UNIVERSITI PUTRA MALAYSIA

OPTIMIZATION ALGORITHMS FOR MULTIPATH TRANSFER OVER ASYMMETRIC PATHS USING CONCURRENT MULTIPATH TRANSFER STREAM CONTROL TRANSMISSION PROTOCOL

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FSKTM 2016 7

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By

ABDULRIDHA HANASH ABASS

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

February 2016

DEDICATIONS

I dedicate my thesis work to my family and friends. A special feeling of gratitude to my loving parents, whose love for me knew no bounds and taught me the value of hard work. My sisters and brothers have never left my side and are very special. I also dedicate this thesis to people who have supported me throughout the entire doctorate program. I will always appreciate all they have done for me.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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The Internet has evolved in three directions over the past decades. First, content has evolved from relatively low-bandwidth content static text and web pages to high-bandwidth content multimedia which results in a significant and growing amount of bandwidth demand. Second, its usage has explosively globalized. Third, Internet access nature has changed from fixed access through desktop computers to a mobile access via smart phones and tablets. As a result, the principles of the Internet design are no longer suitable for current and future applications (e.g., mission-critical and time-critical applications). Network resources management is a key success for the future Internet.

Furthermore, in the last decade hosts have equipped with multiple interfaces. Clearly, that led to the desire of applying load sharing to utilize all paths simultaneously to enhance application payload timeliness, and improve resilient to problems on a particular path.

Readily apparent, Transport layer is the only layer that realizes a path congestion control and flow control. In addition, a Transport layer that realizes multi-homing does not require modifying the applications or changing the Network layer protocol. The Stream Control Transmission Protocol (SCTP) is an emerging multi-homing general purpose Transport layer protocol. An extension of SCTP denoted as Concurrent Multipath Transfer Stream Control Transmission Protocol (CMT-SCTP) realizes load sharing functionality. This protocol works well for symmetric paths. But, in reality symmetric paths are unlikely in networks such as Internet. More, multi-homing offers link failure tolerance at Network layer by using different access technologies simultaneously to connect through. Different access technologies clearly imply highly asymmetric paths. CMT-SCTP over asymmetric paths does not work that neatly.

In this thesis, phenomena affects CMT-SCTP in asymmetric paths are demonstrated. A comprehensive analysis to understand its nature is presented. Mechanisms that promote CMT-SCTP performance are implemented and evaluated in simulation in order to show their effectiveness. In particular, a combination of multiple mechanisms is vital to make CMT-SCTP works more neatly under a wide range of network and system parameters.

Intrinsically, retransmission strategy controls retransmission behavior when a sender fails to receive acknowledgements for sent data due to reorder, lost or corrupted packets. An efficient retransmission strategy would help to vitiate buffer blocking. A new retransmission strategy denoted as Rtx-HYBRIDMETRIC takes into account path's loss rate and delay is explored. The simulation results show that Rtx-HYBRIDMETRIC retransmission strategy performs well for both failure and non-failure scenarios in a real configuration. In addition, Taxonomy for SCTP retransmission strategies is developed.

More, an accurate ROUND TRIP TIME (RTT) is crucial since it is the core of the RTO. The RTO must be correctly set to achieve good performance. Interestingly, CMT-SCTP efficiency is improved by delayed acknowledgement despite additional delay is introduced. However, delayed acknowledgement may lead to inaccurate RTT on asymmetric paths. A new strategy called as Immediate SACK RTT samples (IS-RTT) is developed for accurate RTT on asymmetric paths. The simulation results show that IS-RTT strategy can significantly optimize the RTT estimation on asymmetric paths.

Finally, CMT buffer split strategy holds equipoise distribution of buffer space among asymmetric paths. It reveals tradeoff between giving individual path application payload throughput guarantees and maximizing application payload throughput. A new strategy denoted as Quick Response Delayed Acknowledgement for CMT (QR-DAC) is integrated with buffer split strategy. The simulation results show that application payload throughput in a real configuration is optimized over asymmetric paths loss rate.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ALGORITMA PENGOPTIMUMAN UNTUK PEMINDAHAN PELBAGAI ARAH LEBIH LALUAN ASIMETRI DENGAN MENGGUNAKAN PEMINDAHAN SECARA SERENTAK DALAM PELBAGAI ARAH PROTOCOL PENGHANTARAN KAWALAN

Oleh

ABDULRIDHA HANASH ABASS

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Dalam beberapa dekad ini, Internet dan kandungannya telah berkembang pesat kepada 3 hala tuju. Yang pertama, daripada laman web yang static dan berasaskan teks yang menggunakan jalur lebar yang rendah kepada aplikasi web yang mengandungi ciri multimedia. Maka, ia memerlukan jalur lebar yang tinggi untuk menampung perubahan ini. Yang kedua, penggunaan internet pada masa sekarang telah berkembang pesat secara global. Ketiga, kaedah untuk mengakses internet telah berubah, daripada akses tetap menerusi penggunaan komputer peribadi kepada akses secara mudah alih menerusi telefon pintar ataupun *tablet*. Perkembangan pesat ini menunjukkan bahawa rekabentuk internet pada masa sekarang adalah tidak sesuai untuk aplikasi terkini dan juga masa hadapan. (Sebagai contoh, untuk aplikasi misi-kritikal dan kritikal-masa). Maka, pengurusan sumber rangkaian adalah satu kunci utama untuk kemajuan internet pada masa hadapan.

Tambahan pula, dalam dekad yang lalu, setiap hos rangkaian telah dilengkapi dengan pelbagai antara muka. Jelas sekali, ia membawa kepada hasrat bagi memohon perkongsian beban untuk menggunakan semua laluan serentak dengan tujuan meningkatkan peluang muatan aplikasi dan juga daya tahan untuk masalah di atas laluan yang tertentu.

Secara jelasnya, lapisan pengangkutan adalah satu-satunya lapisan yang melaksanakan kawalan kesesakan jalan dan aliran. Di samping itu, lapisan pengangkutan ini, yang melaksanakan berbilang homing (*multi-homing*), tidak memerlukan pengubahsuaian aplikasi ataupun penukaran protokol pada lapisan rangkaian. *Stream Control Transmission Protocol* (SCTP) adalah protokol berbilang homing (*multi-homing*) yang baru, terbit daripada lapisan umum pengangkutan. Pengembangan SCTP ditandakan sebagai Concurrent Multipath Transfer Stream Control Transmission Protocol (CMT-SCTP) yang melaksanakan fungsi perkongsian beban. Protokol ini berfungsi dengan baik untuk laluan simetri. Walaubagaimanapun, realitinya laluan simetri tidak mungkin berlaku dalam rangkaian seperti Internet. Tambahan pula, teknik berbilang *homing* ini menawarkan pautan toleransi sesar (*fault tolerance*) di lapisan rangkaian dengan menggunakan teknologi akses yang berbeza pada masa yang sama untuk peyambungan rangkaian. Teknologi akses yang berbeza jelas menandakan adanya laluan asimetri. Tetapi, protokol CMT-SCTP tidak berfungsi yang kemas dalam laluan asimetri.

Dalam tesis ini, fenomena kesan CMT-SCTP dalam laluan asimetri ditunjukkan. Satu analisis yang menyeluruh untuk memahami ciri-cirinya dibentangkan. Mekanisme yang menggalakkan prestasi CMT-SCTP dilaksanakan dan dinilai dalam simulasi untuk menunjukkan keberkesanannya Secara khususnya, gabungan pelbagai mekanisme penting bagi menjadikan CMT-SCTP bekerja lebih kemas di bawah pelbagai rangkaian dan parameter system ditunjukkan.

Strategi penghantaran semula mengawal perilaku penghantaran semula apabila pengirim yang tidak menerima pemakluman bagi data yang dihantar kerana penyusunan semula paket yang hilang atau rosak. Strategi penghantaran semula yang cekap akan membantu untuk membatalkan penghalang penimbal. Strategi penghantaran semula baru ditandakan sebagai *HybridMetric*, yang mempertimbangkan kadar kehilangan laluan dan perlengahan. Keputusan simulasi menunjukkan bahawa strategi penghantaran semula *HybridMetric*, Berjaya menunjukkan prestasi yang baik untuk kedua-dua keadaan iaitu; kegagalan dan bukan-kegagalan dalam konfigurasi sebenar. Selain itu, taksonomi dua pembalikan untuk penghantaran semula strategi SCTP telah dibangunkan.

Selain itu, nilai ROUND TRIP TIME (RTT) tepat adalah penting kerana ia adalah teras kepada RTO. RTO mesti ditetapkan dengan betul untuk mencapai prestasi yang baik. Menariknya, kecekapan CMT-SCTP bertambah baik apabila pemakluman perlengahan pengakuan ditangguhkan walaupun tambahan perlengahan diperkenalkan. Walau bagaimanapun, pemakluman perlengahan boleh menyebabkan nilai RTT yang tidak tepat dalam laluan asimetri. Satu strategi baru yang dinamakan *Immediate SACK RTT sampel (IS-RTT)* dibangunkan untuk mendapatkan RTT yang lebih tepat dalam laluan asimetri. Keputusan simulasi menunjukkan bahawa strategi IS-RTT secara ketara boleh meningkatkan anggaran RTT di laluan asimetri.

Akhir sekali, strategi perpecahan penimbal CMT mempertahankan pengedaran keseimbangan ruang penimbal antara laluan asimetri. Ia menunjukkan keseimbangan antara jaminan pemberian laluan pemprosesan individu dan memaksimumkan daya pemprosesan beban aplikasi. Strategi baru dinamakan sebagai Quick Response Delayed Acknowledgement untuk CMT (QR-DAC)

disepadukan dengan strategi pemisahan penimbal. Keputusan simulasi menunjukkan bahawa daya pemprosesan aplikasi dalam konfigurasi sebenar meningkat sedikit.
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ACKNOWLEDGEMENTS

First and for most, I am thankful to Allah Almighty the most beneficent, the most merciful who gave me guidance and wisdom to complete this thesis.

I am greatly indebted to my supervisor, Dr. Azizol Abdullah for his constructive comments and critical thinking has been a great value in my work. I have learned a lot from him. This will help me throughout my career.

I wish to express my sincere thanks to my committee members: Professor Mohamed Othman and Dr. Zurina Hanapi for their time, support, pertinent advices that guided me throughout my work.

My warm thanks are due to all my colleagues at the Department of Communication Technology and Networking, Universiti Putra Malaysia for their valuable help in my daily life.

Lastly, my deepest appreciation goes to my mother, sisters and brothers for their unwavering support.

I certify that a Thesis Examination Committee has met on 4 February 2016 to conduct the final examination of Abdulridha Hanash Abass on his thesis entitled "Optimization Algorithms for Multipath Transfer Over Asymmetric Paths Using Concurrent Multipath Transfer Stream Control Transmission Protocol" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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I hereby confirm that:

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LIST OF ABBREVIATIONS

ABC	Appropriate Byte Counting
ACK	Acknowledgement
ADSL	Asymmetric Digital Subscriber Line
AIMD	Additive Increase, Multiplicative Decrease
API	Application Programming Interfaces
ARQ	Automatic Repeat Request
BDP	Bandwidth Delay Product
BEC	Backward Error Correction
BER	Bit Error Rate
BGP	Border Gateway Protocol
CDMA	Code Division Multiple Access
CMT-SCTP	Concurrent Multipath Transfer- Stream Control Transmission Protocol
CRC	Cyclic Redundancy Check
CS	Complete Sharing
CUC	Congestion window Update for CMT
CumAck	Cumulative Acknowledgement
CWND	Congestion Window
DAC	Delayed Acknowledgement for CMT
DOS	Denial Of Service
ECC	Error Correcting Code
ECMP	Equal-Cost Multipath
ECN	Explicit Congestion Notification
FEC	Forward Error Correction
FIFO	First In First Out
FTP	File Transfer Protocol
GPRS	General Packet Radio Service
GSM	Global System for Mobile
HTTP	Hypertext Transfer Protocol
ICMP	Internet Control Message Protocol
IP	Internet Protocol
IPCC-SCTP	Independent Per Path Congestion Control SCTP
IPFIX	IP Flow Information Export
IPTV	Internet Protocol Television
IPV4	Internet Protocol, version 4

IPV6	Internet Protocol, version 6
IRTF	Internet Research Task Force
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
IS-RTT	Immediate SACK RTT Samples
LAN	Local Area Network
LRC	Longitudinal Redundancy Check
LS-SCTP	Load Sharing SCTP
MDTP	Multi-Network Datagram Transmission Protocol
MPI	Message Passing Interface
MPT	Multipath Transport
MPTCP	Multipath TCP
MTU	Maximum Transmission Unit
NAT	Network Address Translation
NIC	Network Interface Card
NR-SACK	Non-Renegable Selective Acknowledgement
NS-2	Network Simulator 2
OMNeT++	Objective Modular Network Testbed in C++
OTcl	Object Oriented Tool Command Language
PEL	Protocol Engineering Laboratory
PF CMT-SCTP	Potentially Failed CMT-SCTP
PR-SCTP	Partial Reliability SCTP
pTCP	Parallel TCP
QR-DAC	Quick Response DAC
RDE	Relative Delay Estimator
RED	Random Early Detection
R-MTP	Reliable Multiplexing Transport Protocol
RP	Resource Pooling
RR	Round Robin
RSerPoo	Reliable Server Pooling
RTO	Retransmission TimeOut
RTT	Round Trip Time
rwnd	Advertised Receiver Window
SCTP	Stream Control Transmission Protocol
SFR	Split Fast Retransmit
SMTP	Simple Mail Transfer Protocol
SPOF	Single Point Of Failure

SRP	Selective Retransmission Protocol
SS7	Signal System 7
SSN	Stream Sequence Number
SSTHRESH	Slow Start Threshold
TELNET	Terminal Network
TSN	Transport Sequence Number
UMTS	Universal Mobile Telecommunications Systems

CHAPTER 1

INTRODUCTION

This chapter identifies potential problems of this thesis, describes the motivation, states the scope, defines the objectives, introduces research significant and finally shortly introduces its outlines.

1.1 Overview

The Internet has evolved in three directions over the past decades. First, content has evolved from relatively low-bandwidth content static text and web pages to high-bandwidth content multimedia which results in a significant and growing amount of bandwidth demand. Second, its usage has explosively globalized. Third, Internet access nature has changed from fixed access through desktop computers to a mobile access through smart phones and tablets. As a result, the principles of the Internet design are no longer suitable for current and future applications (e.g., mission-critical and time-critical applications). Network resources management is a key success for the future Internet (Kende, 2012).

Mission-critical applications over the Internet (e.g., e-health, e-commerce and emergency services) should eliminate Single Point Of Failure (SPOF) to provide uninterrupted service during failures. Application layer and Session layer solutions take care of handling server failure scenario via server redundancy like Reliable Server Pooling (RSerPool) described by (Lei *et al.*, 2008; Dreibholz and Rathgeb, 2009). However, a Transport layer that support multi-homing could provide a very seamless resolution of network failures, which is a more likely failure scenario. Transport layer allows multi-homed endpoints to be accessible by redirected traffic to a peer alternate IP address (assuming the end-to-end paths do not share the same failed link) transparently from the applications or user. The problem of link changeover is solved by abstraction in the Transport layer. Furthermore, in mobile sessions where Multipath Transport (MPT) can significantly decrease handover latencies by redirecting flow density to other alternate paths during mobility events (Ahmad *et al.*, 2012). Transport layer is the only layer that realizes a path congestion control and flow control. In addition, a Transport layer that realizes multi-homing does not require modifying the applications or changing the Network layer protocol (i.e. IPv4/IPv6).

On the other hand, time-critical applications over the Internet (e.g., high performance video streaming, video conferencing, and Internet Protocol Television (IPTV)) and the existence of multiple paths leads to the desire of applying load sharing as suggested by (Dong *et al.*, 2007) to utilize all paths simultaneously in order to improve application payload throughput (Natarajan *et al.*, 2006; Natarajan *et al.*, 2006; Natarajan *et al.*, 2007). The basic idea is that if the applications are able to simultaneously use more than one path through different networks, then they will be able to aggregate capacity across multiple paths and more resilient to problems on particular paths. For example, it is possible to shift traffic away from failed or congested paths in favor of uncongested paths to provide seamless handling surges in traffic.

1.2 Problem Statement

In the early days of Internet, endpoints were single-homed (i.e., can be addressed by single IP address) due to Network Interface Cards (NIC) high cost. Today, endpoints are multi-homed (i.e., can be addressed by multiple Network layer addresses (Braden, 1989). Wireless devices may use multiple access technologies such as wireless LANs (e.g., Wi-Fi) and cellular networks (e.g., CDMA, GSM).For instance, Apple's iPhone comes standard with Wi-Fi and cellular technologies (e.g., GSM or CDMA). Multiple active interfaces connected to different networks imply coexist of multiple paths between multi-homed endpoints.

The Stream Control Transmission Protocol (SCTP) (Stewart *et al.*, 2000; AL Caro *et al.*, 2003) is a reliable Transport layer protocol defined by Internet Engineering Task Force (IETF) which natively supports multi-homing for redundancy purpose. The Protocol Engineering Laboratory (PEL), University of Delaware has proposed an extension of SCTP denoted as Concurrent Multipath Transfer (CMT) realizes the load sharing functionality by simply modifying the SCTP sender to transmit new application payload to all IP peer addresses (Iyengar *et al.*, 2005; Iyengar *et al.*, 2006). At first glance, CMT-SCTP seems quite simple and straightforward. However, load sharing produces a set of potential challenges over symmetric paths (e.g., unnecessary fast retransmissions, crippled congestion window growth, superfluous network traffic, buffer blocking and TCP-friendliness) which adds protocol overhead (Jungmaier and Rathgeb, 2006; Wallace and Shami, 2012).

Initially, CMT-SCTP performance over asymmetric paths revealed some of the application payload throughput degradation. Even worse, certain scenarios with a CMT-SCTP application payload throughput even lower than standard SCTP application payload throughput (Dreibholz et al., 2010). For instance, buffer blocking may deteriorate transmission on all paths or even may cause interrupt transmission due to the asymmetric paths and reasonably small buffer size used by CMT-SCTP association. The deployment of CMT-SCTP on the Internet will exacerbate challenges due to standard protocol designed towards symmetric paths (i.e. roughly have similar bandwidth, delay and loss rate) (Qiao *et al.*, 2007). But, in reality, symmetric paths are unlikely in networks such as Internet. Moreover, multi-homing offers fault tolerance at Network layer by using different access technologies (e.g., ADSL and UMTS). Different access technologies clearly imply highly asymmetric paths. On the other hand, in any realistic configuration, the size of buffer must be reasonably small due to memory constraint requirements (e.g. the default buffer size setup of FreeBSD released 8.2 kernel SCTP is 233,016 bytes) (Rüngeler, 2009). As a challenge in this situation, asymmetric paths and small buffer size causes CMT-SCTP performance degradation.

The following points are represented the thesis problem statement.

- The buffer blocking is more likely to occur during courses of timeout recovery. Moreover, a larger timeout recovery period due to exponential backoff (i.e., back-to-back timeouts) results in an even higher probability to block the CMT-SCTP sender. Therefore reducing the number of timeouts and/or the number of back-to-back timeout will vitiate the buffer blocking phenomenon.
- CMT-SCTP applies Delayed Acknowledgement for CMT (DAC) to save storage and processing at routers on the return path despite additional delay is introduced (Iyengar *et al.*, 2006). But, delayed acknowledgement leads to inaccurate RTT estimation in asymmetric paths.
- Delayed Acknowledgement for CMT overly conservative behavior causes a real DATA chunk loss recovery triggered by the SACKs would be delayed. That is, the loss is detected after at six more chunks have been sent due to DAC. Using standard SCTP behavior, it would have been detected after only three chunks.

1.3 Objectives

The main objectives of this work are to develop solutions for the revealed challenges of the CMT-SCTP in asymmetric paths and limited buffer size configuration (i.e., a realistic configuration scenario).

1. To propose a new retransmission strategy based on retransmission strategies (Caro Jr *et al.*, 2006) takes into account path loss rate and delay in order to vitiate further application payload throughput degradation.
2. To propose a new strategy for more accurate RTT estimation in asymmetric paths for CMT-SCTP.
3. To propose a new delayed acknowledgement integrated with buffer split strategy to promote the application payload throughput by vitiating some of the buffer blocking.

1.4 Motivation

SCTP has remarkable advanced features over TCP. The main features of SCTP are multi-homing, multi-streaming, partial ordered delivery and resistance to Denial Of Service (DOS) attacks among the others. Consequently, SCTP can replace TCP as a general Transport layer protocol (Dreibholz and Rathgeb, 2008). While (Iyengar *et al.*, 2006) has only evaluated CMT-SCTP in symmetric paths setups (i.e., use paths have nearly the same bandwidth, delay and loss rate). However, symmetric paths cannot be assured for networks like the Internet.

However, operate in a multipath environment is not trivial and several potential issues could result from several actions that can be taken to handle normal data transmission, chunk loss recovery, failover management, and path recovery. The research on challenges and solutions for further vitiate of the application payload throughput degradation has become a very actively discussed topic.

1.5 Scope

The theme of this thesis discusses CMT-SCTP optimizing strategies in asymmetric paths and limited buffer configuration. We note that these considerations apply to multipath transfer at other protocols as well (e.g., Multipath TCP MPTCP which denotes a multipath transfers extension for the TCP protocol (Handley *et al.*, 2011). We use SCTP due to its relative maturity (Caro Jr *et al.*, 2006) and our focus on Transport layer protocols that exploits endpoint multi-homing feature for simultaneous data transfer application payload across multiple paths in a multi-homed association. In addition, SCTP provides TCP-like reliability, congestion, and flow-controlled data transfer to applications (Natarajan *et al.*, 2006).

In this work, we operate under the strong assumption that DATA chunks are transmitted over asymmetric paths and the buffer size is limited and disjoint or at least do not share the same bottlenecked paths.

1.6 Contributions

The main contributions of this work are; of course; to evaluate CMT-SCTP optimizing strategies in asymmetric paths environment and limited buffer configuration to improve its performance behavior.

The main contributions of this work are as follows:

1. A new retransmission strategy; namely Rtx-HYBRIDMETRIC retransmission strategy; based on retransmission strategy Rtx-CWND to mitigate some of the buffer blocking in order to vitiate further application payload throughput degradation.
2. A new strategy; namely Immediate SACK RTT Samples (IS-RTT); for more accurate RTT estimation on asymmetric paths for CMT-SCTP.
3. A new delayed acknowledgement strategy denoted as Quick Response DAC (QR-DAC) in order to further enhance CMT-SCTP application payload throughput.

In addition to the main contributions listed above, we have introduced Taxonomy for MPT retransmission strategies. More, our taxonomy consists of two classification schemes: one that classifies retransmission strategies with respect to retransmission path designation and the other classifies them with respect to their decision-based scheme to select retransmission path.

1.7 Research Significance

The deployment of CMT-SCTP on the Internet will exacerbate challenges due to standard protocol designed towards symmetric paths. The significance of this work stems from optimizing CMT-SCTP performance in a realistic configuration.

1.8 Thesis Organization

The rest of this thesis is organized as follows:

Chapter 2 describes the most important ways to multi-homed an endpoint. More, it presents an overview of load sharing approaches on different layers of the network stack; in particular Transport layer. In addition, Chapter 2 illustrates CMT-SCTP basic design and deployment challenges. Finally, Chapter 2 presents the "state of the art" of CMT-SCTP optimizing strategies literatures review.

Chapter 3 introduces commonly used research methodologies to understand and investigate network performance. It also briefly illustrates network simulator NS-2 and its CMT-SCTP model. More, it presents the framework of this thesis and explores the stages in detail. General experiment setup, topology, performance metrics and their evolution methods, CMT-SCTP model validation are presented in this chapter.

Chapter 4 presents an overview of SCTP retransmission strategies. Taxonomy for SCTP retransmission strategies is presented in this chapter. It also introduces a new smart retransmission strategy Rtx-HYBRIDMETRIC for further promote application payload throughput over asymmetric. The performance of a new strategy is demonstrated in this chapter.

Chapter 5 introduces CMT-SCTP RTT estimation technique. More, delayed acknowledgement for CMT-SCTP adversely affects RTT accuracy is illustrated in this chapter. It also introduces Immediate SACK round trip time samples IS-RTTY strategy for more accurate RTT on asymmetric paths. Performance of IS-RTT is demonstrated in Chapter 5.

Chapter 6 explores nitty-gritty details of the "state of the art" buffer split strategy. It also introduces Quick Response DAC QR-DAC further optimizes CMT-SCTP application payload throughput in line with buffer split. The performance of QR-DAC is evaluated using simulations in this chapter.

Finally, Chapter 7 summarizes the key results and an outlook to future study.

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