Multipath Transmission for Wireless Internet Access -
From an End-to-End Transport Layer Perspective

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Abstract

With the growing demand of Internet services, network operators have put significant efforts to improve network error resilience and efficiency. Since there exist different wired/wireless technologies for Internet access such as digital subscriber line (DSL), Ethernet, and worldwide interoperability for microwave access (WiMax), a mobile host can use multiple access networks simultaneously with multipath transmission. Taking the advantage of heterogeneous environment, multipath transmission through the Internet can improve service reliability and network flexibility. Ensuring a reliable end-to-end connection-oriented communication with satisfactory quality of service (QoS) and maintaining congestion control and flow control are the main responsibilities of the Transmission Control Protocol (TCP), the dominant transport layer protocol in the Internet. In this paper, we survey the state-of-the-art of multipath transmission techniques for QoS provisioning in wireless Internet access, focusing on the end-to-end transport layer protocols. The main challenges for the design of multipath TCP are reviewed, and the existing transport layer congestion control schemes are categorized. Multipath TCP and stream control transmission protocol (SCTP)-based transport layer protocols are discussed, and their limitations and/or impractical assumptions are addressed. Open research issues on the development of an effective, efficient, and practical multipath TCP protocol are summarized.

Keywords: Multipath, TCP, Internet, transport layer, congestion control

1 Introduction

The Internet is a global information platform which consists of interconnected computer networks linked by wirelines, fiber-optic cables, wireless links, etc. The success of the Internet comes from its capabilities to provide robust and reliable end-to-end data transmission services for various applications. It provides a transmission infrastructure for a wide range of services such as email, file sharing, and media streaming, using packet switching technologies and the Transmission Control Protocol/Internet Protocol (TCP/IP) protocol stack. Data packets of various traffic flows share network resources on a "best effort" basis. In this way, each carrier in the network does its best to deliver the packets to their destinations.

The global IP traffic in the year 2005 was 2 exabytes per month. In 2010, it has been increased to 20.2 exabytes per month and, according to the Cisco VNI forecast, eventually it is anticipated to reach 80.5 exabytes per month by 2015. Also, the busy-hour traffic will increase fivefold by 2015 as compared to 2010, while the average traffic will increase fourfold [**1**,**2**]. These statistics show the urgent need of higher network capacity and more intelligent management. In addition to the growth of Internet traffic volume, new applications also require more stringent and diversified quality-of-service (QoS). High-speed, always-connected, everywhere-available Internet access with much restrictive failure tolerance becomes necessary in the near future. Providing all these necessities forces the Internet to become an increasingly complex system.

As the demand on the Internet services grows, network operators have begun to use traffic engineering to improve resilience against link or node failure and to increase transmission efficiency. This can be viewed as a significant evolution which results in the Internet to be reshaped [**2**]. This evolution makes end systems to be involved in managing traffic. By simultaneous use of multiple paths on the Internet by a pair of end hosts, there is a potential to greatly improve information delivery performance, efficiency, and flexibility [**3**]. In this paper, we focus on multipath transmission through wired/wireless networks as a solution to manage resources for the ever-growing Internet.

The Internet growth in the wired networks has been successful over the past decades. The convergence of wireless systems and the Internet in information infrastructure was predicted because of the increasing demand for ubiquitous Internet access [**4**,**5**]. However, there are many technical challenges in mobile wireless networks that do not exist in the wired Internet. Multipath fading, path loss, and shadowing degrade transmission performance. Error control and diversity techniques can mitigate the channel impairments. However, user mobility, multiple access interferences, and channel characteristics result in variable throughput in these networks [**5**]. QoS support in wireless networks has been a focus of recent research [**6**,**7**,**8**,**9**]. Especially for multimedia services, various applications have different QoS requirements and traffic characteristics, which lead to more complicated engineering problems [**5**]. Challenges in mobile wireless networks are considered as an important part of the Internet quality improvement research, so interworking with the Internet is an important aspect in the development of new wireless networks. Recently, new wireless infrastructures are designed to be more compatible with the Internet. As an example, wireless broadband networks such as 3G LTE and WiMax[1] are IP-based with over-the-top services at the application layer, which is similar to the Internet design [**10**].

There are various wireless networks with different access technologies and applications. Each has its own unique features and is optimized for its target applications and networking environment. Thus, the challenges in providing Internet access through wireless networks vary in different networks. There are four major characteristics in mobile wireless communications: channel fading, mobility, channel contention, and limited transmission power [**11**]. Using different wired/wireless network capabilities together can benefit the Internet QoS provisioning. Therefore, multipath transmission through the Internet becomes attractive, which has already been a hot research area [**12**,**13**,**14**,**15**,**16**,**17**,**18**].

In this paper, we survey on the state-of-the-art of multipath transmission for QoS provisioning in wireless Internet access, from an end-to-end transport layer perspective. In Section 2, we introduce multipath transmission through the Internet. Existing solutions in the network layer and lower layers are reviewed briefly. Multipath transmission challenges from the transport layer as an important aspect are discussed. Section 3 presents various issues in multipath TCP design. Multihoming is a necessity for a multipath TCP connection. Concurrent multipath transmission is introduced as the next step to get the benefits of multipath transmission. Load sharing and resource pooling are categorized to improve the multipath transmission throughput in the transport layer. Fairness and stability measurements for the transport layer algorithms are also discussed in Section 3. Transport layer algorithm categorization and recent multipath TCP algorithms are gathered in Section 4. Finally, open research issues are discussed in Section 5.

2 Multipath transmission through the Internet

Nowadays, there are different wired/wireless technologies for the Internet access such as DSL[2], Ethernet, and WiMax. So, multiple networks become available to a mobile host. For example, various wireless interfaces can be available for a mobile device such as a cell phone. Various wireless networks can cooperate with each other, if their coverage areas overlap, in order to improve service quality. An environment or region in which the coverage areas of different wireless networks overlap is called heterogeneous wireless environment and those networks are heterogeneous networks [**19**]. Multipath transmission is to use multiple paths from different networks in a heterogeneous environment to

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[1] Third generation (3G) Long Term Evolution (LTE) cellular systems and Worldwide Interoperability for Microwave Access (WiMax).

[2] Digital Subscriber Line

connect a source and a destination. Generally, cooperation among available networks is expected to improve data transmission throughput, and to utilize resources in each network more efficiently [**20**]. Multipath transmission can be applicable using transport layer solutions without any cooperation among different networks. As various network resources are available in a region, end hosts can enjoy increased network capacity via simultaneous multipath utilization [**21**]. Therefore, this heterogeneous scenario is expected to be much beneficial for the future Internet.

Multipath TCP is proposed by the Internet Engineering Task Force (IETF) working group [**16**]. It allows one data stream to split over multiple paths in transmission. This has many advantages such as improving reliability, so that a connection can be maintained when one of its paths fails. Also, it can help to achieve load balancing at multihomed servers and data centers [**22**]. It should be noted that, for a long period, multipath algorithms were being designed for the Internet layer and below. Thus, for each end-to-end connection, the data streams transmitted over multiple paths are considered equivalent to a single stream from the transport and application layers' perspective [**23**].

Multipath transmission should be established through different paths. The paths can be wired paths in the Internet or wired/wireless paths in a heterogeneous environment [**22**].

Examples of both multipath schematics are illustrated in Figure 1, where the mobile user has access to the Internet through three different networks (a WiMax system, a 3G cellular network, and a wired network). Multipath transmission can be done through different layers or be transparent to them. For example, many previous multipath schemes have been proposed for the network layer, which is seen as a single stream at the transport layer. The user should be capable of simultaneously connecting to several networks. Some other conditions should also be met based on the multipath strategy to be discussed later.

Internet traffic flows can have various characteristics because of the variety of Internet services and applications. A flow may last for a long time (long-lived flow), so that the multipath transmission controller can decide how to manage it in multipath links. On the other hand, a flow may last only for a short period (short-lived flow), which may make it not worthy to send the flow over multiple paths [**24**].

2.1 Potential benefits of multipath Internet

As networking technologies advance, it is expected that more end users are equipped with multiple wireless network interfaces for Internet access. Therefore, multiple paths become available between a pair of source and destination hosts. Multipath transmission between a pair of source and destination hosts is defined simply as sending some packets along one path and other packets along other paths, which is an elegant solution to enhance end-to-end information delivery over a heterogeneous environment [**25**].

It is obvious that the only way to achieve reliable end-to-end transmission is through redundancy to overcome unreliable components due to unreliable and/or congested links, and multipath transmission is such an approach. Thus, when a path fails, the connection interruption can be avoided by switching from that path to another one. However, switching (or handoff in a wireless environment) between paths may cause intolerable delay and/or packet loss. Therefore, a well-designed mechanism for multipath transmission is needed to provide required reliability [**23**].

As another potential, flexibility in sharing resources in different networks is achievable through multipath transmission by splitting the traffic into independent paths [**25**]. For example, a mobile host can have access to the Internet via multiple access links such as Bluetooth, WiFi and cellular network modem, each of which has its corresponding service provider. The decision of selecting which network to use for a specific data transfer should be made considering bandwidth, throughput, latency, jitter, QoS requirements, cost, power consumption, interference, and traffic patterns [**23**]. The simultaneous use of multiple paths in data transmission to enhance the overall bandwidth available to a wireless node is an advantage of multipath transmission, in terms of high transmission rate, low packet loss rate, and low transmission delay [**22**,**26**,**27**,**28**]. As a result, it is desirable to stream data packets across all interfaces simultaneously whenever necessary.

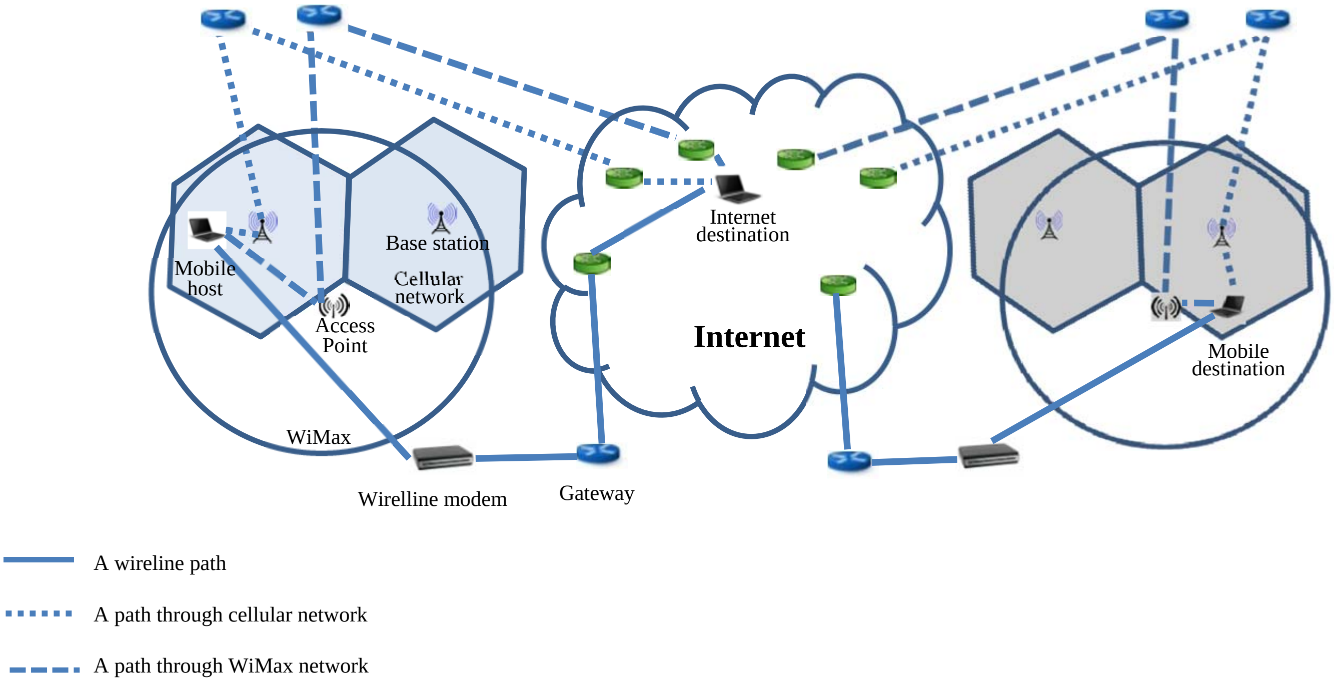


Figure 1. Multipath transmission through different wired/wireless networks

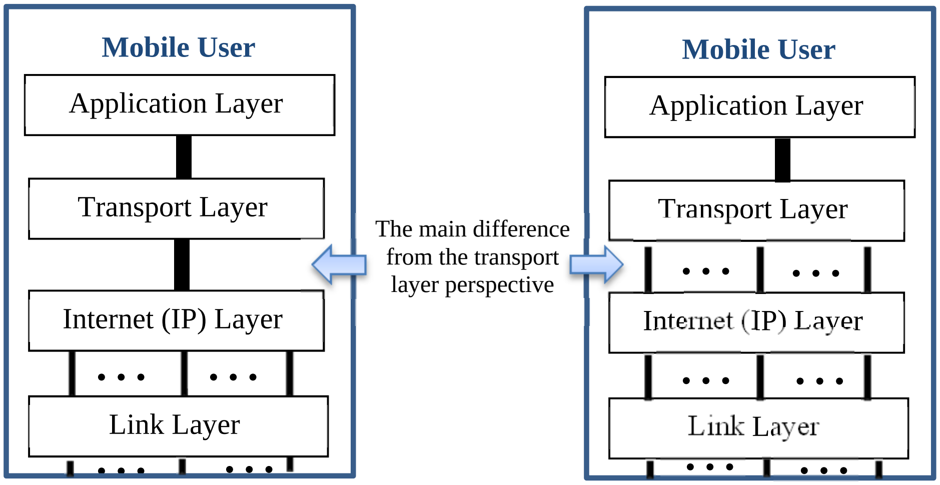
2.2 Multipath transmission at different protocol layers

Multipath transmission has been considered for different network protocol layers. Different solutions are proposed to make use of available paths to improve transmission reliability. Dividing an end-to-end traffic flow to send information on independent paths and making path selection decisions can be associated with any layer. As unique responsibilities are defined for each of the network protocol stack layers, multipath solutions at different layers have different philosophies, advantages, and limitations. Mathematical description of the protocol layers makes these differences clear [**29**]. In the following, some multipath solutions from the network layer and link layer are reviewed briefly. More information can be found in [**30**,**31**].

The issue of simultaneous data striping across multiple network paths is discussed in [**23**,**30**] (and references therein) for the network (IP) layer (layer 3). Multipath routing formulation is described in [**29**]. Layer 3 is chosen to prevent the transport layer and higher layers from any modifications. Therefore, the data flow looks like a single stream for the transport layer as illustrated in Figure 2(a). It is assumed that there is a single network interface with different routes available to the destination. The solution is IP encapsulation similar to tunnelling in the mobile IP standard [**23**]. Generally, multipath routing can improve end-to-end reliability and avoid congested paths. However, it also introduces extra overhead in both the control plane and data plane of the routers and/or packet reordering which is very harmful to TCP [**30**].

Bandwidth aggregation has also been done at the link layer. For example, Cisco provides bandwidth aggregation across multiple Ethernet links [**1**]. However, link layer design is mainly internetwork solutions which are not applicable in a heterogeneous environment [**32**]. There are also many cross-layer design solutions for multipath transmission especially between the link layer and network layer. The joint problem of multipath routing and link-layer resource allocation is considered in [**29**], while joint network layer and transport layer approaches are proposed in [**3**,**33**].

All these approaches, except the cross-layer design, are transparent to the transport and application layers [**32**]. However, new studies focus on end-to-end transport layer algorithms as congestion avoidance and reliability provisioning can be achieved directly at the transport layer.



(a) The Internet layer approach

(b) The transport layer approach

Figure 2. Network protocol stack with multipath transmission

2.3 Multipath Internet from the transport layer viewpoint

TCP as the most well-known transport layer protocol for the Internet performs well in the primary Internet scenario in which only one path is exploited, delay and congestion losses are tolerable or avoidable. When these homogeneities do not exist, multipath transmission can help to improve network performance. It is shown that one-path TCP design does not work for a heterogeneous case in which different paths have different delays and bandwidths [**19**]. Multipath TCP, as proposed by the IETF working group, allows a single data stream to be split across multiple paths. Thus, from an end-to-end point of view, a new mechanism is needed to manage this association and to control traffic congestion.

The end-to-end connection should be considered to achieve simultaneous connections via different paths between two end hosts. Ensuring a reliable end-to-end connection while delay, congestion, and flow are under control to satisfy the required QoS is the transport layer responsibility [**34**]. Generally, the following issues should be dealt with at the transport layer in order to manage multipath transmission among different networks:

1. How to manage data segments in simultaneous transmissions
2. How to avoid or eliminate congestion occurrence using multipath transmission
3. How to avoid packet loss due to handover of mobile hosts between heterogeneous wireless networks
4. How to avoid packet reordering due to different delays from different paths/networks.

All these issues in multipath transmission can be addressed from an end-to-end transport layer point of view. Dealing with multipath transmission at the transport layer becomes more attractive recently, as the design transparency strategy at the transport layer is shown to be impossible. The lower layers cannot completely remove all differences in delay, packet orderings and losses to make multiple paths act as a single path for the transport layer. Also, transport layer design has some unique advantages. Below the transport layer, shifts of traffic between paths cannot be controlled as the information is too coarse [**35**]. Therefore, the transport layer design is necessary for an efficient implementation of multipath transmission.

In the following, multipath transmission is considered from an end-to-end transport layer viewpoint.

TCP over wireless networks

TCP designed for the wired Internet faces inevitable challenges for wireless networks. In wired communications, traffic congestion is the main cause of packet losses. Unfortunately, wired and wireless networks are significantly different in terms of bandwidth, propagation delay, and link reliability. Thus, the original TCP by itself is not a good solution for wireless environment [**36**].

With layered Internet architecture, it is assumed that channel fading due to user mobility affects only the physical layer, and other layers are independent of channel behaviours. However, it is well known that TCP performance degrades in mobile wireless environment. Hence, we need to understand mobile wireless network characteristics from the transport layer and its influence on the TCP mechanism.

In mobile wireless network, the fading dispersive channel causes a high bit error rate. The unreliable nature of the wireless medium results in significant packet losses, which are treated as indication of network congestion. Also, bursts of packet loss can occur during the handoff of mobile hosts between base stations, access points, or networks. Packet loss due to channel fading and shadowing can be eliminated at the physical layer and link layer as much as possible. But, congestion control suffers from the remaining loss as TCP cannot distinguish between different error sources. It assumes that all packet losses are due to congestion. Thus, providing the mobile host with a high level of QoS is a challenging issue in a wireless Internet [**7**,**37**]. Another characteristic of wireless networks is the broadcasting nature of wireless channel, which may lead to channel contention. Depending on channel access mechanisms, signals may interfere with each other. Hence, a collision occurs and the transmissions fail. On the other hand, it is shown that the total energy consumed for TCP is inversely proportional to its goodput [**34**]. Taking account of the limited power and energy of a mobile device, to conserve energy, it is very important to minimize the number of transmissions and perform necessary operations in an efficient manner.

Various solutions have been proposed in the literature to improve TCP performance in mobile wireless networks [**5**,**7**,**11**,**12**,**22**,**38**,**39**]. These approaches can be divided into three categories. The first category is congestion detection approaches, in which the researchers try to distinguish random loss and burst loss from congestion. Congestion detection approaches can be reactive, which use the feedback from acknowledgements to update the TCP parameters and choose the proportional TCP phase. Congestion detection can also be proactive, which uses the network condition to estimate link bandwidth or other link parameters. Then, the flow rate is managed based on the TCP phases. In reactive approaches, after a packet is dropped and the event is reported to the sender, TCP makes a necessary adjustment. But in proactive methods, packet loss is avoided as much as possible based on the estimation and decision accuracy. The second category in existing solutions is state suspension, which stops any changes in the flow rate until the mobility or burst loss stops completely. The third category is response postponement in which the receiver waits before making any decision for sending time-out notification or duplicate acknowledge. Therefore, the transmission condition becomes clear, and incorrect decisions can be avoided [**4**,**11**].

Heterogeneity in wireless technologies and multipath transmission

Heterogeneous wireless networks make it possible to access the Internet anytime and anywhere [**40**]. In a heterogeneous scenario where mobile users are equipped with multiple radio interfaces, the transport layer faces new challenges. Existing transport layer protocols cannot manage an end-to-end connection in which the source node transmits data through different radio interfaces simultaneously [**11**]. TCP requires a strict byte-order delivery that cannot tolerate various path delays. In heterogeneous wireless networks, segments experience different delays because of the disparity in network infrastructures. Also, propagation attenuation, shadowing and fading can result in different transmission delays in wireless networks. When segments are delivered with different delays, one segment may arrive later than its subsequent segments. This phenomenon is called out-of-order delivery and causes the TCP congestion control algorithm to reduce the sending rate mistakenly.

As a result, a new transport layer algorithm is needed to manage this concurrency. The algorithm should support bandwidth aggregation by exploiting the availability of multiple radio interfaces [**6**,**39**]. For multipath transmission in heterogeneous networks, modifications are required to the congestion control algorithm. Context-aware evaluation and management of heterogeneous wireless connectivity is discussed in [**38**]. Transport layer design for heterogeneous wired/wireless networks has become the most important research issue in multipath transmission.

Transport layer challenges

The most well-known transport layer protocol in the Internet is TCP [**34**]. An obvious question for multipath transmission from the transport layer viewpoint is why not just run the regular TCP congestion control on each path. One reason is the introduced complexity in the application layer for the path discovery, which is not desirable. Another reason is the unfairness problem in parallel TCP. For example, in a scenario of two paths with similar round trip times (RTTs), if we run the regular TCP on both paths, the multiple path flow would obtain twice as much throughput as the single path flow, which is not fair. A straightforward solution is to run weighted TCP on each sub-flow based on the available bandwidths, as discussed in [**22**]. However, for the paths with heterogeneous characteristics such as having different RTTs, this approach can degrade throughput performance [**23**]. That is, using multiple paths can result in much worse performance than when a single path is used alone. Thus, new congestion control algorithms are needed for a heterogeneous scenario, which are briefly discussed in the following sections.

For TCP multipath transmission, it is necessary to know how network capacity should be shared efficiently among competing flows. The multipath TCP problem for the Internet is somewhat similar to cooperation in heterogeneous networks from an end-to-end connection point of view.

3 Multipath TCP

Multipath TCP is a general concept that needs multihoming as a necessary condition to make multipath transmission possible for end users. Concurrent multipath transmission, load sharing, and resource pooling can be added to the multihoming necessity to improve multipath transmission throughput. Along with these conditions, fairness and stability of multipath TCP should be studied.

3.1 Multihoming

In general, in an end-to-end connection over the Internet, each of the two end hosts has a unique IP address. When an end host has multiple interfaces for transmission, it has multiple IP addresses, each associated with one interface. Supporting the connection between two end users via multiple IP addresses is called multihoming (transport layer support for multihoming). It allows binding of one transport layer's association to multiple IP addresses at each end of the association. This binding allows a sender to transmit data to a multihomed receiver through different destination addresses [**32**,**41**,**42**]. Thus, multihoming is essential for simultaneous connections in heterogeneous networks. In [**43**], an analysis is presented on how much benefit multihoming can provide, in terms of path diversity across available service providers in an overlapped area of networks. It includes two case studies: data center and enterprise multihoming, where the latter has more than 25% of performance improvement from multihoming in the specified experiment. Inexpensive Internet access makes content providers have simultaneous connections between Internet service providers (ISPs) using multihoming [**41**]. Currently, multihoming is a common requirement in many networks to provide link redundancy and bandwidth usage optimality.

However, TCP and UDP[3] do not support multihoming. There are proposals to modify TCP, so that it can support multihoming [**44**]. In [**41**], multihoming is implemented using the well-designed Fast-TCP protocol [**45**]. But, most of the ideas are not applicable in a heterogeneous scenario. The first reliable transport layer standard which supports multihoming is the stream control transmission protocol (SCTP) [**46**]. Datagram congestion control protocol (DCCP), as an unreliable datagram congestion control protocol, also supports multihoming, but only for mobility support. It means that DCCP multihoming is useful only for connection migration and cannot be used for concurrent multipath transmission [**47**,**48**,**49**]. Therefore, most of the multihoming solutions for the transport layer are based on the existing SCTP protocol [**42**,**50**,**51**,**52**,**53**,**54**,**55**,**56**].

SCTP is standardized by the IETF as a reliable transport protocol [**57**]. It has many important features of TCP, such as window-based congestion control, error detection and retransmission [**42**,**46**]. It also has new features that are not available in TCP. The two most valuable features are multihoming and multi-streaming. In SCTP, multihoming is enabled by letting two endpoints set up a connection with multiple IP

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[3] User datagram protocol used at the internet transport layer

addresses (an association) for each endpoint. One of those addresses is labelled as a primary and the others as backup addresses. This makes SCTP able to communicate between two endpoints using multiple links. One of the IP addresses is designated as the primary, while the others are used as a backup in case of failure of the primary path. Retransmission of lost packets can also be done over a secondary address [**57**]. Selection of the primary path (which should be the best available path) is considered in [**51**] for SCTP multihoming. In [**50**], the authors implement a native IPv6 UMTS–WLAN test-bed to investigate the multihoming SCTP performance. Their results show that the SCTP performance is significantly affected by the SCTP parameter setup. Using well-chosen parameters, connection interruptions can be minimized. In [**42**,**56**,**58**], SCTP is discussed as a seamless handoff management solution in heterogeneous wireless networks. A survey on multihoming management for the future Internet from different protocol layer perspectives is presented in [**59**].

3.2 Concurrent multipath transmission

Load sharing is a bandwidth aggregation technique that utilizes the available paths for simultaneous transmission of data packets [**60**]. This can be achieved in the transport layer through concurrent multipath transmission (CMT). CMT is the concurrent transfer of new data from a source to a destination via two or more independent paths. The idea of CMT is to use the multihoming feature to distribute data across multiple end-to-end paths. Hence, CMT is one of the most important motivations for making SCTP support multihoming [**54**].

In multi-homed algorithms for the transport layer, load sharing cannot be performed efficiently by itself. This is due to the significant packet reordering observed at the destination, when different paths with different delays are used for data delivery. Reported reordering makes TCP-based algorithms react with congestion window reduction and unnecessary fast retransmission, which limits the overall throughput. Also, since window-based congestion control only increases the congestion window for a path when an incoming ACK advances the highest sequence number acknowledged, the congestion window grows too slowly. When packets are delivered to the receiver out of order over multiple paths, the receiver will send back too many ACKs even if packet loss does not happen. Therefore, the rate of ACKs should be reduced when load sharing is used [**54**]. To resolve the inefficient load sharing problem, different approaches are suggested [**17**,**18**,**52**,**54**,**61**]. LS-SCTP and CMT-SCTP are two successful methods based on which many multipath TCP algorithms are developed.

Load sharing SCTP (LS-SCTP), a SCTP-based load sharing technique, has been proposed in [**52**], in which the congestion control is performed on a path basis, while the flow control is on an association basis. Thus, both source and destination endpoints use their association buffers to hold the data packets regardless their transmission paths. As congestion control is performed on a per path basis, the source has separate congestion control for each path. This provides the sender endpoint with a virtual congestion window size equal to the aggregate of the congestion windows of all the paths within the association. It should be noted that the standard SCTP does not separate the flow and congestion control mechanisms. To support load sharing, LS-SCTP has two sequence numbers for each data block in the transmitted path, one for the packet block in the whole flow (Association Sequence Number) and the other for the packet block in the transmitted path (Path Sequence Number). In the ACK, the packet arrival is verified by both association and path sequence numbers. Also, the time that the ACK is sent is included in the ACK to let the sender be aware of the information update time. This is to deal with the fact that different links have different delays. On the other hand, out of order arrivals of ACK packets can cause the sender to develop an incorrect view of the receiver’s information. Thus, the reception of an old ACK does not change its window size based on the old ACK. As LS-SCTP utilizes multiple paths for a transmission, a failure of a single path or an increase in the packet loss rate can affect the whole association throughput. Hence, LS-SCTP includes a path monitoring mechanism that is responsible for updating quality of paths in terms of loss rate, delay, etc. It can be done using the association feedback. With a specific threshold for path quality, some paths may be removed or added to the load sharing paths. The path monitoring mechanism continues to monitor the removed paths for adding them back again later when necessary, if their conditions improve.

CMT-SCTP is another algorithm which distributes data packets across multiple end-to-end paths. It consists of three sub-algorithms to overcome the above reordering side-effects [**17**,**54**]. CMT schedules new data packets to different paths as bandwidth becomes available on corresponding paths, i.e. if the corresponding congestion windows permit to do so. When a congestion window space is available simultaneously for two or more destinations, data packets are sent to these destinations in an arbitrary order. The choice of using the full bandwidth of a path before using the other paths is to reduce reordering. It is shown in [**61**] that, using CMT, payload throughput increases by increasing the number of disjoint paths. However, the throughput decreases by decreasing the destination buffer [**17**]. Also, CMT performance degrades due to buffer blocking. The buffer blocking is a side effect of CMT, in which the destination buffer becomes full of out-of-order packets, and the receiver is waiting for the in-order packet to arrive. Mobile CMT is an algorithm to decrease the buffer blocking occurrence by eliminating handover packet loss [**18**].

It is necessary for the CMT to have enough information about the paths (such as congestion level or path delay) in order to make the best decision on path selection and bandwidth aggregation. SCTP has some kind of path probing for path condition, but these path samplings are infrequent. Therefore, increasing the sampling rate is inevitable for CMT, which leads to overload the traffic in the system [**58**]. Many multipath transport layer improvements have been proposed based on The CMT over SCTP [**18**,**62**,**61**,**63**,**64**].

3.3 Load balancing

Load balancing is the act of moving data traffic away from more-congested paths to less-congested paths until the congestion level of all the paths becomes equalized. This issue is mostly addressed in the routing level at the network (IP) layer. However, congestion control should be responsible for congestion and should shift the traffic from congested paths to uncongested ones for multipath capable flows. In this way, the Internet will be more capable to manage traffic surges and utilizing the available resources [**65**]. When the traffic is removed away from congested paths, the packet loss rate over the congested paths decreases and that over the new paths increases. The changes continue until the associated packet loss rates tend to equalize. This is a kind of load balancing in the transport layer. Furthermore, load balancing is desirable at the transport layer since it has the most accurate information about end-to-end transmission characteristics. CMT can use feedback to get sufficient information on the congested paths (such as in terms of the transmission delay or packet loss rate) and make the best decision [**66**]. Therefore, load balancing or more generally resource pooling [**24**] becomes a new challenge in multipath transmission as different paths with concurrent multipath transmissions become available [**24**,**66**,**67**,**68**,**69**,**70**,**71**,**72**]. One way to achieve local balancing, fairness, and stability is joint tuning the congestion windows of different paths [**66**]. Three main objectives can be set for congestion control based on CMT-SCTP and the idea of resource pooling [**61**]. First, a concurrent multipath transmission/resource pooling (CMT/RP) flow should have a throughput gain over a single-homed flow. Thus, it should get at least as much bandwidth via the best path as a single-homed flow. Second, a CMT/RP protocol should be fair. It should not take more bandwidth on a shared bottleneck path than a single-homed flow via the same bottleneck. Third, resource pooling should be carried out in such a way that a CMT/RP flow should balance congestion on all of its paths. Aiming at these goals, the slow start thresholds are used as a useful metric for the available bandwidth of paths. The congestion window is increased based on the normalized slow start threshold, for similar link characteristics [**61**]. The problem of load balancing for dissimilar links is considered by the IETF [**55**] and more recently in [**63**]. . As resource pooling can provide higher throughput, lower latency, and better error resiliency, how to achieve load balancing in the context of multipath transmission is a main challenge in a heterogeneous wireless environment.

Multihoming, concurrent multipath, and load balancing are discussed as the main issues for the multipath transmission from the transport layer perspective. However, there are other issues which should be considered in every transport layer design. Fairness and stability are the two performance criteria that should be met in every algorithm/protocol designed for the transport layer [**73**]. Fairness from an end-to-end viewpoint is achieved if, at the equilibrium, the bandwidth is shared equally among the sources using only the information available to the end hosts without any help from intermediate nodes or routers [**74**,**75**]. The existence of any fair end-to-end congestion control scheme is studied in [**75**]. Different solutions have been proposed for a fair multipath transport layer algorithms [**13**,**61**,**62**,**67**,**75**,**76**]. With independent congestion control for each path, fairness is not applicable against non-CMT flows. In such a scenario, multipath association with N paths takes the bandwidth, which is

N times of single non-CMT path bandwidth. Authors in [**62**] combine CMT with resource pooling, taking account the fairness of congested links. They use the multihoming capability of SCTP and improve the data throughput along with fair bandwidth sharing among the existing flows. Having an improved fair resource sharing across non-CMT algorithms is also considered in the MPTCP algorithm [**65**] and CMT/RPv2 [**61**]. In the most cases, fairness can be achieved at the cost of an end-to-end delay increase [**76**]. A special kind of fairness, which is important in the Internet, is TCP-friendliness. TCP-friendliness means that a protocol should behave as TCP from the traffic viewpoint, in such a way that the average throughput of non-TCP supported flows remains around the average throughput of TCP flows [**7**,**60**,**77**]. Therefore, the protocols can be deployed in the Internet without much concern on fairness to other traffic [**62**]. The SCTP congestion control for each individual path is TCP-friendly. TCP-friendliness of the CMT SCTP is discussed in [**62**], while DCCP-based TCP-friendliness is considered in [**7**] for hybrid wired/wireless networks. Stability is another performance measure which should be considered for every transport layer protocol as any unstable system may experience unpredictable behaviours. A stable system avoids performance oscillations in the steady-state [**78**]. Stability of Internet congestion control with heterogeneous delays is discussed in [**79**,**80**]. It is shown that congestion control algorithms tend to be unstable in multiple non-similar paths.

4 Transport layer protocols

Various proposals appear in the literature over the past decade in the area of multipath transport layer design. But, existing protocols suffer from difficulties in guaranteeing QoS, while seeking optimal resource allocation, managing delays, and having scalable additive increase-multiplicative increase (AIMD) congestion control mechanism. A new congestion control protocol is required to be scalable, reliable, and stable for the future Internet and be suitable for a heterogeneous environment [**2**].

Regular congestion control algorithms for the one-path scenario are reviewed in [**6**,**34**,**81**], and congestion control for the best effort traffic in the Internet is discussed in [**60**]. In this section, different types of congestion control algorithms are reviewed, and existing algorithms for a multipath transport layer are discussed. Basically, multipath transport layer protocols include two categories: SCTP-based solutions and multipath-TCP ones, as discussed in Subsections 4.2 and 4.3 respectively.

4.1 Transport layer congestion control

In order to develop a congestion control protocol for multipath TCP, it is necessary to understand different types of congestion control protocols for single-path flows. In the following, existing congestion control protocols are categorized and summarized.

Multicast vs. unicast: Based on the application, a congestion control protocol should be unicast for a one-source to one-destination flow, or multicast for one-source to many-destination flows in Internet. Multicast congestion control is more challenging than unicast as traffic should be distributed along many paths to different destinations [**82**]. Thus, a multicast scenario is similar to multipath TCP in terms of more than one path, but is completely different from multipath TCP in the number of destinations. Multipath TCP is always between one source and one destination, which is a unicast scenario. Examples of multicast congestion control protocols for multimedia traffic are given in [**83**,**84**].

Loss-based vs. delay-based: There are two kinds of congestion control appeared in the literature, delay-based and loss-based congestion control. The congestion control in current mainstream TCP (TCP-Reno) is loss-based, which reacts to packet loss occurrences indicated by receiver acknowledgements. Most of the TCP congestion control algorithms are loss-based. They change the congestion window based on the detected congestion losses from the feedback. Any losses are treated as a congestion indication. SCTP is also a loss-based protocol. Recently, delay-based congestion control becomes more attractive because of its congestion predictability [**85**]. In delay-based congestion control protocols, the queuing delay is used as a congestion measure to prevent packet loss [**45**,**86**] such as in Fast-TCP. Delay-based congestion avoidance provides more performance improvement than loss-based approaches at a higher transmission rate [**45**]. For a large window size, the queuing delay is not an accurate predictor of congestion level. In large bandwidth-delay product applications, using a delay-based protocol to augment the basic AIMD of TCP is not a good approach. Instead, a fully delay-based protocol can be useful [**45**], where congestion loss rarely happens but the queuing delay can be estimated more accurately. Another advantage of delay-based design in wireless networks is the ability to distinguish random loss due to dispersive fading channels from that due to congestion loss. In loss-based protocols, it is needed to apply a threshold or mechanism to distinguish random loss from congestion loss. Different aspects of delay-based congestion control are discussed in [**80**,**87**,**88**,**89**]. The delay may be affected by many factors such as the time-varying wireless channel and the dynamics of routing. Therefore, using the delay as the only congestion indication can also be error prone.

Flow-level vs. packet-level: The congestion control can be implemented at two levels: packet level and flow Level. The flow-level design has a macroscopic view of the congestion control. It aims at achieving high utilization, low queuing delay and loss, proper fairness and stability. The packet-level design implements the flow-level goals within the constraints imposed by end-to-end control. Historically, in congestion control protocol development such as TCP-Reno, the packet-level control is first developed, and the flow-level control is then added for the required stability and fairness. For more recent protocols such as Fast-TCP and SCTP, the packet-level design is guided by the flow-level design [**2**,**45**].

Rate-based vs. window-based: Congestion control can be window-based or rate-based [**2**]. Window-based congestion control protocols are mainly based on the generic AIMD algorithm or similar approaches. All strategies used in window-based protocols are to find the best increment and decrement steps given the congestion window size [**75**,**90**,**91**]. Most AIMD-based congestion control algorithms halve the sending rate in response to a single congestion occurrence, which can be unnecessary especially for streaming multimedia applications [**92**] Rate-based congestion control is equation-based, different from the AIMD implementation. Equation-based congestion control finds the maximum acceptable data rate according to the recent loss rate. Thus, the sender updates its transmission rate based on the control equation [**93**,**94**,**95**,**96**]. Generally, developing a rate-based congestion control algorithm is more complicated than developing a window-based one [**45**].

4.2 SCTP-based solutions

SCTP standardization with the multihoming capability is followed by various proposals on SCTP-based multipath congestion control algorithms [**42**]. LS-SCTP [**52**] and CMT-SCTP [**54**], as discussed in Subsection 3.2, are the most important SCTP based algorithms which perform multipath transmission simultaneously. CMT/RP [**91**] is a resource pooling scheme for the CMT SCTP, as indicated in Subsection 3.3. As another transport layer algorithm, cmpSCTP adds concurrent multipath transmission capability to SCTP [**53**]. The cmpSCTP attempts to transmit a given set of packets at the corresponding paths based on the paths available resources. It has separate flow control and congestion control mechanism. The flow control is managed over the association and the congestion is controlled per path. Generally, for any transport layer stripping mechanism to be effective, congestion control must be performed for each network path independently [**53**]. An extension of SCTP for CMT with Parallel Subflows is wireless multi-path multi-flow SCTP (WM^2-SCTP) that allows the streams to be grouped in subflows based on the required QoS. In this approach, both flow and congestion controls are performed based on subflows instead of association [**97**]. Thus, a separate source buffer is assigned to each subflow to make it independent from other subflows. This protocol is implemented, and is shown to have better performance comparing to the CMT-SCTP.

SCTP-based multipath protocols have some lateral issues. For example, when an SCTP receiver window is too small, which is known as the small window syndrome (SWS), the sender cannot get enough ACKs (or it takes too long) to change the congestion state as necessary. Thus, the SCTP sender experiences a long idle period, which degrades SCTP throughput. This problem becomes worse in the case of multipath, as a path's idle period forces the other paths to wait, because in-order sequences are expected at the receiver. A scheme is proposed in [**98**] which detects idle period and starts transmitting the data to partially overcome the SWS problem. However, idle-period detection errors pump more data into an already congested network. Another problem in the SCTP-based multipath congestion control comes from the inherent nature of a mobile wireless network. Although SCTP was initially designed as a transport protocol for wired networks, there are many research activities in the application of SCTP to wireless mobile networks. SCTP suffers from random loss in wireless networks as TCP does. Thus, TCP-based strategies for wireless networks may be applicable for SCTP-based protocols. In order to support mobility, a performance improvement method is proposed for mobile SCTP in integrated heterogeneous networks [**46**]. The error recovery scheme is basically designed to improve the SCTP performance during vertical handover by multicasting the buffered and new data over both links associated with the handover when a loss due to handover happens.

To solve the buffer blocking problem for concurrent transmission based on SCTP, CMT with a Potentially-failed destination state (CMT-PF) is proposed [**99**], and its performance is compared to CMT in failure and non-failure scenarios. CMT-PF considers the fact that a packet loss detected by a timeout can be due to either severe congestion or route failure. Thus, after a single timeout on a path, the corresponding destination is set as PF. A PF destination is checked for a period and is not used for data transmission or retransmission. If it responds by regular ACKs, the state comes back to the active state. It is shown that CMT-PF performs as well as CMT in symmetric path failures, and has better results in asymmetric path failures. Also, its throughput degradation in non-failure scenarios is slightly less than CMT.

4.3 Multipath TCP

Generally, there are two requirements for multipath congestion control [**22**]:

- A multipath flow should give a connection at least as much throughput as the connection would get with single-path TCP on the best of its paths;
- A multipath flow should take no more capacity on any collection of paths than if it was a single-path TCP flow using the best of those paths. This guarantees that it will not harm other flows at a bottleneck link.

Multipath TCP is to use multiple paths simultaneously based on a regular TCP. In the following, we discuss some algorithms proposed for multipath TCP. The basic idea of providing multipath transmission capability for the TCP is to eliminate the dependency between a TCP connection and its host address (and also port number), as suggested in an IETF Internet draft [**100**].

One proposed algorithm, named pTCP, is a bandwidth aggregation scheme which strips data over multiple paths at the transport layer, regardless of its previous works in the link layer and application layer. The pTCP is composed of stripped connection manager (SM) and TCP-virtual (TCP-v). TCP-v controls one path, independent of other paths, by probing the path, detecting loss, and carrying out loss recovery. The SM manages independent TCP-vs. These two functions lead to intelligent congestion control for each path. However, flow control and congestion control are managed by a centralized algorithm, which makes the method complex. Also, high resource usage due to implementation of one TCP for each path makes pTCP not practical [**21**]. Another bandwidth aggregation scheme which modifies TCP to aggregate bandwidth across multiple end-to-end paths is called mTCP [**101**]. The mTCP has the sequence numbering and handles packet reordering like CMT-SCTP. Data and ACKs are sent on the same path for simplicity. Also, mTCP proposes shared bottleneck detection in order to respond to the bottlenecks correctly. A heuristic mechanism is proposed in [**101**] to stop using the paths with low throughput. An underlying routing layer, resilient Overlay network, is required for this scheme to support multipath transmission.

The out-of-order packets are a group of packets which arrive at the destination in a non-monotonically increasing sequence which is different from the sending sequence. The out-of-order packets are the result of the different transmission delays along different paths. In [**70**], an adaptive load balancing algorithm (ALBAM) is proposed with the priority of less-congested and lower-delay paths. It uses one parameter for the queuing delay and another for the traffic weighting (to ensure that the traffic ratio between candidate paths conform the requirements) for each path. The goal is to minimize summation of these parameters. The ALBAM is known as a solution to asymmetric paths.

CMT is mostly designed for the SCTP because of the SCTP’s multihoming capability and its other advantages over the TCP. However, CMT is extended in [**64**] to the TCP by optimizing cost and performance to dynamically strip data packets into multiple paths through different ISPs. The idea is to use CMT in the existing Internet transport layer protocols, mainly TCP.

Multipath TCP is managed for each path separately in equally-weighted TCP (EWTCP) [**102**]. Each path has a congestion window for itself. The congestion window is decreased / increased as in the regular TCP. Thus, each path is controlled independent of other paths. The congestion window increases proportional to a weighting parameter under the assumption that the RTTs of all paths are similar. However, in reality different paths have different RTTs due to different routings (different path length) and/or different technologies in heterogeneous networks. The COUPLED algorithm in [**103**] is a window-based TCP, which is derived from a rate-based multipath version of Scalable-TCP [**104**]. It follows the idea that a multipath flow should shift all its traffic onto the least congested path. It is shown that the goal can be achieved in theory without any need to separately measure congestion on each path. Thus, the congestion window size decreases/increases based on the overall congestion window size. Moving traffic away from the congested paths leads to balancing the loss rates across the whole network. But, performance of the COUPLED algorithm suffers from different RTTs, similar to EWTCP. And finally, Multipath TCP (MPTCP) is proposed in [**22**], based on a more realistic multipath congestion control algorithm for the Internet. An end-to-end algorithm for sharing capacity is proposed with some modification to the TCP. It is assumed that the TCP controls the traffic to be sent on each path, but does not perform resource allocation to specify the paths. Via the studying the COUPLED and EWTCP algorithms, it is concluded that the least congested path should be used, but keeping sufficient traffic on the other paths. In TCP, insufficient traffic means insufficient feedback. Thus, the SEMICOUPLED algorithm is proposed based on the two congestion control requirements, which increases congestion window based on the overall congestion window with some weightings and decrease it based on its own path’s congestion window [**22**].

Kelly et al. have presented some theoretical work on multipath TCP [**3**,**67**,**73**]. Also, Zhang et al. derive uniform bounds of flow’s congestion windows and round trip times for a heterogeneous adaptive AIMD (with adaptive increase and decrease parameters) flows sharing the link with certain AQM parameters [**105**]. They present the sufficient conditions to guarantee the system stability. Stochastic packet-level behaviours of some proposed multipath congestion control algorithms are studied. It is shown that the congestion control flap among available paths due to changes in packet drop probability over time. As an example, a more congested path is less congested in some moments as the probability of packet loss varies with time. It is proposed to use smoothed loss probability as a measure of congestion or accept non-ideal resource pooling [**13**].

5 Open issues

Multipath transport layer protocols have become more attractive in the recent years, as evidenced by the fact that many workshops, conferences, and journal special issues in the Internet research area, along with IETF Internet drafts that focus on it [**12**,**27**,**35**,**51**]. So far, various protocols are proposed for simultaneous data transmission over multiple paths. However, an effective, efficient, and practical protocol is yet to be developed, due to the limitations of the existing protocols. There are many open issues that need further studies.

The existing multipath congestion control protocols have three main limitations. First, there are many impractical assumptions in the protocol development. Second, most of the congestion control protocols are very sensitive to disparate networking conditions in a heterogeneous scenario which is the case for the multipath transmission. Third, increasing the number of ACKs and retransmissions lead to traffic overload, which is not desired. In the following, these three aspects and related future works are discussed.

Existing multipath congestion control protocols are designed for the ideal cases due to current theoretical limitations or complexity of practical scenarios. As an example, the congestion loss is assumed to be detected accurately in loss-based protocols, which is not achievable due to channel errors and random packet losses. Also, congestion prediction based on the queuing delay is not accurate when the queuing delay is small or the end-to-end delay is affected by other factors such as link layer retransmissions. Therefore, each path is likely to have an inaccurate view of its congestion level from time to time, which can cause inefficient bandwidth aggregation and congestion management. Moderately long-lived flow is another common assumption model for the Internet, which does not encompass all the Internet flows. Many flows in the Internet are short-lived streams, and a hybrid scenario for various flow durations should be considered in the future for the Internet. In addition, an infinity buffer size is assumed for both sender and receiver, which is impractical.

Another problem associated with multipath transmission is the sensitivity of congestion control algorithms to the heterogeneous parameters of the paths, such as the delay, which varies in almost every multipath transmission. However, most of the proposed protocols assume that the delay is approximately the same for all the paths. Unfortunately, the performance of the protocols degrades with a small difference in the delays. Another parameter which affects the congestion control mechanisms in the heterogeneous environment is RTT. Only the MPTCP protocol [**35**] deals with the RTT differences at a cost of increased complexity. Therefore, variety in parameters of heterogeneous networks should be studied further.

Internet traffic overloads and surges are possible at each moment in the transmission. It affects the system performance, because some packets in congested links are dropped as the network cannot manage them at the moment. In such a scenario, more ACKs are sent to the sender, based on which a decision on changing paths is made. However, the bottleneck link remains in a congested state. Recovery from this situation cannot be easily done. Hence, more packets are dropped and congestion control throughput further degrades. Thus, the problem should be addressed in the multipath transport layer protocol design.

Along with solving the above problems, other issues should be further studied, including the following.

- **Merging SCTP-based and multipath TCP designs**: SCTP has the most important advantage of multihoming over the TCP. This protocol also resolves some existing problems of TCP. Generally, SCTP-based protocols have less complexity and better performance over their parallel multipath TCP designs. However, SCTP is far from being widely implemented in the Internet to replace the dominant TCP. It may not happen ever. Thus, it can be a good idea to gather existing solutions of multipath TCP and SCTP-based designs to merge them in an efficient manner for applications in the future Internet.
- **Cross-layer designs**: With an understanding of the importance of the transport layer in multipath transmission, cross-layer designs based on the latest link layer and/or Internet layer designs should be explored to improve transport layer performance. Transport layer designs can benefit from the information of random loss in the link layer, and/or routing information of the IP layer. Resource allocation along with multipath congestion control may lead to an optimized solution, and path selection should adapt to congestion states.
- **Cooperation in multipath transmission**: Almost all the existing multipath congestion protocols treat the available paths as independent paths with separate congestion control decisions. As different paths have different characteristics, it is possible to make use of this diversity in a cooperative way. The traffic can be moved from congested paths to non-congested ones based on the congestion level. Retransmissions can also be done using an non-congested path (different from its original path). Also, congestion control can make use of diversity by sending data or ACKs through multiple paths.

6 Conclusion

In this paper, different methods on multipath transmission from an end-to-end transport layer viewpoint have been discussed. Multihoming as a necessary condition for multipath transmission, concurrent multipath as the best strategy to improve performance, and load balancing as an effective Internet traffic manager have been considered. Congestion control methods have been reviewed. Afterward, SCTP-based and Multipath TCP protocols for simultaneous data transmission have been considered. However, these methods have serious limitations such as impractical assumptions and sensitivity to heterogeneous characteristics. These limitations can be addressed by merging SCTP-based and multipath TCP designs, taking a cross-layer design approach, and using cooperation in multipath transmission. Being aware of the importance of multipath transmission for the future Internet, reviewing the existing multipath transmission strategies, and potential solutions for the current limitations, one may design a more efficient and practical multipath transmission protocol in the near future.

References

[1] *Cisco Visual Networking Index: Forecast and Methodology 2010-2015,* Cisco and its affiliates, 2011, http://www.cisco.com

[2] K. Jacobsson, *Dynamic Modeling of Internet Congestion Control*. Ph.D. thesis, Royal Institute of Technology (KTH), Sweden, 2008.

[3] F. Kelly and T. Voice, *Stability of End-to-End Algorithms For Joint Routing and Rate Control, SIGCOMM Comput Commun.*, Rev. 35, No. 2, 2005, pp. 5-12.

[4] F. Hu and N.K. Sharma, *Enhancing Wireless Internet Performance, IEEE Commun. Surveys & Tutorials,* vol. 4, No. 1, 2002, pp. 2-15.

[5] L. Cai, X. Shen and J. Mark, *Multimedia Services in Wireless Internet*, John Wiley & Sons Ltd, UK, 2009.

[6] B. Ouldooz, M. Fathy and S. Yousefi, *Adaptive End-to-End QoS for Multimedia over Heterogeneous Wireless Networks*, *Springer,* Berlin Heidelberg, Vol. 6, 2009, pp. 160-167.

[7] L. Cai, X. Shen, J. Mark and J. Pan, *QoS Support in Wireless/Wired Networks Using the TCP-Friendly AIMD Protocol*, *IEEE Trans. Wireless Commun.*, Vol. 5, No. 2, 2006, pp. 469- 480.

[8] L. Cai, X. Shen, J. W. Mark and J. Pan, *Performance Modeling and Analysis of Window-Controlled Multimedia Flows in Wireless/Wired Networks, IEEE Trans. Wireless Commun.*, Vol. 6 No. 4, 2007, pp. 1356-1365.

[9] R. Zhang, L. Cai, J. Pan and X. Shen, *Resource Management for Video Streaming in Ad Hoc Networks, Elsevier Ad Hoc Networks, Special Issue on Multimedia Ad Hoc and Sensor Networks*, Vol. 9, No. 4, 2011, pp. 623-634.

[10] W. Lehr and J. Chapin, *On the Convergence of Wired and Wireless Access Network Architectures, J. Information Economics and Policy, Wireless Technologies*, Vol. 22, 2010, pp. 33-41.

[11] L. Ka-Cheong, *Transmission control protocol (TCP) in Wireless Networks: Issues, Approaches, and Challenges*, *IEEE Communications Surveys & Tutorials*, Vol. 8, No. 4, 2006, pp. 64-79.

[12] A. Ford, C. Raiciu, M. Handley and O. Bonaventure, *TCP Extensions for Multipath Operation with Multiple Addresses, IETF draft mptcp multi addressed,* Draft No. 01 , March, 2005.

[13] D. Wischik, M. Handley and C. Raiciu, *Control of Multipath TCP and Optimization of Multipath Routing in the Internet, Springer,* Berlin Heidelberg, Vol. 5894, 2009, pp. 204-218.

[14] C. Raiciu, M. Handley and A. Ford, *Multipath TCP Design Decisions*, Technical report, Department of Computer Science, UCL University, London, UK, 2009.

[15] A. Kostopoulos, H. Warma, T. Leva, B. Heinrich, A. Ford and L. Eggert, *Towards Multipath TCP Adoption: Challenges and opportunities, Proc. 6th EURO-NF Next Generation Internet (NGI),* Paris, France, 2010, pp. 1-8.

[16] A. Ford, C. Raiciu, M. Handley and J. Iyengar, *Architectural Guidelines for Multipath TCP Development, IETF draft mptcp architecture*, Draft No. 05, Jan. 2011.

[17] J. Iyengar, *End-to-End Concurrent Multipath Transfer Using Transport Layer Multihoming*, Ph.D. thesis, CIS Department, University of Delaware, US, 2006.

[18] C. Huang, M. Lin and L. Chang, *The Design of Mobile Concurrent Multipath Transfer in Multihomed Wireless Mobile Networks, J. Computer*, Oxford University Press, Vol. 53, No. 10, 2010, pp. 15.

[19] C. Barakat, E. Altman and W. Dabbous, *On TCP Performance in a Heterogeneous Network: a Survey, IEEE Commun. Magazine*, Vol. 38, No. 1, 2000, pp. 40-46.

[20] Z. Sun and W. Wang, *Investigation of Cooperation Technologies in Heterogeneous Wireless Networks, J. Hindawi Publishing Corporation Comput. Systems, Networks, and Commun.*, 2010, Article ID 413987.

[21] H. Hsieh, R. Sivakumar, *A Transport Layer Approach for Achieving Aggregate Bandwidths on Multi-Homed Mobile Hosts, J. Wireless Networks*, Springer, Netherlands, Vol. 11, 2005, pp. 99-114.

[22] D. Wischik, C. Raiciu, A. Greenhalgh and M. Handley, *Design, Implementation and Evaluation of Congestion Control for Multipath TCP*, Proc. NSDI, Boston, USA, 2011.

[23] D. Phatak and T. Goff, *A Novel Mechanism for Data Streaming Across Multiple IP Links for Improving Throughput and Reliability in Mobile Environments, Proc. IEEE INFOCOM,* New York, USA, 2002

[24] D. Wischik, M. Handley and M. Bagnulo Braun, *The Resource Pooling Principle, ACM SIGCOMM,* Seattle, USA, Vol. 38, No. 5, 2008.

[25] D. Wischik, *Technical Perspective Multipath: A New Control Architecture for the Internet, ACM J. Commun*, Vol. 54, No. 1, 2011.

[26] S. Barré, C. Paasch and O. Bonaventure, *MultiPath TCP: From Theory to Practice*, Springer, Berlin Heidelberg, Vol. 6640, 2011, pp. 444-457.

[27] A. Ford, C. Raiciu, M. Handley and O. Bonaventure, *Coupled Congestion Control for Multipath Transport Protocols, IETF draft mptcp congestion,* Draft No. 07, July 2011.

[28] A. Ford, C. Raiciu, M. Handley and O. Bonaventure, *TCP Extensions for Multipath Operation with Multiple Addresses, IETF draft*

mptcp multi addressed, Draft No. 03 , March, 2011

[29] C. Mung, S. Low, A. Calderbank and J. Doyle, *Layering as Optimization Decomposition: A Mathematical Theory of Network Architectures, Proc. IEEE,* Vol. 95, No.1, 2007, pp. 255-312.

[30] H. Jiayue and J. Rexford, *Toward internet-wide multipath routing, IEEE Network*, Vol. 22, 2008, p.p.16 – 21.

[31] S. Prabhavat, H. Nishiyama, N. Ansari and N. Kato, *On Load Distribution over Multipath Networks, IEEE Commun. Surveys and Tutorials*, (accepted), 2011

[32] T. Goff, D. Phatak, *Unified Transport Layer Support for Data Striping and Host Mobility, IEEE J. Selected Areas Commun.*, Vol. 22, No. 4, 2004, pp. 737- 746.

[33] H. Han, S. Shakkottai, C. V. Hollot, R. Srikant and Don Towsley, *Multi-path TCP: a Joint Congestion Control and Routing Scheme to Exploit Path Diversity in the Internet, IEEE/ACM Trans. Netw.* Vol. 14, No. 6, 2006, pp. 1260-1271.

[34] A. Afanasyev, N. Tilley, P. Reiher and L. Kleinrock, *Host-to-Host Congestion Control for TCP, IEEE Commun. Surveys & Tutorials,* Vol. 12, No. 3, 2010, pp. 304-342.

[35] J. Arkko, B. Briscoe, L. Eggert, A. Feldmann and M. Handley, *Dagstuhl Perspectives Workshop on End-to-End Protocols for the Future Internet. Proc. ACM SIGCOMM,* Barcelona, Rev. 39, No. 2, 2009, pp. 42-47.

[36] J. Mark, J. Pan, and X. Shen, *Mobility Support in Hybrid Wireless/IP Networking, Elsevier J. of Computer Commun.*, Vol. 26, No. 17, 2003, pp. 1990-1997

[37] G. Rittenhouse, *Next Generation Wireless Networks, Proc. INFORMS*, Denver, 2004.

[38] P. Bellavista, A. Corradi, C. Giannelli, *Unifying Perspective on Context-aware Evaluation and Management of Heterogeneous Wireless Connectivity, IEEE Commun. Surveys and Tutorials,* Issue 3, 2011.

[39] D. Cavalcanti, D. Agrawal, C. Cordeiro, X. Bin and A. Kumar, *Issues in Integrating Cellular Networks WLANs, and MANETs: A Futuristic Heterogeneous Wireless Network, IEEE J. Wireless Commun.*, Vol. 12, No. 3, 2005, pp. 30- 41.

[40] S. Pack, H. Rutagemwa, X. Shen, J. W. Mark and L. Cai, *Performance Analysis of Mobile Hotspots with Heterogeneous Wireless Links, IEEE Trans. Wireless Commun.*, Vol. 6, No. 10, 2007, pp. 3717-3727.

[41] M. Arshad and M. Mian, *Issues of Multihoming Implementation Using FAST TCP: a Simulation Based Analysis, J. IJCSNS,* Vol. 8, 2008, pp. 104–114.

[42] L. Budzisz, *Stream Control Transmission Protocol (SCTP): A Proposal for Seamless Handoff Management at the Transport Layer in Heterogeneous Wireless Networks*, PhD Thesis, Department of Signal Theory and Commun., Universitat Politecnica de Catalunya, Barcelona, 2009.

[43] A. Akella, B. Maggs, S. Seshan, A. Shaikh and R. Sitaraman, *A Measurement-Based Analysis of Multihoming, Proc. ACM SIGCOMM*, Karlsruhe, Germany, 2003.

[44] A. Matsumoto, M. Kozuka, K. Fujikawa and Y. Okabe, *TCP Multi-Home Options, IETF Internet draft*, Draft No. 00, 2003.

[45] D. Wei, C. Jin, S. Low and S. Hegde, FAST TCP: Motivation, Architecture, Algorithms, Performance, IEEE/ACM Trans. Netw. Vol. 14, No. 6, 2006.

[46] A. Jungmaier and E. Rathgeb E., *On SCTP Multi-homing Performance*, Springer Science & Business Media, LLC, 2006.

[47] S. Floyd and E. Kohler, *Profile for Datagram Congestion Control Protocol (DCCP) Congestion Control ID 2: TCP-like Congestion Control, J. The Internet Society*, 2006.

[48] M.A. Azad, R. Mahmood and T. Mehmood, *A Comparative Analysis of DCCP Variants (CCID2, CCID3), TCP and UDP for MPEG4 Video Applications, Proc. Information and Commun. Technologies (ICICT)*, 2009, pp.40-45.

[49] E. Kohler, M. Handley and S. Floyd, *Designing DCCP: Congestion Control Without Reliability, Proc. SIGCOMM*, Rev. 36, No. 4, 2006, p.p. 27-38.

[50] L. Bokor, A. Huszak and G. Jeney, *Novel Results on SCTP Multihoming Performance in Native IPv6 UMTS-WLAN Environments, J. Commun. Networks and Distributed Systems*, Vol 5, 2010, p.p. 25 – 45.

[51] K. Kamphenkel, S. Laumann, J. Bauer and G. Carle, *Path Selection Techniques for SCTP Multihoming, Proc. ICC Workshops,* 2009. pp. 1-6.

[52] A. Abd A., T. Saadawi and M. Lee, *LS-SCTP: a Bandwidth Aggregation Technique for Stream Control Transmission Protocol, J. Computer Commun.*, Vol. 27, Issue 10, 2004, pp. 1012-1024.

[53] I. Liao, J. Wang and X. Zhu, *cmpSCTP: An Extension of SCTP to Support Concurrent Multi-Path Transfer," Proc. ICC*, 2008, pp. 5762-5766.

[54] J. Iyengar, P. Amer, R. Stewart, *Concurrent Multipath Transfer Using SCTP Multihoming Over Independent End-to-End Paths, IEEE/ACM Trans. Netw.*, Vol. 14, No. 5, 2006, pp. 951-964.

[55] Abd El Al, T. Saadawi and M. Lee, *Load Sharing in Stream Control Transmission Protocol, IETF draft ls-sctp*, Draft No. 00, 2003.

[56] S. Joo Koh, M. Jeong Chang and M. Lee, *mSCTP for Soft Handover in Transport Layer, IEEE Commun. Letters*, Vol. 8, No. 3, 2004, pp. 189- 191.

[57] F. Shaojian and M. Atiquzzaman, *SCTP: State of*

the Art in Research, Products, and Technical Challenges, IEEE Commun. Mag., Vol. 42, No. 4, 2004, pp. 64- 76.

[58] C. Huang and C. Tsai, *The Handover Control Mechanism for Multi-path Transmission Using Stream Control Transmission Protocol (SCTP), J. Computer Commun.* Vol. 30, 2007, pp. 3239–3256.

[59] B. Sousa, k. Pentikousis and M. Kostas, *Multihoming Management for Future Networks*, Springer, Netherlands, Vol. 16, No. 4, 2011, p.p. 505-517.

[60] J.-Y. Boudec, *Rate Adaptation, Congestion Control and Fairness: A Tutorial*, Technical Report, EPFL University, 2008, http://icapeople.epfl.ch/leboudec.

[61] T. Dreibholz, M. Becke, H. Adhari and E. Rathgeb, *On the Impact of Congestion Control for Concurrent Multipath Transfer on the Transport Layer, Proc. Telecommun*., 2011.

[62] T. Dreibholz, M. Becke, J. Pulinthanath and E. Rathgeb, *Applying TCP-Friendly Congestion Control to Concurrent Multipath Transfer, Proc. Advanced Information Netw. and Applications*, 2010, pp. 312-319.

[63] T. Dreibholz, M. Becke, E. Rathgeb andM. uxen, *On the Use of Concurrent Multipath Transfer over Asymmetric Paths. Proc. IEEE GLOBECOM*, Miami, USA, 2010.

[64] Y. Wang; X. Li, D. Liu and M. Chen, Optimizing Cost and Performance for Concurrent Multipath Transferring using extended shim6, Proc. ICCT, 2006, pp.1-4.

[65] C. Raiciu, D. Wischik and M. Handley, *Practical Congestion Control for Multipath Transport Protocols*, Technical Report., University Collage of London, 2009, http://nrg.cs.ucl.ac.uk/mptcp/mptcp-techreport.pdf.

[66] D. Wischik, C. Raiciu and M. Handley, *Balancing Resource Pooling and Equipoise in Multipath Transport, Proc. ACM SIGCOMM,* 2010.

[67] F. Kelly, L. Massoulié and N. Walton, *Resource Pooling in Congested Networks: Proportional Fairness and Product Form, J. Queueing Syst.*, Vol. 63, No. 1, 2009, pp. 165–194.

[68] D. Yu, W. Dingding, N. Pissinou and W. Jian, *Multi-Path Load Balancing in Transport Layer, Proc. Next Generation Internet Networks (EuroNGI),* 2007, pp.135-142.

[69] X. Pei, G. Zhu, Q. Wang, G. Liu and W. Yuan, *Cooperative Load-Balancing Strategy Based on N-hops Routing Algorithm of Ad Hoc Network in Heterogeneous Overlapping Networks*, Springer, Paris, Vol. 63, 2008, pp. 597-606.

[70] S. Lee, *Adaptive Load Balancing Algorithm for Multi-Homing Mobile Nodes in Local Domain, Proc. IEEE CCNC*, 2011, pp.482-486.

[71] M. Fiore and C. Casetti, *An Adaptive Transport Protocol for Balanced Multihoming of Real-time traffic, Proc. IEEE GLOBECOM*, Vol. 2, 2005, pp. 22-28.

[72] H. Son, S. Lee, S. Kim and Y. Shin, *Soft Load Balancing Over Heterogeneous Wireless Networks, IEEE Trans. Vehicular Technology*, Vol. 57, No. 4, 2008, pp. 2632-2638.

[73] F. Kelly, A. Maulloo and D. Tan, *Rate Control for Communication Networks: Shadow Prices, Proportional Fairness and Stability, J. Operational Research Society*, Vol. 49, No. 3, 1998, pp. 237-252.

[74] F. Paganini, Z. Wang, J. Doyle and S. Low, *Congestion Control for High Performance, Stability, and Fairness in General Networks, IEEE/ACM Trans. Netw*., Vol. 13, No. 1, 2005, pp. 43-56.

[75] J. Mo and J. Walrand, *Fair End-to-End Window-Based Congestion Control, IEEE/ACM Trans. Netw.,* Vol. 8, No. 5, 2000, pp. 556-567.

[76] M. Neely, E. Modiano and L. Chih-Ping, *Fairness and Optimal Stochastic Control for Heterogeneous Networks*, *Proc. IEEE INFOCOM*, Vol. 3, 2005, pp. 1723- 1734.

[77] L. Cai, X. Shen, J. Pan and J. W. Mark, *Performance Analysis of TCP-friendly AIMD Algorithms for Multimedia Applications, IEEE Trans. Multimedia*, Vol. 7, No. 2, 2005, pp. 339—355.

[78] Y. Zhang, *Stable and Scalable Congestion Control for High-speed Heterogeneous Networks*, PhD Thesis, Texas A&M University, 2008.

[79] L. Ying, G. Dullerud and R. Srikant, *Global Stability of Internet Congestion Controllers With Heterogeneous Delays, IEEE/ACM Trans. Netw.*, Vol. 14, No. 3, 2006, pp. 579-591.

[80] Z. Yueping and D. Loguinov, *Local and Global Stability of Delayed Congestion Control Systems, IEEE Trans. Automatic Control,* Vol. 53, No. 10, 2008, pp. 2356-2360.

[81] R. Seungwan, C. Rump, Q. Chunming, *Advances in Internet Congestion Control, IEEE Commun. Surveys & Tutorials*, Vol. 5, No. 1, 2003, pp. 28-39.

[82] S. Golestani and K. Sabnani, *Fundamental Observations on Multicast Congestion Control in the Internet, Proc. IEEE INFOCOM*, Vol. 2, 1999, pp. 990-100.

[83] E. Mohamed and H. Abdel-Wahab, *Multicast Congestion Control for Multimedia Collaborative Applications in Packet Switched Networks, IEEE Symp. Computers and Communications*, 2008, pp. 755-761.

[84] W. Huang and X. Kong, *Research on Layered Multicast Congestion Control, Proc. Computing, Communication, Control, and Management (CCCM),* Vol. 2, 2009, pp. 509-512.

[85] J. Martin, A. Nilsson and R. Injong, *Delay-Based Congestion Avoidance for TCP, IEEE/ACM Trans. Netw.*, Vol. 11, No. 3, 2003, pp. 356-369.

[86] S. Bhandarkar, A. Narasimha Reddy, Y. Zhang and D. Loguinov, *Emulating AQM from End Hosts, Proc. SIGCOMM*, Rev. 37, No. 4, 2007, pp. 349-360.

[87] G. McCullagh, *Exploring Delay Based TCP Congestion Control*, Master's Thesis, Hamilton Institute, NUI Maynooth, Ireland, 2008.

[88] R. Prasad, M. Jain and C. Dovrolis, *On the Effectiveness of Delay-Based Congestion Avoidance, Proc. Protocols for Fast Long-Distance Networks Workshop*, 2004.

[89] A. Schlote, R. Shorten and F. Baker, *Delay Based Congestion Control for Heterogeneous Environments, IEEE/ACM Trans. Netw.*, 2010.

[90] S. Jin, L. Guo, I. Matta and A. Bestavros, *A Spectrum of TCP-friendly Window-Based Congestion Control Algorithms, IEEE/ACM Trans. Netw.*, Vol. 11, No. 3, 2003, pp. 341-355.

[91] A. Tang, L. Andrew, K. Jacobsson, K. Johansson, k. Hjalmarsson and S. Low, *Queue Dynamics With Window Flow Control, IEEE/ACM Trans. Netw.*, Vol. 18, No. 5, 2010, pp. 1422-1435.

[92] S. Floyd, M. Handley, J. Padhye and J. Widmer, *Equation-Based Congestion Control for Unicast Applications, Proc. SIGCOMM*, 2000.

[93] G. Nalân, H. Peter, R. Berç, A. Tansu, *Distributed and Robust Rate Control for Communication Networks*, Springer, New York, Vol.4, 2011, pp.1-32.

[94] S. Gaonkar, R. Choudhury, L. Magalhaes and R. Kravets, *Designing a Rate-based Transport Protocol for Wired-Wireless Networks, Proc. Broadband Commun., Networks and Systems*, 2007.

[95] Z. Xiaoqing, P. Agrawal, J. Singh, T. Alpcan and B. Girod, *Distributed Rate Allocation Policies for Multihomed Video Streaming Over Heterogeneous Access Networks*, *IEEE Trans. Multimedia*, Vol. 11, No. 4, 2009, pp. 752-764.

[96] H. Shen, L. Cai and X. Shen, Performance Analysis of TFRC over Wireless Links with Truncated Link Level ARQ, *IEEE Trans. Wireless Commun*., Vol. 5, No. 6, 2006, pp. 1479—1487.

[97] Y. Ya, Z. Zidi, L. Juan, S. Jinglin, Z. Jihua, F. Gengfa and E. Dutkiewicz, *Extension of SCTP for Concurrent Multi-Path Transfer with Parallel Subflows, Proc. IEEE WCNC*, 2010, pp. 1-6.

[98] M. Li, F. Yu and V. Leung, *Performance Improvements of Mobile SCTP in Integrated Heterogeneous Wireless Networks, IEEE Trans. Wireless Commun.*, Vol. 6, No. 10, 2007, pp. 3567-3577.

[99] N. Ekiz, P. Amer, J. Iyengar and P Natarajan, *Concurrent Multipath Transfer Using SCTP Multihoming: Introducing the Potentially-Failed Destination State*, Springer, 2011.

[100] C. Huitema, *Multihomed TCP*, IETF Internet draft, Draft No. 00, 1995.

[101] M. Zhang, J. Lai, A. Krishnamurthy, L. Peterson and R. Wang, *A Transport Layer Approach for Improving End-to-End Performance and Robustness Using Redundant Paths*, *In USENIX*, 2004.

[102] M. Honda, Y. Nishida, L. Eggert, P. Sarolahti and H. Tokuda, *Multipath Congestion Control for Shared Bottleneck, Proc. PFLDNeT workshop*, 2009.

[103] P. Key, L. Massoulie and P. Towsley, *Path Selection and Multipath Congestion Control*, *Proc. IEEE INFOCOM*, 2007, pp. 143-151.

[104] T. Kelly, *Scalable TCP: Improving Performance in Highspeed Wide Area Networks. Proc. ACM SIGCOMM*, Rev. 33, No. 2, 2003, pp. 83–91.

[105] H. Zhang, L. Cai, X. Liu and X. Shen, *Boundedness of Heterogeneous TCP Flows with Multiple Bottlenecks, Proc. IEEE WCNC*, 2010, pp. 1-6.