted over the second subflow has been acknowledged over the first subflow, it could decide to terminate the second subflow by sending a RST segment. If the interface associated to this subflow is still up, a new subflow could be immediately reestablished. It would then be immediately usable to send new data and would not be forced to first retransmit the previously transmitted data. As of this writing, this dynamic management of the subflows is not yet implemented in the Multipath TCP implementation in the Linux kernel.

Some studies have started to analyze the performance of Multipath TCP on smartphones with real applications. In contrast with the bulk transfers that are used by many publications, many deployed applications do not exchange huge amounts of data and mainly use small connections. [COMMAG2016] proposes a software testing framework that allows to automate Android applications to study their interactions with Multipath TCP. [PAM2016] analyses a one-month packet trace of all the packets exchanged by a dozen of smartphones utilized by regular users. This analysis reveals that short connections are important on smartphones and that the main benefit of using Multipath TCP on smartphones is the ability to perform seamless handovers between different wireless networks. Long connections benefit from these handovers.

2.3. Multipath TCP Proxies

As Multipath TCP is not yet widely deployed on both clients and servers, several deployments have used various forms of proxies. Two families of solutions are currently being used or tested.

A first use case is when an MPTCP-enabled client wants to use several interfaces to reach a regular TCP server. A typical use case is a smartphone that needs to use both its WiFi and its cellular interface to transfer data. Several types of proxies are possible for this use case. An HTTP proxy deployed on a MPTCP-capable server would enable the smartphone to use Multipath TCP to access regular web servers. Obviously, this solution only works for applications that rely on HTTP. Another possibility is to use a proxy that can convert any Multipath TCP connection into a regular TCP connection. MPTCP-specific proxies have been proposed [HotMiddlebox13b] [HAMPEL].

Another possibility leverages the SOCKS protocol [RFC1928]. SOCKS is often used in enterprise networks to allow clients to reach external servers. For this, the client opens a TCP connection to the SOCKS server that relays it to the final destination. If both the client and the SOCKS server use Multipath TCP, but not the final destination, then Multipath TCP can still be used on the path between the clients and the SOCKS server. At IETF 93, Korea Telecom announced that they have deployed (in June 2015) a commercial service that uses Multipath TCP on smartphones. These smartphones access regular TCP servers through a SOCKS proxy. This enables them to achieve throughputs of up to 850 Mbps [KT].

Measurements performed with Android smartphones [Mobicom15] show that popular applications work correctly through a SOCKS proxy and MPTCP-enabled smartphones. Thanks to Multipath TCP, long-lived connections can be spread over the two available interfaces. However, for short-lived connections, most of the data is sent over the initial subflow that is created over the interface corresponding to the default route and the second subflow is almost not used [PAM2016].

A second use case is when Multipath TCP is used by middleboxes, typically inside access networks. Various network operators are discussing and evaluating solutions for hybrid access networks [TR-348]. Such networks arise when a network operator controls two different access network technologies, e.g., wired and cellular, and wants to combine them to improve the bandwidth offered to the end users [HYA-ARCH]. Several solutions are currently investigated for such networks [TR-348]. Figure 2 shows the organization of such a network. When a client creates a normal TCP connection, it is intercepted by the Hybrid CPE (HPCE) that converts it in a Multipath TCP connection so that it can use the available access networks (DSL and LTE in the example). The Hybrid Access Gateway (HAG) does the opposite to ensure that the regular server sees a normal TCP connection. Some of the solutions currently discussed for hybrid networks use Multipath TCP on the HCPE and the HAG. Other solutions rely on tunnels between the HCPE and the HAG [GRE-NOTIFY].

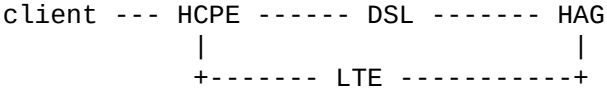

Figure 2: Hybrid Access Network

3. Operational Experience

3.1. Middlebox Interference

The interference caused by various types of middleboxes has been an important concern during the design of the Multipath TCP protocol. Three studies on the interactions between Multipath TCP and middleboxes are worth discussing.

The first analysis appears in [IMC11]. This paper was the main motivation for Multipath TCP incorporating various techniques to cope with middlebox interference. More specifically, Multipath TCP has been designed to cope with middleboxes that:

- change source or destination addresses
- change source or destination port numbers
- change TCP sequence numbers
- split or coalesce segments
- remove TCP options
- modify the payload of TCP segments

These middlebox interferences have all been included in the MBtest suite [MBTest]. This test suite is used in [HotMiddlebox13] to verify the reaction of the Multipath TCP implementation in the Linux kernel [MultipathTCP-Linux] when faced with middlebox interference. The test environment used for this evaluation is a dual-homed client connected to a single-homed server. The middlebox behavior can be activated on any of the paths. The main results of this analysis are:

- the Multipath TCP implementation in the Linux kernel is not affected by a middlebox that performs NAT or modifies TCP sequence numbers
- when a middlebox removes the MP_CAPABLE option from the initial SYN segment, the Multipath TCP implementation in the Linux kernel falls back correctly to regular TCP
- when a middlebox removes the DSS option from all data segments, the Multipath TCP implementation in the Linux kernel falls back correctly to regular TCP
- when a middlebox performs segment coalescing, the Multipath TCP implementation in the Linux kernel is still able to accurately extract the data corresponding to the indicated mapping
- when a middlebox performs segment splitting, the Multipath TCP implementation in the Linux kernel correctly reassembles the data corresponding to the indicated mapping. [HotMiddlebox13] shows, in Figure 4 in Section 3.3, a corner case with segment splitting that may lead to a desynchronization between the two hosts.

The interactions between Multipath TCP and real deployed middleboxes are also analyzed in [HotMiddlebox13]; a particular scenario with the FTP Application Level Gateway running on a NAT is described.

Middlebox interference can also be detected by analyzing packet traces on MPTCP-enabled servers. A closer look at the packets received on the multipath-tcp.org server [TMA2015] shows that among the 184,000 Multipath TCP connections, only 125 of them were falling back to regular TCP. These connections originated from 28 different client IP addresses. These include 91 HTTP connections and 34 FTP connections. The FTP interference is expected since Application Level Gateways used for FTP modify the TCP payload and the DSS Checksum detects these modifications. The HTTP interference appeared only on the direction from server to client and could have been caused by transparent proxies deployed in cellular or enterprise networks. A longer trace is discussed in [COMCOM2016] and similar conclusions about the middlebox interference are provided.

From an operational viewpoint, knowing that Multipath TCP can cope with various types of middlebox interference is important. However, there are situations where the network operators need to gather information about where a particular middlebox interference occurs. The tracebox software [tracebox] described in [IMC13a] is an extension of the popular traceroute software that enables network operators to check at which hop a particular field of the TCP header (including options) is modified. It has been used by several network operators to debug various middlebox interference problems. Experience with tracebox indicates that supporting the ICMP extension defined in [RFC1812] makes it easier to debug middlebox problems in IPv4 networks.

Users of the Multipath TCP implementation have reported some experience with middlebox interference. The strangest scenario has been a middlebox that accepts the Multipath TCP options in the SYN segment but later replaces Multipath TCP options with a TCP EOL option [StrangeMbox]. This causes Multipath TCP to perform a fallback to regular TCP without any impact on the application.

3.2. Congestion Control

Congestion control has been an important challenge for Multipath TCP. The coupled congestion-control scheme defined in [RFC6356] in an adaptation of the NewReno algorithm. A detailed description of this coupled algorithm is provided in [NSDI11]. It is the default scheme in the Linux implementation of Multipath TCP, but Linux supports other schemes.

The second congestion-control scheme is OLIA [CONEXT12]. It is also an adaptation of the NewReno single path congestion-control scheme to support multiple paths. Simulations [CONEXT12] and measurements [CONEXT13] have shown that it provides some performance benefits compared to the default coupled congestion-control scheme.

The delay-based scheme proposed in [ICNP12] has also been ported to the Multipath TCP implementation in the Linux kernel. It has been evaluated by using simulations [ICNP12] and measurements [PaaschPhD].

BALIA, defined in [BALIA], provides a better balance between TCP friendliness, responsiveness, and window oscillation.

These different congestion-control schemes have been compared in several articles. [CONEXT13] and [PaaschPhD] compare these algorithms in an emulated environment. The evaluation showed that the delay-based congestion-control scheme is less able to efficiently use the available links than the three other schemes.

3.3. Subflow Management

The multipath capability of Multipath TCP comes from the utilization of one subflow per path. The Multipath TCP architecture [RFC6182] and the protocol specification [RFC6824] define the basic usage of the subflows and the protocol mechanisms that are required to create and terminate them. However, there are no guidelines on how subflows are used during the lifetime of a Multipath TCP session. Most of the published experiments with Multipath TCP have been performed in controlled environments. Still, based on the experience running them and discussions on the mptcp-dev mailing list, interesting lessons have been learned about the management of these subflows.

From a subflow viewpoint, the Multipath TCP protocol is completely symmetrical. Both the clients and the server have the capability to create subflows. However, in practice, the existing Multipath TCP implementations have opted for a strategy where only the client creates new subflows. The main motivation for this strategy is that often the client resides behind a NAT or a firewall, preventing passive subflow openings on the client. Although there are environments such as datacenters where this problem does not occur, as of this writing, no precise requirement has emerged for allowing the server to create new subflows.

3.4. Implemented Subflow Managers

The Multipath TCP implementation in the Linux kernel includes several strategies to manage the subflows that compose a Multipath TCP session. The basic subflow manager is the full-mesh. As the name implies, it creates a full-mesh of subflows between the communicating hosts.

The most frequent use case for this subflow manager is a multihomed client connected to a single-homed server. In this case, one subflow is created for each interface on the client. The current implementation of the full-mesh subflow manager is static. The subflows are created immediately after the creation of the initial subflow. If one subflow fails during the lifetime of the Multipath TCP session (e.g., due to excessive retransmissions or the loss of the corresponding interface), it is not always reestablished. There is ongoing work to enhance the full-mesh path manager to deal with such events.

When the server is multihomed, using the full-mesh subflow manager may lead to a large number of subflows being established. For example, consider a dual-homed client connected to a server with three interfaces. In this case, even if the subflows are only created by the client, six subflows will be established. This may be excessive in some environments, in particular when the client and/or the server have a large number of interfaces. Implementations should limit the number of subflows that are used.

Creating subflows between multihomed clients and servers may sometimes lead to operational issues as observed by discussions on the mptcp-dev mailing list. In some cases, the network operators would like to have a better control on how the subflows are created by Multipath TCP [MPTCP-MAX-SUB]. This might require the definition of policy rules to control the operation of the subflow manager. The two scenarios below illustrate some of these requirements.

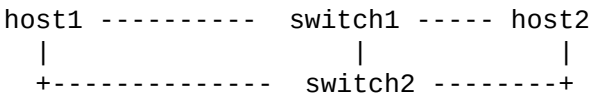

Figure 3: Simple Switched Network Topology

Consider the simple network topology shown in Figure 3. From an operational viewpoint, a network operator could want to create two subflows between the communicating hosts. From a bandwidth utilization viewpoint, the most natural paths are host1-switch1-host2 and host1-switch2-host2. However, a Multipath TCP implementation running on these two hosts may sometimes have difficulties to obtain this result.

To understand the difficulty, let us consider different allocation strategies for the IP addresses. A first strategy is to assign two subnets: subnetA (resp. subnetB) contains the IP addresses of host1's interface to switch1 (resp. switch2) and host2's interface to switch1 (resp. switch2). In this case, a Multipath TCP subflow manager should only create one subflow per subnet. To enforce the utilization of these paths, the network operator would have to specify a policy that prefers the subflows in the same subnet over subflows between addresses in different subnets. It should be noted that the policy should probably also specify how the subflow manager should react when an interface or subflow fails.

A second strategy is to use a single subnet for all IP addresses. In this case, it becomes more difficult to specify a policy that indicates which subflows should be established.

The second subflow manager that is currently supported by the Multipath TCP implementation in the Linux kernel is the ndiffport subflow manager. This manager was initially created to exploit the path diversity that exists between single-homed hosts due to the utilization of flow-based load-balancing techniques [SIGCOMM11]. This subflow manager creates N subflows between the same pair of IP addresses. The N subflows are created by the client and differ only in the source port selected by the client. It was not designed to be used on multihomed hosts.

A more flexible subflow manager has been proposed, implemented and evaluated in [CONEXT15]. This subflow manager exposes various kernel events to a user space daemon that decides when subflows need to be created and terminated based on various policies.

3.5. Subflow Destination Port

The Multipath TCP protocol relies on the token contained in the MP_JOIN option to associate a subflow to an existing Multipath TCP session. This implies that there is no restriction on the source address, destination address and source or destination ports used for the new subflow. The ability to use different source and destination addresses is key to support multihomed servers and clients. The ability to use different destination port numbers is worth discussing because it has operational implications.

For illustration, consider a dual-homed client that creates a second subflow to reach a single-homed server as illustrated in Figure 4.

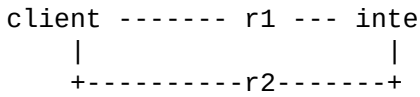

Figure 4: Multihomed-Client Connected to Single-Homed Server

When the Multipath TCP implementation in the Linux kernel creates the second subflow, it uses the same destination port as the initial subflow. This choice is motivated by the fact that the server might be protected by a firewall and only accept TCP connections (including subflows) on the official port number. Using the same destination port for all subflows is also useful for operators that rely on the port numbers to track application usage in their network.

There have been suggestions from Multipath TCP users to modify the implementation to allow the client to use different destination ports to reach the server. This suggestion seems mainly motivated by traffic-shaping middleboxes that are used in some wireless networks. In networks where different shaping rates are associated with different destination port numbers, this could allow Multipath TCP to reach a higher performance. This behavior is valid according to the Multipath TCP specification [RFC6824]. An application could use an enhanced socket API [SOCKET] to behave in this way.

However, from an implementation point-of-view supporting different destination ports for the same Multipath TCP connection can cause some issues. A legacy implementation of a TCP stack creates a listening socket to react upon incoming SYN segments. The listening socket is handling the SYN segments that are sent on a specific port number. Demultiplexing incoming segments can thus be done solely by looking at the IP addresses and the port numbers. With Multipath TCP however, incoming SYN segments may have an MP_JOIN option with a different destination port. This means that all incoming segments

that did not match on an existing listening-socket or an already established socket must be parsed for an eventual MP_JOIN option. This imposes an additional cost on servers, previously not existent on legacy TCP implementations.

3.6. Closing Subflows

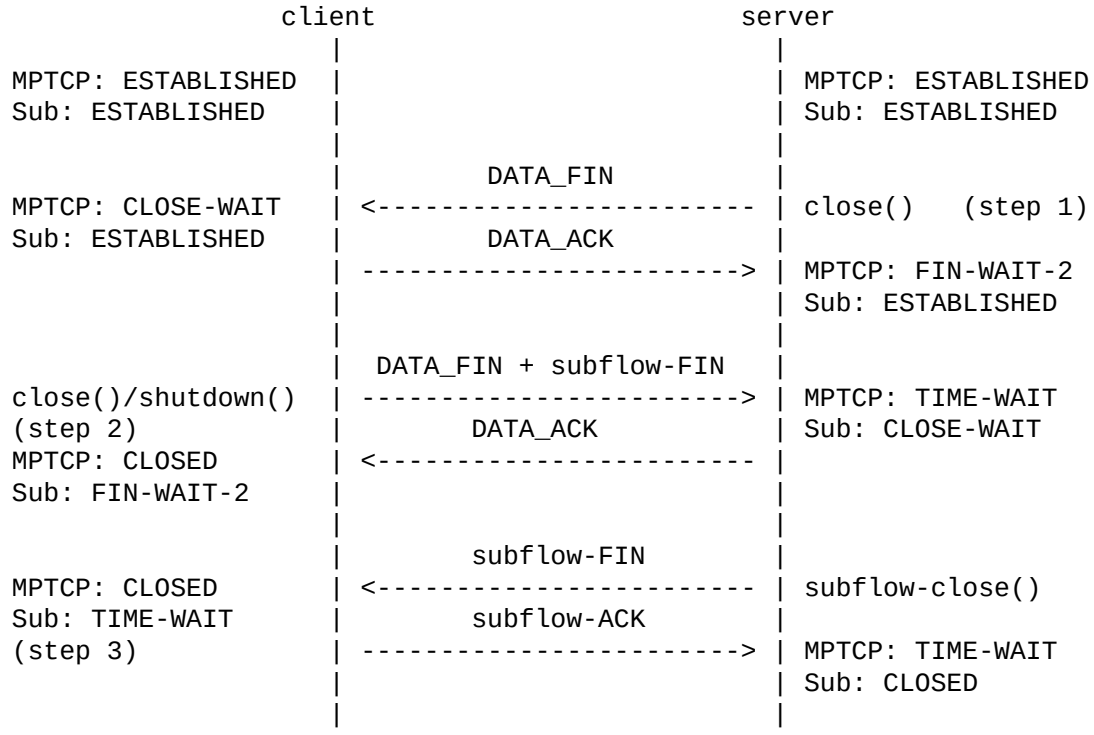

Figure 5: Multipath TCP may not be able to avoid time-wait state on the subflow (indicated as Sub in the drawing), even if enforced by the application on the client-side.

Figure 5 shows a very particular issue within Multipath TCP. Many high-performance applications try to avoid TIME-WAIT state by deferring the closure of the connection until the peer has sent a FIN. That way, the client on the left of Figure 5 does a passive closure of the connection, transitioning from CLOSE-WAIT to Last-ACK and finally freeing the resources after reception of the ACK of the FIN. An application running on top of an MPTCP-enabled Linux kernel might also use this approach. The difference here is that the close() of the connection (step 1 in Figure 5) only triggers the

sending of a DATA_FIN. Nothing guarantees that the kernel is ready to combine the DATA_FIN with a subflow-FIN. The reception of the DATA_FIN will make the application trigger the closure of the connection (step 2), trying to avoid TIME-WAIT state with this late closure. This time, the kernel might decide to combine the DATA_FIN with a subflow-FIN. This decision will be fatal, as the subflow's state machine will not transition from CLOSE_WAIT to Last-ACK, but rather go through FIN_WAIT-2 into TIME-WAIT state. The TIME-WAIT state will consume resources on the host for at least 2 MSL (Maximum Segment Lifetime). Thus, a smart application that tries to avoid TIME-WAIT state by doing late closure of the connection actually ends up with one of its subflows in TIME-WAIT state. A high-performance Multipath TCP kernel implementation should honor the desire of the application to do passive closure of the connection and successfully avoid TIME-WAIT state -- even on the subflows.

The solution to this problem lies in an optimistic assumption that a host doing active-closure of a Multipath TCP connection by sending a DATA_FIN will soon also send a FIN on all its subflows. Thus, the passive closer of the connection can simply wait for the peer to send exactly this FIN -- enforcing passive closure even on the subflows. Of course, to avoid consuming resources indefinitely, a timer must limit the time our implementation waits for the FIN.

3.7. Packet Schedulers

In a Multipath TCP implementation, the packet scheduler is the algorithm that is executed when transmitting each packet to decide on which subflow it needs to be transmitted. The packet scheduler itself does not have any impact on the interoperability of Multipath TCP implementations. However, it may clearly impact the performance of Multipath TCP sessions. The Multipath TCP implementation in the Linux kernel supports a pluggable architecture for the packet scheduler [PaaschPhD]. As of this writing, two schedulers have been implemented: round-robin and lowest-rtt-first. The second scheduler relies on the round-trip time (rtt) measured on each TCP subflow and sends first segments over the subflow having the lowest round-trip time. They are compared in [CSWS14]. The experiments and measurements described in [CSWS14] show that the lowest-rtt-first scheduler appears to be the best compromise from a performance viewpoint. Another study of the packet schedulers is presented in [PAMS2014]. This study relies on simulations with the Multipath TCP implementation in the Linux kernel. They compare the lowest-rtt-first with the round-robin and a random scheduler. They show some situations where the lowest-rtt-first scheduler does not perform as well as the other schedulers, but there are many scenarios where the

opposite is true. [PAMS2014] notes that "it is highly likely that the optimal scheduling strategy depends on the characteristics of the paths being used."

3.8. Segment Size Selection

When an application performs a write/send system call, the kernel allocates a packet buffer (sk_buff in Linux) to store the data the application wants to send. The kernel will store at most one MSS (Maximum Segment Size) of data per buffer. As the MSS can differ amongst subflows, an MPTCP implementation must select carefully the MSS used to generate application data. The Linux kernel implementation had various ways of selecting the MSS: minimum or maximum amongst the different subflows. However, these heuristics of MSS selection can cause significant performance issues in some environments. Consider the following example. An MPTCP connection has two established subflows that respectively use an MSS of 1420 and 1428 bytes. If MPTCP selects the maximum, then the application will generate segments of 1428 bytes of data. An MPTCP implementation will have to split the segment in two (1420-byte and 8-byte) segments when pushing on the subflow with the smallest MSS. The latter segment will introduce a large overhead as this single data segment will use 2 slots in the congestion window (in packets) therefore reducing by roughly twice the potential throughput (in bytes/s) of this subflow. Taking the smallest MSS does not solve the issue as there might be a case where the subflow with the smallest MSS only sends a few packets, therefore reducing the potential throughput of the other subflows.

The Linux implementation recently took another approach [DetalMSS]. Instead of selecting the minimum and maximum values, it now dynamically adapts the MSS based on the contribution of all the subflows to the connection’s throughput. For each subflow, it computes the potential throughput achieved by selecting each MSS value and by taking into account the lost space in the congestion window. It then selects the MSS that allows to achieve the highest potential throughput.

Given the prevalence of middleboxes that clamp the MSS, Multipath TCP implementations must be able to efficiently support subflows with different MSS values. The strategy described above is a possible solution to this problem.

3.9. Interactions with the Domain Name System

Multihomed clients such as smartphones can send DNS queries over any of their interfaces. When a single-homed client performs a DNS query, it receives from its local resolver the best answer for its request. If the client is multihomed, the answer in response to the DNS query may vary with the interface over which it has been sent.

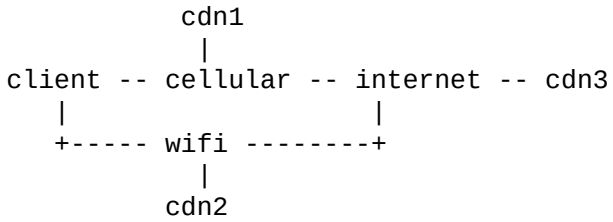

Figure 6: Simple Network Topology

If the client sends a DNS query over the WiFi interface, the answer will point to the cdn2 server while the same request sent over the cellular interface will point to the cdn1 server. This might cause problems for CDN providers that locate their servers inside ISP networks and have contracts that specify that the CDN server will only be accessed from within this particular ISP. Assume now that both the client and the CDN servers support Multipath TCP. In this case, a Multipath TCP session from cdn1 or cdn2 would potentially use both the cellular network and the WiFi network. Serving the client from cdn2 over the cellular interface could violate the contract between the CDN provider and the network operators. A similar problem occurs with regular TCP if the client caches DNS replies. For example, the client obtains a DNS answer over the cellular interface and then stops this interface and starts to use its WiFi interface. If the client retrieves data from cdn1 over its WiFi interface, this may also violate the contract between the CDN and the network operators.

A possible solution to prevent this problem would be to modify the DNS resolution on the client. The client subnet Extension Mechanisms for DNS (EDNS) defined in [RFC7871] could be used for this purpose. When the client sends a DNS query from its WiFi interface, it should also send the client subnet corresponding to the cellular interface in this request. This would indicate to the resolver that the answer should be valid for both the WiFi and the cellular interfaces (e.g., the cdn3 server).

3.10. Captive Portals

Multipath TCP enables a host to use different interfaces to reach a server. In theory, this should ensure connectivity when at least one of the interfaces is active. However, in practice, there are some particular scenarios with captive portals that may cause operational problems. The reference environment is shown in Figure 7.

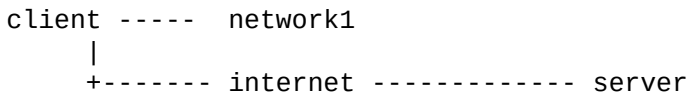

Figure 7: Issue with Captive Portal

The client is attached to two networks: network1 that provides limited connectivity and the entire Internet through the second network interface. In practice, this scenario corresponds to an open WiFi network with a captive portal for network1 and a cellular service for the second interface. On many smartphones, the WiFi interface is preferred over the cellular interface. If the smartphone learns a default route via both interfaces, it will typically prefer to use the WiFi interface to send its DNS request and create the first subflow. This is not optimal with Multipath TCP. A better approach would probably be to try a few attempts on the WiFi interface and then, upon failure of these attempts, try to use the second interface for the initial subflow as well.

3.11. Stateless Webservers

MPTCP has been designed to interoperate with webservers that benefit from SYN-cookies to protect against SYN-flooding attacks [RFC4987]. MPTCP achieves this by echoing the keys negotiated during the MP_CAPABLE handshake in the third ACK of the three-way handshake. Reception of this third ACK then allows the server to reconstruct the state specific to MPTCP.

However, one caveat to this mechanism is the unreliable nature of the third ACK. Indeed, when the third ACK gets lost, the server will not be able to reconstruct the MPTCP state. MPTCP will fall back to regular TCP in this case. This is in contrast to regular TCP. When the client starts sending data, the first data segment also includes the SYN-cookie, which allows the server to reconstruct the TCP-state. Further, this data segment will be retransmitted by the client in case it gets lost and thus is resilient against loss. MPTCP does not include the keys in this data segment and thus the server cannot reconstruct the MPTCP state.

This issue might be considered as a minor one for MPTCP. Losing the third ACK should only happen when packet loss is high; in this case, MPTCP provides a lot of benefits as it can move traffic away from the lossy link. It is undesirable that MPTCP has a higher chance to fall back to regular TCP in those lossy environments.

[MPTCP-DEPLOY] discusses this issue and suggests a modified handshake mechanism that ensures reliable delivery of the MP_CAPABLE, following the three-way handshake. This modification will make MPTCP reliable, even in lossy environments when servers need to use SYN-cookies to protect against SYN-flooding attacks.

3.12. Load-Balanced Server Farms

Large-scale server farms typically deploy thousands of servers behind a single virtual IP (VIP). Steering traffic to these servers is done through Layer 4 load-balancers that ensure that a TCP-flow will always be routed to the same server [Presto08].

As Multipath TCP uses multiple different TCP subflows to steer the traffic across the different paths, load-balancers need to ensure that all these subflows are routed to the same server. This implies that the load-balancers need to track the MPTCP-related state, allowing them to parse the token in the MP_JOIN and assign those subflows to the appropriate server. However, server farms typically deploy several load-balancers for reliability and capacity reasons. As a TCP subflow might get routed to any of these load-balancers, they would need to synchronize the MPTCP-related state -- a solution that is not feasible on a large scale.

The token (carried in the MP_JOIN) contains the information indicating to which MPTCP-session the subflow belongs. As the token is a hash of the key, servers are not able to generate the token in such a way that the token can provide the necessary information to the load-balancers, which would allow them to route TCP subflows to the appropriate server. [MPTCP-LOAD] discusses this issue in detail and suggests two alternative MP_CAPABLE handshakes to overcome these.

4. Security Considerations

This informational document discusses use cases and operational experience with Multipath TCP. An extensive analysis of the remaining security issues in the Multipath TCP specification has been published in [RFC7430], together with suggestions for possible solutions.

From a security viewpoint, it is important to note that Multipath TCP, like other multipath solutions such as SCTP, has the ability to send packets belonging to a single connection over different paths. This design feature of Multipath TCP implies that middleboxes that have been deployed on-path assuming that they would observe all the packets exchanged for a given connection in both directions may not function correctly anymore. A typical example are firewalls, Intrusion Detection System (IDS) or deep packet inspections (DPIs) deployed in enterprise networks. Those devices expect to observe all the packets from all TCP connections. With Multipath TCP, those middleboxes may not observe anymore all packets since some of them may follow a different path. The two examples below illustrate typical deployments of such middleboxes. The first example, Figure 8, shows an MPTCP-enabled smartphone attached to both an enterprise and a cellular network. If a Multipath TCP connection is established by the smartphone towards a server, some of the packets sent by the smartphone or the server may be transmitted over the cellular network and thus be invisible for the enterprise middlebox.

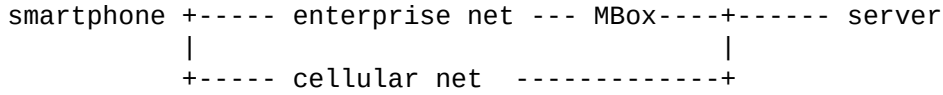

Figure 8: Enterprise Middlebox May Not Observe
All Packets from Multihomed Host

The second example, Figure 9, shows a possible issue when multiple middleboxes are deployed inside a network. For simplicity, we assume that network1 is the default IPv4 path while network2 is the default IPv6 path. A similar issue could occur with per-flow load-balancing such as ECMP [RFC2992]. With regular TCP, all packets from each connection would either pass through Mbox1 or Mbox2. With Multipath TCP, the client can easily establish a subflow over network1 and another over network2 and each middlebox would only observe a part of the traffic of the end-to-end Multipath TCP connection.

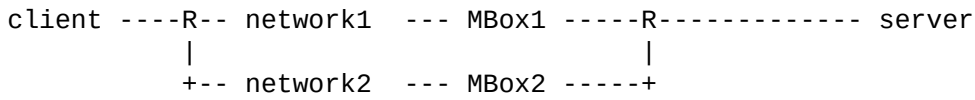

Figure 9: Interactions between
Load-Balancing and Security Middleboxes

In these two cases, it is possible for an attacker to evade some security measures operating on the TCP byte stream and implemented on the middleboxes by controlling the bytes that are actually sent over each subflow and there are tools that ease those kinds of evasion [PZ15] [PT14]. This is not a security issue for Multipath TCP itself

since Multipath TCP behaves correctly. However, this demonstrates the difficulty of enforcing security policies by relying only on on-path middleboxes instead of enforcing them directly on the endpoints.

5. References

5.1. Normative References

[RFC6182] Ford, A., Raiciu, C., Handley, M., Barre, S., and J. Iyengar, "Architectural Guidelines for Multipath TCP Development", RFC 6182, DOI 10.17487/RFC6182, March 2011, <http://www.rfc-editor.org/info/rfc6182>.

[RFC6824] Ford, A., Raiciu, C., Handley, M., and O. Bonaventure, "TCP Extensions for Multipath Operation with Multiple Addresses", RFC 6824, DOI 10.17487/RFC6824, January 2013, <http://www.rfc-editor.org/info/rfc6824>.

5.2. Informative References

[BALIA] Peng, Q., Walid, A., Hwang, J., and S. Low, "Multipath TCP: analysis, design, and implementation", IEEE/ACM Trans. on Networking (TON), Volume 24, Issue 1, February 2016.

[CACM14] Paasch, C. and O. Bonaventure, "Multipath TCP", Communications of the ACM, 57(4):51-57, April 2014, <http://inl.info.ucl.ac.be/publications/multipath-tcp>.

[Cellnet12] Paasch, C., Detal, G., Duchene, F., Raiciu, C., and O. Bonaventure, "Exploring Mobile/WiFi Handover with Multipath TCP", ACM SIGCOMM workshop on Cellular Networks (Cellnet12), August 2012, <http://inl.info.ucl.ac.be/publications/exploring-mobilewifi-handover-multipath-tcp>.

[COMCOM2016] Tran, V., De Coninck, Q., Hesmans, B., Sadre, R., and O. Bonaventure, "Observing real Multipath TCP traffic", Computer Communications, DOI 10.1016/j.comcom.2016.01.014, April 2016, <http://inl.info.ucl.ac.be/publications/observing-real-multipath-tcp-traffic>.

[COMMAG2016] De Coninck, Q., Baerts, M., Hesmans, B., and O. Bonaventure, "Observing Real Smartphone Applications over Multipath TCP", IEEE Communications Magazine Network Testing Series, 54(3), March 2016, <http://inl.info.ucl.ac.be/publications/observing-real-smartphone-applications-over-multipath-tcp>.

[CONEXT12] Khalili, R., Gast, N., Popovic, M., Upadhyay, U., and J. Leboudec, "MPTCP is not Pareto-Optimal: Performance Issues and a Possible Solution", CoNEXT '12: Proceedings of the 8th international conference on Emerging networking experiments and technologies, DOI 10.1145/2413176.2413178, December 2012.

[CONEXT13] Paasch, C., Khalili, R., and O. Bonaventure, "On the Benefits of Applying Experimental Design to Improve Multipath TCP", Conference on emerging Networking EXperiments and Technologies (CoNEXT), DOI 10.1145/2535372.2535403, December 2013, <http://inl.info.ucl.ac.be/publications/benefits-applying-experimental-design-improve-multipath-tcp>.

[CONEXT15] Hesmans, B., Detal, G., Barre, S., Bauduin, R., and O. Bonaventure, "SMAPP: Towards Smart Multipath TCP-enabled APPlications", Proc. Conext 2015, Heidelberg, Germany, December 2015, <http://inl.info.ucl.ac.be/publications/smapp-towards-smart-multipath-tcp-enabled-applications>.

[CSWS14] Paasch, C., Ferlin, S., Alay, O., and O. Bonaventure, "Experimental evaluation of multipath TCP schedulers", CSWS '14: Proceedings of the 2014 ACM SIGCOMM workshop on Capacity sharing workshop, DOI 10.1145/2630088.2631977, August 2014.

[DetalMSS] Detal, G., "dynamically adapt mss value", Post on the mptcp-dev mailing list, September 2014, <https://listes-2.sipr.ucl.ac.be/sympa/arc/mptcp-dev/2014-09/msg00130.html>.

[FreeBSD-MPTCP] Williams, N., "Multipath TCP For FreeBSD Kernel Patch v0.5", <http://caia.swin.edu.au/urp/newtcp/mptcp>.

[GRE-NOTIFY] Leymann, N., Heidemann, C., Wasserman, M., Xue, L., and M. Zhang, "GRE Notifications for Hybrid Access", Work in Progress, draft-lhwxz-gre-notifications-hybrid-access-01, January 2015.

[HAMPEL] Hampel, G., Rana, A., and T. Klein, "Seamless TCP mobility using lightweight MPTCP proxy", MobiWac '13: Proceedings of the 11th ACM international symposium on Mobility management and wireless access, DOI 10.1145/2508222.2508226, November 2013.

[HotMiddlebox13] Hesmans, B., Duchene, F., Paasch, C., Detal, G., and O. Bonaventure, "Are TCP Extensions Middlebox-proof?", CoNEXT workshop Hot Middlebox, December 2013, <http://inl.info.ucl.ac.be/publications/are-tcp-extensions-middlebox-proof>.

[HotMiddlebox13b] Detal, G., Paasch, C., and O. Bonaventure, "Multipath in the Middle(Box)", HotMiddlebox '13, December 2013, <http://inl.info.ucl.ac.be/publications/multipath-middlebox>.

[HotNets] Raiciu, C., Pluntke, C., Barre, S., Greenhalgh, A., Wischik, D., and M. Handley, "Data center networking with multipath TCP", Hotnetx-IX: Proceedings of the 9th ACM SIGCOMM Workshop on Hot Topics in Networks Article No. 10, DOI 10.1145/1868447.1868457, October 2010, <http://doi.acm.org/10.1145/1868447.1868457>.

[HYA-ARCH] Leymann, N., Heidemann, C., Wasserman, M., Xue, L., and M. Zhang, "Hybrid Access Network Architecture", Work in Progress, draft-lhwxz-hybrid-access-network-architecture-02, January 2015.

[ICNP12] Cao, Y., Xu, M., and X. Fu, "Delay-based congestion control for multipath TCP", 20th IEEE International Conference on Network Protocols (INCP), DOI 10.1109/ICNP.2012.6459978, October 2012.

[IETF88] Stewart, L., "IETF 88 Meeting minutes of the MPTCP working group", November 2013, <https://www.ietf.org/proceedings/88/minutes/minutes-88-mptcp>.

[IETFJ] Bonaventure, O. and S. Seo, "Multipath TCP Deployments", IETF Journal, Vol. 12, Issue 2, November 2016.

[IMC11] Honda, M., Nishida, Y., Raiciu, C., Greenhalgh, A., Handley, M., and H. Tokuda, "Is it still possible to extend TCP?", IMC '11: Proceedings of the 2011 ACM SIGCOMM conference on Internet measurement conference, DOI 10.1145/2068816.2068834, November 2011, <http://doi.acm.org/10.1145/2068816.2068834>.

[IMC13a] Detal, G., Hesmans, B., Bonaventure, O., Vanaubel, Y., and B. Donnet, "Revealing Middlebox Interference with Tracebox", Proceedings of the 2013 ACM SIGCOMM conference on Internet measurement conference, DOI 10.1145/2504730.2504757, October 2013, <http://inl.info.ucl.ac.be/publications/revealing-middlebox-interference-tracebox>.

[IMC13b] Chen, Y., Lim, Y., Gibbens, R., Nahum, E., Khalili, R., and D. Towsley, "A measurement-based study of MultiPath TCP performance over wireless network", ICM '13: Proceedings of the 2013 conference on Internet measurement conference, DOI 10.1145/2504730.2504751, October 2013, <http://doi.acm.org/10.1145/2504730.2504751>.

[IMC13c] Pelsser, C., Cittadini, L., Vissicchio, S., and R. Bush, "From Paris to Tokyo: on the suitability of ping to measure latency", IMC '13: Proceedings of the 2013 conference on Internet measurement Conference, DOI 10.1145/2504730.2504765, October 2013, <http://doi.acm.org/10.1145/2504730.2504765>.

[INFOCOM14] Lim, Y., Chen, Y., Nahum, E., Towsley, D., and K. Lee, "Cross-layer path management in multi-path transport protocol for mobile devices", IEEE INFOCOM'14, DOI 10.1109/INFOCOM.2014.6848120, April 2014.

[KT] Seo, S., "KT's GiGA LTE", July 2015, <https://www.ietf.org/proceedings/93/slides/slides-93-mptcp-3.pdf>.

[MBTest] Hesmans, B., "MBTest", October 2013, <https://bitbucket.org/bhesmans/mbtest>.

[Mobicom15]
De Coninck, Q., Baerts, M., Hesmans, B., and O. Bonaventure, "Poster - Evaluating Android Applications with Multipath TCP", Mobicom 2015 (Poster), DOI 10.1145/2789168.2795165, September 2015.

[MPTCP-DEPLOY]
Paasch, C., Biswas, A., and D. Haas, "Making Multipath TCP robust for stateless webservers", Work in Progress, draft-paasch-mptcp-syncookies-02, October 2015.

[MPTCP-LOAD]
Paasch, C., Greenway, G., and A. Ford, "Multipath TCP behind Layer-4 loadbalancers", Work in Progress, draft-paasch-mptcp-loadbalancer-00, September 2015.

[MPTCP-MAX-SUB]
Boucadair, M. and C. Jacquenet, "Negotiating the Maximum Number of Multipath TCP (MPTCP) Subflows", Work in Progress draft-boucadair-mptcp-max-subflow-02, May 2016.

[MPTCPBIB] Bonaventure, O., "Multipath TCP - Annotated bibliography", Technical report, April 2015, <https://github.com/obonaventure/mptcp-bib>.

[MultipathTCP-Linux]
Paasch, C., Barre, S., and . et al, "Multipath TCP - Linux Kernel implementation", <http://www.multipath-tcp.org>.

[NSDI11] Wischik, D., Raiciu, C., Greenhalgh, A., and M. Handley, "Design, implementation and evaluation of congestion control for multipath TCP", NSDI11: In Proceedings of the 8th USENIX conference on Networked systems design and implementation, 2011.

[NSDI12] Raiciu, C., Paasch, C., Barre, S., Ford, A., Honda, M., Duchene, F., Bonaventure, O., and M. Handley, "How Hard Can It Be? Designing and Implementing a Deployable Multipath TCP", NSDI '12: USENIX Symposium of Networked Systems Design and implementation, April 2012, <http://inl.info.ucl.ac.be/publications/how-hard-can-it-be-designing-and-implementing-deployable-multipath-tcp>.

[PaaschPhD]
Paasch, C., "Improving Multipath TCP", Ph.D. Thesis , November 2014, <http://inl.info.ucl.ac.be/publications/improving-multipath-tcp>.

[PAM2016] De Coninck, Q., Baerts, M., Hesmans, B., and O. Bonaventure, "A First Analysis of Multipath TCP on Smartphones", 17th International Passive and Active Measurements Conference (PAM2016) volume 17, March 2016, <http://inl.info.ucl.ac.be/publications/first-analysis-multipath-tcp-smartphones>.

[PAMS2014] Arzani, B., Gurney, A., Cheng, S., Guerin, R., and B. Loo, "Impact of Path Selection and Scheduling Policies on MPTCP Performance", PAMS2014, DOI 10.1109/WAINA.2014.121, May 2014.

[Presto08] Greenberg, A., Lahiri, P., Maltz, D., Patel, P., and S. Sengupta, "Towards a next generation data center architecture: scalability and commoditization", ACM PRESTO 2008, DOI 10.1145/1397718.1397732, August 2008, <http://dl.acm.org/citation.cfm?id=1397732>.

[PT14] Pearce, C. and P. Thomas, "Multipath TCP Breaking Today's Networks with Tomorrow's Protocols", Proc. Blackhat Briefings, 2014, <http://www.blackhat.com/docs/us-14/materials/us-14-Pearce-Multipath-TCP-Breaking-Todays-Networks-With-Tomorrows-Protocols-WP.pdf>.

[PZ15] Pearce, C. and S. Zeadally, "Ancillary Impacts of Multipath TCP on Current and Future Network Security", IEEE Internet Computing, vol. 19, no. 5, pp. 58-65, DOI 10.1109/MIC.2015.70, September 2015.

[RFC1812] Baker, F., Ed., "Requirements for IP Version 4 Routers", RFC 1812, DOI 10.17487/RFC1812, June 1995, <http://www.rfc-editor.org/info/rfc1812>.

[RFC1928] Leech, M., Ganis, M., Lee, Y., Kuris, R., Koblas, D., and L. Jones, "SOCKS Protocol Version 5", RFC 1928, DOI 10.17487/RFC1928, March 1996, <http://www.rfc-editor.org/info/rfc1928>.

[RFC2992] Hopps, C., "Analysis of an Equal-Cost Multi-Path Algorithm", RFC 2992, DOI 10.17487/RFC2992, November 2000, <http://www.rfc-editor.org/info/rfc2992>.

[RFC4987] Eddy, W., "TCP SYN Flooding Attacks and Common Mitigations", RFC 4987, DOI 10.17487/RFC4987, August 2007, <http://www.rfc-editor.org/info/rfc4987>.

[RFC6356] Raiciu, C., Handley, M., and D. Wischik, "Coupled Congestion Control for Multipath Transport Protocols", RFC 6356, DOI 10.17487/RFC6356, October 2011, <http://www.rfc-editor.org/info/rfc6356>.

[RFC7430] Bagnulo, M., Paasch, C., Gont, F., Bonaventure, O., and C. Raiciu, "Analysis of Residual Threats and Possible Fixes for Multipath TCP (MPTCP)", RFC 7430, DOI 10.17487/RFC7430, July 2015, <http://www.rfc-editor.org/info/rfc7430>.

[RFC7871] Contavalli, C., van der Gaast, W., Lawrence, D., and W. Kumari, "Client Subnet in DNS Queries", RFC 7871, DOI 10.17487/RFC7871, May 2016, <http://www.rfc-editor.org/info/rfc7871>.

[SIGCOMM11] Raiciu, C., Barre, S., Pluntke, C., Greenhalgh, A., Wischik, D., and M. Handley, "Improving datacenter performance and robustness with multipath TCP", SIGCOMM '11: Proceedings of the ACM SIGCOMM 2011 conference, DOI 10.1145/2018436.2018467, August 2011, <http://doi.acm.org/10.1145/2018436.2018467>.

[SOCKET] Hesmans, B. and O. Bonaventure, "An enhanced socket API for Multipath TCP", Proceedings of the 2016 Applied Networking Research Workshop, DOI 10.1145/2959424.2959433, July 2016, <http://doi.acm.org/10.1145/2959424.2959433>.

[StrangeMbox] Bonaventure, O., "Multipath TCP through a strange middlebox", Blog post, January 2015, <http://blog.multipath-tcp.org/blog/html/2015/01/30/multipath_tcp_through_a_strange_middlebox.html>.

[TMA2015] Hesmans, B., Tran Viet, H., Sadre, R., and O. Bonaventure, "A First Look at Real Multipath TCP Traffic", Traffic Monitoring and Analysis, 2015, <http://inl.info.ucl.ac.be/publications/first-look-real-multipath-tcp-traffic>.

[TR-348] Broadband Forum, ., "TR 348 - Hybrid Access Broadband Network Architecture", Issue: 1, July 2016, <https://www.broadband-forum.org/technical/download/TR-348.pdf>.

[tracebox] Detal, G. and O. Tilmans, "Tracebox: A Middlebox Detection Tool", 2013, <http://www.tracebox.org>.

Acknowledgements

This work was partially supported by the FP7-Trilogy2 project. We would like to thank all the implementers and users of the Multipath TCP implementation in the Linux kernel. This document has benefited from the comments of John Ronan, Yoshifumi Nishida, Phil Eardley, Jaehyun Hwang, Mirja Kuehlewind, Benoit Claise, Jari Arkko, Qin Wu, Spencer Dawkins, and Ben Campbell.

Authors' Addresses

Olivier Bonaventure
UCLouvain

Email: Olivier.Bonaventure@uclouvain.be

Christoph Paasch
Apple, Inc.

Email: cpaasch@apple.com

Gregory Detal
Tessares

Email: Gregory.Detal@tessares.net