Enriching the internet control-plane for improved traffic engineering

Chi Dung Phung

LABORATOIRE D'INFORMATIQUE DE PARIS 6

ENRICHING THE INTERNET CONTROL-PLANE FOR IMPROVED TRAFFIC ENGINEERING

Advisor:
Dr. Stefano SECCI

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Chi Dung PHUNG

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Chi Dung PHUNG

AMELIORATION DU PLAN DE CONTRÔLE D'INTERNET AVEC DE NOUVELLES SOLUTIONS D'INGENIERIE DE TRAFIC

Soutenue le 30 mars 2018 devant le jury composé de :

Rapporteurs:	Dr. Mathieu BOUET	Thales Communications & Security.
	Prof. Guillaume URVOY-KELLER	Université de Nice Sophia Antipolis.
Examinateurs:	Prof. Nadia BOUKHATEM	Télécom ParisTech.
	Prof. Dominique GAITI	Université de technologie de Troyes.
	Dr. Luigi IANNONE	Télécom ParisTech.
	Prof. Guy PUJOLLE	Sorbonne Université.
	Dr. Damien SAUCEZ	Inria.
Invité:	Mohamed BOUCADAIR	Orange.
Directeur de thèse:	Dr. Stefano SECCI	Sorbonne Université.

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Author: **Chi Dung PHUNG.**

Defended on March 30, 2018, in front of the committee composed of:

Referees:	**Dr. Mathieu BOUET**	**Thales Communications & Security.**
	Prof. Guillaume URVOY-KELLER	**Université de Nice Sophia Antipolis.**
Examiners:	**Prof. Nadia BOUKHATEM**	**Télécom ParisTech.**
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Invited:	**Mohamed BOUCADAIR**	**Orange.**
Advisor:	**Dr. Stefano SECCI**	**Sorbonne Université.**

To my father and my family!

Abstract

One of the major challenges in the evolution of the Internet architecture is the definition of a protocol architecture that allows to solve the following major issues in Internet routing and traffic forwarding capabilities: (i) keeping a routing state that is manageable with current and forthcoming computing infrastructure – i.e., with few millions of states; (ii) offering a scalable pull architecture in support of data-plane programmability; (iii) offering a scalable forwarding plane able to be regularly optimized with only active flows information; (iv) offering locator/identifier separation for advanced IP mobility; (v) is incrementally deployable; (vi) can enhance the support of over-the-top services.

The Locator/Identifier Separation Protocol (LISP) has been identified as one of the rising protocols in this respect. In its current status, it supports the above mentioned requirements at a level that is acceptable for basic networking environments. However, it shows too limited capacities when it comes to take into consideration fault resiliency and capability to react fast to network state updates. These shortcomings can be compensated by enhancing the control-plane architecture, and the routing algorithms therein. In this dissertation, we propose new protocol features and experiment novel control-plane primitives, as well as hybrid distributed-centralized routing state dissemination algorithms, to scale with different network conditions.

We first design and build own open source LISP data-plane and control plane node, comparing it with other implementations, showing how our implementation can scale for large networks and reach performances suitable for real deployments. We present how our implementation served to operate all network nodes (data-plane and control-plane nodes) of a large scale experimentation testbed, the LISP-Lab testbed.

Then we propose a novel LISP-based solution for VM live migrations across geographically separated datacenters over wide area IP networks. Experimenting it at large scale, we show that with our approach we can easily reach sub-second downtimes upon Internet-wide migration, even for very distant clients.

Moreover, we investigate cross-layer network optimization protocols, in particular in relation with the Multipath Transport Control Protocol (MPTCP) to which LISP can

deliver path diversity in support of bandwidth increase, confidentiality support and connection reliability, also using LISP traffic engineering network overlays. Despite we could benefit from only few overlay network nodes, we could experimentally evaluate our proposals showing the positive impact by using our solution, the negative impact of long round-trip times on some MPTCP subflows, and the strong correlation between the differential round-trip time among subflows and the throughput performance.

Finally, we worked on a framework to improve LISP operation at the Internet scale, by facilitating cooperation between LISP Mapping Systems and introducing more automation in the LISP connectivity service delivery procedure. We believe such optimization could raise awareness among the service providers' community, yielding new business opportunities related to LISP mapping services and the enforcement of advanced inter-domain traffic engineering policies for the sake of better quality of service guarantees.

Résumé en Langue Française

L'un des défis majeurs de l'évolution de l'architecture Internet est la définition d'une architecture protocolaire permettant d'améliorer le routage, et en particulier (i) conserver un système de routage gérable avec les technologies actuelles et futures - c'est-à-dire, avec quelques millions d'états ; (ii) offrir une architecture apte à faciliter la programmabilité du plan de transfert ; (iii) proposer un système de routage évolutif pouvant être régulièrement optimisé avec uniquement les informations sur les flux actifs ; (iv) fournir une séparation entre localisateurs et identificateurs pour la mobilité IP avancée ; (v) faciliter un déploiement incrémental ; (vi) mieux servir les services applicatifs "over-the-top".

Le protocole LISP (*Locator/Identifier Separation Protocol*) a été identifié comme l'un des protocoles émergents à ce égard. Dans son état actuel, il répond très bien aux besoins susmentionnés. Cependant, il subit des limitations lorsqu'il s'agit de prendre en compte la résilience et la capacité à réagir rapidement aux mises à jour de l'état du réseau. Ces inconvénients peuvent être compensés en améliorant l'architecture du plan de contrôle et ses algorithmes de routage. Dans cette thèse, nous proposons un nouvelle architectures réseau-système et expérimentons de nouvelles primitives de plan de contrôle, ainsi que d'algorithmes de diffusion des états, en testant son passage à l'échelle avec différentes conditions de réseau.

Nous concevons et construisons d'abord un nœud de plan de données et de plan de contrôle LISP open source. Nous le comparons avec d'autres implémentations en montrant que notre implémentation atteint des performances adaptées aux vrais déploiements. Nous montrons comment notre implémentation a permis la mise en oeuvre d'une plateforme d'experimentation à grande échelle, la plate-forme LISP-Lab, en opération aussi bien les fonctions de plan de transfert que les fonctions de plan de contrôle.

En suite, nous proposons une nouvelle solution pour les migrations à chaud de machines virtuelles à travers des centres de données géographiquement répartis sur des réseaux IP étendus. Des tests dans un testbed réel connecté nativement à Internet montrent qu'avec notre approche, nous pouvons facilement atteindre des temps d'arrêt inférieurs à la seconde lors de la migration sur une grande échelle, même pour des clients très distants.

En outre, nous avons étudié des protocoles d'optimisation de réseau multicouche, en particulier en relation avec le protocole MPTCP (Multipath Transport Control Protocol), auquel LISP peut offrir une diversité de chemins pour l'agrégation de bande passante, ainsi qu'une plus grande confidentialité et fiabilité des connexions. Bien que nous ne puissions bénéficier que de quelques nœuds de réseau superposés, nous avons pu évaluer expérimentalement nos propositions en montrant l'impact positif de notre solution, l'impact négatif des longs temps d'aller-rétour sur certains sous-flux MPTCP, et la forte corrélation entre le temps d'aller-rétour différentiel et le débit.

Enfin, nous avons travaillé sur une refonte du plan de contrôle de LISP afin d'améliorer son fonctionnement du à l'échelle d'Internet, en facilitant la coopération entre le ssystèmes de mapping LISP et en introduisant plus d'automatisation dans la procédure de fourniture de services de connectivité LISP. Nous croyons qu'une telle optimisation pourrait sensibiliser la communauté des fournisseurs de services, générant de nouvelles opportunités commerciales liées aux services de cartographie LISP et l'application de politiques d'ingénierie de trafic interdomaines avancées dans le but d'obtenir de meilleures garanties de qualité de service.

Contents

List of Figures

List of Tables

Acronyms

ALT	Alternative LISP Topology.
AMPTCP	Augmented MPTCP.
APNIC	Asia Pacific Network Information Center.
AS	Autonomous System.
BGP	Border Gateway Protocol.
CDF	Cumulative Distribution Functions.
CP	CHANGE PRIORITY.
CPNP	Connectivity Provisioning Negotiation Protocol.
DDT	Delegated Database Tree.
DFZ	Default-Free Zone.
DNS	Domain Name Service.
EID	Endpoint IDentifier.
ETR	Egress Tunnel Router.
FIFO	First In First Out.
HA	Home Agents.
IaaS	Infrastructure as a Service.
IETF	Internet Engineering Task Force.
ITR	Ingress Tunnel Router.
LCAF	LISP Canonical Address Format.
LISP	Locator/Identifier Separation Protocol.

LISP-MN	LISP Mobile Node.
LISP-TE	LISP Traffic Engineering.
LSA	Link State Advertisements.
MIB	Mapping Information Base.
MIP	Mobile IP.
MPTCP	Multipath TCP.
MR	Map Resolver.
MS	Map Server.
MSFD	Mapping Service Function Discovery.
NTP	Network Time Protocol.
NVGRE	Network Virtualization using Generic Routing Encapsulation.
OOR	Open Overlay Router.
OS	Operating System.
OSPF	Open Shortest Path First.
PETR	Proxy Egress Tunnel Router.
PID	Path Identifier.
PITR	Proxy Ingress Tunnel Router.
PQO	Provision Quotation Order.
PxTR	PITR/PETR.
RLOC	Routing LOCators.
RTR	Re-Encapsulating Tunneling Router.
RTT	round-trip-time.
SMR	Solicit-Map-Request.
STT	Stateless Transport Tunneling.
TCP	Transmission Control Protocol.
TLV	Type-Length-Value.
TRILL	TRansparent Interconnection of a Lot of Links.
VM	Virtual Machines.

VXLAN Virtual eXtensible LAN.

xTR ITR/ETR.

Chapter 1

Introduction

One of the major challenges in the evolution of the Internet architecture is the definition of a protocol architecture that allows to solve the following major issues in Internet routing and traffic forwarding:

1. Keeping a routing state that is manageable with current and forthcoming computing infrastructure – i.e., few millions of states. The aforementioned growth has evolved exponentially for many years [1]: there were approximately 10,000 IPv4 routes in 1994 and there are now (end 2017) more than 690,000 of such routes . Likewise, there were a few hundreds of IPv6 routes before 2004 and there are more than 44,000 IPv6 routes as of December 2017 [2, 1];

2. Offering a scalable pull architecture in support of data-plane programmability [3], i.e., an architecture that having to manage a higher complexity due to broader routing context information, relieves to a pull solution instead than a push solution to let the network control-plane scale;

3. Offering a scalable forwarding plane able to be regularly optimized with only active flows information [4], i.e., that can adapt the forwarding behavior to the detection of new flows and the expiry of old flows;

4. Offering locator/identifier separation for advanced IP mobility, i.e., able to offering the necessary abstraction to distinguish end-point identifiers from routing locators;

5. Is incrementally deployable, i.e., can be integrated in existing network infrastructures with minor upgrades;

6. Can better support over-the-top services, i.e., can give to edge networks additional features for the routing of their flows across the Internet.

Among the various proposals that have been discussed over the years to improve Internet traffic forwarding efficiency, those that consist in separating the information that is specific to the location where a terminal is connected to the Internet ("where") from the information that is specific to the identity of the terminal ("who") have attracted a growing interest within the Internet community.

It is generally admitted that the ability to separate the "where" from the "who" allows to get rid of a highly polluting single addressing space, thereby reducing the size of the tables maintained by Internet routers. Multiple Identifier/Locator split addressing protocols were discussed in the last two decades, as documented in [5]. Among them, the Locator/ID Separation Protocol (LISP) is a protocol that differentiates from most of the other approaches in that it does not imply any modification of terminal devices. Also, LISP has been the subject of an important standardization effort for several years [6].

In its current status, LISP supports the above mentioned requirements at a level that is acceptable for basic networking environments. However, it shows too limited capacities when it comes to take into consideration fault resiliency and capability to react fast to network state updates [7]. These shortcomings can be compensated by enhancing the control-plane architecture, and the routing algorithms therein. In this dissertation, we propose new protocol features and experimenting novel control-plane primitives, as well as hybrid distributed-centralized routing state dissemination algorithms, to scale with different network conditions.

The remainder of this dissertation is as follows:

- **Chapter 2** presents the design and implementation aspect of our open source LISP data-plane and control plane node, comparing it with other implementations, showing that our implementation is scalable enough for large networks and reaches performances suitable for real deployments. We then describe the LISP-Lab experimentation platform that was built solely relying on it.

- **Chapter 3** presents a novel LISP-based solution we proposed for live virtual machine migration across geographically distant datacenters over wide area IP networks. We tested it experimentally at large scale, showing that with our approach we can easily reach sub-second downtimes upon Internet-wide migration, even for very distant clients.

- **Chapter 4** describes a cross-layer network optimization protocol proposal that addresses the enhancement of the Multipath Transport Control Protocol (MPTCP) to which LISP can deliver path diversity in support of bandwidth increase, confidentiality support and connection reliability, also using LISP traffic engineering network

overlays. Despite we could benefit from only few overlay network nodes, we could experimentally evaluate our proposals showing the positive impact by using our solution, the negative impact of long Round-Trip Times (RTTs) on some MPTCP subflows, and the strong correlation between the differential RTT among subflows and the throughput performance.

- **Chapter 5** proposes a framework to improve LISP cooperation at the Internet scale, by facilitating cooperation between LISP Mapping Systems and introducing more automation in the LISP connectivity service delivery procedure.
- **Chapter 6** concludes the dissertations and opens up new perspectives.

Chapter 2

Routing node design and experimentation

In this chapter, after an introduction about the LISP protocol, we introduce the LISP experimentation facilities we built and leveraged on for our research. More precisely, we detail data-plane and control-plane design aspects, document the system performance, and describe the testbed that was built and used in our experimentations.

2.1 LISP introduction

The Internet is suffering from scalability concerns, mainly due to the BGP routing infrastructure, and provides limited support to new advanced services [10]. As discussed in Internet Architecture Board's October 2006 Routing and Addressing Workshop [10, 11], a way to improve Internet scalability is separating the IP space into locator and identifier spaces, often referred to as the "Loc/ID split". Since the IAB workshop, several proposals based on this concept has been published or improved. The [5] splits these solutions into 3 groups, depending on where the new solution is applied. We summarize here what exposed in detail in [5]:

- Host-based core-edge separation: the new solution requires changes to both the client and server side behaviors.

  HIP - Host Identity Protocol [12]: it introduces a Host Identity (HI) name space, based on a public key security infrastructure, and a new related layer (the Host Identity Layer) between the Transport and Network Layers. The hosts are identified by HI instead of IP addresses. To get mapping between an HI and the IP

The contents of this chapter are presented in [8, 9].

address, HIP can use several ways like a new DNS Resource Record or a distributed hash table.

LIN6 - Location Independent Addressing for IPv6 [13]: it is a protocol supporting multihoming and mobility in IPv6. Similarly to HIP, LIN6 also adds a new layer between the Transport and Network Layers, but instead of dividing the network addresses into two separate namespaces as in HIP, it is based on an "embedded" addressing model: the LIN6 generalized ID (the identifier of the node used in the transport and upper layers) and the LIN6 address (used in network layer) are 128 bits in length and share the same common lower 64 bits (LIN6 ID).

MAT - Mobile IP with Address Translation [14]: it uses two addresses for a mobile node: the "Home Address" to specify a node's identity, and, the "Mobile Address" for the network layer. Similar HIT, MAT also divided network layer into two sublayers: a "MAT sublayer" that performs address translation, and a "Delivery sublayer" that delivers packets according to the translated destination address. For the mapping resolving, MAT uses DNS like LIN6.

FARA - Forwarding directive, Association and Rendezvous Architecture [15]: it uses an Association Id (Aid) to identify a communication between two hosts. To set up the Aid, the source host looks up for a "Forward Directive (FD)" of the destination host by querying the so-called FARA directory service, which resembles DNS.

MILSA - Mobility and Multihoming Supporting Identifier-Locator Split Architecture [16]: it introduces a new HUI Mapping Sublayer at the network layer to perform the mapping between identifiers and locators. The end host registers their mapping with the responsible Realm Zone Bridging Servers (RZBS) and sends map request to its RZBS which then follows the resolution hierarchy until a mapping is found.

SHIM6 - Level 3 Multihoming Shim Protocol for IPv6 [17]: it adds a new sublayer within the network layer (called the SHIM6 layer). SHIM6 creates a context between two communicating parties with a 4-way handshake with a set of available addresses for the nodes. One of these addresses is used as Upper Layer Identifier, useful for session identification, while all the other available addresses are used as locators.

Six/One [18]: it has a similar concept than SHIM6. However, what makes it different from SHIM6, is the fact that all the host addresses differ only in their 64 lower order bits.

ILNP - Identifier Locator Network Protocol [19]: it introduces two new terms, "Node Identifier (NID)", which is the unique name of a node, and the Locator, which is topologically tied and used for routing and packet forwarding. Applications use FQDNs instead of using the identifier directly. The mapping from an FQDN to a set of Identifiers and Locators is for each host stored in new DNS resource records. Packets contain the source and destination in the form of a pair Identifier-Locator. These pairs are encoded in IPv4 and IPv6 packet headers in different ways.

- Gateway-based solutions: they require changing both the end-hosts and the middleboxes.

  TRIAD - Translating Relaying Internet Architecture [20]: it was proposed to solve the problem of IPv4 address depletion in the NATted Internet without the painful transition to IPv6. Internet is viewed as a hierarchical set of interconnected realms and the firewall or border router is extended to act as TRIAD relay agent between realms. TRIAD advocates the use of DNS names to identify each end-host uniquely from different contexts.

  IPNL - Internet Protocol Next Layer [21]: it is a NAT-extended Internet protocol architecture designed to scalably solve the address depletion problem of IPv4 like TRIAD. The architecture requires changing both hosts and NAT boxes.

  I3 - Internet Indirection Infrastructure [22]: when a sender has some data to send, it sends out a pair ("id", "data"), where "id" is the logical address of the destination and "data" is the actual payload it wishes to send. The Chord lookup protocol [23] is used for creating an overlay of I3 servers which are responsible for handling the rendezvous and forwarding between senders and receivers.

  4+4 [24]: A 4+4 extended address is formed by concatenating a 32-bit public address with a 32-bit private address. They are also called "level 1" and "level 2" addresses. Hosts use DNS to check which level of address is needed to use for its outer/inner packet. The gateway swaps between the level 1 and level 2 address. This approach has its own drawbacks which include failure of end-to-end security mechanisms, a significant overhead involved with assigning a FQDN to each host and having two entries in the DNS system, thus, requiring two lookups.

  NodeID - Node Identity Internetworking Architecture [25]: it builds on HIP to provide identity based overlay routing for hosts to discover their mutual, routable IP addresses. Thus, NodeID avoids the use of a special DNS Resource Record or a HIP proxy for determining the address corresponding to a Host Identity.

  NUTSS [26]: it introduces two types of middleboxes: policy-boxes, which

handle policy decisions (firewall-like entities), and forwarding middleboxes, such as NATs, which forward traffic and perform address/port translation. Each network has at least one P-box, which is connected to a P-box at a higher hierarchical level and a host registers itself through a hierarchy of P-boxes.

HRA - Hierarchical Routing Architecture [27]: HRA has two levels of mapping similarly to HIP. When an end-host A wishes to communicate with another end-host B, it firstly obtains the locator and the Locator Domains (LD) ID information of destination host B from a distributed hash table before initializing a communication. Upon obtaining the LD ID and locator information, A fills in the destination IP address with the destination host locator of B, if the LD ID obtained is the same as its own. Otherwise, it fills the destination IP address in the IP header with that of its LD Border Routers (LDBR) locator. In such a scenario, the LDBR of A rewrites the source IP address with its own locator, and the destination IP address with the LDBR address matching the LD ID of B.

Mobile IP [28, 29]: MobileIP defines Home Address acts as the identifier and a Care-of Address as the locator. In contrast to many other approaches, both the identifiers and the locators in Mobile IP are routable addresses. It is not a solution for multihomed networks and causes problems in site renumbering [30]. Mobile IP requires additional infrastructure elements called Home Agents.

- Network-based core-edge separation: these solutions are realized at the middle boxes (e.g., at edge-routers) without changing the end-point behavior.

  GSE - Global, Site, and End-system address elements [31]: it is an alternate IPv6 architecture. The proposed IPv6 address contains a 6-Byte "Routing Goop (RG)", a 2-Byte "Site Topology Partition (STP)" and an 8-Byte "End System Designator (ESD)". When creating a packet, the source host fills the destination address with a 128-bit IPv6 address that it receives from a DNS lookup for the destination. This address includes the RG of the destination as provided in the DNS response. The packet leaves the site through one of the border routers, which modifies the source RG to be used for the packets on the return path of this communication session.

  LISP - Locator/ID Separation Protocol [6], which we describe in details in the following.

Tables 2.1 and 2.2 summarizes and draws a complete comparison between the above protocols in terms of namespace related characteristics and deployment strategies.

Architecture	IPv4	IPv6	Multihoming	Mobility	Site renumbering	Internet transparency	Disjoint	Structured
HIP	√	√	√	√	√	√	√	
LIN6		√	√	√			√	√
MAT	√	√		√				√
FARA	√	√		√				√
MILSA	√	√	√	√			√	√
SHIM6		√	√					√
Six/One		√	√		√		√	√
ILNP	√	√	√	√			√	√
TRIAD	√					√	√	√
IPNL	√		√	√	√	√		√
i3	√	√	√	√	√		√	
4+4	√		√		√	√	√	√
NodeID	√	√	√	√		√	√	
NUTSS	√	√	√	√	√	√	√	√
HRA	√	√	√	√	√	√		
Mobile IP	√	√		√				√
GSE		√	√		√		√	√
LISP	√	√	√	√	√	√	√	√

Table 2.1: Namespace related characteristics of the architectures [5].

Architecture	Data-plane operation	Deployment	Legacy apps	Infrastructure changes
HIP	Rewrite, Tunnel	Host-based	√	New FQDN record per host (optional)
LIN6	Rewrite	Host-based		Mapping Agents for nodes, FQDN/MA
MAT	Rewrite	Host-based	√	IMS for nodes with DNS entry for each IMS
FARA	Rewrite	Host-based		FARA directory service (fDS)
MILSA	Rewrite	Host-based		DNS like names for every node, RZBS servers
SHIM6	Rewrite	Host-based		IPv6 Options
Six/One	Rewrite	Host-based		Changes to edge network routers (Optional)
ILNP	Rewrite	Host-based	√	FQDN/node, ARP modied for ILNPv4
TRIAD	Rewrite	Gateway-based	√	FQDN/Node, WRAP supporting Relay Agents
IPNL	Rewrite, Tunnel	Gateway-based	√	DNS name for every node, upgraded Routers
i3	Rewrite	Gateway-based	√	i3 servers
4+4	Rewrite	Gateway-based	√	DNS name for every node, upgraded NATs
NodeID	Rewrite	Gateway-based	√	NodeID Routers for routing in static core
NUTSS	Rewrite	Gateway-based	√	P-boxes and M-boxes
HRA	Rewrite	Gateway-based		LDBRs, IPv6 ext. headers, new IPv4 payload, FQDN/host
Mobile IP	Tunnel	Gateway-based	√	Home Agents
GSE	Rewrite	Network-based		Two-faced DNS
LISP	Tunnel	Network-based	√	Tunnel Routers

Table 2.2: Deployment related characteristics of the reviewed architectures [5].

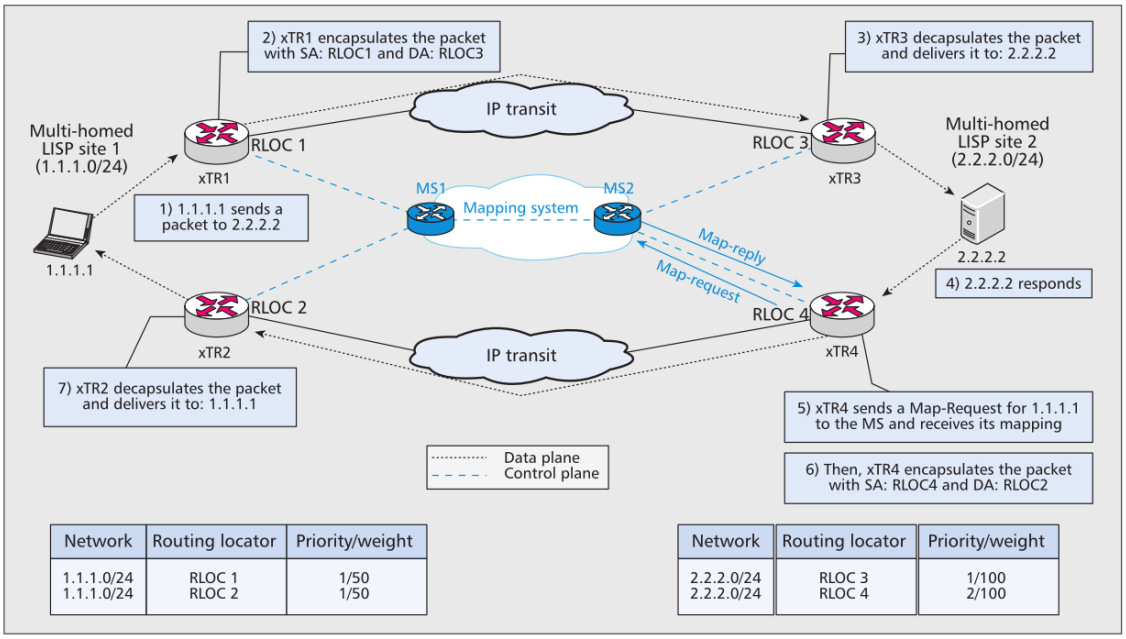


Figure 2.1: An example of LISP communications between two LISP sites.

The Locator/Identifier Separation Protocol (LISP) [6] was architected to introduce a two-level routing infrastructure on top of the current BGP+IP architecture, mapping an endpoint identifier (EID) to one or several routing locators (RLOCs). RLOCs remain globally routable, while EIDs become provider-independent and only routable in the local domain. The resulting hierarchical routing architecture opens the way to benefits ranging from BGP routing table size reduction and efficient traffic engineering, up to seamless IP mobility. Moreover, LISP enables a large set of applications and use cases such as virtual machine mobility management, layer 2 and layer 3 virtual private networks, intra-autonomous system (AS) traffic engineering, and stub AS traffic engineering.

Since April 2009, the LISP IETF Working Group has completed a first set of Experimental Requests for Comments (RFCs) describing the Locator/ID Separation Protocol. By the end of 2017, 17 RFCs documents and 35 Internet-Drafts documents were published.

We explain in the following LISP in detail especially the aspects that are required to position and understand our contributions.

2.1.1 Data-plane

More technically, LISP uses a map-and-encap approach, where a mapping (i.e., a correspondence between an EID-Prefix and its RLOCs) is first retrieved and used to encapsulate the packet in a LISP-specific header that uses only RLOCs as addresses. Such a map-and-encap operation in LISP is performed using a distributed mapping database for the

first packet of a new destination EID; then the mapping is cached locally for all subsequent packets. The LISP control plane is based on signaling protocols necessary to handle EID-to-RLOC registrations and resolutions, dynamically populating mapping caches at LISP network nodes. Since several RLOCs can be registered for the same EID, priority and weight metrics are associated with each RLOC in order to decide which one to use (highest priority) or how to do loadbalancing (proportionally to the weights if priorities are equal) [32].

In practice, when a host sends a packet to another host at another LISP site, it sends a native IP packet with the EID of the targeted host as the destination IP address; the ingress tunnel router (ITR), maps EID to RLOCs, appends a LISP header and an external IP/UDP header with the ITR as source node, and, as the destination address, an RLOC selected from the mapping of the destination EID. The egress tunnel router (ETR) that owns the destination RLOC strips the outer header (i.e., decapsulates) and sends the native packet to the destination EID.

For example, in Fig. 2.1 the traffic from host 1.1.1.1 to host 2.2.2.2 is encapsulated by the ITR toward one of the RLOCs (the one with the highest priority, i.e., RLOC3), which acts as the ETR and decapsulates the packet before forwarding it to its final destination. On the way back to 1.1.1.1, RLOC4's xTR queries the mapping system and gets two RLOCs with equal priorities, hence performing load-balance as suggested by the weight metric.

2.1.2 Control-plane

In LISP, data-plane and control-plane are quite clearly separated. The advantage of creating network control functions disjoint from the data plane is the possibility of programming the control plane independent of the forwarding logic, and thus to implement advanced and personalized functionalities, as done in [33] for instance, for virtual machine mobility management. This approach is ex-ante in line with the later developed software defined networking paradigm [34].

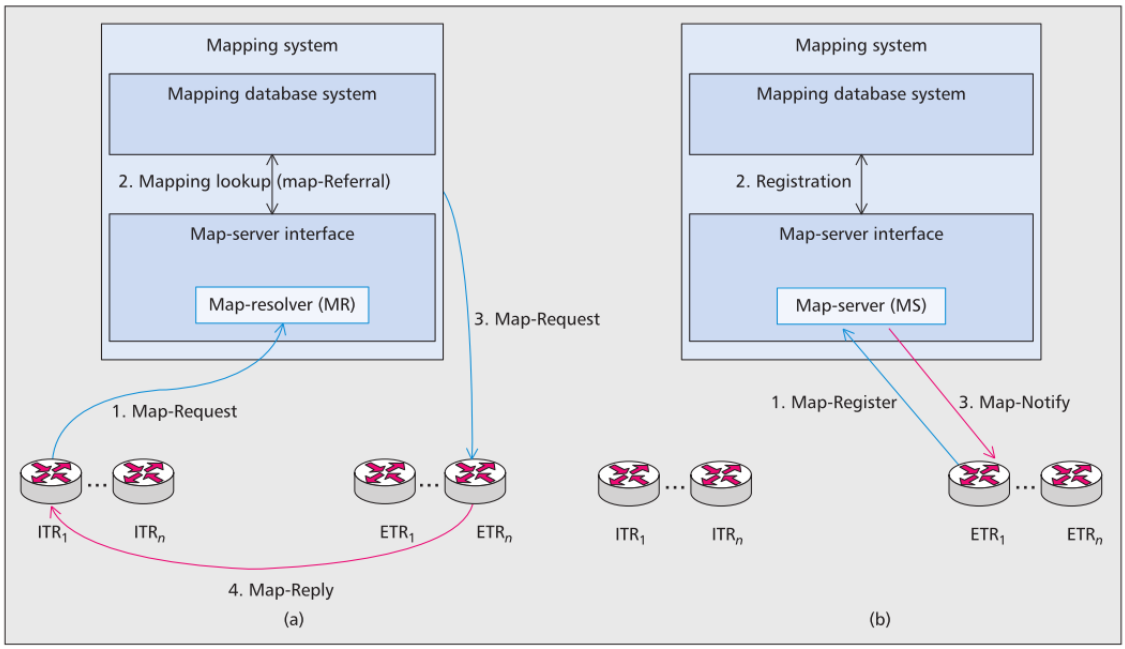


Figure 2.2: LISP mapping system workflow: (a) mapping retrieval; (b) mapping registration.

For scalability reasons, ITRs learn mappings on-demand via the so-called mapping system. The mapping system is composed of the mapping database system and the map-server interface [35]. The mapping system workflow is summarized in Fig. 2.2. On one hand, the mapping database system constitutes the infrastructure that stores mappings on the global scale, potentially using complex distributed algorithms [35, 36, 37]. On the other hand, the map-server interface hides this complexity via two network elements, the map resolver (MR) and map server (MS), deployed at the edge of the mapping database system, which LISP sites contact to retrieve and register mappings. More precisely, when an ITR is willing to obtain a mapping for a given EID, it sends a Map-Request message to an MR.

The MR is connected to the mapping database system and implements the lookup logic in order to determine at which LISP site the Map-Request must be delivered (to any of its ETRs), and delivers it. The ETR receiving the query returns the mapping directly to the requesting ITR with a Map-Reply message. It is worth noting that the ETR of a LISP site is not directly involved in the mapping database system but is instead connected to an MS. The ETR sends a Map-Register message to that MS, which later ensures that the mapping is registered in the mapping database system. Optionally, the MS can acknowledge the registration with a Map-Notify message.

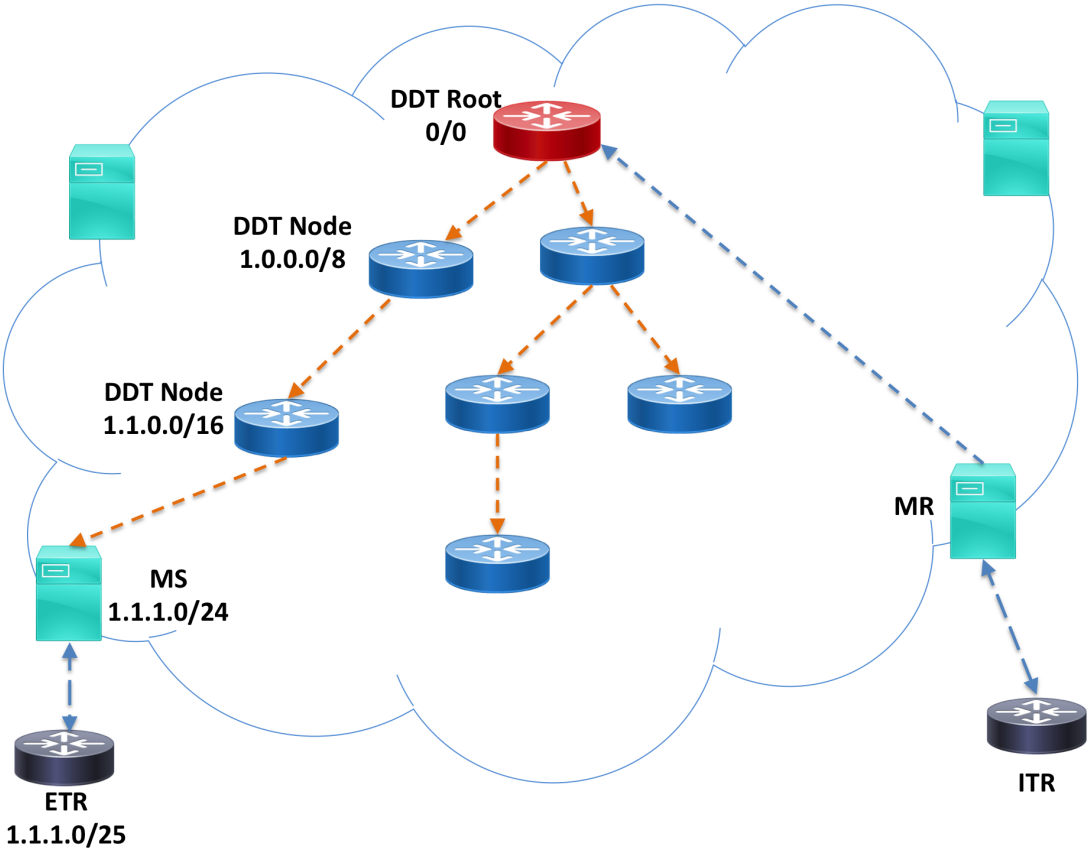


Figure 2.3: A representation of LISP DDT protocol signaling.

Several mapping database systems have been proposed, and in particular LISP-ALT [36] and LISP-DDT [37]). While the former relies on the BGP protocol to build a mapping distribution architecture, in LISP-DDT the MR discovers where to send the Map-Request by iteratively sending Map-Requests and receiving Map-Referral messages via the hierarchical LISP-DDT infrastructure, similarly to DNS [37]. Fig. 2.3 depicts a DDT mapping system where (i) an ETR sends Map-Register messages to a statically configured MS; (ii) DDT nodes have static pointers to their authoritative node for more specific resolution, with the MS as leaf; (iii) the MR queried by a ITR has a static pointer to a DDT root. More precisely, the process to resolve an EID to RLOC entry can be summarized as follows:

- the ITR sends a Map-Request message to its configured MR (for example asking for a mapping for the EID 1.1.1.1);
- the MR relays the Map-Request message to its configured DDT root;
- the DDT root sends back a Map-Referral message to MR, providing so the list of authoritative DDT Node for more specific resolutions;

- the MR chooses one of the DDT nodes to send the Map-Request message to, and then receives a new list of authoritative DDT node for more specific resolutions. This process is repeated until the Map-Request message reaches the MS to which the ETR registers the EID prefix to which the EID belongs.
- the MS send back a Map-Referral message (including an acknowledgement) to the MR and forwards the Map-Request message to an authoritative ETR (or directly sends back a Map-Reply message if the ETR sets a proxy bit in the Map-Register message to allow for proxied replies).
- the ETR (or the MS in case of proxied reply) sends a Map-Reply message with the requested mapping information to the ITR.

2.2 LISP implementations

In this section, we synthetically review existing and publicly known LISP implementations, both commercial and open source ones.

2.2.1 Cisco IOS

Cisco has been the major driver for LISP standardization and experimentation since its inception. Both LISP data-plane and control-plane functions are supported and available across a wide range of Cisco router and switch operating systems. Cisco continues to introduce new LISP features and functions to provide within the network expect in the data-center network environment.

The current LISP implementation in Cisco nodes include the standard LISP features, as well as some proprietary features that are partially documented related to virtual machine mobility management [38]. Nevertheless, the current implementation does not include all the features we needed for this thesis, such as LISP traffic engineering and canonical address format features, as elaborated in the following chapters.

2.2.2 OpenLISP

OpenLISP [39] is an open source implementation of the LISP data plane in a FreeBSD environment.

The standard core LISP data-plane functions are patched to the FreeBSD kernel and a socket is introduced to allow communication with the control plane in the user space. [39] shows that the cost of running LISP in terms of forwarding latency is acceptable and the impact on end-to-end flows is minimal.

Very partial control-plane features are present, essentially limited to map-request and map-reply message processing. Hence as a standalone node, an OpenLISP node is not able to handle all control plane signaling within a LISP network, and is able to deploy only the xTR behavior.

2.2.3 LISPMob

LISPMob is a multi-platform implementation of the LISP mobile node (LISP-MN) variant [40] intended for mobile devices (e.g., smartphones); in LISP-MN, mobile nodes are full-fledged xTRs relying on a lightweight version of the control plane. LISPMob is implemented in the user space and compatible with Linux and Android. Even though LISPMob is intended for mobile devices, it does not preclude its usage on routers; however, the limited control plane functionalities and its user space implementation would make it innapropriate for large-scale operational networks.

Since 2016, the project is renamed to OOR [41] (Open Overlay Router) to full supporting LISP function in SDN/NFV environments. The control-plane extent is however still limited.

2.2.4 PyLISP

PyLISP [42] is a Python implementation of LISP. This library provides basic data-plane and control-plane functions for the xTR behavior, and some command line tools to perform actions like asking a map resolver for a mapping and directly querying a DDT node. Although it was planned to add other LISP behaviors such as MS, MR or DDT node, in fact, these parts have never been released for PyLISP. Nonetheless, it is a good training tool for a beginner, as it is simple to install and to run in the user space.

2.2.5 Other implementations

Among the above mentioned implementations, three are open source: OpenLISP, LISPMob, and PyLISP. The Cisco implementation is quite well documented but only in terms of user interface.

In addition, we resume in the following additional implementations that have either a limited scope, or are only marginally documented.

- AVM GmbH announced in 2012 that they support LISP in firmware for their FRITZ!Box-devices in FRITZ!OS 6.00 (a residential broadband access device), and also supported in later versions. It is unfortunately not well documented.

- OpenDayLight (ODL) [43] is an SDN controller that offers, since 2013, LISP as one of its SouthBound Interface (SBI) protocols under the so-called LISP Flow Mapping Service. This service provides Map-Server and Map-Resolver behaviors, for data plane nodes, as well as to ODL applications. Mapping data can go beyond basic EID-to-RLOC entries, and can include a variety of routing policies and traffic engineering metrics. ODL applications and services can use a northbound interface to define specific mappings and policies in the LISP Mapping Service.

- Open Network Operating System (ONOS) [44] is another SDN controller that also introduces LISP as one of its southbound protocols, since 2017. All basic LISP features are offered in the current version. At the time being, LISP mapping entries do not exploit distributed core primitives that historically differentiate ONOS from ODL. Performance tests were recently run against the LISP SBI [45], leading to important improvement making the SBI more scalable for large networks.

- OpenVSwitch (OVS) [46] is a software switch that, since 2013, supports LISP as one of its layer 3 tunneling protocols. OVS code is mostly contributed by Cisco. The implementation requires the use of static LISP tunnel endpoints, and LISP routing rules are not implemented as standard switching rules; they are instead implemented by means of ad-hoc tunneling interfaces.

- LISPERS.net [47] is a closed source software of LISP developed by Dino Farinacci. It supports all the LISP behaviors, and offers GUI management interface as well. Unfortunately, it is not well documented and runs at user space.

2.3 Enhancement of the OpenLISP data-plane

Among the open source implementations, the single one being well documented and scientifically evaluated, while allowing for high-performance networking is the OpenLISP implementation. Hence we selected OpenLISP as starting implementation for our experimental research activity.

In order to make OpenLISP data-plane usable to build a fully-fledge LISP network, we extended it to add the following standard features:

- LISP Proxy Ingress Tunnel Router (Proxy-ITR): used to provide connectivity between sites which use LISP EIDs and those which do not. They act as gateways between those parts of the Internet which are not using LISP (the legacy Internet) A given Proxy-ITR advertises one or more highly aggregated EID prefixes into the public Internet and acts as the ITR for traffic received from the public Internet.

- LISP Proxy Egress Tunnel Router (Proxy-ETR): Proxy-ETRs provide a LISP (Routable or Non-Routable EID) site's ITRs the ability to send packets to non-LISP sites in cases where unencapsulated packets (the default mechanism) would fail to be delivered. Proxy-ETRs function by having an ITR encapsulate all non-LISP destined traffic to a pre-configured Proxy-ETR.

- Re-Encapsulating Tunneling Router (RTR): An RTR acts like an ETR to remove a LISP header, then acts as an ITR to prepend a new LISP header. This is known as Re-encapsulating Tunneling. Doing this allows a packet to be re-routed by the RTR without adding the overhead of additional tunnel headers.

Specific features were also added to the data-plane node, in the frame of the solutions presented in the next chapters where these features are described.

2.4 Control plane implementation and evaluation

Although OpenLISP supports both data-plane and control-plane functions, as a standalone node, an OpenLISP node is not able to handle all control plane signaling within a LISP network. Only map-request and map-reply message processing was made available in OpenLISP.

In order to cope with such limitations, we worked on a complete control plane implementation, with the goal to integrate it with the OpenLISP node, while keeping the data and control plane parts independent of each other for performance and modularity reasons, as detailed hereafter.

In the following, we detail the resulting control plane architecture, and related implementation aspects, before describing a performance evaluation we run against some of the implementations described in the previous section.

2.4.1 Control-plane system architecture

We describe the design of our control plane implementation, issued under a BSD licence. Given that the main role of the LISP control plane is the management of EID-to-RLOC mappings with the mapping system, in the following we first focus on the design of the mapping database, and then we detail the different modules.

The heart of the OpenLISP control plane is the EID-to-RLOC mapping database, synthetically referred to as map-table in the following. Each map-entry of the map-table consists of an EID prefix with a list of RLOCs, each RLOC associated with a structure that contains the RLOC address and related attributes (i.e., priority and weight). The

three network elements involved in the control plane, ETR, MS, and MR, serve different purposes; hence, they implement their own map-table logic, as detailed hereafter.

ETR's map-entries correspond to the mappings for the different EID prefixes of the LISP site it serves and should register via an MS. Each such map-entry must have at least one RLOC address.

Map-Servers maintain EID prefix registrations for the LISP sites they serve and for EID prefixes not assigned yet. Therefore, we distinguish the following two map-entry types:

- *Registered map-entries* are built on Map-Register messages received from ETRs and are associated with meta-information about the registering site (e.g., cryptographic keys authorized to register mappings, contact addresses). The MS can use these entries to directly reply to Map-Request messages on behalf of ETRs if commissioned to do so.
- *Negative map-entries* are used to define range of IP prefixes that belong to the EID space but do not require LISP encapsulation. Requests for such prefixes generate negative map-replies.

Map-Resolvers maintain a map-table to speed up mapping resolution, and we distinguish the next two types of entries:

- *Negative map-entries* are similar to an MS's negative map-entries. An MR hence immediately sends a negative Map-Reply for not yet assigned EID prefixes.
- *Referral map-entries* contain the addresses of other DDT nodes (MRs) that are supposed to provide more specific LISP-DDT mappings (i.e., have a longer EID prefix match). Even though they are logically separated, map-tables are implemented within a compact radix tree data structure instance optimized for fast IP prefix lookup [48]. Actually, as our implementation is dual-stack, we maintain two radix tree instances, one for IPv4 EIDs and the other for IPv6 EIDs.

2.4.2 Control-plane modules

Our control plane implementation includes the essential features to operate a multi-site LISP network, including all the LISP-DDT logic and complete support of both IPv4 and IPv6. In order to operate the control plane independent of the data plane, it is divided into independent modules with different functionalities (Fig. 2.2).

As depicted in Fig. 2.2, the control plane receives the messages from a dedicated queue, which gets them in turn from the kernel's UDP socket queue. The control plane is based on

one general orchestration processes (i.e., control) and three specialized processes that implement MR, MS, and xTR network element logics. The treatment of mapping-resolution related and registration-related messages within these processes is isolated thanks to the use of threads. Each process is composed of several modules, as described in the following.

The xTR process includes the following three modules:

- MAP-REGISTER module: Implemented at the ETR interface; it sends periodic information (each 60s, as recommended in [6]) about map-entry registration to at least one MS. Note that ETRs are authenticated by an MS using their preconfigured shared key.

  In order to support mapping system multitenancy, going beyond the current standards, the module allows specifying different keys for different MSs to allow an xTR to join LISP networks managed by independent MS stakeholders.

- MAP-REPLY module: Implemented at the ETR interface, it receives and processes Map-Requests coming from the ITR or MSs. According to the standard, Map-Requests must be encapsulated (Encapsulated Control Message, ECM) Map-Request when sent to MRs, but are sent natively to ETRs. Our implementation supports these two modes with any combination of IPv4/IPv6 encapsulation. Upon reception of a Map-Request, an ETR replies with the corresponding Map-Reply.

- PLANE-INTERWORKING module: This module allows the control plane to interact with the data plane and hence to form a full-fledged OpenLISP xTR. In order to perform data plane functions, the OpenLISP data plane maintains a mapping information base (MIB) consisting of the LISP cache (storing short lived mappings in an on-demand fashion) and LISP database. OpenLISP also provides a low-level abstraction called Mapping Socket to add or remove mappings from the MIB locally on the machine (e.g., by means of a daemon or using the command line). This interworking module uses the control plane to maintain the database interacting with the data plane through the Mapping Socket [39].

The MS process includes the following two modules:

- MAP-REGISTER module: Implemented at the MS interface, it receives Map-Register messages from ETRs and updates the MS map-table accordingly. The MS verifies the authenticity of the Map-Register messages and ensures that their EID-prefixes belong to the LISP sites of which it is in charge.

  In normal operations, mappings of given sites are stable with time. However, the specification requires periodically re-registering mappings. Therefore, to improve

performance, our control plane hashes the Map-Register message to check whether the mapping has changed since the last registration, complete registration being done only upon a mapping update. If the ETR asks for a notification, a Map-Notify message is sent back to the ETR.

- MAP-REQUEST module: Upon Map-Request reception, the module has a choice between two actions, depending on the map-table entry that corresponds to the EID in the Map-Request. If the EID corresponds to the EID prefix of a registered map-entry, the MS sends a Map-Reply back or forwards the Map-Request to one of the RLOCs in the map-entry, depending on the value of the proxy bit in the Map-Register message. If, instead, the EID corresponds to a site managed by the MS but has no active registration, a negative Map-Reply is sent back.

The Map-Resolver process contains the following two modules:

- MAP-REQUEST module: It accepts and processes Map-Requests from xTRs. For DDT signaling, the Map-Request follows the map-referral chain until it reaches an MS or an ETR, or the number of referral nodes it passed through exceeds the maximum allowed number. To speed up performance, the MR caches map-referral messages in its map-table so that it can reuse it for further Map-Requests covered by the EID prefix.
- MAP-REFERRAL module: It accepts the LISP-DDT Map-Requests to which it replies with a map-referral message. We provide in the control plane package a sample configuration that can be used to set up a DDT root [37].

Finally, the control process aims to orchestrate other processes. It is in charge of receiving control plane messages from the LISP network and dispatching them to the appropriate control plane process. A first-in first-out (FIFO) queue is used to absorb demand burstiness and catch messages coming from the UDP socket kernel queue. This process also populates the map-table, used by control plane processes, according to the device configuration file.

2.4.3 Running the control plane

The OpenLISP control plane process listens on the UDP 4342 LISP control port. It runs in the user space to allow easier programmability of its features, while the OpenLISP data plane runs in the kernel to give higher performance to data plane functions. Even though our control plane is designed for a FreeBSD environment, it can be adapted to Linux.

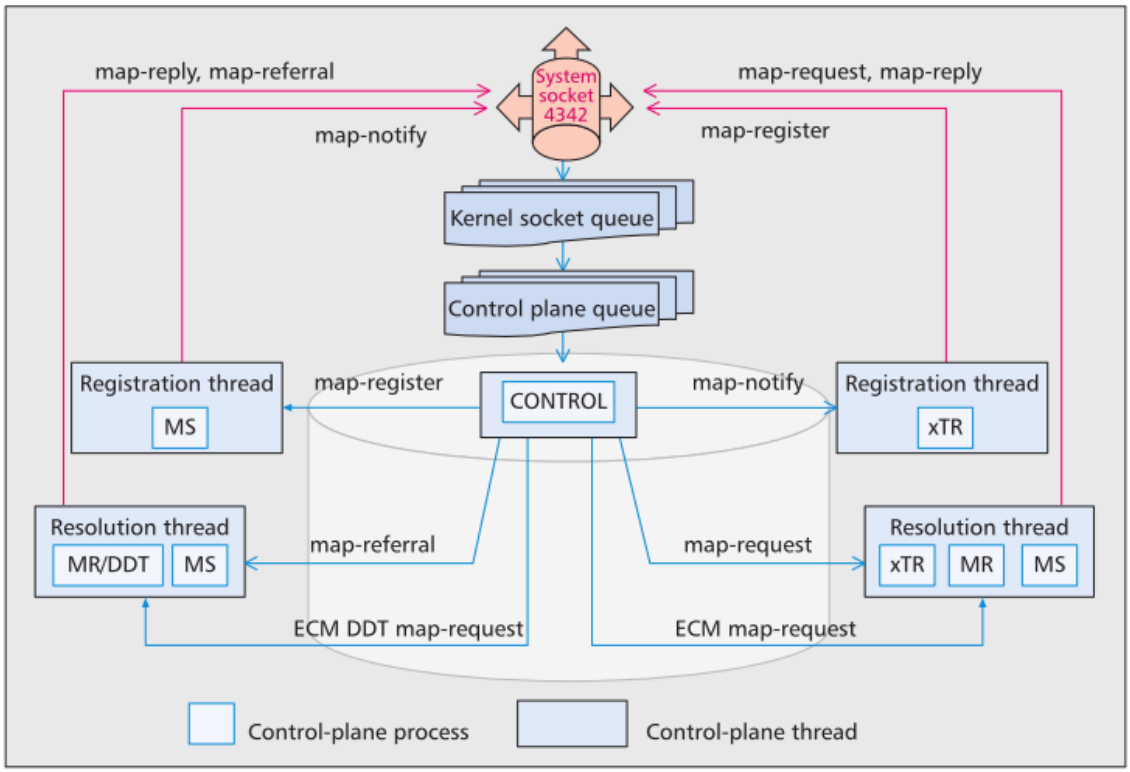


Figure 2.4: System-level OpenLISP control plane multi-thread architecture.

As depicted in Fig. 2.4, the control plane program handles three types of resident threads besides the main thread: one thread runs the control process, one thread is dedicated to mapping registrations, and the other threads are dedicated to Map-Request/Referral processing (resolution threads). The main thread accepts LISP control plane packets coming from the kernel socket queue and pushes them to a FIFO control plane queue in the user space based on a dynamic list. For load balancing, the control thread can dynamically create several resolution threads up to a maximum number, which is also left as a tunable parameter for the user via configuration files. The choice of using several pre-instantiated threads to process control plane messages and create a packet queue for the control plane fed by the kernel socket queue is dictated by scalability and robustness against attacks. It is worth noting that using multiple cores could create moderate processing time variances due to the dynamic thread-core binding operating system (OS) operations.

Finally, it is worth mentioning that a command line interface is also provided to allow an operator to interact with the control plane. More details on the configuration are provided in the documentation files of the software release.

2.4.4 Evaluation

We evaluated the performance of our LISP control plane by stressing an OpenLISP node running on a physical machine with a 2.67 GHz dual-core CPU and 2 Gbytes RAM. The evaluation focuses on the OpenLISP node system performance itself, independent of the LISP Beta Network topology. We do not account for packets not handled by the control plane due to drops in the network. Indeed, since LISP uses UDP to deliver both data plane and control plane messages, some of them may be dropped and definitely lost by intermediate nodes in an operational context, and the sender eventually retransmits the packet after timeout. Therefore, the number of messages the control plane can handle depends on the provisioning of the kernel's UDP queue size, but also on the frequency with which the control plane program picks up packets from a kernel's queue and how fast it processes the messages. In order to avoid modifying the system configuration, we added in our control plane, more specifically in the control thread, a FIFO queue that is overprovisioned so that the kernel's queue occupancy remains as small as possible. In the tests we used a control plane queue size of 100,000 packets; we tested the feasibility using smaller sizes (1000, 500, and 100), with no visible effects on performance, as well as with very high rates (more than 4000 packets/s).

In the following we evaluate the control plane processing latency. For the MS, it corresponds to the time taken to check the validity of the Map-Register message, update the mapping into the mapping system, and send back Map-Notify messages when needed. When generating the Map-Register messages in the tests, around 5 percent are randomly set to require a Map-Notify. For the MR, the processing latency corresponds to the mapping lookup time and the time to send the Map-Reply back. Fig. 2.5 displays the processing latency for both MS and MR as a function of the number of connected LISP sites (i.e., the number of different mappings).

To carry out our measurements, we use a LISP site composed of two xTRs and one MS/MR node. xTRs send traffic at the maximum rate over a 100 Mb/s link with the MS/MR, stressing the control plane with almost 3000 packets/s in the control plane input queue. For the sake of realism, we fed the EID-to-RLOC database IPv4 prefixes of the DANTE public routing table, fragmenting /16 prefixes into /24 prefixes: thus, we obtain a mapping database of more than 260,000 different EID prefixes. Randomly picking up EID prefixes from the database, we construct s sites, each site having from 1 to e EID prefixes (e.g., for multihoming TE or IP mobility management). We vary s from 200 to 2000 (roughly from one to 10 times the number of sites currently connected to the LISP Beta Network), with a step of 100 sites; e takes a random value between 1 and 100, so as to also include LISP sites intensively performing multihoming traffic engineering and

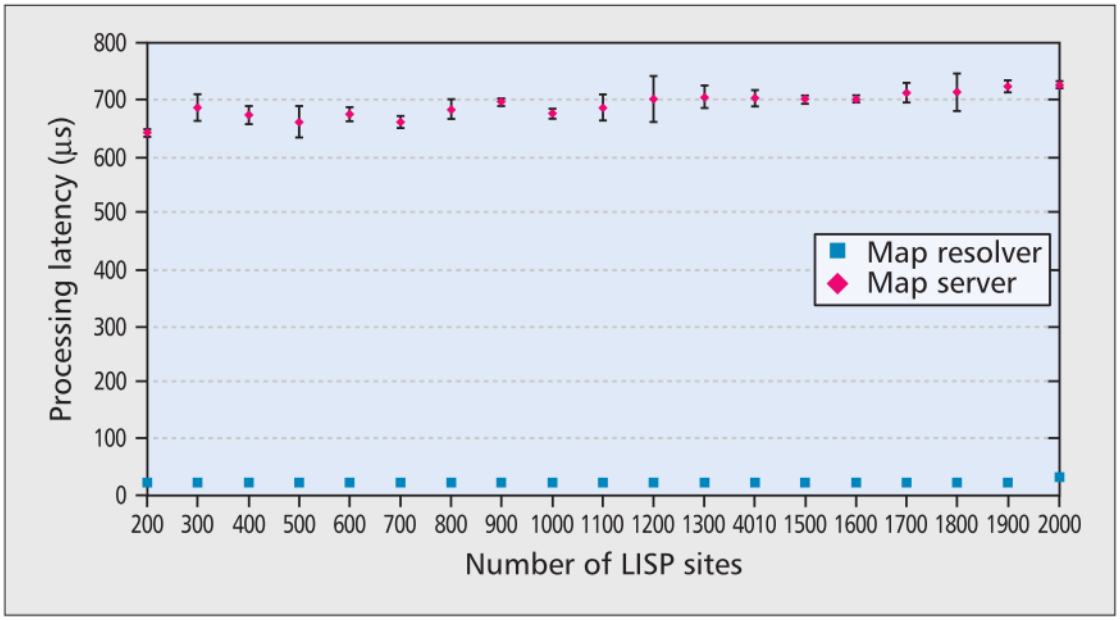


Figure 2.5: Control plane processing latency as a function of the number of LISP sites.

IP/prefix mobility across RLOCs. It is worth noting that the number of RLOCs only directly affects the memory size used to store the radix tree without affecting the height (or depth) of the tree so it does not affect the time to search in the tree. Once this setting is loaded in the MS/MR node, one of the xTR is used to send map-register messages for all sites to the MS, while the other xTR to send Map-Request messages to the MR. To prevent time-dependent artifacts, control plane mes-sages are sent sequentially in about 20 different spaced test periods, with 20 messages sent per period on average. To avoid biases, the two signaling flows have not been sent concurrently.

Fig. 2.5, showing both average and 99 percent confidence intervals of the obtained results, leads to two main conclusions. First, the processing time increases only by a limited amount, roughly 10 percent, while increasing the number of registered LISP sites from 200 to 2000, for both MS and MR. This result suggests that the logic implemented for the lookup represents a light portion of the overall processing load. We verified and the processing latency slightly decreases at certain steps with respect to the previous step because the second core started being used by the operating system. The relatively remarkable variance is likely the symptom of CPU differently assigning threads to cores at different executions.

Furthermore, under such severe load conditions, the Map-Server processing latency stays at very acceptable values (around 700 μs) for the provided computing power, and is about 30 times higher than the Map-Resolver latency; this is essentially due to the very

high number of sites and prefixes to register, the fact that first, Map-Register messages need to be authenticated via HMAC, and then the mapping database possibly may need to be updated (hence roughly a quadratic time complexity). Map-Reply and Map-Notify messages that are close in size and written with a linear complexity have a similar light impact on the processing latency of MR and MS, respectively.

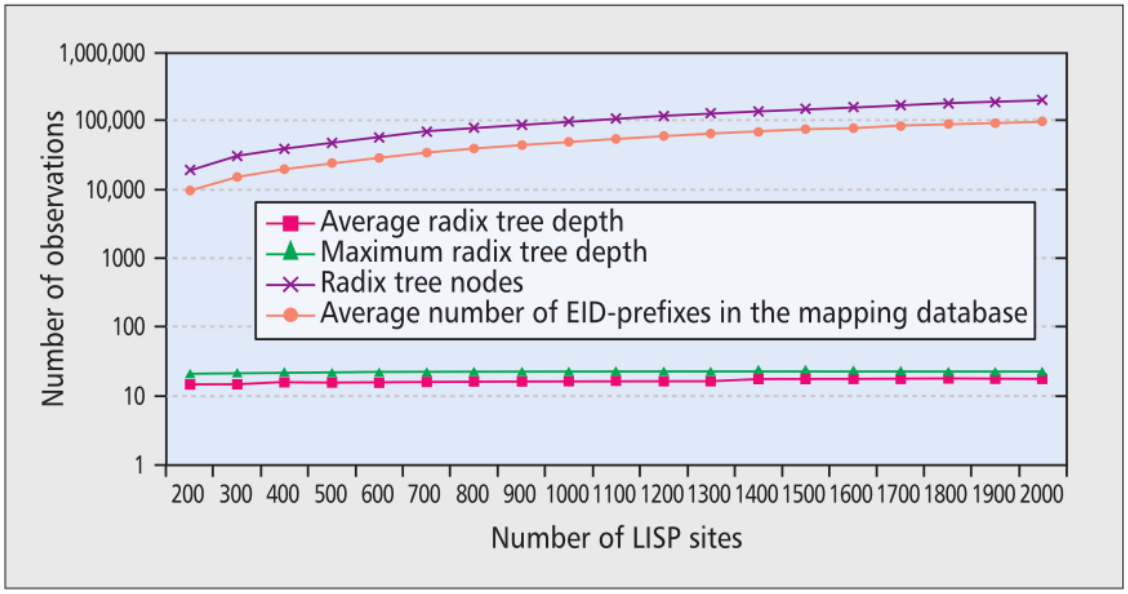


Figure 2.6: Insight on the mapping database radix tree structure.

The processing latency performance also depends on the dispersion of the EID-prefix in the mapping database, which, as already mentioned, is built using a radix tree [48]. Fig. 2.6 reports the average radix tree depth, the maximum tree depth, the total number of nodes, and the average number of EID prefixes in the mapping database (obviously, the same for the MR and MS cases; the confidence intervals are not visible). It is worth noting that the number of tree nodes is slightly higher than the total number of EID prefixes because of the necessary addition of branching nodes in the radix tree. Fig. 2.7 shows that when the number of registered LISP sites increases, the radix tree depth does not increase significantly, despite the fact that the total number of nodes (directly affecting the size of memory used to store and manage the mapping database) increases exponentially. This explains why the number of LISP sites, as shown in Fig. 2.6, only marginally affects the processing latency.

Our evaluation shows that our control plane implementation is scalable and offers the level of performance needed for operational deployment suffering from very high loads. Moreover, the overhead due to LISP encapsulation is proven to be negligible with the OpenLISP data plane implementation [39]. These results and our efforts to be in confor-

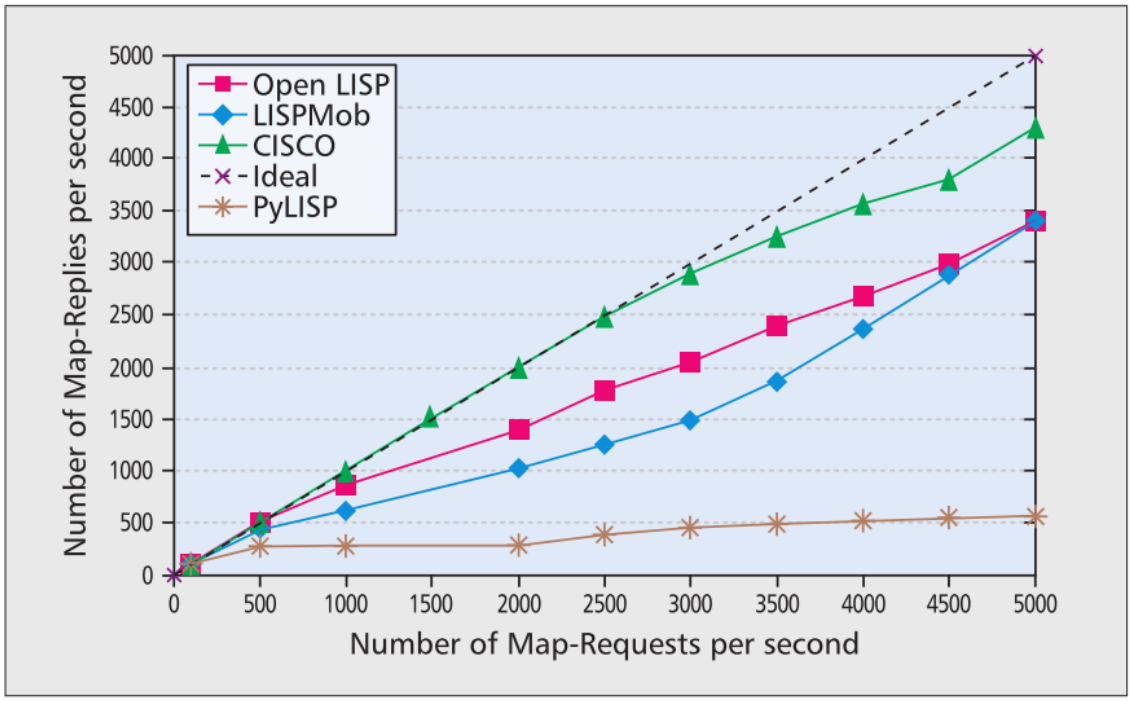


Figure 2.7: Average number of received.

mance with the standards position the combination of the OpenLISP data plane and our control plane implementation as a viable and efficient alternative to closed-source vendor-specific implementations. The proof is that one DDT root using our implementation is already integrated in the official LISP Beta Network control plane.

We compare the LISPMob, Cisco, enhanced OpenLISP and PyLISP implementations, which are the single ones available to us.

Fig. 2.7 compares the LISP implementations (for the FritzBox there is no public complete information to date); all respect the reference RFC [6] and are hence interoperable. The OpenLISP and Cisco IOS implementations are the most complete. Morever, to the best of our knowledge, OpenLISP is the only one supporting LISP traffic engineering (LISP-TE) [49] and map versioning, as well as the only open source implementation supporting Proxy-ITR/ETR features.

We quantitatively compared these implementations by measuring their reliability when replying to Map-Request messages. Fig. 2.7 gives the scatter plot of the Map-Request rate vs. the Map-Reply rate for an increasing Map-Request rate. Ideally, the Map-Reply rate should be equal to the Map-Request rate, but because of processing time and buffer limitations, some requests are eventually dropped. OpenLISP, LISPMob, and PyLISP were executed in the same single-core node of 2.67 GHz and 1 GB of RAM. We ran the Cisco implementation of a multi-core carrier grade router, the 3900 one, since

tested lower-grade Cisco routers did stop the LISP control plane when approaching a few thousand Map-Requests per second. Results between the open source implementation and the Cisco implementations are therefore not directly comparable, but are reported for the sake of clarity. The Cisco one consequently appears as the most robust implementation, dropping about 10 percent of the control plane messages, only starting at around 4000 messages/s. Among the open source implementations, OpenLISP slightly outperforms LISPMob for low and mid-range rates, despite the additional features to manage, but has similar performance at higher rates. PyLISP in its current implementation is not very scalable and shows very poor performance already at 500 Map-Requests/s. Overall, these results show that the more mature implementations are those with a longer history.

2.4.5 Perspectives

Thanks to our development effort, an OpenLISP node can today run as the single fully featured open source LISP implementation.

Our performance evaluation combined with the data plane performance evaluation in [33] shows that our implementation is scalable enough for large networks and reaches performances suitable for real deployments. Our implementation is currently mature enough to be deployed in operational networks, and is actually used to interconnect at least seven LISP sites to the worldwide LISP Beta Network testbed and to the LISP-Lab testbeds, correctly handling both data plane and control plane operations. Moreover, we have just integrated an OpenLISP DDT root server into the current worldwide LISP DDT hierarchy. We are currently enhancing the traffic engineering features to support various working modes concurrently, and we plan to add security features, integrating the related upcoming Internet Engineering Task Force (IETF) specification on the matter. We recently ported the control plane to the Linux environment; another important milestone already planned is to port the data plane to Linux as well, and the whole Open-LISP node to other BSD flavors (e.g., OpenBSD and Net-BSD).

2.5 LISP experimental platforms

We describe in the following two open LISP platforms. One managed by Cisco, and one by the ANR LISP-LAB project coordinated by Université Pierre et Marie Curie - Sorbonne Université. I strongly contributed to the construction, integration and management of the LISP-LAB platform.

2.5.1 LISP4.net platform

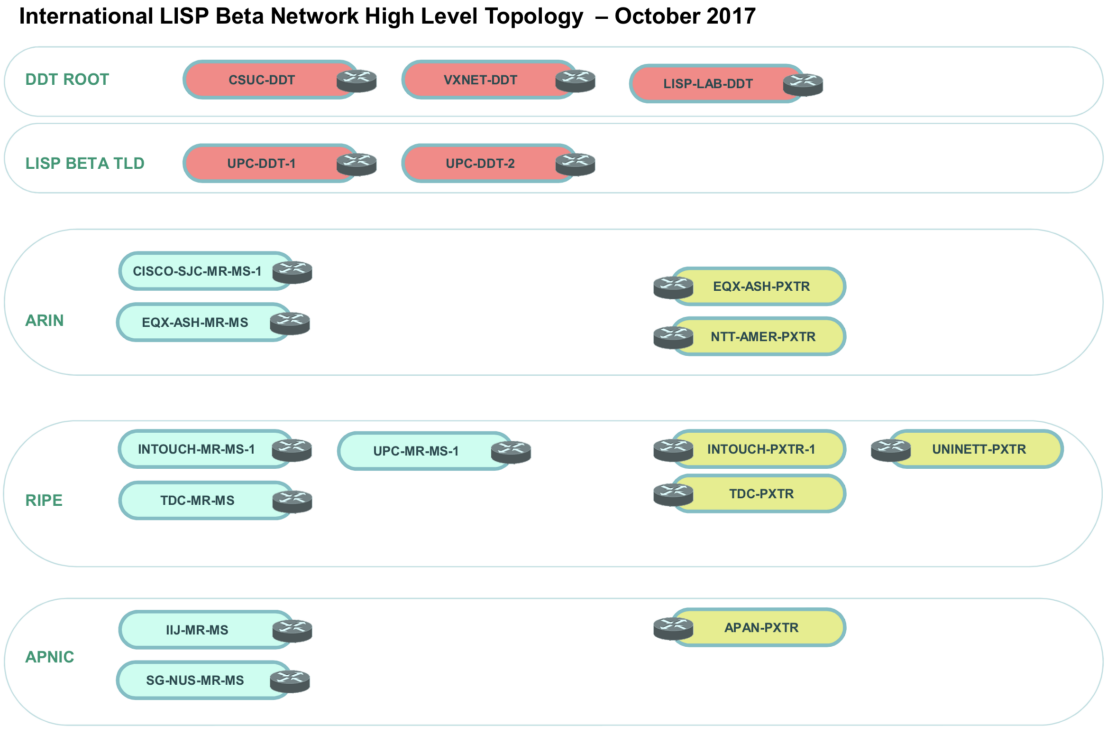


Figure 2.8: LISP4.net network, 2018. Source: `lisp4.net`.

The LISP Beta Network is a multi-company multi-vendor effort to run experiments with LISP. It is build using multiple Map-Servers, Map-Resolvers, Proxy Routers and xTRs. Participants host one or more of these components. Involvement can range from hosting full-blown mapping services to being an end user and just enjoy the various advantages of LISP.

The testbed also manages IP address spaces for the EID block, and is able to distribute EID sub-blocks to users. These IP prefixes are originated by AS3943. Although there is no official statistics, based on the public list, as of January 2018, there are 510 organizations and individuals registered and connected to the testbed. A representation of the platform architecture is given in Fig. 2.8.

The LISP.net use the LISP-DDT as the mapping signaling protocol. The LISP Beta Network control-plane is essentially based only of Cisco routers, except for the LISP-Lab nodes. At this time, there are three DDT roots, one in the US and two other ones in Europe. One of them is maintained by LISP-Lab using our OpenLISP control-plane.

2.5.2 LISP-Lab platform

The LISP-Lab platform was created as an experimental research project funded by the French national research agency. It aims at building an open platform, based on the LISP architecture, providing the environment to perform high-quality research and support the design, development, and thorough assessment of new services and use-cases. The range of technical tasks planned in the LISP-Lab project, from cloud networking, to access technology, through inter-domain connectivity, traffic engineering, and mapping management, has a larger scope than the LISP beta network, boosting innovation beyond the LISP technology itself.

The geographical scope of the platform is depicted in Figure 2.9 and the IP configuration and network interconnection simplified in Figure 2.10.

Figure 2.9: LISP-Lab partners locations.

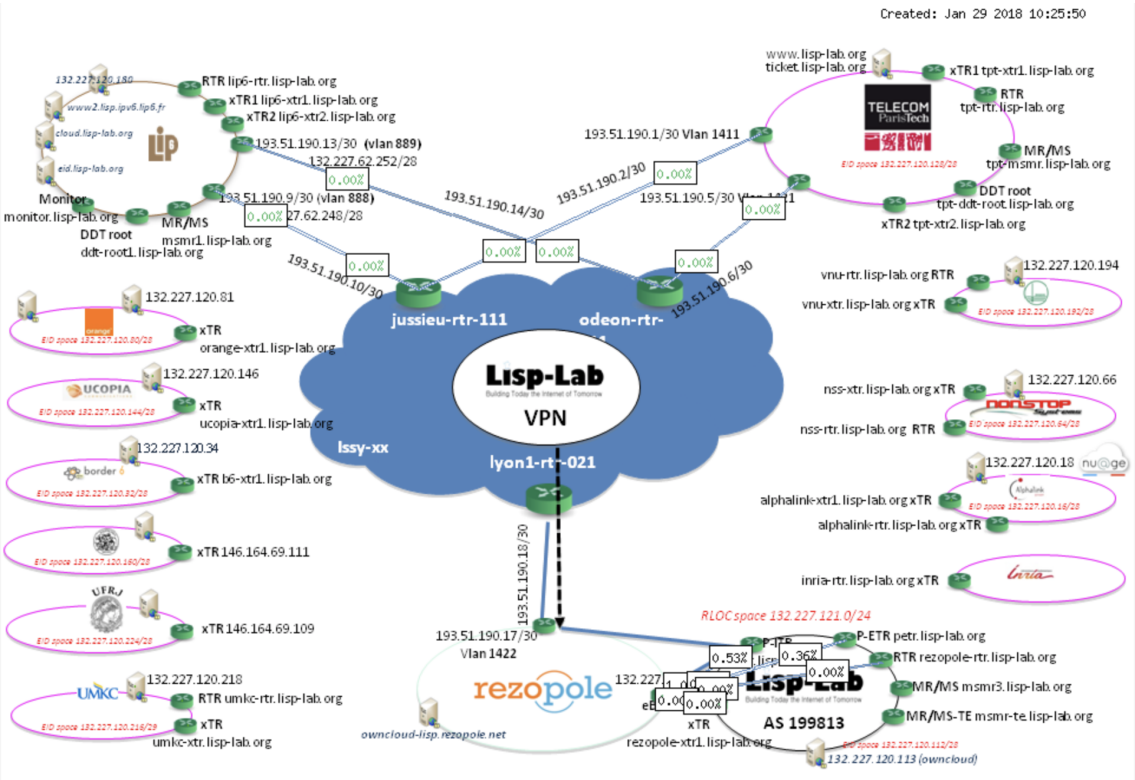


Figure 2.10: LISP-Lab platform IP topology.

The LISP-Lab platform is multi-party in its very nature, being the collaborative result of a first class consortium composed of academic institutions (Université Pierre et Marie Curie - Sorbonne Université, Télécom ParisTech), public interest groups (RENATER, Rezopole) and industrial partners (Border6, AlphaLink, NonStopSystems, Orange, Ucopia). The LISP-Lab project aims at becoming the main actor in driving future evolution of the LISP standardization, with a strong impact on the networking industry and the Internet ecosystem at large.

Although LISP4.net provide a free LISP testbed, they limit on the capacity to test new proposal in the mapping system because almost all main LISP network nodes (except xTRs) use Cisco devices, with closed source code. Moreover, each organization which joins the LISP4.net has to use the EID-prefix which is assigned by the testbed, limiting the scope of possible experimentations.

By deploying a new testbed based on open source nodes, LISP-lab allows testing new proposals that are not locked to a proprietary implementation. Besides, the LISP-lab DDT root being also deployed in the LISP4.net, it allows the interconnection between two platforms while guaranteeing each organization to use own IP addressing space.

Fig. 2.10 illustrates the main topology of LISP-lab. The three main sites are the LIP6

laboratory of Université Pierre et Marie Curie - Sorbonne Université, Télécom ParisTech, and RENATER. The interconnect between the main site is provided over RENATER with a layer-3 VPN mesh with links of 1 Gbps. For load balancing and the stability of the system, the mapping system is deployed in the three sites, each site includes at least one MS and one MR. For communication with non-LISP networks, we deployed two PxTRs, one beyond RENATER and Rezopole, and one beyond the Alphalink network.

Chapter 3

Large-Scale Virtual Machine Migrations with LISP

Nowadays, the rapid growth of Cloud computing services is stressing the network communication infrastructure in terms of resiliency and programmability. This evolution reveals missing blocks of the current Internet Protocol architecture, in particular in terms of virtual machine mobility management for addressing and locator-identifier mapping. In this chapter, we propose some changes to the Locator/Identifier Separation Protocol (LISP) to cope with this gap. We define novel control-plane functions and evaluate them exhaustively in the worldwide public LISP testbed, involving five LISP sites distant from a few hundred kilometers to many thousands kilometers.

3.1 Introduction

As a matter of fact, network virtualization has revolutionized datacenter networking. Once solely based on physical server and mainframe interconnections, Cloud datacenters increasingly deploy virtualization servers that host, send and receive virtual machines (VMs), to and from local and distant locations. This evolution raises many networking issues in terms of address continuity and traffic routing. When and how should VMs maintain (or use) the same (or multiple) Ethernet and/or IP addresses upon migration, have been and still are open research questions in Cloud networking. Similar challenges appear with the emergence of advanced services such as Infrastructure as a Service (IaaS) [52], often requiring multiple VMs physically located at different sites to communicate with each other as well as with its users, which keep communicating while moving across datacenters [53].

The contents of this chapter are presented in [33, 50, 51]. My contribution included both the protocol solution design and its implementation in strong coordination with P. Raad.

In virtualization nodes, the hypervisor is a software-level abstraction module essential to concurrently manage several VMs on a physical machine. VM migration is a service included in most hypervisors to move VMs from one physical machine to another, commonly within a datacenter. Migrations are executed for several reasons, ranging from fault management, energy consumption minimization, and quality-of-service improvement. In legacy Cloud networks, VM location was bound to a single facility, due to storage area network and addressing constraints. Eventually, thanks to novel protocols and high-speed low-latency networks, storage networks can span metropolitan and wide area networks, and VM locations can span the whole Internet over very long distances.

Multiple solutions are being tested to make VMs' location volatile [54, 55, 56]. The main trend is to allow transparent VM migrations by developing advanced functionalities at the hypervisor level [54]. In terms of addressing, the main problem lies in the possibility of scaling from public Clouds and intra-provider Clouds to private and hybrid Clouds, i.e., seamlessly migrating a virtual server with a global IP across the Internet and wide area IP networks. Multiple solutions exist to handle addressing issues, ranging from simple ones with centralized ad-hoc address mapping using MAC-in-MAC or IP-in-IP encapsulation, or a mix of both of them, to more advanced ones with a distributed control-plane supporting VM mobility and location management. Several commercial (non-standard) solutions extend (virtual) local area networks across wide area networks, such as [55] and [56] handling differently layer-2 and layer-3 inter-working.

Among the standards to handle VM mobility and addressing issues, we can mention recent efforts to define a distributed control-plane in TRILL (Transparent Interconnection of a Lot of Links) architecture [57] to manage a directory that pilots layer-2 encapsulation. However, maintaining layer-2 long-distance connectivity is often economically prohibitive, a too high barrier for small emerging Cloud service providers, and not scalable enough when the customers are mostly Internet users (i.e., not privately interconnected customers). At the IP layer, the addressing continuity can be guaranteed using ad-hoc VM turntables as suggested in [58], or Mobile IP as proposed in [59], which however can increment propagation and transmission delays due to triangular routing: the traffic has to pass through the VM original network, before being encapsulated and sent to the new VM location.

More recently, the Location/Identifier Separation Protocol (LISP) [6], mainly proposed to solve Internet routing scalability and traffic engineering issues, is now considered for VM mobility and has already attracted the attention for some commercial solutions [38]. In order to efficiently handle locator-identifier mappings, LISP offers a distributed control-plane, decoupled from the data-plane. An advantage of LISP is that it can avoid

triangular routing, with encapsulations performed at the first LISP capable IP node. Nevertheless, based on current standards and literature, there are missing functionalities to guarantee low VM migration downtimes with LISP. Moreover, those experiments cannot be reproduced in absence of open source solutions.

The contribution of this chapter is the definition and the evaluation of novel LISP functionalities to obtain high performance in large-scale live VM migration. We provide all the elements to reproduce the results, including reference to an open source implementation of our proposition. Our solution is based on the definition of LISP control-plane messages to fast update EID-locator mappings, hence overcoming the long latency of basic LISP mechanisms. We validate and evaluate our solution using the worldwide LISP Beta Network and LISP-Lab nodes, piloting five LISP sites in four countries worldwide. The chapter is organized as follows. Section 3.2 briefly presents the background. Section 3.3 describes our protocol extension proposition. Section 3.4 reports experimental results. Section 3.5 concludes the chapter and discusses future works.

3.2 Background

In this section we describe the state of the art live VM migration networking.

3.2.1 Live VM migration and IP mobility

Live VM migration is a feature introduced in recent hypervisors; it allows moving a running VM between two (physical) host containers without disconnecting the client or application. For most of the hypervisors, live migration is limited to situations in which source and destination hosts look like connected to the same local area network. The main reason is that the machine being migrated needs to keep the same routing view of the network (e.g., gateway, IP subnet) before and after the migration. Alternatively, in some legacy solutions, upon migration the VM changes its IP address, e.g., via the DHCP, to avoid the additional complexity needed to ensure that the origin IP address is not already used in the destination network, and to transfer the routing table; VM's IP readdressing implies, however, long convergence and loss of too many packets.

In order to perform Internet-wide migrations with IP continuity, authors in [59] and [60] propose an IP mobility solution. The logic is implemented in the hypervisor, interacting with the VM before and after its migration to update IP addresses in the VM routing table. While [59] succeeds in bringing lower service downtime compared to [60], the hypervisor has to alter the VM configuration to support the IP mobility feature, which leads to scalability concerns. Moreover, as the authors state, the performance of their solution is

expected to worsen in large-scale global live migrations, because of the online signaling nature of the proposition and many-way signaling latencies.

Authors in [61] propose to adapt the Mobile IP (MIP) protocol [62] to pilot Internet-scale VM migrations, implementing it in the hypervisor. Their solution, called HyperMIP, is invoked whenever a VM is created, destroyed or migrated; as in MIP, it involves Home Agents (HA) to keep the connection alive. Whenever a VM changes a location, a tunnel is established between the HA and the source hypervisor to keep the client connected to the VM. The destination hypervisor then destroys the tunnel when the VM registers its new IP address to the HA. However, HyperMIP still introduces an important signaling overhead due to HA tunnel establishment.

Alternatively, to minimize signaling latencies, authors in [58] propose to use an external agent to orchestrate the migration from the beginning to the end, by proactively establishing circuits between the involved containers (source and destination hypervisors) offline, so as to rapidly switch the traffic upon migration, then redirecting the client-VM traffic via dynamic reconfiguration of IP tunnels. They achieve a near second network downtime while migrating machines across wide area networks, with a maximum network downtime around 3.8 seconds. Despite being a more secure approach, with respect to [59], [60] and [61] their solution involves lower-layer technologies, hence can be excessively costly.

3.2.2 Layer 2 over Layer 3 overlay tunneling solutions

The above described solutions tackle large-scale VM live migration using Layer 3 tunneling ([59], [60] and [61]), or Layer 3-Layer 1 interaction [58]. More recently, at the IETF, attention has been given to Layer 2 over Layer 3 (L2o3), Ethernet over IP, virtual network overlay solutions, so as to avoid IP reconfiguration to the VM, and service continuity upon migration of VMs across virtualization servers. Virtual eXtensible LAN (VXLAN) [63], Stateless Transport Tunneling (STT) [64], and Network Virtualization using Generic Routing Encapsulation (NVGRE) [65], are recent propositions, already implemented by many commercial stakeholders (e.g., Microsoft, VMWare) and open source virtual switches (e.g., OpenVSwitch), worth being discussed hereafter.

VXLAN [63] is a stateless L2o3 logic that extends the Layer 2 communication domain over IP networks, extending a VLAN broadcast domain thanks to MAC-to-IP encapsulation between hypervisors, even if communicating VMs and endpoints are in different IP segments. Basically, when a VM wants to communicate with another VM on a different host, a 'tunnel endpoint' implemented in the hypervisor receives the frame, verifies that the target VM is on the same VXLAN segment via standard signaling, and then appends

an IP address corresponding to the destination tunnel endpoint, and a VXLAN header. Upon reception, the destination tunnel endpoint verifies the packet, decapsulates it and forwards it to the VM target. Therefore, thanks to the VLAN broadcast domain extension, a VM belonging to a VXLAN segment can migrate to a VXLAN endpoint in another IP segment, and its traffic is consequently encapsulated by the source VXLAN endpoint toward the destination VXLAN endpoint.

Functionally, NVGRE [65] is a similar L2o3 tunneling solution, with a different header (VXLAN uses a UDP shim header to easily pass through middle-boxes, while NVGRE does not hence limiting its scope to a single administrative network), and with no specified control-plane to distribute MAC-to-IP mappings (in VXLAN, multicast mechanisms do allow resolving these mappings). Encapsulating Ethernet traffic over IP allows a better bottleneck management thanks to various IP traffic engineering and load-balancing mechanisms. Both VXLAN and NVGRE, however, do not allow typical Ethernet network interface controllers to perform TCP offloading (intermediate fragmentation done by the hardware to boost performances). This is instead allowed by Stateless Transport Tunneling [64] (STT), another stateless L2o3 tunneling protocol, which uses a fake TCP header inside the IP header to allow interface-level TCP optimizations. From a VM mobility and traffic routing perspective, it offers the same encapsulation path than VXLAN and NVGRE, but as NVGRE it has difficulties to pass through Internet middle-boxes and its deployment is also limited to a single administrative domain such as a DC network.

All these technologies (VXLAN, NVGRE, STT) share as reference use-cases intra-DC and inter-DC communications, i.e., between VMs hosted in different virtualization servers potentially in different IP subnets. Therefore, they are not readily applicable to the Cloud access communication usecase, involving an IP user and a VM-based IP server, mainly targeted by our LISP proposition. The user endpoint is typically not a virtualization server and is not connected to the same DC fabric than the server, and can potentially be everywhere in the Internet.

3.2.3 Triangular routing solutions vs LISP rerouting

From the IP routing perspective of an Internet client accessing a server running in a VM, the legacy approaches can be considered as triangular routing (or indirect forwarding) solutions - the traffic has to reach the VM source network and/or container before being encapsulated and sent to the new VM location. Triangular routing solutions typically offer higher client-server path latency, than LISP-enabled direct rerouting. A higher path latency implies a higher transfer time, namely for TCP-based connections given that the round-trip-time (RTT) has an impact on TCP acknowledgments reception. Therefore, as

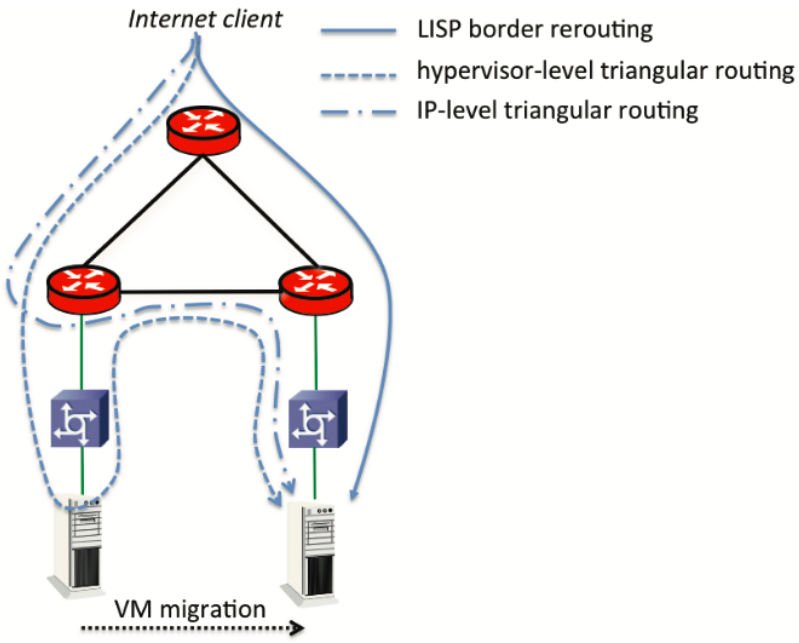


Figure 3.1: Triangular routing vs LISP rerouting.

far as the LISP tunneling node is implemented closer to the source endpoint than the triangular routing re-encapsulating node, a LISP-based Cloud network certainly outperforms triangular routing solutions in terms of transfer time.

As depicted in Fig. 3.1, the rerouting logic of the above described solutions can be either implemented at the hypervisor level, or at the IP border level (e.g., DC or rack border) at a Mobile IP or similar agent. With LISP, client traffic can be redirected to the new location at the first LISP network ingress point, which can potentially be the client terminal itself (if a solution such as LISP mobile node is used [40]), a client's network provider router, any intermediate router between the client and the VM source DC, or (at last) the VM source DC's egress router if the standard IP path is taken by client traffic and the VM's prefix is announced by DC nodes. In all cases (but the latter that is topologically identical) the path latency offered by LISP is better than the path latency reachable with a non-LISP method alone. In common situations, triangular routing solutions alone add the source DC - destination DC latency to application connections, hence leading to longer forwarding latency, and transfer time, for Cloud access communications.

It is worth stressing that LISP is orthogonal to the existence of emerging hypervisor-level L2o3 triangular routing solution such as VXLAN, NVGRE or STT: LISP reroutes Cloud access user traffic while hypervisor-level mechanisms reroute VM-to-VM communications. It is worth noting that the LISP enhancement we propose in the following to support VM migration is independent of the existence of such inter-VM virtual network

overlay mechanisms. Their integration with our LISP-based Cloud access solution could bring advantages in terms of transfer time only for inter-VM communications.

As compared to legacy IP-level triangular routing solution, with our proposition described in the next sections, we can obtain service downtime between 150 and 200 ms, depending on the signaling scope. With respect to the alternative methods at the state of the art described in 3.2.1, we can assess that:

- with HyperMIP [66], authors experienced 2 to 4 s of downtime, which is many times more than our approach;
- similarly in [60] Mobile IPv6 signaling is used to detect VM location change, reaching a minimum overhead around 2500 ms, linearly increasing with the network delay, hence significantly higher than our approach;
- authors in [58] went a step further implementing pro-active circuit provisioning, reaching an application downtime varying between 800 and 1600 ms, which is more than 4 times higher than with our approach.

3.2.4 Existing LISP-based mobility management solutions

In a LISP network, the VM can keep the same IP. Two mechanisms at the state of the art can perform this operation. One is a host-based LISP implementation called LISPmob [40]: the host implements a tiny xTR with basic LISP functions, using the network-assigned IP(s) as RLOC(s) and registering mapping updates for its EID with the mapping servers. Essentially conceived for mobile equipment, LISPmob could also be installed in the VM; there would be, however, a problem with most current hypervisors that impose the VM external address to be in the same subnet before and upon migration, which practically limits the LISPmob usability only to situations where source and destination networks are either LISP sites themselves, or layer-2 over wide area network (WAN) solutions. In the first case, a double encapsulation is needed, which could increase mapping latency, overhead and create MTU issues. There may also be scalability issues with a high number of VMs.

Another method to handle VM mobility via LISP is actually implemented in some Cisco products, only partially documented in [38]. The xTR automatically changes the mapping upon reception of outgoing data-plane traffic from an EID that has been registered as mobile node. The solution has an attracting light impact on IP operations, yet it seems to be weak against EID spoofing, and it seems not to have authentication mechanisms. Moreover, in order to guarantee fast mapping convergence, it seems that

additional logic would need to be implemented in the VM or in the hypervisor to allow sending outgoing artificial data traffic even if no real outgoing traffic exists.

3.3 Proposed LISP-based VM migration solution

We propose a novel solution to support WAN VM live migration exploiting the LISP protocol. We implemented our solution in the open source OpenLISP control-plane implementation [8] [67], which complements the OpenLISP data-plane [68].

As described above, a live migration technique should be able to move a VM keeping its unique EID, from its actual DC to a new DC maintaining all VM connections alive. As a preliminary step, the source and destination DCs have to share the same internal subnet, i.e., the VM unique EID should be routable beyond its RLOC, wherever it is. LISP supports a large number of locators, and does not set constraints on RLOC addressing – i.e., the RLOCs can take an IP address belonging not simply to different subnets, but also to different Autonomous System networks. The current VM location can be selected leveraging on RLOC metrics. We introduce two main enhancements:

- a new LISP control-plane message to speed up RLOC priority update;
- a migration process allowing hypervisor-xTR coordination for mapping system update.

Our solution involves the following network nodes: the source VM container and the destination VM container, both managed by an hypervisor, the VM being migrated from one to the other, LISP border routers at the source DC and at the destination DC, the Cloud user accessing the VM.

In the following, we present the novel LISP control-plane message we introduce for communications between the involved LISP nodes, then we describe the VM migration process, and finally we discuss implementation aspects.

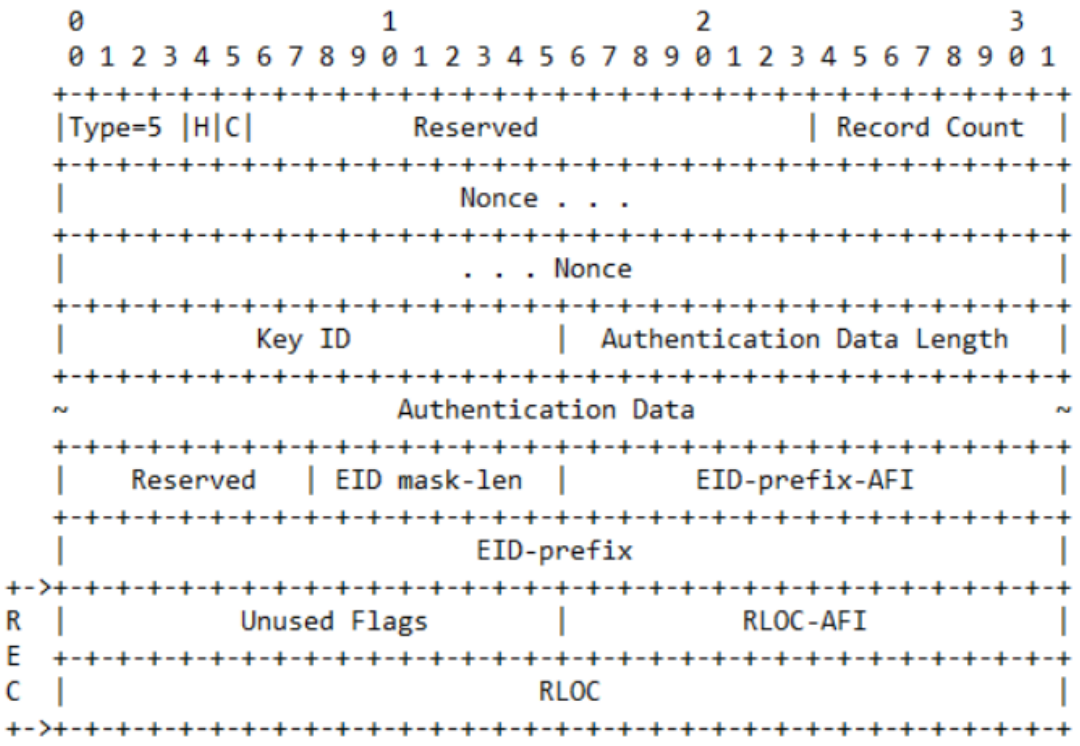


Figure 3.2: CHANGE PRIORITY message format.

3.3.1 Change priority message format

We introduce a new type of LISP control-plane message we call CHANGE PRIORITY (CP).

As depicted in Fig. 3.2, we use a new control-plane type field value equal to 5, and use two bits to define message sub-types to be managed by both xTR and VM containers' hypervisors:

- H (Hypervisor) bit: this bit is set to 1 when the message is sent by the destination hypervisor (the hypervisor that receives the VM), indicating to the xTR that it has just received a new EID. With the H bit set, the record count should be set to 0 and the REC field is empty;

- C (Update Cache) bit: this bit is set to 1 when an xTR wants to update the mapping cache of another xTR. With the C bit set, the record count is set to the number of locators and the REC field contains the RLOC information to rapidly update the receiver mapping cache.

The other fields have the same format and function as for the MAP-REGISTER message fields [6], i.e., with EID and RLOC fields, a nonce field used to guarantee session controls,

and HMAC authentication fields useful to secure the communication (with the important feature that the authentication key used for CP messages can be different than the key used by MAP-REGISTER, provided that the xTR is able to handle different keys as provided in [8] [67]).

3.3.2 VM migration process

The LISP mapping system has to be updated whenever the VM changes its location. Before the migration process starts, the xTRs register the VM's EID as a single /32 prefix or as a part of larger EID (sub-)prefix. The involved devices communicate with each other to atomically update the priority attribute of the EID-to-RLOC mapping database entries. The following steps describe the LISP-based VM migration process we propose and demonstrate.

1. The migration is initialized by the hypervisor hosting the VM; once the migration process ends, the destination hypervisor (the container that receives the VM) sends a CP message to its xTR (also called destination xTR) with the H bit set to 1, and the VM's EID in the EID-prefix field.

2. Upon reception, the destination xTR authenticates the message, performs an EID-to-RLOC lookup and sets the highest priority to its own locators in the mapping database with a MAP-REGISTER message. Then, it sends a CP message, with H and C bits set to 0, to update the mapping database of the xTR that was managing the EID before the migration (also called source xTR).

3. Before the VM changes its location, the source xTR keeps a trace file of all the RLOCs that have recently requested it (we call them client xTRs), i.e., that have the VM RLOCs in their mapping cache.

4. When the source xTR receives the CP message from the destination xTR, it authenticates it and updates the priorities for the matching EID-prefix entry in its database.

5. In order to redirect the client traffic, there are two different client-redirection possibilities, whether the client xTR is a standard router not supporting CP signaling (e.g., a Cisco router implementing the standard LISP control-plane [6]), or an advanced router including the CP logic (e.g., an OpenLISP router with the control-plane [8] [67]).

    - For the first case, the source xTR sends a SMR to standard client xTRs, which

triggers mapping update as of [6] (MAP-REQUEST to the MR and/or to the RLOCs, followed by a MAP-REPLY to the xTR).

- For the second case, in order to more rapidly redirect the traffic to the VM's new location (destination xTR), the source xTR sends a CP message with C bit set to 1 directly to all the client xTRs, which will therefore process it immediately (avoiding at least one client xTR-MR round-trip-time).

6. Upon EID mapping update, the client xTRs update their mapping cache and start redirecting the traffic to the VM's new routing locator(s).

All in all, updating the mapping database of the nodes involved in a VM migration requires two compulsory message exchanges (one message that notifies the destination DC about the migration process and another one that is used to notify the source DC), and optionally a number of additional messages equal to the number of clients that are communicating with the VM to inform the xTR clients' about the updates. Considering only the location update messages for the LISP mapping system does not make our solution heavier than triangular routing solution (e.g., Mobile IP). Additional signaling messages are generated with respect to triangular routing solutions if VM clients's mapping updates are considered. The limited increase of control messages is indeed counterbalanced by more significant benefits, in terms of resiliency and convergence, of our solution with respect to triangular routing ones.

It is worth noting that our solution fully relies on control-plane features. It is our methodology choice to avoid mixing data-plane and control-plane functions (for example proposing a specific usage of Map-Versioning or Locator Status Bit field in the data-plane [69]). The main advantage of creating network control functions disjoint from the data-plane is the possibility to program the control-plane independently of the forwarding logic, hence to implement advanced and personalized functionalities. This separation respects the current design trend in networking called Software Defined Networking [70]. Thanks to that, new functionalities can be added rapidly to the OpenLISP control-plane and allow rapid deployment even using pre-existing basic data-plane elements.

3.3.3 Implementation aspects

Algorithm 1 Algorithm 1 CP processing.

Ensure: authenticity of CP message and extract EID from EID-prefix field
if H bit is set to 1 **then**
  set own locators' priority to 1
  send CP to xTR group with H bit and C bit set to 0
  register mapping to Map Server.
end if
if H bit and C bit are both set to 0 **then**
  set own locators' priority to 255
  set locators' priority in RLOC field to 1
  send CP with C bit set to 1 to all locators that have requested the VM's EID
  stop registering for EID
end if
if C bit is set to 1 **then**
  update mapping cache according to the received message
end if

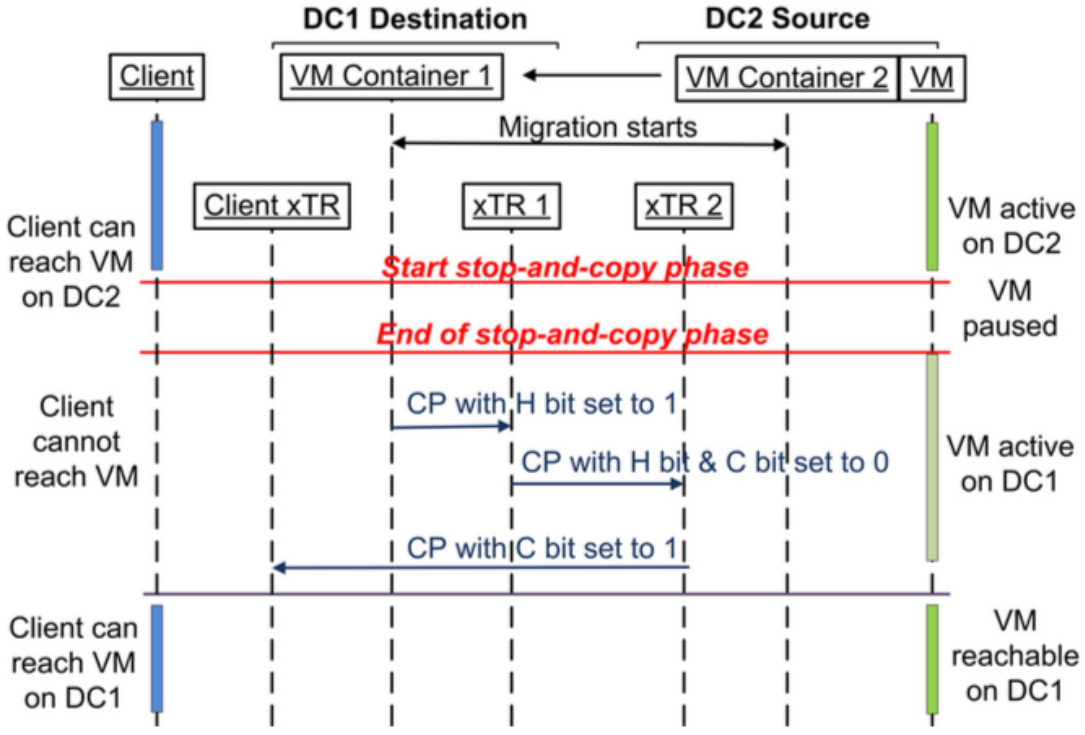


Figure 3.3: Example of CP signaling exchange during a VM migration.

The proposed solution has been implemented using opensource software (i.e., OpenLISP [8] [67]), and its implementation involves both the hypervisor and the xTR sides.

1. On the hypervisor: we integrated a new function that interacts with LIBVIRT (a management kit handling multiple VMs in the KVM hypervisor) [71] to trigger CP message generation. When a live migration starts, the hypervisor creates a "paused" instance of the VM on the destination host. Meanwhile, LIBVIRT monitors the migration phase from the start to the end. If the migration is successfully completed, LIBVIRT checks if the VM is running on the target host and, if yes, it sends a CP message to its xTR on the UDP LISP control port 4342. The VM EID is included in the EID-prefix field.

2. On the xTR: we implemented the Algorithm 1 function in the OpenLISP control-plane [8]. While the OpenLISP data-plane logic runs in the kernel of a FreeBSD machine, the control-plane runs in the user space. The control-plane has a new feature to capture control-plane message type 5 and the logic to handle CP signaling5.

3. A signaling example: upon receiving a client request, or as triggered by a consolidation engine, a VM needs to be migrated to another public DC. As in the Fig. 3.3 example, VM Container 2 starts migrating VM from DC2 to DC1 while the Client is still connected. When the migration reaches the so called stop-and-copy phase (i.e., the phase dedicated to transfer the "dirty pages", which are pages updated too frequently to be transferred while the VM runs [72]), the VM stops and begins transferring its last memory pages. Meanwhile, the Client loses the connection, but keeps directing the traffic to DC2.

   The hypervisor on VM Container 1 detects that VM is now successfully running, indicating the end of the migration. Then the VM Container 1 announces that the VM has changed its location by sending to xTR 1 a CP message with the H bit set. Upon reception, xTR 1 sends a CP with H bit and C bit set to 0 to notify xTR 2 about the new location of VM: xTR 1 updates the priorities for VM's EID entry in its database.

   When xTR 2 receives the CP message, it matches the EID-prefix to the entries within its mapping database, and modifies the priorities accordingly, then it stops registering VM's EID. As mentioned in Section 3.3.2, xTR 2 keeps a trace file of all the locators that recently requested the VM's EID. In this example, only one client is communicating with VM, so xTR 2 sends a CP message with C-bit set to the Client's xTR.

   Finally, the Client's xTR receives the CP message, maps VM's EID, and updates its cache, then starts redirecting Client's traffic to VM's new location (DC1).

3.4 Testbed evaluation

We performed live migrations of a FreeBSD 9.0 VM, with one core and 512 MB RAM (corresponding to a typical service VM like a lightweight web server), via the LISP-Lab plateform, from UROMA1 (Rome) to LIP6 (Paris), using KVM [73] as hypervisor. Please note that the size of the VM has no direct impact on live migration downtime for a given service type; different services may have a more or less intensive usage of memory pages, so that the stop-and-copy phase duration may have a more or less important impact on the downtime.

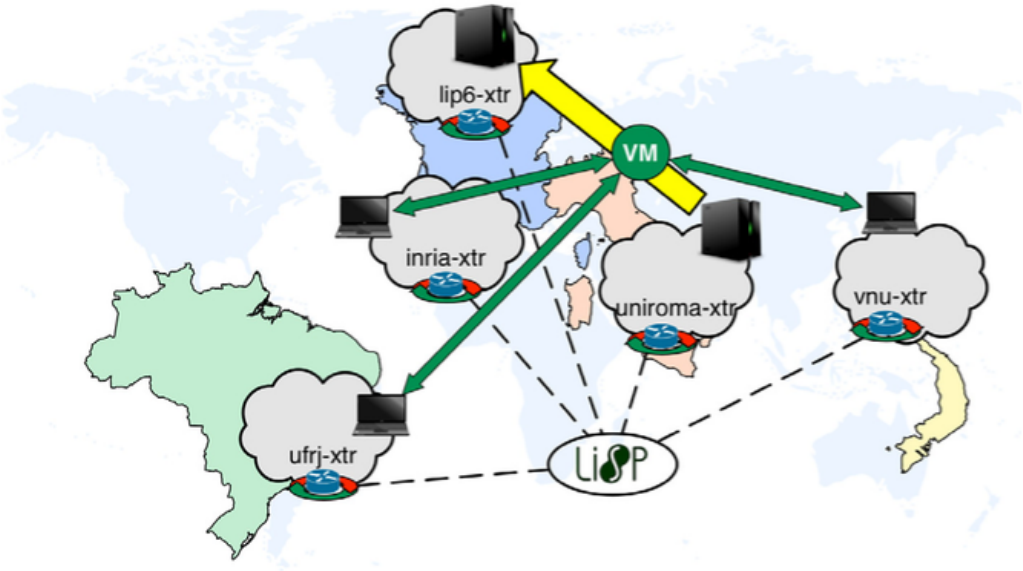


Figure 3.4: Testbed network scope.

Fig. 3.4 gives a representation of the testbed topology. As distributed storage solution, we deployed a Network File System shared storage between source and destination host containers. Hence, only RAM and CPU states are to be transferred during the live migration. The VM containers are Ubuntu 12.04 servers, dual core, with 2048 RAM and using KVM and Libvirt 0.9.8.

We measured node reachability by 20 ms spaced pings from different clients: distant ones at VNU (Hanoi, Vietnam), UFRJ (Rio de Janeiro, Brazil) LISP sites, and a close one at the INRIA (Sophia Antipolis, France) LISP site. It is important to mention that:

- the clocks on all LISP sites were synchronized to the same Network Time Protocol (NTP) stratum [74], so that a same VM migration can be monitored concurrently at the different client sites;

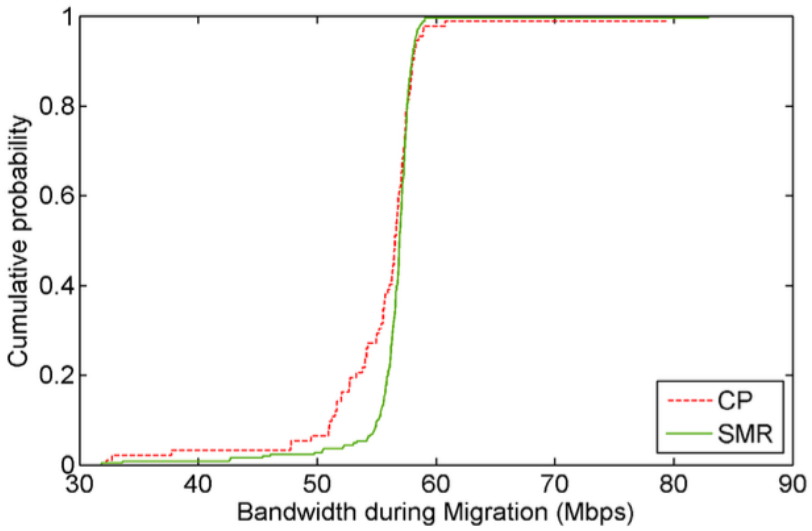


Figure 3.5: Bandwidth during migration with SMR and CP approaches.

- all LISP sites' xTRs register to a same MS/MR located in Denmark (www.lisp4.net), hence avoiding the DDT latency in the mapping convergence.

The latter is a possibility left to the datacenter manager, depending on the quality of the DDT architecture the Cloud provider could choose to which MS/MR to connect both the client and the Cloud networks. In our experimentations, we chose so also to get around some of the instabilities on the Asian (APNIC) MS/MR.

We performed hundreds of migrations from the UROMA1 site to the LIP6 site, over a period of three months at different times of the day, with two migrations per hour, to obtain a statistical population representative enough to capture the bandwidth, latency and routing variations of the Internet paths. We measured the experienced bandwidth; we report its experimental distribution in Fig. 3.5, where we can see that most of the migrations experienced between 50 and 60 Mbps.

We used the two possible inter-xTR mapping update modes with the proposed control-plane enhancement: SMRs to simulate standard client xTRs, and CP to encompass the case with enhanced xTRs at client LISP sites. Given the Internet wideness of the testbed, both the bottleneck bandwidth and RTTs were floating, depending by the time and day, hence we did a statistical evaluation as described hereafter. The average measured RTTs between each site during the migration are reported in Fig. 3.8; having both close and far clients' sites allows us to precisely assess the migration performance.

In order to experimentally assess the relationship between different time components and network situations, we measured the following different parameters:

- number of lost packets for each client (i.e., the number of ICMP messages that are

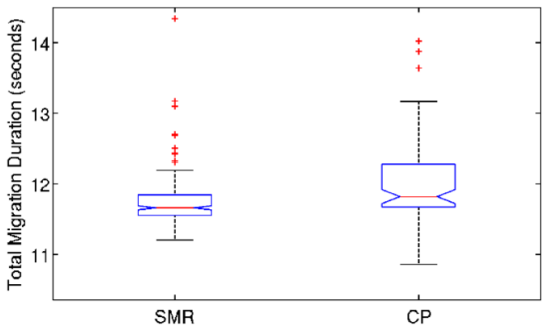


Figure 3.6: Total migration duration (boxplot statistics).

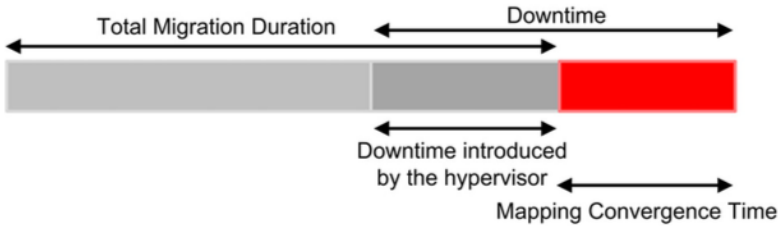


Figure 3.7: Migration duration and downtime composition.

lost on each client during migration);

- mapping convergence time for each client: the time between the transmission of CP by the hypervisor and the mapping cache update on each client.
- downtime perceived by each client: the time during which the client could not communicate with the VM;
- total migration duration;
- inter-container bandwidth during migration;
- offset for each client: the difference between the clocks on each client and the NTP server;
- RTT between the VM and the clients.

For the sake of completeness, we report in Fig. 3.6 statistics about the total migration duration. It has a median around 11.75 s for both signaling modes. It includes the downtime introduced by the hypervisor (stop-and-copy phase), not including the mapping convergence downtime component. As depicted in Fig. 3.7 and as of previous arguments, it is worth underlining that one should expect that the overall downtime is greater or

equal than the downtime introduced by the hypervisor (the stop-and-copy phase duration to transfer the dirty pages as already mentioned6) plus the mapping convergence time. Therefore, the mapping convergence time reflects our protocol overhead, which is differently affected by the RTT between LISP sites (Fig. 3.8) depending on the client xTR support of CP signaling.

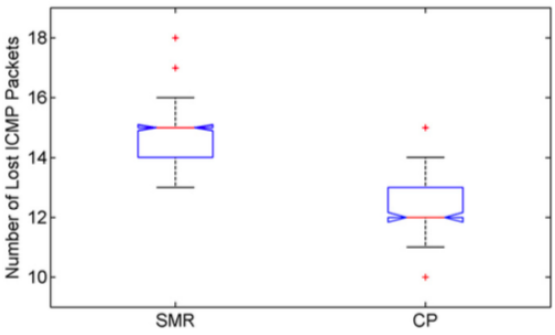
LISP Sites	Average RTT
LIP6-UROMA1	30.47 ms
LIP6-VNU	299.86 ms
LIP6-INRIA	16.47 ms
LIP6-UFRJ	246.07 ms
UROMA1-VNU	321.27 ms
UROMA1-INRIA	27.27 ms
UROMA1-UFRJ	259.13 ms

Figure 3.8: Average measured RTT during migrations.

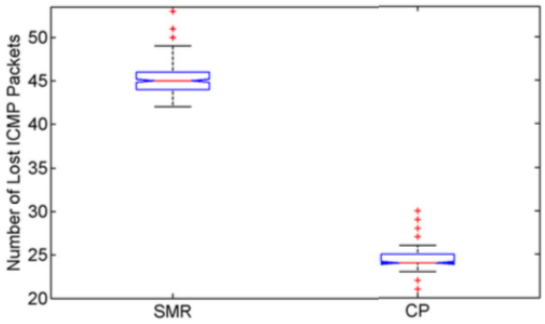
In order to characterize absolute service downtimes suffered by clients, Fig. 3.9 - 3.12 reports the boxplots (minimum, 1st quartile, median with the 95% confidence interval, 3rd quartile, maximum, outliers) of the obtained number of lost packets, offset, downtime, and mapping convergence time. We measured the results with the two possible modes for inter-xTR mapping update, using SMR signaling and using CP signaling.

Using SMR signaling: as explained in Section 3.3.2, as of LISP standard control-plane, the SMR message is sent by an xTR to another to solicit mapping update for a given EID. Upon reception of a SMR, the target xTR sends a MAP-REQUEST to mapping system, followed by a MAP-REPLY. The overall SMR signaling time should therefore be lower bounded by one and a half the RTT between the two xTRs, which impacts the mapping convergence time and hence the service downtime. As of our experimentations, we obtained a median downtime of about 320 ms for the INRIA client, 1.2s for VNU (Fig. 3.9 - 3.12). This large gap between the downtimes of close and distant clients can be explained not only by the distance that separates each client from the VM, impacting the propagation delay (see Fig. 3.8 I), but also by the fact that the Map Resolver is closer to INRIA than to VNU and UFRJ, as mentioned in Section 3.4. We find this gap also in the number of lost ICMP packets, two to three times higher for distant clients than for close ones (Fig. 3.9 - 3.12).

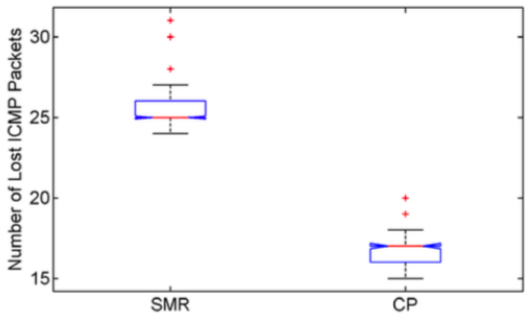
Using CP signaling: as explained in Section 3.3.2, using CP signaling the mapping convergence time can be decreased of at least one RTT between xTRs, with an authenticated oneway message that directly updates xTR cache upon reception. For the INRIA client, we obtain a median downtime of 260 ms gaining a few dozens of ms, whereas we could



(a) INRIA

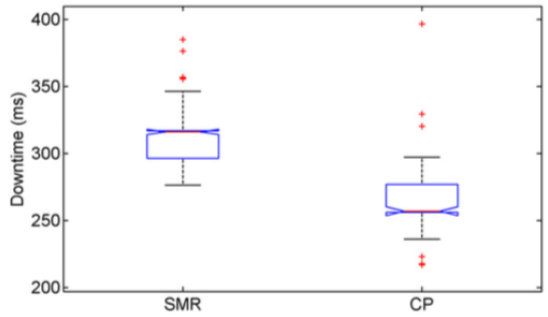


(b) VNU

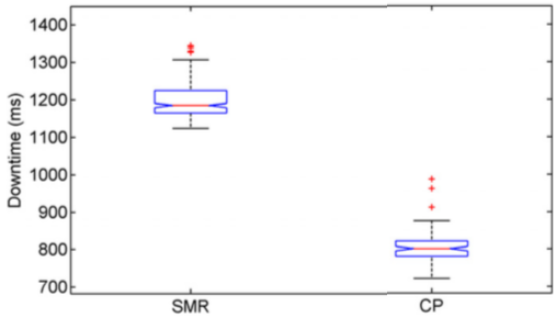


(c) UFRJ

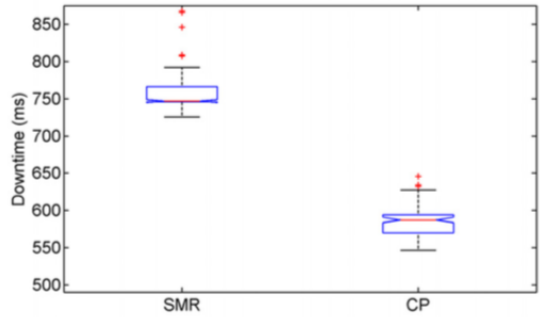
Figure 3.9: Boxplot statistics of lost packets for the three LISP sites (INRIA, VNU, UFRJ).



(a) INRIA

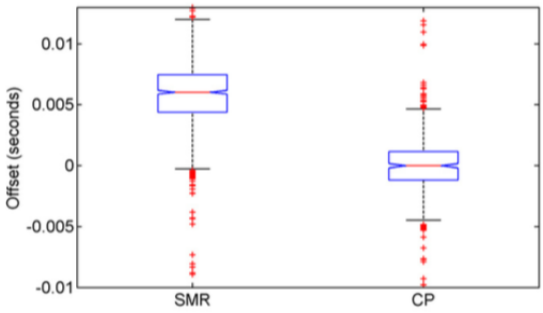


(b) VNU

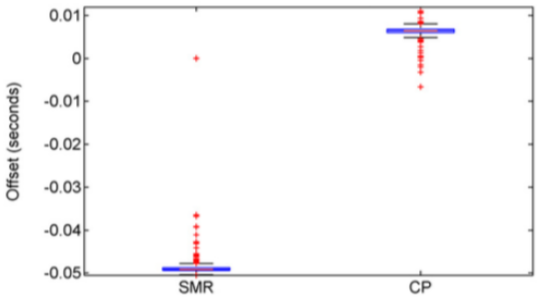


(c) UFRJ

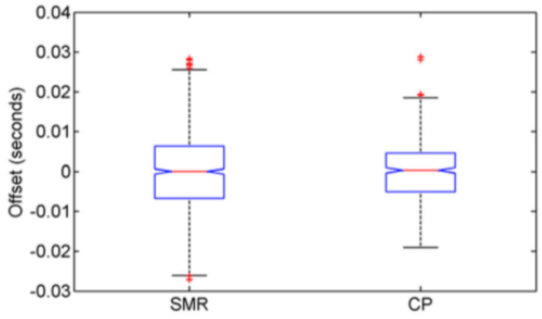
Figure 3.10: Boxplot statistics of downtime the three LISP sites (INRIA, VNU, UFRJ).



(a) INRIA

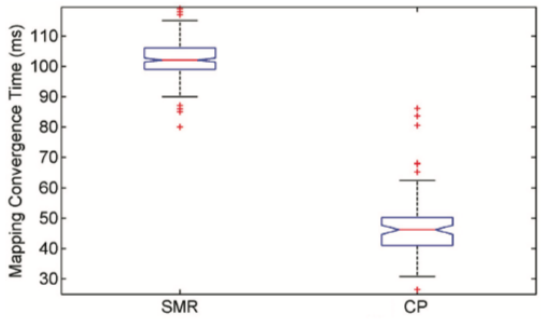


(b) VNU

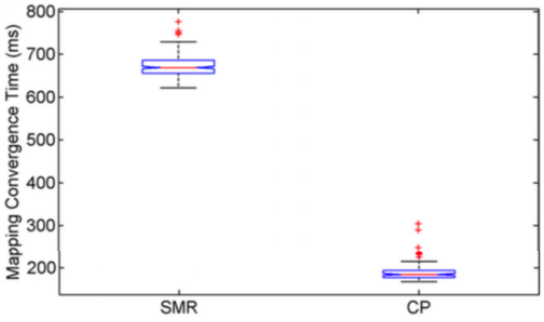


(c) UFRJ

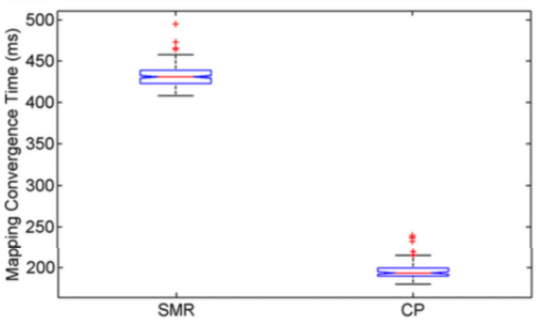
Figure 3.11: Boxplot statistics of offset for the three LISP sites (INRIA, VNU, UFRJ).



(a) INRIA



(b) VNU



(c) UFRJ

Figure 3.12: Boxplot statistics of mapping convergence for the three LISP sites (INRIA, VNU, UFRJ).

gain 200 ms for VNU and 400 ms for UFRJ. Moreover, we notice that the number of lost ICMP packets for distant clients has exponentially decreased. This important decrease is due to the fact that xTRs have no longer to pass via the Map Resolver to update their mapping cache. Finally, Fig. 3.12 show that the mapping convergence time component of the downtime decreases with CP signaling for all cases. While it is roughly between one-third and one-half the downtime with SMR signaling, it falls to between one-sixth and one-third with CP signaling, and this ratio is higher for distant clients. This implies that the hypervisor downtime (stop-and-copy phase) is less sensible to the RTT than the mapping convergence is (likely, the last page transfer profits from an already established TCP connection with an already performed three-way handshake).

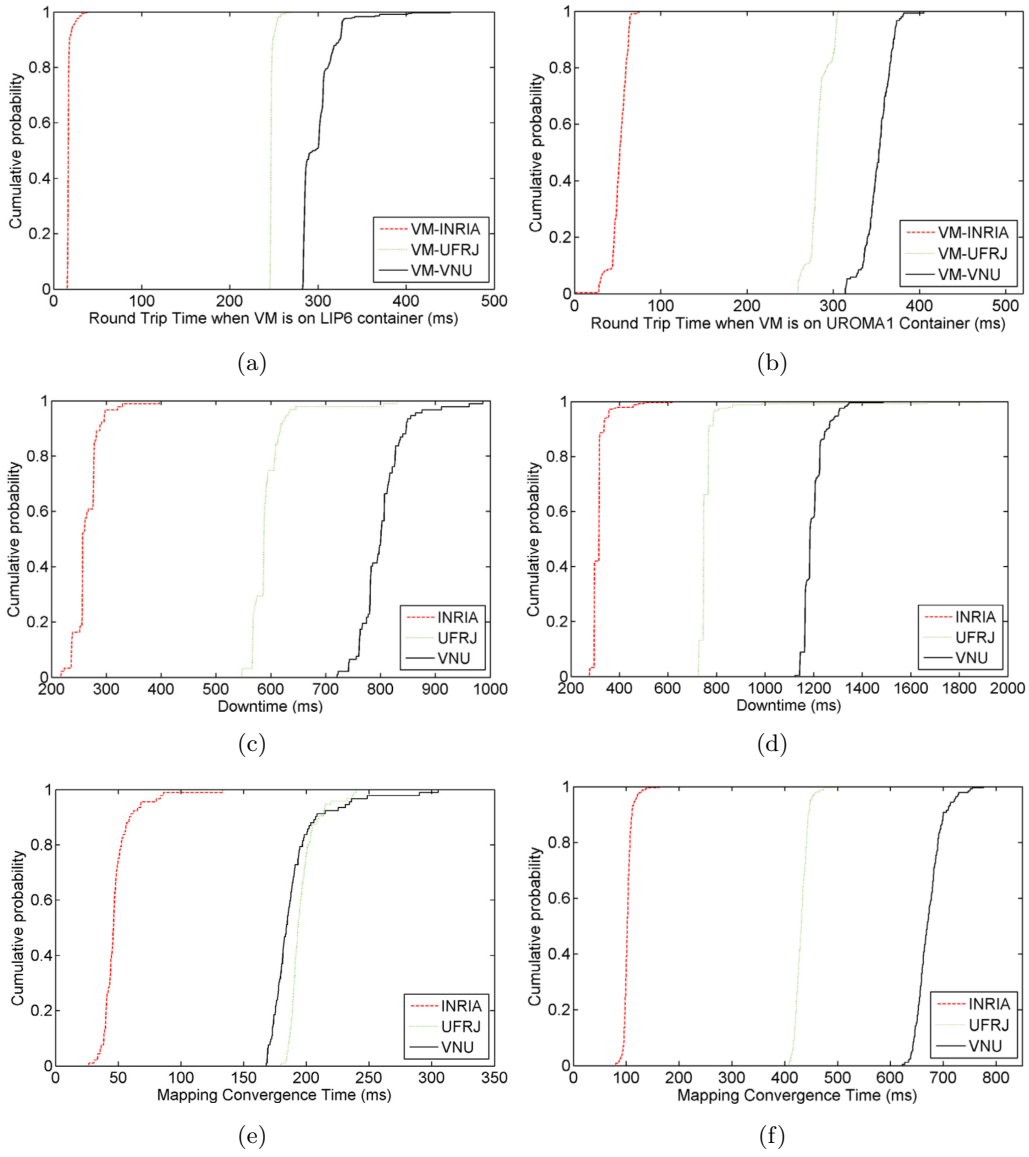


Figure 3.13: Average measured RTT during migrations.

It is worth noticing that these measurements may suffer from a small error due to clock synchronization. As mentioned above, the xTRs have synchronized clocks over the same NTP stratum. The median of the offsets is represented in Fig. 3.11. While it is negligible for close clients, it is of a few dozens of ms for distant clients, however less than the 5% of the downtime. A more precise insight on the simulation parameters is given by the cumulative distribution functions (CDFs) in Fig. 3.13. The RTT CDFs show us that, from an Internet path perspective, VNU appears as more distant than UFRJ from the VMs, with a similar RTT gap before and after the migration. With respect to the downtime, the relative gap between VNU and UFRJ clients with CP and SMR is similar. In terms of mapping convergence time, the VNU-UFRJ gap changes significantly, the reason is likely due to the RTT amplification with SMR.

3.5 Conclusion

In this chapter, we propose a novel LISP-based solution for VM live migrations across geographically separated datacenters over wide area IP networks. We tested it via the global LISP testbed. We can summarize our major contributions as follows:

- we defined and implemented a new type of LISP control-plane message to update VM location upon migration, with the interaction between hypervisors and LISP routers;
- we performed extensive (hundreds) Internet-wide migrations between LISP sites (LIP6 in Paris, UROMA1 in Rome) via the LISP testbed, including the case of clients close to source and destination containers (INRIA - Sophia Antipolis), and the case of distant clients (VNU - Hanoi, UFRJ - Rio de Janeiro);
- by exhaustive statistical analysis on measured relevant parameters and analytical discussions, we characterized the related functionalities is publicly available, see [8] [67]. Part of the CP signaling logic was implemented into LIBVIRT.
- relationship between the service downtime, the mapping convergence time and the RTT; we showed that with our approach we can easily reach sub-second downtimes upon Internet-wide migration, even for very distant clients.

It is worth mentioning that the technology described in this chapter was used in a further work exploring how to trigger virtual machine mobility based on user mobility, described in [75].

Chapter 4

Enhancing MPTCP with LISP traffic engineering extensions

In this chapter we describe further extensions to the LISP architecture we propose to support Multipath Transmission Control Protocol (MPTCP) communications over multiple paths. In particular, we describe how to leverage on LISP traffic engineering and further extensions for enhancing MPTCP communications.

4.1 Introduction

The Internet relies heavily on two protocols - the Internet Protocol (IP) and the Transmission Control Protocol (TCP). In the network layer, IP provides an unreliable datagram service trying to ensure that any host can exchange packets with any other host. In transport layer, TCP provides a reliable byte-stream service on top of IP. Indeed, even if TCP and IP are separate protocols, the separation between them is not complete. To differentiate the individual data stream among incoming packets, a receiving end host demultiplexes the packets based on source and destination IP addresses, port numbers, and protocol identifiers. This implies that a TCP connection is bound to the IP addresses used on the client and the server at connection-establishment time. TCP connections cannot move from one IP address to another. When a host changes the active interface, it obtains a new IP address. All existing TCP connections must be torn down and new connections must be created.

The MPTCP protocol architecture allows packets of the same TCP connection to be sent via different paths to an MPTCP-capable destination. The MPTCP paths are called subflows and are defined by pairs of source and destination IP addresses or ports.

The contents of this chapter are presented in [76].

MPTCP uses the same signaling as the one used for initiating a normal TCP connection, but the SYN, SYN/ACK, and ACK packets also carry the MP_CAPABLE header option, and the connection initialization is the one corresponding to the first subflow. Additional subflows also begin in the same way as when initiating a normal TCP connection, but the SYN, SYN/ACK, and ACK packets carry the MP_JOIN header option. The subflows are terminated similarly to a regular TCP connection with a four-way FIN handshake, while the MPTCP connection is terminated by a connection-level FIN with a DATA_FIN signaled in the Data Sequence Signal (DSN) option.

MPTCP adoption is expected to explode in the next few years, as it is readily available in many mobile devices (e.g., in Apple iOS 7 and OSX 10.10,and for the Linux kernel). Even if multi-homed endpoint situations are certainly becoming a reality for mobile devices (where a portable device typically has multiple interfaces like 3/4G, WiFi, etc) and servers (that can be equipped with several high-speed interfaces), the de-facto strongly dominant network interconnection configuration today uses a single network interface by an application connection for both outgoing and incoming traffic forwarding at a given time. Indeed, the potential of MPTCP may get unexploited because, even if multiple subflows can be created by modifying the source port numbers while keeping the same pair of IP interfaces, their routing in the wide-area Internet segment is subject to non deterministic bottlenecks.

Passing from multipath communications within a local area network to communications across the wide area network, bottleneck is commonly experienced in the Internet segment (typically because of traffic shaping and node/link congestion). Moreover, load balancing at the autonomous system (AS) level is typically not done today, as investigated in [77]. One of the reasons is that such extensions in the Border Gateway Protocol (BGP) failed to be standardized [78], even if a few vendors and open source implementations support it (e.g., [79]). Even if Multipath BGP had to be massively deployed, it would not to guarantee deterministic end-to-end multipath forwarding for MPTCP subflows. In order to compensate for such BGP shortcomings, building network overlays appear as a viable solution as shown in [66]

Recently, for cases where at least one of the two endpoints belongs to a multihomed network registered to a Locator/Identifier Separation Protocol (LISP) [6] network, authors in [80][81] investigate the opportunity of building a network overlay exploiting LISP border routers as multipath forwarding nodes for MPTCP subflows - the solution was named the Augmented MPTCP (A-MPTCP). The idea is to exploit endpoint network loose path diversity information, i.e., the IP routing locators (RLOCs), to balance different subflows over different loose paths that have chances of not sharing a bottleneck in the wide area

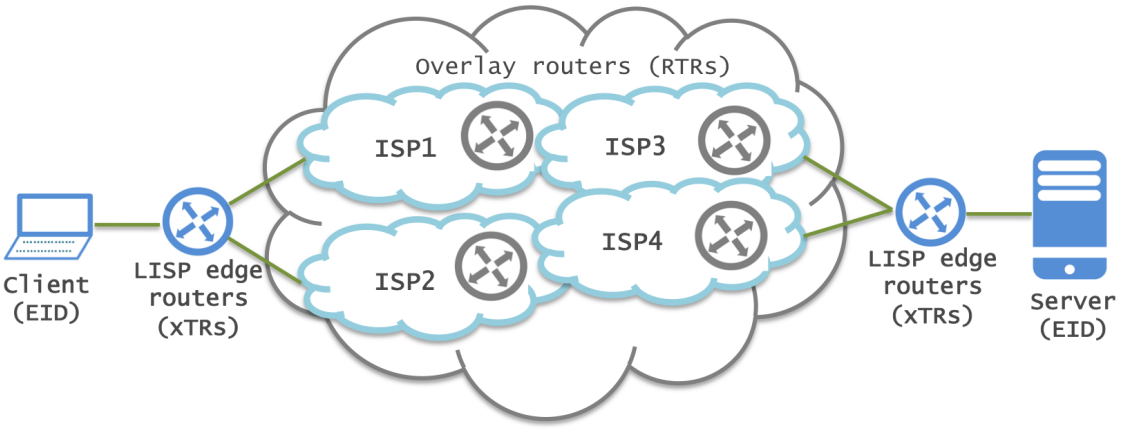


Figure 4.1: A 2-subflow A-MPTCP scenario.

network. The proposed method in [80, 81] relies on a custom signaling between an MPTCP endpoint and the LISP mapping system to obtain RLOC information, used to compute the number of MPTCP subflows to which different edge-to-edge paths can be deterministically stitched playing on the 5-tuple identifier, assuming the hashing load-balancing logic at LISP routers is known by the MPTCP endpoint. While representing a novel promising approach, the proposal in [80, 81] has three main limitations in many IP operations: (i) deterministically knowing the correct hashing function at LISP routers may be impossible; (ii) modifying the MPTCP endpoint kernel as proposed may be unpractical; (iii) the loose edge-to-edge LISP-enabled paths may not systematically lead to a throughput increase due to subflow delay differences.

We overcome these drawbacks by proposing to exploit Traffic Engineering (TE) features we propose to add to the LISP architecture [49, 82], without the need to modify the MPTCP implementation at end-points. As depicted in Fig. 4.1, our proposal consists of building a LISP-TE network overlay that, combined with subflow state management and route selection functions, can transparently offer deterministic multipath forwarding to MPTCP connections, especially to large (elephant) flows. Transparently here means that MPTCP endpoints can keep working in their 'greedy' mode (opening as many subflows as set or needed) and that the overlay does not need any support from the underlay networks between LISP routers. Our proposal was implemented using open source nodes and the code is made available in `github.com/lip6-lisp`.

In the following, Section 4.2 presents LISP-TE extensions. In Section 4.3, we describe different modes to guaranteeing deterministic forwarding of MPTCP subflows. In Section 4.2, we specify the provisioning steps. In Section 4.6 we report experimental results. Section 4.7 concludes the chapter.

4.2 LISP traffic engineering

When two LISP networks exchange traffic, a source endpoint identifier (EID) in a site sends a packet to a destination EID in the other LISP site. Packets are encapsulated by an ingress tunnel router (ITR) toward the decapsulating egress tunnel router (ETR). The path from the ITR to the ETR is determined by the underlying routing protocol and metrics it uses to select a shortest path (typically BGP and interior gateway protocols). The ITR creates an IP-(UDP-LISP-)IP tunnel to ETR so that all the packets between the EIDs are encapsulated and sent via the tunnel.

The LISP Mapping System [35] defines a control-plane based on two main interfaces:

- Map-Resolver (MR): accepts MAP-REQUESTs from ITRs and allows resolving the EID-to-RLOC mapping using a distributed mapping database;
- Map-Server (MS): learns authoritative EID-to-RLOC mappings from ETR via Map-Register messages and publishes them in the mapping database.

The LISP Delegated Database Tree (LISP-DDT) is a hierarchical, distributed database protocol, which embodies the delegation of authority to provide mappings from LISP EIDs to RLOCs, forwarding MAP-REQUEST across Map-Resolvers and Map-Servers.

The xTR (i.e., ITR/ETR) functionality is present in source and destination LISP routers [6]. For packets from source to destination, source xTR acts as ITR and destination xTR acts as ETR; for reverse traffic their role is reversed, i.e., destination xTR acts as ITR and source xTR acts as ETR.

In LISP Traffic Engineering (LISP-TE) extensions to the basic LISP mode are specified to allow using a loose path between ITR and ETR by introducing intermediate re-encapsulating tunneling routers (RTRs) [49]. There are several reasons why these features can be interesting. For instance:

- There may not be sufficient capacity or degraded performance provided by the networks over a given subpath.
- There may be a policy set to avoid a particular subpath.
- There may be specific network functions (e.g., monitoring, traffic inspection nodes) or even a chain of network functions performed along one or many subpaths.

The ability to pilot RTRs allows us to explicitly manage subpaths between RTRs. This makes the ITR-ETR direct path, from a basic LISP perspective, a composition of subpaths between ITR, RTRs, and ETR. This somehow is a form of Internet-scale segment routing; indeed there is recently also interest to use LISP-TE for segment routing [83]:

segment routing combines source routing and tunneling to steer traffic through the transit network. In LISP-TE, the ETR can register multiple Explicit Locator Paths (ELPs) each identifying a path as a chain of RLOCs from source to destination. An RTR is a router that acts as both an ETR, by decapsulating packets where the destination address in the 'outer' IP header is one of its own RLOCs, and an ITR, by making a decision where to encapsulate the packet based on the next locator in the ELP towards the ETR.

In addition to the set of EID prefixes to register, the MAP-REGISTER message includes one or more RLOCs to be used by the MS when forwarding MAP-REQUESTs received through the mapping system. An ETR may request that the MS answers MAP-REQUESTs on its behalf by setting the "proxy MAP-REPLY" flag (P-bit) in the MAP-REGISTER message.

In a LISP-TE context, building a LISP-TE overlay for A-MPTCP communications between two endpoints, say a source endpoint and a destination endpoint, shall be done in such a way that:

1. The destination xTRs register a set of ELPs on a per-EID-prefix basis (e.g., based on local information on the path states and traffic statistics);

2. The mapping system replies to MAP-REQUESTs coming from clients with one or many ELPs to use as loose forwarding inter-domain paths;

3. Different subflows from the source to the destination are forwarded over different ELPs, at least on the most unloaded direction, so that intermediate RTRs deterministically guarantee no bottleneck.

As far as communications are asymmetric, using A-MPTCP in a single direction can be sufficient. Otherwise, its implementation in both directions shall be decorrelated from each other, especially because Internet routing is often not symmetric. Different modes are conceivable to implement the above three steps. To ensure a deterministic binding of subflows to ELP, and hence ensure high performance, states have to be maintained at the LISP network nodes. Implementing the subflow forwarding can imply only control-plane operations, and also data-plane operations. The control on the overlay usage can be left to the destination, to the source, or inter-domain controllers, as elaborated in the next sections.

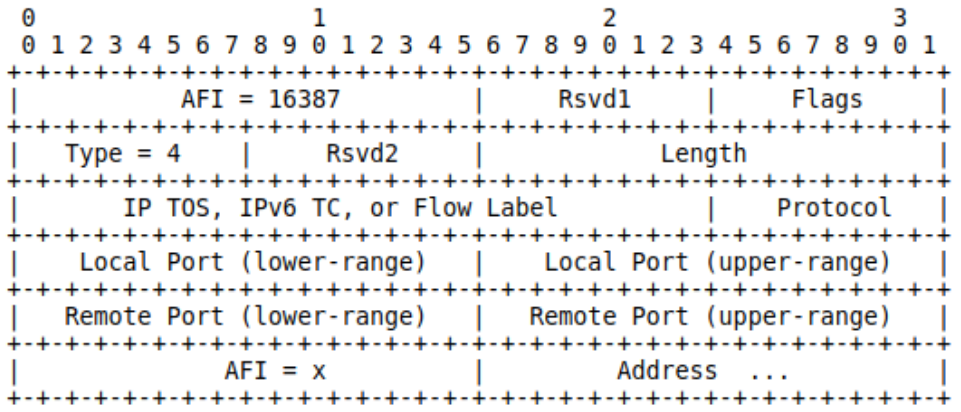
4.3 Explicit locator path binding modes

We propose two possible ELP binding modes for MPTCP communications, describing protocol-level features needed. The specific signaling is later detailed in Section 4.4.

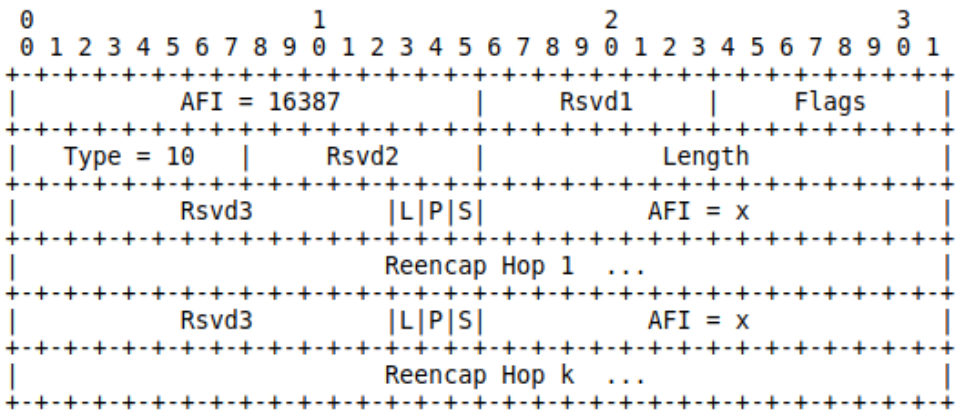
When the source EID sends a packet to the destination EID, source ITR sends a MAP-REQUEST message to the map resolver to get the ETR RLOC. When there are multiple ELPs defined leading to the destination ETR, that ETR may be reachable by different paths. The MAP-REPLY is sent by the destination ETR supposing MAP-REPLY proxying is not enabled. The mapping of ELP to subflows can be decided either at the destination ETR before replying with a single ELP or at the source ITR. Such a decision needs to be taken for each new subflow upon the detection of the MPTCP connection at the source xTR. Hence we have two modes of ELP-to-subflow binding operation described hereafter.

4.3.1 Destination-based stateful ELP binding

In this mode of operation, the destination ETR, upon receiving the MAP-REQUEST triggered by the detection of a new MPTCP subflow at the source ITR, sends one single ELP to the source so that the source associates that ELP with the subflow. When the source sends another requests upon the detection of an additional subflow, it sends a different ELP from the list of ELPs it has. In order to allow the ETR differentiate among different subflows, the source ITR first and the RTRs then must send the flow information in the MAP-REQUEST. This is possible by sending MAP-REQUEST with the LISP Canonical Address Format (LCAF) [82] message type 4 (see Fig. 4.2a) transporting four fields: source EID, destination EID, source TCP port and destination TCP port. The fifth field of the 5-tuple is protocol identifier and in this case it is TCP. In the reference single-homed endpoint situation, a TCP subflow is then identified based on source port because the other fields are equal for all subflows.



(a) LCAF type 4



(b) LCAF type 10

Figure 4.2: Two LISP Canonical Address Format (LCAF) control-plane header types.

This mode is therefore stateful in the sense that the LISP network nodes serving the destination (ITRs, RTRs and the ETRs) need to maintain a subflow-to-ELP association table. Therefore, the best ELP selection algorithm runs on the destination ETR for each subsequent subflow-related MAP-REQUEST. When intermediate RTRs (situated between source ITR and destination ETR) send the request, the ETR must first do a local lookup and see if the subflow is already associated with an ELP. Since the binding should be triggered by the source ITR, requests from RTR should be dropped if the sub-flow indicated in the map request from that RTR is not already associated to any ELP. The benefits in keeping the state of all sub-flows of all incoming connection at the destination ETR and RTR level derive from a better system control by the destination network. The main drawback is scalability, as an important processing load is on the stateful nodes, in particular the RTRs that could be used by multiple destination networks.

4.3.2 Source-based stateless ELP binding

An alternative is to let the LISP nodes serving the destination network stay stateless. This is possible by letting the destination ETR send the complete list of all ELPs along with their priorities to the source ITR and intermediate RTRs. Source ITR and RTRs can therefore send a standard non-LCAF MAP-REQUEST upon detection of a new subflow. The response is encapsulated using LCAF type 10 (see Fig. 4.2b) containing all the ELPs. The source ITR then selects the best path from the set of ELPs and associates each subflow with different ELP; the best ELP selection algorithm is later described. In this mode, the destination ETR and the RTRs do not need to keep any state about sub-flows associations to ELPs. This makes it a more scalable solution in [81]). However, the destination network does not have any control over sub-flow forwarding. There is still a missing brick: intermediate RTRs still need to identify the ELP associated to a given subflow. In absence of alternative techniques to uniquely identify the best ELP, we propose two light-way alternative methods:

1. Path Identifier (PID): the source ITR uses a field in the LISP data plane shim header (the flag field or the instance-ID field) to code an ELP identifier corresponding to the binding, that is a consecutive number of the ELP in the LCAF-10 MAP-REPLY. In a convergent state, this order is later maintained also in the replies to RTRs. The mechanism would be altered if the set of registered ELPs changes during the transmission, which can be considered a rare event during a single connection.

2. ELP Link-Disjointness (ELD): in case ELPs do not share any RTR-to-RTR link,then identifying the path in the data-plane is not necessary. Upon receiving the LCAF-10 MAP-REPLY, the RTR can recognize the ELP based on the previous RTR address included in the outer header source address field. This implicit ELP recognition avoids therefore extra-work at the source ITR, yet it requires the destination to register link-disjoint ELP, which could be a best practice as it is a win-win option, if the RTR topology is sufficiently rich.

4.4 A-MPTCP overlay provisioning steps

We specify in the following the A-MPTCP overlay provisioning steps for the two binding modes.

4.4.1 Destination-based stateful ELP binding

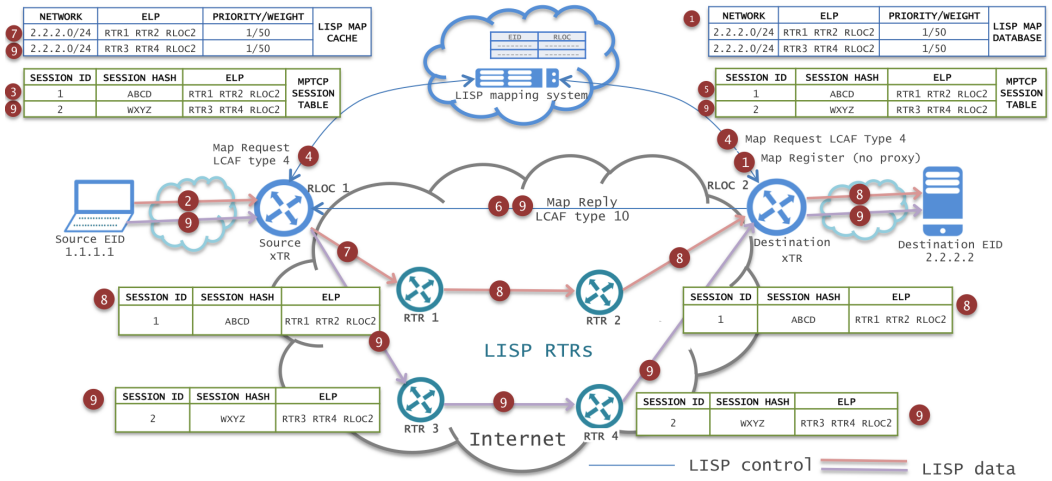


Figure 4.3: A-MPTCP stateful provisioning steps.

Fig. 4.3 depicts an example configuration to describe the provisioning steps for the stateful case. They are as follows:

1. The destination xTR registers ELPs using MAP-REGISTER messages with no MAP-REPLY proxying.

2. The source endpoint opens a MPTCP session with the destination endpoint.

3. The source xTR catches the MPTCP-CAPABLE option and identifies the first MPTCP subflow in a local table with the hash of the 4-tuple source-destination EID IPs and TCP ports (the ELP column is empty at this stage), plus a local MPTCP subflow session identifier.

4. The source xTR sends a MAP-REQUEST with LCAF type 4 (Fig. 4.2a), transporting the 4-tuple source-dest TCP ports and EID IPs, which reaches the destination xTR.

5. The destination xTR selects the best ELP from its set based on the local TE policy (the candidate ELP set should be precomputed for the sake of scalability) and binds it with the subflow. It stores in a local subflow table the subflow's 4-tuple, a local MPTCP session ID (created for the first subflow), and the ELP bound to it.

6. The destination xTR replies to the received encapsulated MAP-REQUEST using a MAP-REPLY with LCAF type 10 (Fig. 4.2b) containing the selected ELP.

7. The source xTR processes the MAP-REPLY, adds the content to the local mapping cache, binds the ELP to the subflow in the local table, and encapsulates accordingly.

8. Afterwards, upon reception of the first encapsulated packet(s), intermediate RTRs first send a MAP-REQUEST to the destination ETR as in step 4, which replies with a LCAF type 10 MAP-REPLY as in step 6, acting then as in step 7. Depending on single-layer or multi-layer path signaling mode, they may either encapsulate the packet and send it to the ELP next hop or send another map request for the next hop, get the intra-domain ELP for next hop and then send the packet to the first entry in the ELP.

9. The source xTRs catches each additional subflow for each MPTCP flow, based on variation of source port only and MPTCP SYN+MP-JOIN options, update the subflow table and send for each new subflow a MAP-REQUEST as in point 4 - 8.

10. When source and destination xTRs catch the termination of a subflow (based on MPTCP option FIN) or a subflow is timeout, they clean the entry from the subflow table.

4.4.2 Source-based stateless ELP binding

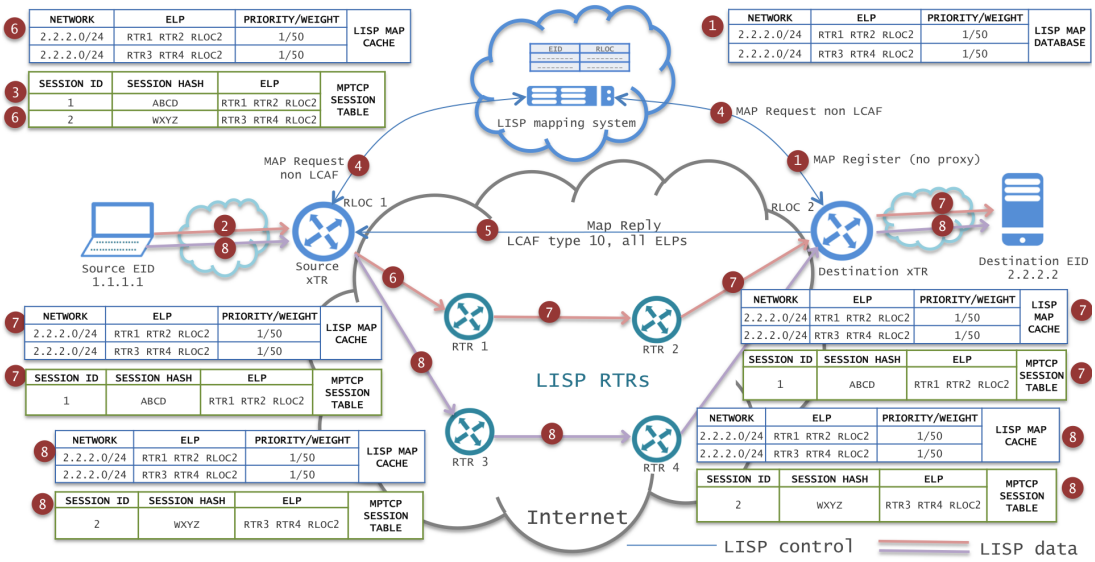


Figure 4.4: A-MPTCP stateless provisioning steps.

Fig. 4.4 depicts an example configuration to describe the provisioning steps for the stateless case. They are as follows:

1. The destination xTR registers ELPs using MAP-REGISTER messages with LCAF type 10. Destination xTR can set the proxy bit indifferently either MAP-REPLY proxy or no proxy.

2. The source endpoint opens a MPTCP session with the destination endpoint.

3. The source xTR catches the MPTCP-CAPABLE option and identifies the MPTCP session in a local table with a hash of the 4-tuple source-destination TCP ports and EID IPs, plus a local identifier.

4. The source xTR sends a standard non-LCAF MAP-REQUEST through the mapping system.

5. The destination xTR (if no proxy reply option) or the Map-Server/Map-Resolver (if proxy reply option) replies to the received encapsulated MAP-REQUEST using a MAP-REPLY with LCAF type 10 containing all the ELPs (Fig. 4.4 shows a MAP-REPLY from destination xTR, for the case when destination xTR registers with no MAP-REPLY proxy).

6. The source xTR processes the MAP-REPLY, adds all ELPs to the local mapping cache, finds the best ELP based on the local TE policy, binds an ELP to the subflow, and encapsulates accordingly to the ELP to the next RTR hop (the path identifier, PID, may be included in the LISP data header as specified in Section 4.3.2).

7. Afterwards, upon reception of the first encapsulated packet(s), intermediate RTRs first send a MAP-REQUEST as in step 4, and receive a LCAF type 10 MAP-REPLY as in step 5, acting then as in step 6. As in the stateful case, they may or not work under multi-layer path signaling mode. To identify the next-hop RTRs can either use the PID in the LISP data header, or identify itself in the ELP under the ELD assumption, as explained in Section 4.3.2.

8. The source xTR catches each additional MPTCP subflow, based on variation of source port only and MPTCP SYN+MP-JOIN options, updates the subflow table and binds the second (best) ELP to it.

9. As in the step 10 of the stateful mode, when source and destination xTRs catch the termination of a subflow (based on MPTCP option FIN) or a subflow is timeout, they clean the subflow entry from the subflow table.

It is worth mentioning that the local TE path selection policies mentioned in step 6 above and in step 5 of the stateful provisioning step need to be carefully drafted so as to grant marginal improvement to ELP-to-subflow binding with respect to the standard/previous situation. As one of the main factors affecting transport protocol performance is the Round Trip Time (RTT), there is the need to collect RTT information in the overlay network topology composed of xTRs and RTRs. This can be natively done in

a LISP network by enabling the so-called 'RLOC probing'functionality [6] that by piggybacking MAP-REQUEST messages is able to collect RTT information. Once collected, this information can be used for the TE path selection policy run over the weighted overlay network graph.

4.5 Overlay network design

The TE path selection policy is a routing problem that requires finding an efficient set of ELPs for a given ITR/ETR pair with constraints specific to the A-MPTCP scenario.

The most important parameter when transmitting data of a same MPTCP connection over different subflows, each experiencing an RTT independent of the other subflows, is not the overall RTT, but rather the differential RTT between subflows. Indeed, a too high difference between subflow RTTs may make some subflows useless (discarded by the local MPTCP scheduling algorithm), and may also cause the head-of-line blocking issue due to packet disordering at the destination endpoint buffer (i.e., the source can no longer transmit packets if the destination has not yet acknowledged previously transmitted packets; this is typically caused by out-of-order packets due to different experienced RTTs) [84].

In the A-MPTCP context, the ELP set computation corresponds to a LISP-TE overlay network design problem. The ETR should compute a set of ELPs based on a representative set of ITRs, which should then be used as default set of ELPs to register with the mapping system. Then, in the stateful case, the ELP set is filtered based on the ITR sending the MAP-REQUEST, and ELPs are sequentially bound to subflows, which needs ELPs to be sorted (based on a reference estimated number of paths per connection).

In the stateless case instead, the ITR receives the full overlay graph (i.e., ELP set) and has to locally extract the ELPs from it. Both cases share the same reference link-disjoint-differential-delay routing problem.

In the following, we present the state of the art on multipath provisioning aiming at differential delay aware routing algorithms, along with the problem's formal definition and our adopted heuristic.

4.5.1 State of the art

Multipath provisioning has been extensively studied to increase resiliency of both transport [85] and wireless networks [86], and to cope with the requirements of high bandwidth applications [87], and for congestion control [88].

When data is routed through multiple disjoint paths, the delay incurred by each phys-

ically disjoint path may differ. Such delay difference is commonly called differential delay (DD). DD imposes buffering requirements at destination to accomplish data reordering.

DD routing was first studied in [89, 90, 91] for Ethernet over optical transport architectures. Minimizing DD when including a new path into a group of paths was modeled as a two sided constraint paths problem and it was demonstrated to be NP-complete [89]; hence, a heuristic based on a modified link weight k-shortest path was proposed. The authors of [90] demonstrated that the DD routing is NP-hard and that it is as hard as the longest path problem; they present heuristics based on the flow maximization over a precomputed set of paths known to satisfy the DD constraints. Cumulative differential aware routing was proposed in [91] to accurately model the memory requirement constraint, by considering the amount of flow on each subpath. However, none of those works considered path disjointness.

To the best of our knowledge [92, 93] are the first works that presented a reliable multipath (disjoint paths) provisioning model with DD constraints, which is also an NP-hard problem. In [92] the specific problem is to provision a connection with requirements on bandwidth, reliability as well as minimum and maximum delay. They proposed a pseudo-polynomial time solution, and a fully polynomial time approximation using a restricted maximum flow formulation over a transformed graph. Due to the complexity of the formulations, a heuristic based on a max flow algorithm followed by a simple differential delay constraint check was proposed. The problem studied in [93] is to provide reliability and reduce backup path bandwidth, by computing the maximum cardinality set of disjoint paths that meet a DD Constraint (DDC). Authors of [93] presented a heuristic to maximize the cardinality of paths set that meets a DDC. This heuristic builds an auxiliary graph using only the merge nodes of k-link-disjoint paths between source and destination, then compute all possible permutations of those paths.

4.5.2 Link-disjoint-differential-delay routing problem (LD3R)

The network is represented as a directed graph $G(V, E, D)$ where V is the set of nodes, E is the set of directed links and D represents the one-way delay experienced on each link. It is important to notice that the routing problem does not account for volume of flow allocation on each subpath, as this will be let to MPTCP congestion control. Thus we can consider unit capacity links to preserve link-disjointness. A connection request $R(s, t, DDC)$, where s, t is the ITR/ETR pair and DDC is the differential delay constraint. Our objective for the source-destination based approach (for one MPTCP connection) is to find the maximal set of link-disjoint paths that meet the DDC and low total cost.

Complexity

An instance of this problem will be to find at least two disjoint paths with equal delay. The problem of finding two paths with equal delay was proven to be harder than the Longest Path Problem [90]. Therefore the LD3R problem is NP-hard.

Heuristic

Due to the NP-hardness of the LD3R problem, we present a modified version of the SPLIT-DDCKDP algorithm [93] in Alg. 2. Additional details about such an optimization problem can be found at [94].

Algorithm 2 k-disjoint ELP permutation.

INPUT: Directed graph $G(V, E, D)$, a demand of MPTCP connection between the pair s, t and the maximal DDC.
PROBLEM: Find P, the set of k-link-disjoint paths from s to t, subject to differential delay of paths is $\leq$ DDC.
Find the initial set P using extension of Bhandari's algorithm [95] to find k-link-disjoint paths from s to t.
if $k < 2$ **then**
  use the shortest path.
else
  Find set of merge nodes (MN) appearing on two or more paths of P.
  Generate G' as a directed multigraph of MN nodes. Every path in G connecting two MNs becomes a directed edge in G with delay equal to the original path delay.
  Generate P with all simple paths from s to t in G'.
  Generate all maximal subsets of P' that are link-disjoint.
  For each subset, calculate which meets the DDC.
  Select the subset of maximum cardinality. If more than one such subset, choose the set with minimum total distance.
end if

4.6 Experimental results

The proposed framework was implemented and tested through large-scale experiments, as described in the following.

We preferred running tests using real routing and end-point nodes rather than simulators because the complexity of the MPTCP+LISP-TE combined network system is such that using discrete-time event simulators would risk to introduce too much determinism with the risk of low credibility.

4.6.1 Implementation details

For running experimental tests, we extended the OpenLISP control-plane [8]) and data-plane implementations adding: (i) LCAF 4 and LCAF 10 processing at the control-plane level; (ii) stateful and stateless functions, with the corresponding subflow table management functions; (iii) an enhanced RLOC probing behavior for collecting RTT measurements between overlay network nodes.

We centralized the collection of RLOC probing results at both ETR and ITR level to support the ELP search on the overlay network graph weighted with RTT probing information. Then, we used as k-shortest path algorithm the one described in Alg. 2, to select ELPs with least differential RTT, with the goal to minimize the occurrence of head-of-line blocking when buffering packets.

The resulting versions v0.3 and v4.0 of the OpenLISP data-plane and control-plane software nodes including these extensions are released with a BSD license (see `github.com/lip6-lisp`).

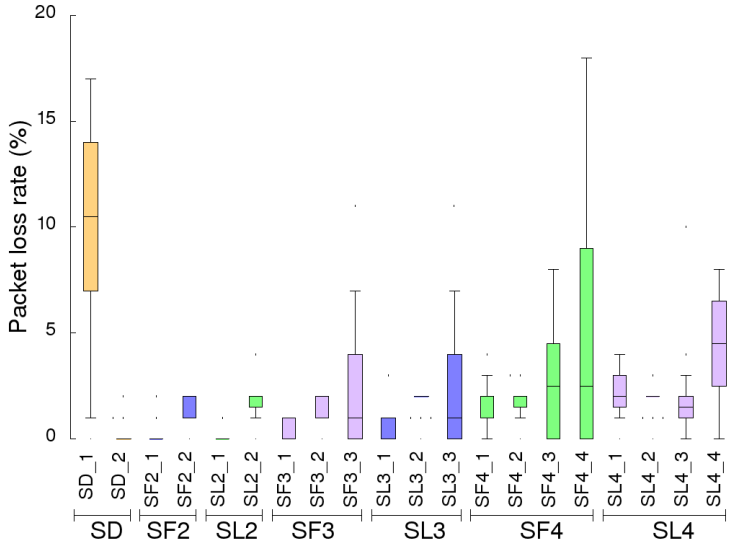
4.6.2 Network testbed

We built an overlay network of RTRs over the LISP-Lab project testbed (`lisplab.lip6.fr`), interconnected to the global LISP network with the OpenLISP DDT root named 'lambda' (see `ddt-root.org`). For the tests, we set as destination the LISP-Lab site of Univ. of Missouri-Kansas City (UMKC), Kansas-City, USA, and used three different source LISP-Lab sites: the LIP6, Paris, France, Rezopole, in Lyon, France, and NSS, in east Paris, France, ones. Each source site deploys one xTR, one RTR and own EID prefix. To complete the overlay network, we use the following additional sites: Inria, in Sophia Antipolis, France, VNU, in Hanoi, Vietnam, POLIMI, in Milan, Italy, each running an RTR. All the nodes, xTRs, RTRs and EIDs run as virtual machines with a number of cores varying from 1 to 4, from 2 to 2.6 Ghz, and live memory from 1 to 4 GB. EIDs implemented the version 0.90 of the open source MPTCP Linux kernel implementation (`multipath-tcp.org`).

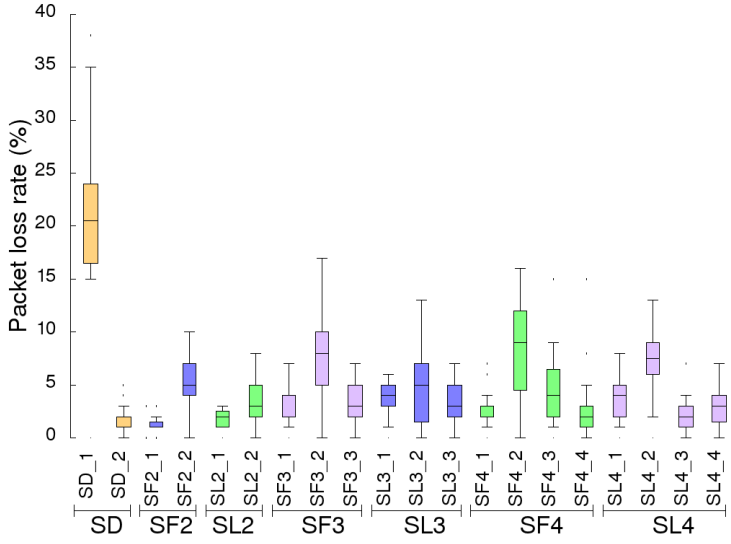
We run 30 transfers for each mode (stateless and stateful), lasting 120 seconds each, using the iperf tool, for each source-destination pair, distributed on a period of two days. For each transfer, we first setup the nodes in the topology, and then use the RLOC probing between all nodes to collect RTTs between each pair of the node (used to calculate the ELP set for both source and destination xTRs). After deploying the computed ELP set to source and destination xTR, we start the transfer. As the overlay topology RTT were quite stable during the experiments, we got a fixed set of ELPs as follows:

- the LIP6-UMKC communications, ELP1 was via LIP6-UMKC, ELP2 via Rezopole-UMKC, ELP3 via NSS-UMKC, and ELP4 via VNU-UMKC;
- for NSS-UMKC communications, ELP1 was via NSS-UMKC, ELP2 via Rezopole-UMKC, ELP3 via LIP6-UMKC, and ELP4 via VNU-UMKC;
- for Rezopole-UMKC communications, ELP1 was via Rezopole-UMKC, ELP2 via LIP6-UMKC, ELP3 via NSS-UMKC, and ELP4 via VNU-UMKC.

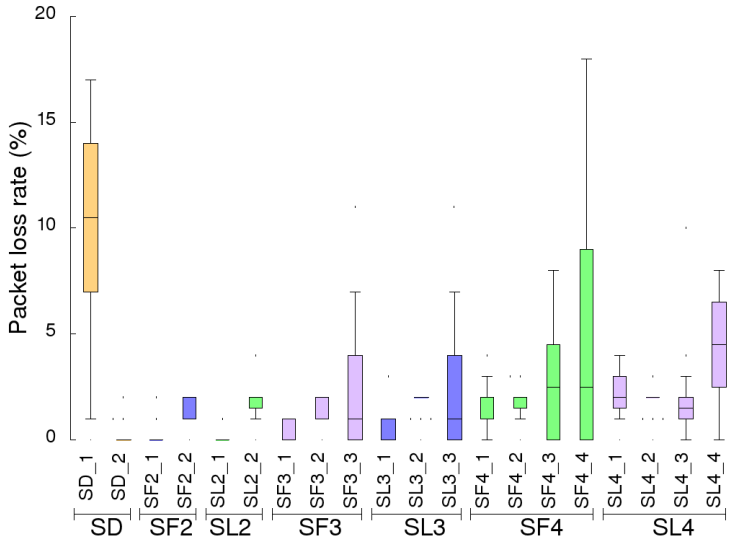
In the following, SLX and SFX indicates the stateless and stateful tests, respectively, run with a number of X ELPs. SD stands for standard transmission, that is using basic LISP-MPTCP communications with LISP-TE stitching as in [96, 81] with two subflows. SD$_Y$, SLX_Y and SFX_Y indicates the Y^th subflow used in SD, SL and SF modes, respectively.



(a) LIP6 source

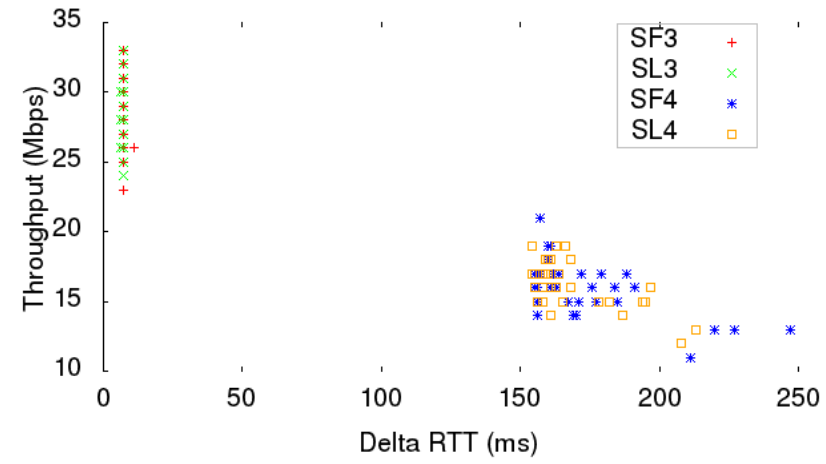


(b) NSS source

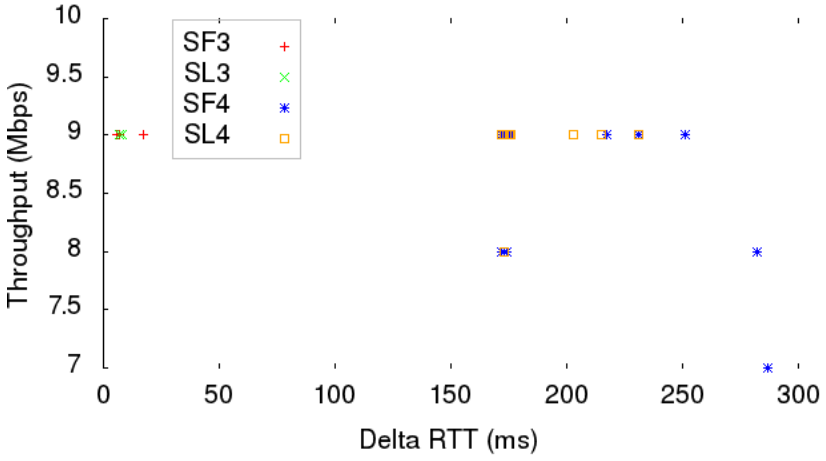


(c) Rezopole source

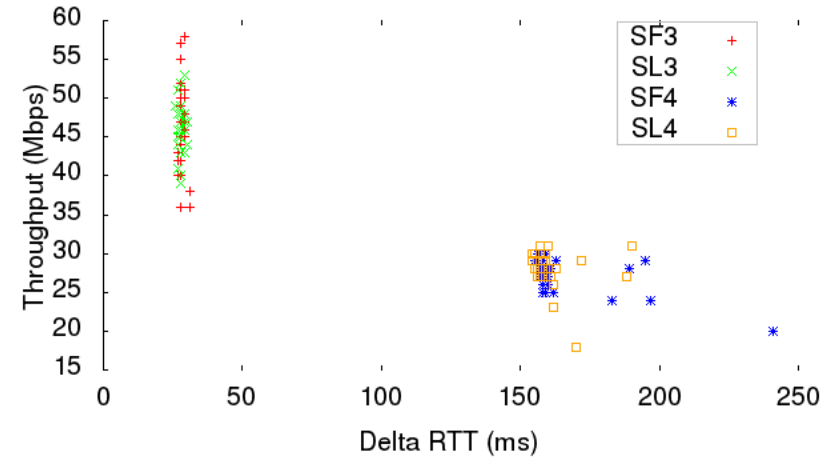
Figure 4.5: Packet loss rate for different number of ELPs, in stateless and statefull modes.



(a) LIP6 source

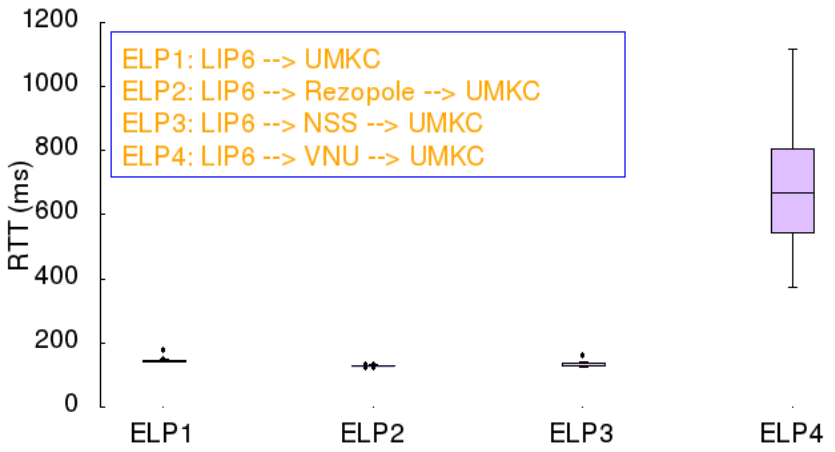


(b) NSS source

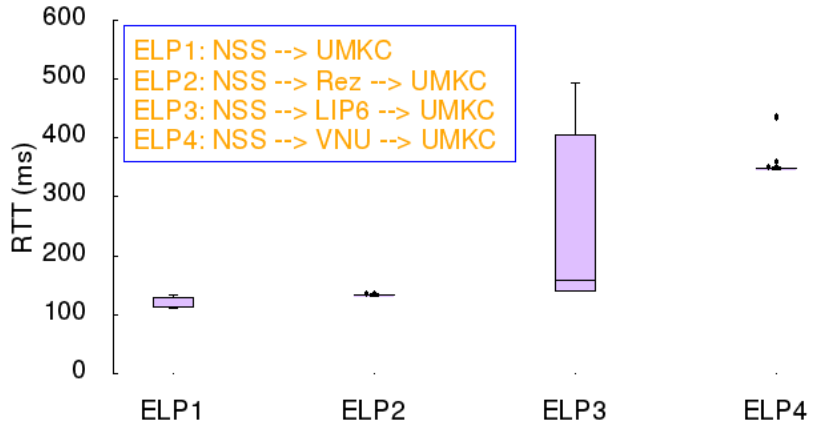


(c) Rezopole source

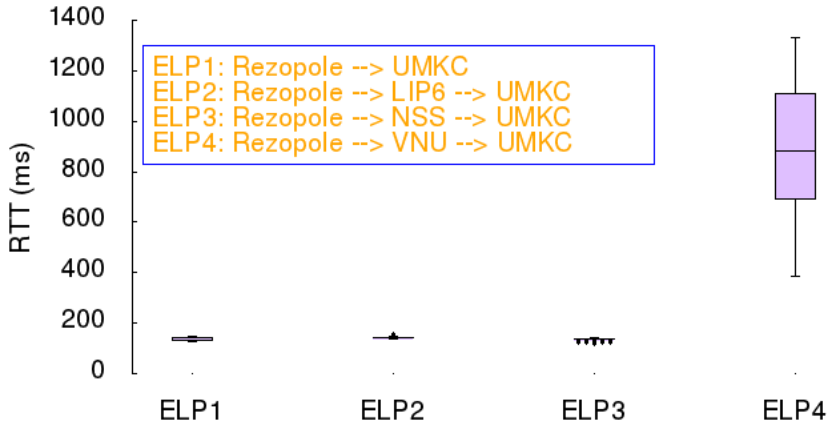
Figure 4.6: Correlation scatter of throughput vs differential RTT.



(a) LIP6 source



(b) NSS source



(c) Rezopole source

Figure 4.7: Average RTT cumulative distribution functions for the different ELPs and sources.

4.6.3 Tests characterization

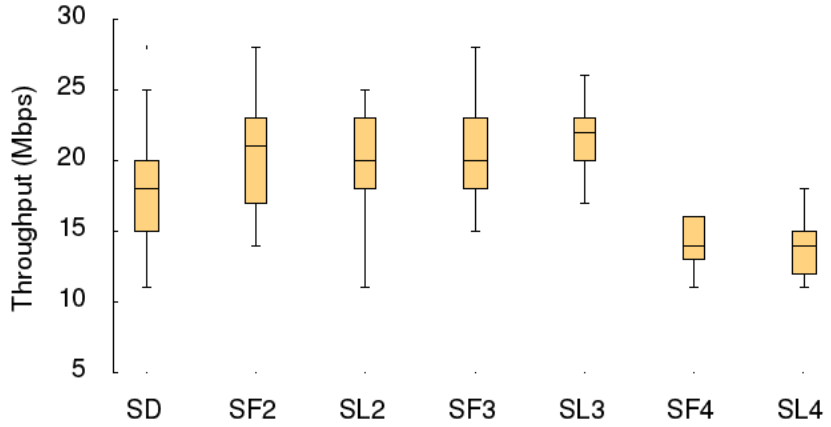
Let us characterize first the tests, in order to better understand the throughput results.

Fig. 4.5 gives the experienced packet loss, at the subflow level, for the various modes with a number of subflows ranging from 2 to 4. The SD mode suffered an important packet loss during the experiments. Among the sources, the NSS one suffered more, essentially because we suspect the employed datacenter run shaping policies at the top-of-rack level.

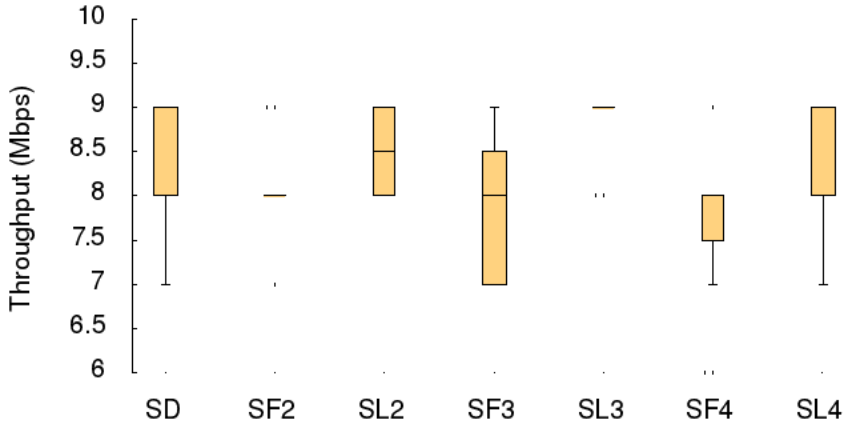
Fig. 4.6 gives three scatter plots, one for each source, correlating the throughput to the differential RTT (the minimum RTT difference among subflows) for all the tests. We can observe the strong positive correlation between the two factors, with highest throughput reached for least differential RTTs.

Fig. 4.7 completes the picture with the distribution of the RTT (average among the RTTs of the single subflows) for the different ELPs. The fourth ELP for all sources suffers from a much higher RTT, hence one can expect its addition can generate head-of-line blocking. For the NSS source, ELP3 has a slightly higher RTT than the others. The remaining ELPs have a differential RTT quite low.

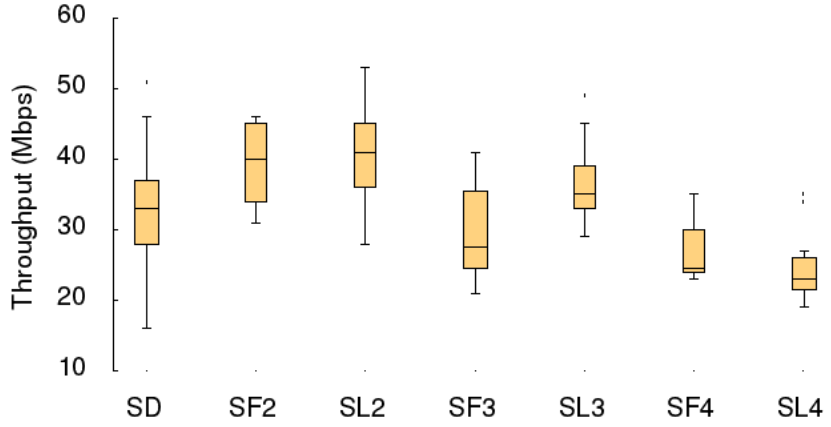
4.6.4 Throughput results



(a) LIP6 source

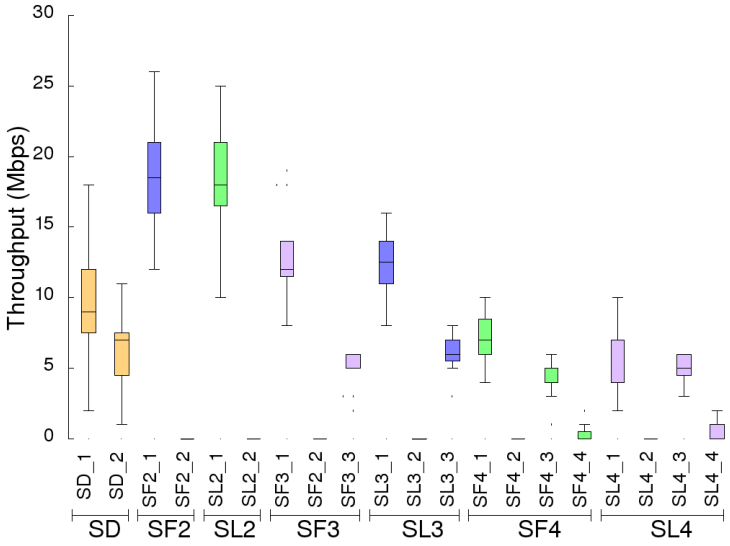


(b) NSS source

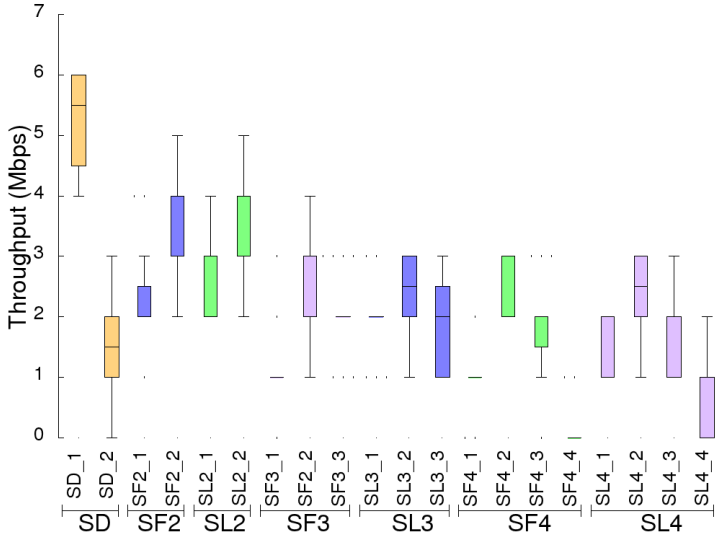


(c) Rezopole source

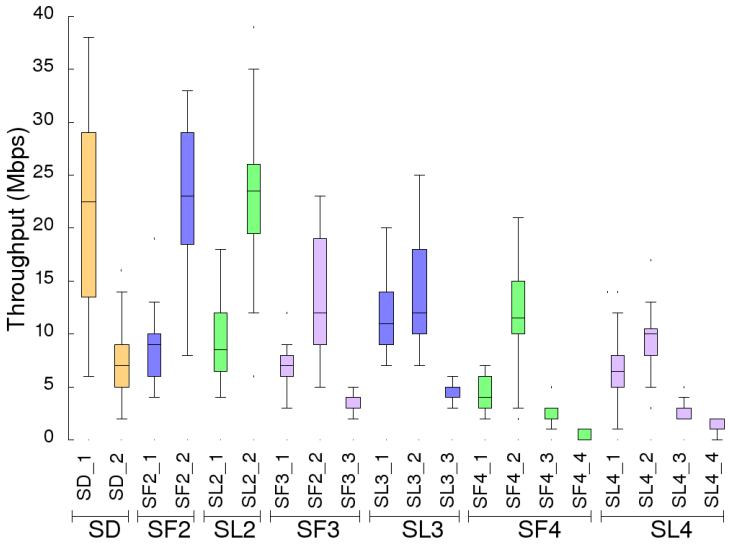
Figure 4.8: Throughput performance for different number of ELPs, in stateless and statefull modes.



(a) LIP6 source



(b) NSS source



(c) Rezopole source

Figure 4.9: ELPs contribution to the MPTCP connection throughput.

Fig. 4.8 reports the achieved performance in terms of throughput for the different source-destination pairs, under the stateful and stateless modes, with the number of ELPs ranging from 1 to 4. We can notice that there is practically no improvement with the NSS source: this is likely the result of the many retransmissions due to the observed higher packet loss rates, likely due to shaping in the source network. For the other two sources, the gain ranges from 10% to 25% with two paths, hence without adding paths with respect to SD, just bypassing the default routes by using the network overlay. Adding a third ELP leads marginal gains only for the LIP6 source. Adding the fourth ELP, with high RTT, does decrease the throughput as expected, likely because of head-of-line blocking. Finally, an important observation is that there is no better mode in terms of throughput performance between stateless and statefull modes.

With a deeper look to the subflow contribution to the throughput, shown in Fig. 4.9, also in perspective with the ELP RTTs qualified in Fig. 4.7, we can observe that the fourth ELP does indeed bring a very low, in practice null contribution, besides causing likely buffering issues. Then, we can see the impact of the scheduler, which load mostly one subflow (the least RTT one), this subflow often being the first one (because we can see there can be a very low difference between the RTTs of ELP1 and ELP2 for all sources). We identify in the scheduler an important potential of further bandwidth aggregation, as other ELPs with very close RTT to the least RTT one could be used more with another type of scheduler. Unfortunately, such an advanced scheduler is still not designed and implemented as of our knowledge.

4.7 Conclusion

We described in this chapter a novel overlay network protocol architecture based on MPTCP and LISP-TE protocols, with some extensions in particular to the overlay routers state management. Despite we could benefit from only few overlay network nodes, we could experimentally evaluate our proposals showing the positive impact by using our overlay network, the negative impact of long RTTs on some MPTCP subflows, and the strong correlation between the differential RTT among subflows and the throughput performance.

Different directions of further investigations are open. First, we believe our approach, making use of an incrementally deployable protocol such as LISP, can be a viable one for building an overlay network across network domains such as via internet exchange points or software-defined network domains. Second, the major limitation to the achievable throughput gain being represented by the MPTCP scheduler, we plan to design a new scheduler able to better aggregate bandwidth on multiple subflows with different RTT performance. As introducing an advanced scheduler may be too difficult to do at the

device level, and as devices may not even be MPTCP capable, one promising direction is to integrate it into MPTCP proxies using frameworks such as the one described in [97].

Chapter 5

Improving the Inter Domain Management of Locator/ID Separation Protocol (LISP) Networks

In this chapter, we propose a framework to improve LISP operations at the Internet scale, by facilitating cooperation between the LISP Mapping Systems and introducing more automation in the LISP connectivity service delivery procedure.

5.1 Introduction

The large majority of the Identifier/Locator split protocols need a Mapping System that maintains mappings between the Identifier and the Locator information, and provides resolution services accordingly [99]. Several LISP mapping database systems have been proposed, but the Delegated Database Tree (LISP-DDT) [37] is the one currently deployed by operational implementations. LISP-DDT proposes a hierarchical resolution model like the DNS (Domain Name Service) system. Such hierarchical structure may affect resolution times, besides raising political concerns due to potential country-centric management, where the mastering of root DNS servers can influence the quality of the resolution service at the Internet scale. In LISP-DDT, when a mapping resolution request is issued, it is relayed from a resolver node to another one, passing through a DDT, un-

The contents of this chapter are presented in [98] and are the result of a collaboration with M. Boucadair and C. Jacquenet from Orange, who defined the main specification I marginally enhanced for its implementation. A tutorial and technical demonstration video is available at `http://www.lisp-lab.org/msx`.

til it reaches an authoritative server. Alternative proposals were discussed, such as ALT (Alternative LISP Topology), which however mandates a parallel node-disjoint separation for the control-plane, with distinct BGP (Border Gateway Protocol) routers. The proposal discussed in this article aims at improving resolution services of LISP networking infrastructures deployed at the scale of the Internet. Such approach is also meant to facilitate the deployment of LISP in the Internet. It provides new services that take advantage of LISP in inter-domain deployment scenarios without requiring the participation of all LISP-enabled domains. Moreover, the optimization of resolution services relies upon a decentralized, peer-to-peer interconnect of independently-operated Mapping Systems, because of the issues raised by a centralized and global Mapping System. This chapter presents a framework for improving LISP operation at the scale of the Internet, based upon new mechanisms to (1) dynamically discover and select remote LISP Mapping Systems, (2) negotiate and then establish interconnect agreements with such Mapping Systems, and (3) optimize LISP connectivity service operation by means of new LISP primitives.

5.2 Challenges of LISP operation at the Internet scale

The deployment of LISP networks at the scale of the Internet raises several issues that may affect the overall quality of a LISP connectivity service. Various LISP players (network operators, service providers, etc.) are likely to deploy and operate different LISP Mapping Systems [7]. Indeed, many proposals were investigated for the past few years, including mobile core networks [4], software-defined networks [100], and prefix de-aggregation control practices [101], leading to independent Mapping Systems that may benefit from interconnecting with each other.

Furthermore, Multiple Mapping Systems will coexist for other reasons, e.g., to avoid country-centric governance, allow for various technologies to implement the mapping service, take advantage of new business opportunities encourage service innovation, etc. The lack of clear policies for the management and operation of the LISP Mapping Systems may encourage such practices.

Moreover, because the LISP Mapping System may provide service differentiation opportunities, IP access and transit providers may be tempted to operate a (local) Mapping System. Mapping Service Providers may offer advanced services to their customers such as the maintenance of local caches, or the update of ITR mapping entries that match some criteria requested by a leaf LISP network. MS providers may also ensure that mapping resolution requests are redirected to the closest Map-Resolvers, whereas the structuring of the mapping resolution service is meant to optimize resolution times, avoid the loss of the first packet, etc.

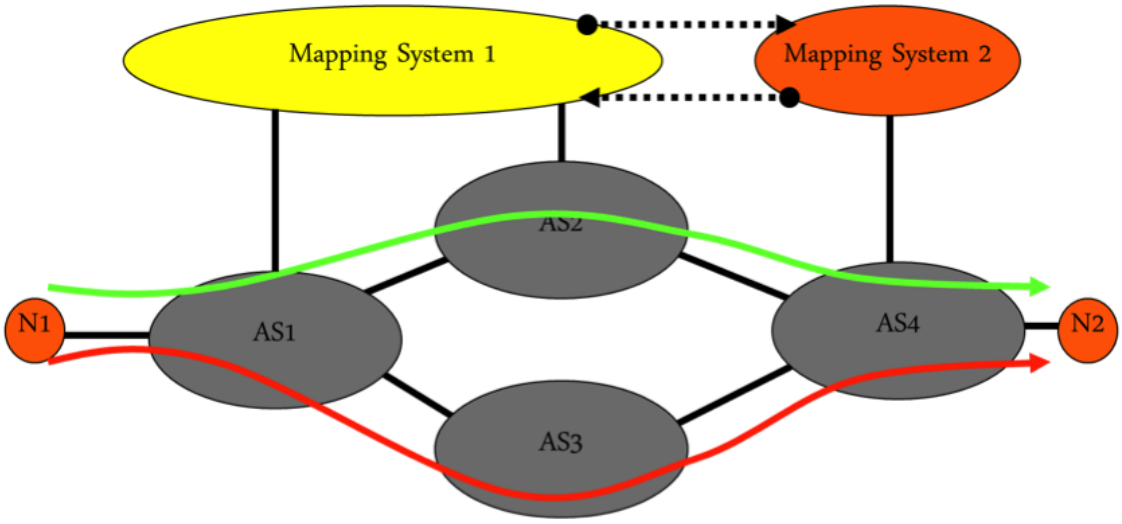


Figure 5.1: MS Interconnect Example.

As represented in Fig. 5.1, a LISP Mapping System may handle one or multiple prefixes that belong to one or multiple Autonomous Systems (ASes). Distinct flavours of Mapping Systems may be deployed; each may rely upon specific technology. As such, a clear interface to ease interconnection between these realms is needed.

A hierarchy in the Mapping System organization for business, governance, control, and regulatory purposes, in particular, is likely. In such contexts, a Mapping System may maintain (a portion of) a global mapping table. An efficient and scalable LISP deployment within an inter-domain context for traffic engineering purposes heavily relies upon the availability of an inter-domain Mapping System that spans several domains. From this perspective, the success of a global LISP adoption and deployment will mainly depend on how LISP-enabled domains will graft to existing Mapping Systems that can guarantee a global reachability scope. To minimize the risk of a fragmented Mapping System that would jeopardize the overall efficiency of an inter-domain LISP routing system, there is a need to encourage and facilitate the coordination of participating Mapping Systems.

5.3 A framework for improving LISP operation at large scale

5.3.1 An interconnect framework for a global Mapping System

In order to extend the reachability of LISP EIDs beyond the boundaries of a single Mapping System, we aim at proposing a framework that does not require to change xTR behaviour such that an xTR would query multiple Mapping Systems concurrently (i.e.,

configured with multiple mapping servers of independent Mapping Systems). These Mapping Systems need to interconnect to extend the reachability scope and avoid pressure on PxTR devices. Also, various Mapping Systems encourage the enforcement of policies that aim at optimizing LISP forwarding: for example, policies that consist in avoiding the solicitation of specific domains or regions (e.g., for security reasons).

It is essential to encourage the deployment and the operation of a global Mapping System at the scale of the Internet instead of a fragmented Mapping System.

Fig. 5.1 depicts an example of LISP Mapping interconnect: while domains 1 and 2 use Mapping System 1, domain 4 uses Mapping System 2. Mapping Systems 1 and 2 are independent, meaning that the LISP traffic exchanged between node N1 and node N2 should use the PxTR. By interconnecting both Mapping Systems, communications between N1 and N2 can be natively LISP-forwarded without invoking any PxTR. Moreover, optimizing such LISP interconnection can also reduce the resolution time compared to the use of a centralized, hierarchical Mapping System such as LISP-DDT.

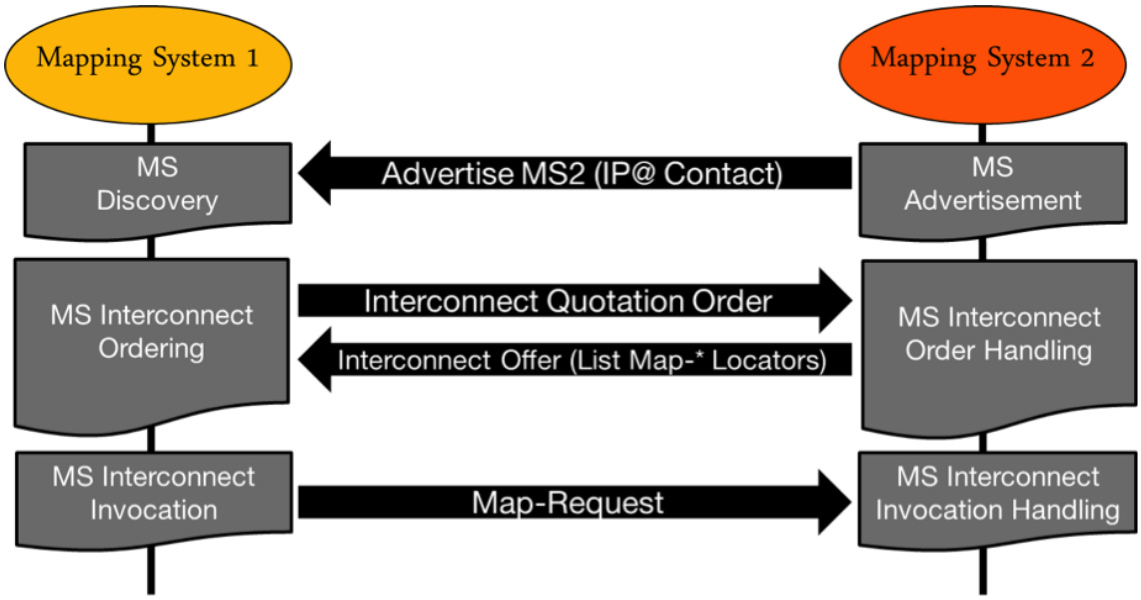


Figure 5.2: Functional Blocks for Inter-Domain LISP Operation.

5.3.2 Functional blocks for inter-domain LISP operation

The settlement of LISP Mapping System interconnects is decomposed into several functional blocks, as represented in Fig. 5.2:

- **Discovery and Advertisement**: Discover and Advertise LISP Mapping Systems that are willing to interconnect as well as those that are ready to service leaf LISP networks. A leaf LISP-enabled network may subscribe to the mapping service pro-

vided by one or several Mapping Service Providers. In Fig. 5.2, Mapping System 2 advertises its reachability information to Mapping System 1.

- **Negotiation**: We identify the mapping negotiation as a viable approach to support the scalability of Internet routing in general, and LISP mapping domain interoperability in particular [102]. The goal of the Negotiation block is to negotiate interconnection agreements with remote Mapping Service Providers. The same mechanism can be used by a leaf LISP network to subscribe to one or multiple Mapping Systems. Subscribing to multiple Mapping Systems is meant to enhance the robustness of the connectivity service. The contribution of each player involved in the provisioning and the operation of a LISP-based connectivity forwarding service needs to be rationalized so that clear interfaces are defined and adequate mechanisms for troubleshooting, diagnosis and repair purposes can be easily implemented and adopted. The inability of identifying what is at the origin of the degradation of a LISP connectivity service is seen as one of the hurdles that are likely to jeopardize LISP deployments at the scale of the Internet. The interconnection agreement can be unidirectional or bi-directional. Dedicated technical clauses may be included in the interconnect agreements to specify whether advanced primitives (such as bulk mapping transfer or record notifications) are supported. Also, the agreement specifies how requests are rate-limited.

- **Mapping System Interconnect**: Implements interconnect agreements with remote Mapping Systems to facilitate the exchange of mapping records between Mapping Systems. The entries of the mapping tables (or a part thereof) are exchanged between these Mapping Systems so that Map-Request messages can be processed as close to the LISP leaf networks as possible.

- **Service Invocation**: Invoke a peer Mapping System for mapping records resolution, in particular. Other services can be offered by the Mapping System, e.g., assist the forwarding of the first packet before a mapping entry is available in the xTR cache.

Also, the Mapping System can be engineered so that a LISP mapping request can be serviced by a Map-Resolver that is close to the end-user. This approach reduces delays related to the processing of the "first packet", which can be quite high with the legacy LISP control plane. We propose two solutions to resolve this issue. The first solution consists in allowing the Mapping System to help forwarding packets that do not match an existing mapping record. The second solution is that the xTR prepares in advance the required mappings so that neither delay nor loss is experienced when receiving the first packet.

This framework advocates for a global Mapping System to be maintained locally. To that extent, we present hereafter new LISP primitives to allow for bulk retrieval of mappings and subscription to notifications when a predefined set of filters are hit.

5.4 Mapping system discovery

We present in the following sub-sections routing protocol extensions to dynamically advertise and discover Mapping Systems within and beyond a network domain.

5.4.1 A new LISP BGP community attribute

Because the design and operation of a consistent LISP Mapping System are critical for the adoption of the protocol at large scale, means to dynamically discover other Mapping Systems that are open to cooperate in inter-domain LISP deployment scenarios are required. A LISP domain may need to discover available Mapping Systems so that it can rely upon those Mapping Systems to extend the reachability scope.

We propose to support the discovery of LISP Mapping Systems that are deployed in distinct administrative domains with a specific Border Gateway Protocol (BGP) community attribute [103]. The detailed format of the new BGP community is described in [104]. An advantage of adopting a BGP community attribute is that Mapping System interconnection functions can be integrated in standard BGP decision-process filters; on the other hand, a disadvantage is that a current practice is to filter out all the unknown BGP community attributes. Standardising this BGP Extended Communities will help this announcement to be safely propagated.

This BGP Extended Communities attribute is used to inform other domains about the support of the mapping service. EID that can be serviced with LISP will be tagged accordingly. Note that an EID can be serviced by multiple Mapping Systems. Remote LISP Mapping Systems will rely upon that BGP-based advertising capability to discover the existence and the status of other Mapping Systems.

Once a Mapping System is discovered, a local Mapping System can solicit the remote Mapping System to enter negotiation discussions for the establishment of an interconnection agreement with that remote Mapping System. The contact IP address provided as part of the BGP Extended Communities attribute will be used to contact a remote Mapping System to request for further LISP-related capabilities, possibly negotiate an interconnection agreement and, consequently, extend the scope of the networks that can be serviced using LISP. Also, leaf LISP-aware networks can rely upon the information carried in the BGP Extended Communities attribute to discover Mapping Systems that may be

solicited to invoke their mapping service. Subscription cycles may then be considered.

5.4.2 A new interior gateway protocol feature

This section focuses on extensions to link-state routing protocols for the discovery and advertisement of LISP Mapping Service functions, especially the Map-Resolver and Map-Server LISP components within a domain. For example, such approach can use an extension of the Open Shortest Path First (OSPF) protocol. Such discovery allows for automatic operations of LISP networks.

Mapping Service reachability information is announced into the domain by a router that embeds a Mapping Service Function instance, or which has been instructed (by means of specific configuration tasks, for example) to advertise such information on behalf of a third party Mapping Service Function.

The proposed mechanism may be used to advertise and learn Mapping Service Functions that are available in the same administrative domain than xTRs. It can also be used to dynamically advertise related reachability information that is learned using other means when the Mapping Service Functions and xTRs do not belong to the same administrative entity.

To do so, a new Type-Length-Value (TLV)-encoded attribute, named the Mapping Service Function Discovery (MSFD) TLV, is defined. This attribute is carried in an OSPF Router Information Link State Advertisements (LSA). More details on the TLV attribute can be found in [105].

The location of each Mapping Service Function is then flooded into the routing domain, as represented in Fig. 5.3 (considering the case the LSA is AS-scoped).

The xTR routers deployed within the OSPF domain must listen to the flooding messages sent by active Mapping Service Function instances.

The information to be announced by means of the MSFD TLV carried in the LSA during the LISP Mapping Service Function Discovery procedure includes (but is not necessarily limited to):

- **Mapping Service Function type**: Indicates whether the MSF acts as Map-Resolver, Map-Server, or both.
- **Mapping Service Function Service locator(s)**: Includes one or several IP addresses. This information lists the set of locators that unambiguously indicate where the Mapping Service Function can be reached. The locator information must be included in the Mapping Service Function Discovery messages.
- **Mapping Service Function unavailability timer**: Indicates the time when the

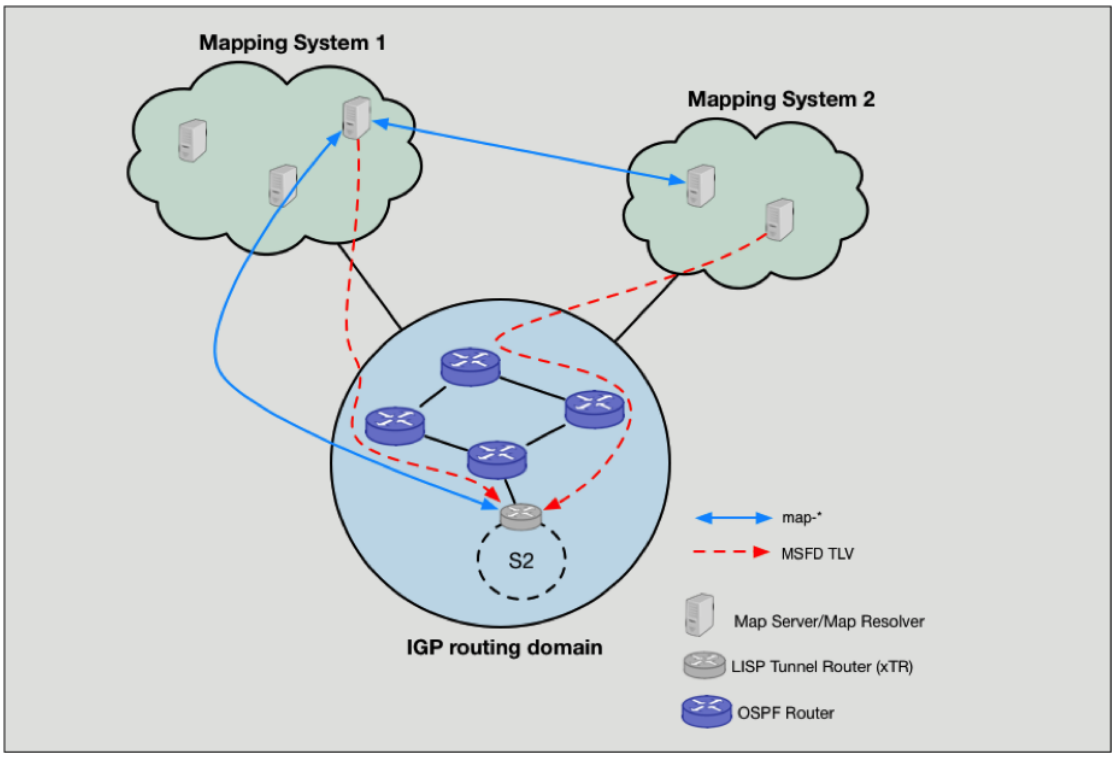


Figure 5.3: Discovering MS Components with OSPF.

Mapping Service Function will be unavailable. This parameter can be used for planned maintenance operations, for instance. This parameter does not provide any indication about when the Mapping Service Function instance will be available again.

- **Mapping Service Function reboot timer**: Operational teams often proceed with a reboot of the devices deployed in the network, within the context of major software upgrade campaigns, for example. This timer is used to indicate that a Mapping Service Function will be unavailable during the reboot of the device that supports the function. Unlike the previous timer, this timer is used to indicate that the Mapping Service Function will be available immediately after the completion of the reboot of the device that supports this function.

- **Mapping Service Function Diagnosis**: Indicates whether this Mapping Service Function instance supports a diagnostic mechanism.

- **Mapping Service Status**: Provides information about the status of the mapping database. In particular, it indicates whether the database is empty, synchronized with other MS servers located in the same OSPF domain, etc.

- **Mapping Service Function Status**: Indicates the status of the Mapping Service

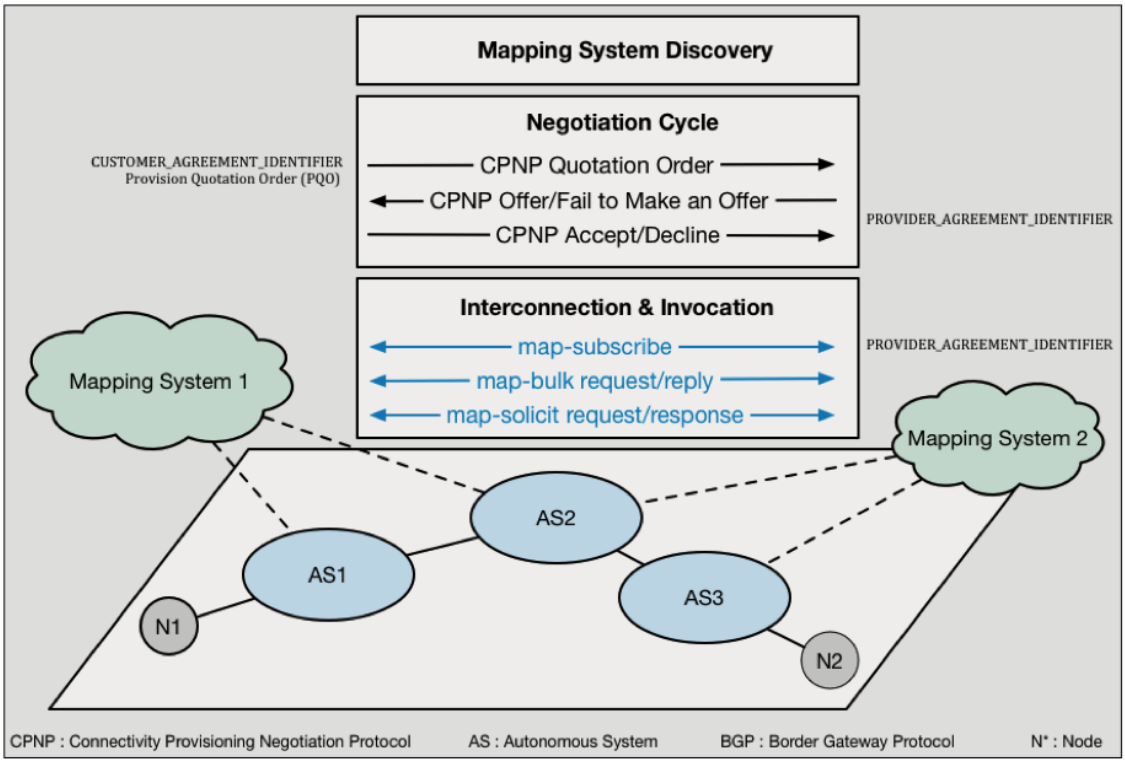


Figure 5.4: CPNP-based negotiation cycle and new LISP primitives used for the interconnection and invocation phases.

Function Instance (Enabled, Disabled).

All but the first two information items are optional and may therefore be included in the Mapping Service Function Discovery messages. Additional capabilities such as the support of mapping bulk retrieval or notifications may also be advertised.

5.5 Negotiation, interconnect and invocation

This section presents the proposed control plane extensions to support the negotiation, interconnection and invocation of functional blocks, as illustrated by Fig. 5.4.

5.5.1 Negotiation cycle

The proposal is to conduct the interMapping System negotiation cycle by means of CPNP (Connectivity Provisioning Negotiation Protocol) [106]. CPNP is meant to dynamically exchange and negotiate the connectivity provisioning parameters between two LISP Mapping Systems. CPNP is used as a tool to introduce automation in the negotiation procedure, thereby fostering the overall mapping service delivery process. CPNP can be used to

negotiate the parameters to connect two Mapping Systems or subscribe to services offered by a given Mapping System. For security reasons, an authentication session can be made before the negotiation begins. With CPNP, each agreement can be identified by a local identifier (the CUSTOMER_AGREEMENT_IDENTIFIER) assigned by a local Mapping System but also with a unique identifier (the PROVIDER_AGREEMENT_IDENTIFIER) assigned by a peer Mapping System.

CPNP accommodates both technical and business-related requirements. Indeed, it supports various negotiation modes, including administrative validation operations. In particular, CPNP adopts a Quotation Order/Offer/Answer model where: (1) the Client specifies its requirements via a Provision Quotation Order (PQO), (2) the Server makes an offer to either address the requirements of the PQO or suggests a counter-proposal that partially addresses the requirements of the PQO or declines the PQO, then (3) the Client either accepts or declines the offer. Fig. 5.4 shows typical CPNP negotiation cycles.

The PROVIDER_AGREEMENT_IDENTIFIER that is returned during the negotiation phase may be included in service invocation messages to ease correlating requests within a negotiation context (e.g., CPNP context). Particularly, the integration of the PROVIDER_AGREEMENT_IDENTIFIER in a Map-Request or a Map-Reply requires some modification to the message formats.

5.5.2 Novel control plane primitives

New LISP control plane primitives are defined to support the subscription and interconnection to Mapping Services, let alone their serviceability:

- Map-Subscribe/Map-Subscribe-Ack messages are exchanged between Mapping Services, possibly including a number of mapping filters that the Mapping Service could support to trigger notifications to maintain the entries of the mapping database; the mapping "filter" is a novel feature of the proposed control plane primitives. A filter is used to transport any useful information, like flow and AS identifiers, for instance.

- Map-Bulk-Request/Map-Bulk-Reply messages are used to bypass the limitation of current LISP control plane primitives as far as the dissemination of mapping information is concerned. They allow to query multiple EID-prefixes with a single mapping request message by exploiting the mapping filter. In practice, the whole mapping database can be retrieved by exchanging one Map-Bulk-Request and as many Map-Bulk-Reply.

- Map-Solicit-Request messages are used, in the proposed framework, to enhance the robustness of LISP networks during such ITR failure events. While recovering from

a failure, an ITR sends a Map-Solicit-Request to discovery other ITRs in the same routing domain. Upon receipt of the Map-Solicit-Request, another ITR replies with a Map-Solicit-Response message. With this process, the ITR has a list of peer ITRs, thanks to this Map-Bulk-Request/Reply signaling that runs between local xTRs to retrieve a copy of their mapping caches.

These features are detailed in [107, 108, 109]. It is worth mentioning that these novel control-plane primitives are not meant to replace existing basic LISP control plane primitives. Rather, they are meant to extend the LISP control plane behaviour in order to make LISP meeting the network management expectations of Internet Services and Network Providers more easily.

5.6 Experimental results

We implemented the Mapping System interconnect scheme described in the previous sections and evaluated it within the LISP-LAB experimental platform. This platform which runs its own mapping system, is connected to the 'LISP4.net' mapping system via DDT. We extended the LIP6-LISP OpenLISP control plane to support the new xTR features as well as and the relevant MS interfaces [8]. Moreover, the Quagga router implementation was extended to include the new TLVs in both BGP and OSPF daemons . Fig. 5.5 reports the time required to retrieve a mapping entry from the Mapping System in three scenarios:

- Proposed framework: the inter-domain mapping system framework as discussed in this chapter.
- Local network DDT root, i.e., the LISP-LAB DDT root, which is also the 'LISP4.net' DDT lambda root , located in LIP6, Paris.
- 'LISP4.net' DDT omega root, which is located in Barcelona.

About seven hundred mapping resolutions (i.e., Map-Requests followed by Map-Replies) were executed for each case during three days. The proposed framework uses two LISP sites, one in LIP6 facility, Paris, France, and another one in the LyonIX facility, Lyon, France. We also deployed three MRs located in LIP6; while the first one utilizes our proposed framework using a dedicated MS in LyonIX for handling mapping resolutions, the two others run the DDT protocol with the lambda DDT root located in the same LIP6 network for one MR, and with the omega DDT located in Barcelona for the other MR3. The ETR located in Lyon registers the same EID-prefix on the dedicated MS in Lyon, and on another standard MS in Lyon linked to the DDT roots.

For each measurement, the ITR in the LIP6 site sends the same Map-Request to the three MRs; we recorded the time when the Map-Request leaves the ITR, and the time when the Map-Reply message from the MS is received by the MR, hence computing the mapping resolution latency. Besides all MRs are put in the same LIP6 subnet, also the two MSs are put in the same subnet. Therefore, the difference in mapping resolution latency only depends on the time when the Map-Request leaves the MR, and the time when that Map-Request message is received by the MS.

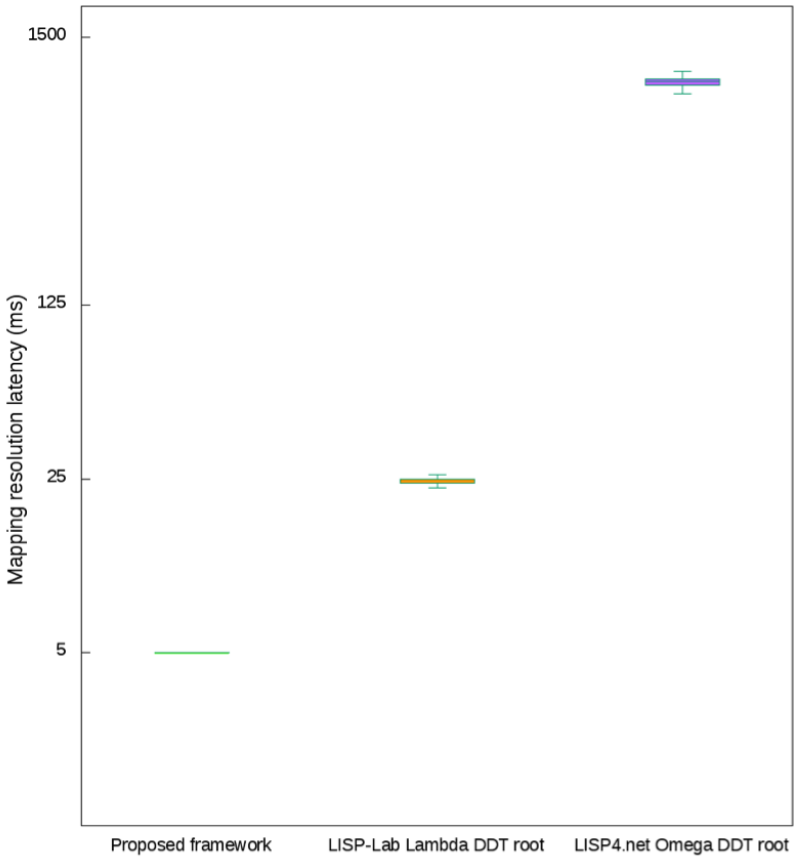


Figure 5.5: Mapping resolution latency results over the LISP-LAB testbed.

The results in Fig. 5.5 are in boxplot format, showing the three quantiles (collapsed in a single line using the logarithmic scale) and the minimum and maximum values. The results show that our framework can dramatically reduce the mapping resolution time, even compared to the resolution service provided by the local DDT root. An in-depth presentation of these experiments are further explained in a video tutorial .

5.7 Perspectives

LISP is a promising protocol to improve the forwarding of Internet traffic while mastering the growth of routing tables. Yet, LISP failed to be massively adopted so far, partly because of the operation of its Mapping System that may undesirably delay forwarding decisions at the cost of jeopardizing the performance of the LISP connectivity service.

This chapter discussed a framework to improve LISP operation at the Internet scale, by facilitating cooperation between LISP Mapping Systems and introducing more automation in the LISP connectivity service delivery procedure.

We believe such optimization could raise awareness among the service providers' community, yielding new business opportunities such as the monetization of LISP mapping services and the enforcement of advanced, service-inferred, inter-domain traffic engineering policies for the sake of better and strict QoS guarantees.

Chapter 6

Conclusions

The design and implementation of LISP control-plane extensions as well as novel LISP data-plane functions in support of Internet routing needs allowed us to conduct the experimental studies documented in this thesis. By means of empirical evaluations of our proposal, we could stress advantages as well as limitations of the LISP architecture, highlighting space of further applied networking research in the field. During our work, we attempted at performing reproducible research and at targeting integration of our proposals in realistic prototypes, making them scalable enough for large networks and trying to reach performances suitable for real deployments.

The novel LISP-based solution in support of live VM migrations across geographically separated datacenters over wide area IP networks showed that with our approach we can easily reach sub-second downtimes upon Internet-wide migration, even for very distant clients. These activities were also run in the frame of the NU@GE investissement d'avenir and FUI RAVIR projects, thanks to which our technology was transferred to Non Stop System, a SME that was active in the area of infrastructure-as-a-service provisioning.

About our work on cross-layer network optimization protocols, despite we could benefit from only a few overlay network nodes, we could experimentally evaluate our proposals showing the positive impact by using our overlay network, the negative impact of long RTTs on some MPTCP subflows, and the strong correlation between the differential RTT among subflows and the throughput performance. We are working toward the definition of advanced scheduling and buffer management techniques, on the line of the work described in [110], as well as the design of an advanced MPTCP scheduler taking into consideration subflow delays. These activities were lead in the frame of the LISP-LAB and European Institute of Technology (EIT) Digital and ICT-Labs projects. They have also recently lead to a collaboration with 21net, an SME active in the area of bandwidth aggregation for trains. We believe the proposed framework, leveraging on LCAF LISP-TE features, is

a more viable way than currently considered OpenFlow-based networks for inter-domain SDN operations, because of the partially distributed logic in forwarding rule configuration.

Finally, the third contribution, about the novel LISP mapping system interconnection architecture, was formulated in tight synergy with Orange labs. It is currently under discussion at the IETF. We believe such solutions could raise awareness among the service providers' community, yielding new business opportunities related to LISP mapping services and the enforcement of advanced inter-domain traffic engineering policies for the sake of better and strict QoS guarantees.

We traced in the corresponding chapters important perspectives for further research. It is worth mentioning the need for a tighter integration of LISP primitives in cloud stack and hypervisors for virtual machine mobility management, the possibility to define advanced MPTCP scheduler to cope with the large RTT variations one can experience at the Internet LISP scale, and the integration of mapping system interconnection primitives into provider network management systems, such as SDN systems.

In this respect, another activity recently started is the enhancement of the integration of LISP in ONOS [44]. This is expected to open many new possibilities of experimental research, namely in the field of multi-domain distributed network control.

Software contributions

We list in the following the open source code contributions developed and used for this thesis.

- LIP6-LISP data-plane - enhanced OpenLISP data-plane implementation, running in the kernel of the FreeBSD Operating System, including additional behaviors (PxTR, RTR) and the advanced features described in Chapter 4: `https://github.com/lip6-lisp/data-plane`.
- LIP6-LISP Control Plane - open source implementation of the LISP Control Plane, including advanced features described in Chapters 3-5: `https://github.com/lip6-lisp/control-plane`.
- Quagga-ext - an extended version of open source network routing software Quagga, to include the new TLVs in both BGP and OSPF daemons described in Chapter 5: `https://github.com/lip6-lisp/quagga-ext`
- ONOS LISP South Bound Interface (SBI) - Open source implementation of LISP as a southbound plugin for the ONOS controller, including the MS and MR behaviors: `https://wiki.onosproject.org/display/ONOS/LISP+Subsystem+Support`.

Publications

International journal with peer review

1. D. Phung Chi, S. Secci, D. Saucez, and L. Iannone. “The OpenLISP control-plane architecture”. In: *IEEE Network Magazine* 38 (2 2014), pp. 34–40

2. P. Raad, S. Secci, D. Phung Chi, A. Cianfrani, P. Gallard, and G. Pujolle. “Achieving Sub-Second Downtimes in Large-Scale Virtual Machine Live Migrations with LISP”. in: *IEEE Trans. Network and Service Managent* 11.2 (2014), pp. 133–143

International conferences with peer review

3. D. Phung Chi, M. Coudron, and S. Secci. “Internet Acceleration with LISP Traffic Engineering and Multipath TCP”. in: *Proc. of 21st Conference on Innovation in Clouds, Internet and Networks (ICIN 2018)* (February 2018)

4. D. Nguyen Ho Dac, D. Phung Chi, S. Secci, B. Felix, and M. Nogueira. “Can MPTCP Secure Internet Communications from Man-in-the-Middle Attacks?” In: *Proc. of 13th International Conference on Network and Service Management (CNSM 2017)* (November 2017)

5. P. Raad, S. Secci, D. Phung Chi, and P. Gallard. “PACAO: Protocol Architecture for Cloud Access Optimization”. In: 1st IEEE Conference on Network Softwarization (NETSOFT). Apr. 2015, pp. 13–17

6. Y. Benchaib, S. Secci, and D. Phung Chi. “Transparent Cloud Access Performance Augmentation via an MPTCP-LISP Connection Proxy”. In: *Proc. of 2015 ACM/IEEE Symposium on Architectures for Networking and Communications Systems (ANCS 2015)* (2015), pp. 201–201

7. P. Raad, G. Colombo, D. Phung Chi, S.Secci A. Cianfrani, P. Gallard, and G. Pujolle. "Achieving sub-second downtimes in Internet virtual machine live migrations with LISP". in: *Proc. IEEE/IFIP Int. Symposium on Integrated Network Management* (2013)

8. D. Phung Chi, S. Secci, G. Pujolle, and P. Radd P. Gallard. "An Open Control-Plane Implementation for LISP networks". In: *Proc. of 2012 International Conference on Network Infrastructure and Digital Content (IC-NIDC)* (September 2012)

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Submitted

10. M. Boucadair, C. Jacquenet, D. Phung Chi, and S. Secci. "Improving the Inter Domain Management of Locator/ID Separation Protocol (LISP) Networks". In: *IEEE Communications Magazine - Network and Service Management Series (submitted)* (2018)

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