# Overhead and Performance Study of the General Internet Signaling Transport (GIST) Protocol

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*Abstract*— **The General Internet Signaling Transport (GIST) protocol is currently being developed as the base protocol component in the IETF Next Steps In Signaling (NSIS) protocol stack to support a variety of signaling applications. In this paper we present our study on the protocol overhead and performance aspects of GIST. We quantify network-layer protocol overhead and observe the effects of enhanced modularity and security in GIST. We developed a first open source GIST implementation at the University of Göttingen, and study its performance in a Linux testbed. A GIST node serving 45,000 signaling sessions is found to consume small amounts of CPU and memory (on average 1.1ms for processing a signaling message and 2.4KB memory for a session). Individual routines in the GIST code are instrumented to obtain a detailed profile of their contributions to the overall system processing. Important factors in determining performance, such as the number of sessions, state management, refresh frequency, timer management and signaling message size are further discussed. We investigate several mechanisms to improve GIST performance so as to be comparable with an RSVP implementation.**

## I. Introduction

The Internet was designed to have simple packet forwarding nodes and complex end systems (where various applications are running over end-to-end protocols like TCP) [1]. However, over the years these design principles have been challenged by new application requirements and an evolving demand for the infrastructure [2]–[4].

With the explosive growth of the Internet, there is an ever increasing demand to provide configuration and maintanence of flow-specific control state in the network (i.e., signaling services) along the data path in IP-based networks. Examples include resource reservation for Quality of Service (QoS) provisioning and the configuration of various middleboxes such as stateful packet firewalls and Network Address Translators (NATs) [5]. Although the *Resource ReSerVation Protocol (RSVP)* [6], [7] has been developed, existing studies on RSVP have tended to focus more on QoS reservation models (initially IntServ [8], later DiffServ [9]) and their performance [10], [11], rather than the signaling services they essentially provide. Apart from this, shortcomings in the RSVP design e.g., a lack of solid security framework and mobility considerations have also played a role in diminishing its market appeal. Approaches like RSVP refresh overhead reduction extensions [12], BGRP [13], Yessir [14], Boomerang [15], Beagle [16], MRSVP [17], Insignia [18] or RSVP Mobility Support [19] investigate QoS signaling with the goal to reduce overhead, improve performance, or extend the signaling scheme to support mobility. These extensions are based on the idea of discovering QoS-aware nodes along the data path by using end-to-end addressed messages (mostly equipped with a Router Alert option) that deliver QoS parameters and rely on a flow identifier to select a signaling session state. In addition, protocol complexity has been issues especially due to the support for multicast flows [20]. These design principles have been a source of limited flexibility, security and mobility. More importantly, although these approaches individually may meet the needs of certain signaling purposes, they lack an extensible framework which allows easy extensions for future signaling applications. Thus, these approaches require a shift to a new *generic signaling* paradigm for IP networks. In turn, in 2001 the IETF formed a new working group, Next Steps in Signaling (NSIS) [21], to investigate the architecture and protocols for generic and application-specific signaling. One pioneering work has been presented by Braden and Lindell [22], who attempted to split RSVP into a two-layer architecture which allows any type of signaling application rather than being QoS centric.

Due to the shortcomings of RSVP and its current extensions, we have presented an alternative extensible signaling approach [23], [24] – *Cross-Application Signaling Protocol*, or *CASP* – for ensuring modularity, flexibility and security without changing the conventional path-coupled signaling paradigm. There are three key ideas that underpin our proposed approach: decoupling message transport from next signaling hop discovery, reuse of existing transport and security protocols, and the introduction of location-independent session identifier. This approach enables us to effectively support generic IP signaling that can be used for various signaling scenarios, with an enhanced protocol flexibility. The NSIS working group reused many ideas from CASP and is standardizing a *General Internet Signaling Transport (GIST)*[1] [25] as the base protocol component of NSIS protocol stack to support a variety of signaling applications.

In this paper, we study the protocol overhead and performance aspects of GIST and compare with RSVP, the preceding path-coupled signaling protocol. While some results are our implementation specific, we believe the tests and results should

[1] The protocol described here was known as GIMPS (General Internet Messaging Protocol for Signaling) until its final name was chosen in August 2005.

approximate some common behavior in other GIST implementations. The results confirm that GIST is meeting its major design goals. Our experience has been that implementation details are very important to achieve all of the benefits of GIST.

The organization of the paper is as follows. Section II provides a short introduction to GIST, Section III discusses the results of a study which indicate that the additional overhead in GIST are largely due to modularity and security. Furthermore, it delineates the limitations of QoS-centric approaches in providing generic signaling services. We then elaborate our GIST performance study and implemetnation details in Section IV. Section V concludes this paper.

## II. An Introduction to GIST

### A. NSIS: A Two-Layer Signaling Framework

In order to meet the requirements for an extensible, generic signaling protocol, the design of the NSIS protocol suite separates the transport functionalities (such as reliability, fragmentation, congestion control and integrity) for signaling message transport from signaling applications. Thus, following [22], [23], signaling functions in NSIS are split into two protocol layers [26]:

- An NSIS Transport Layer Protocol or NTLP, primarily composed of a specialized *messaging* layer, denoted as GIST [25], which is used to transport the *signaling application* layer messages. The GIST layer is running over standard transport and security protocols. Examples of such protocols are UDP, TCP, SCTP and DCCP, with or without IP security (IPsec) or Transport Layer Security (TLS) mechanisms; in the current version, usage of UDP, TCP and TLS over TCP are specified.
- NSIS Signaling Layer Protocols or NSLPs, each run signaling application-specific functionality. Examples of NSLPs include the QoS NSLP for resource reservation signaling [27] and the NAT/Firewall NSLP [28] for middlebox configuration.

The different layers are depicted in Fig. 1.

### B. GIST Overview

The GIST protocol, as described above, forms the fundamental building block of the NSIS protocol suite. The main task of GIST is to deliver signaling messages for various NSLPs between neighboring GIST nodes that support the same NSLP. The NSLP itself is responsible for pushing the signaling message from the NSIS Initiator (NI) towards the NSIS Responder (NR), typically the flow source and destination, respectively, as GIST just provides means to transport from one node to the next on the path. The NI and NR can, however, also be represented by proxies, e.g., to support end systems that do not themselves have NSIS capabilities.

Instead of building a new transport protocol, GIST reuses existing transport and security protocols to provide a universal message transport service. Like RSVP, GIST is a soft-state protocol. It creates and maintains two types of states related to signaling transport: a per-session message routing state (MRS) for managing the processing of outgoing messages, and a message association state (MA) for managing the per-peer state associated with connection mode messaging to a particular peer (signaling destination address, protocol and port numbers, internal protocol configuration and state information). In addition to its neighboring GIST peer information, GIST also maintains certain message routing information, such as flow identifier (flow ID), NSLP type and session identifier (session ID), to uniquely identify the signaling application layer session for a flow.

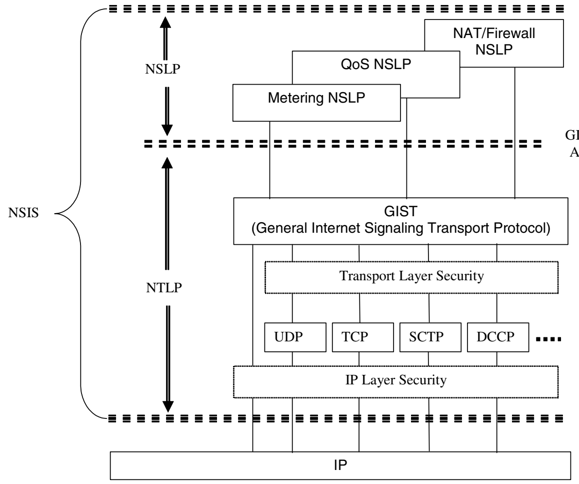


Fig. 1. NSIS: a Two-layer Signaling Framework

GIST has two modes of operation: the *datagram mode (D-mode)*, which uses an unreliable unsecured datagram transport mechanism, with UDP as the initial choice; and the *connection mode (C-mode)*, which uses any stream or message-oriented transport protocol (currently TCP as the initial choice) and may use IPsec security or Transport Layer Security (TLS). It is possible to mix these two modes along a chain of nodes, without coordination or manual configuration. This allows, for example, the use of D-mode at the edges of the network and C-mode in the core of the network.

Let us have a look at a standard GIST operation using an example (cf. Fig. 2), where A is QoS NSLP while B is another type of NSLP). Assume a QoS NSLP message is generated by GIST at the NI (the flow sender). The GIST module first constructs a GIST-query message, namely a UDP datagram addressed to the flow destination and includes an IP Router Alert Option [29] (similar to RSVP). The next downstream NSIS peer which supports QoS NSLP (R2) recognizes this message and replies to it with a GIST-Response message. Upon the receipt of this response, the NI creates a message association with R2, upon which allows all subsequent GIST-Confirm or GIST-Data messages (i.e., GIST messages with NSLP payload) between these two peers to be sent. Upon receipt of such GIST messages in R2, NSLP payload and the flow ID are passed to its QoS NSLP processing. Note it is the responsibility of the NSLP layer to determine the action upon recept of a GIST message. In this example, the QoS NSLP payload is delivered (likely after modification in intermediate nodes) until the NR.

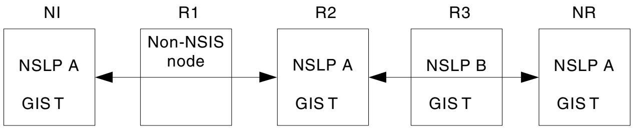
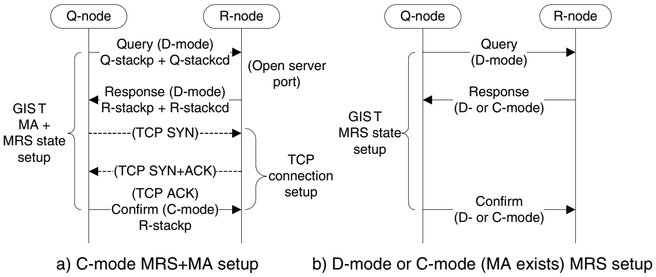


Fig. 2. An example of GIST operation

A GIST message consists of a common header and a sequence of type-length-value (TLV) objects. The common header indicates the message type (Query/Response/etc.), as well as the NSLP ID and hop counter to avoid message loops. In addition, GIST can use query- and response-cookies for protection against spoofing and denial of service attacks.

GIST-Query messages are back-off retransmitted exponentially if a corresponding GIST-Response is not received on time. Other NSLP messages encapsulated in D-mode are not retransmitted; they rely on initial GIST-Query messages that are eventually resent. Whenever possible, re-use of existing reliable transport and security protocols is recommended via the C-mode in GIST. This is necessary with larger data objects, when a fast state setup in the face of packet loss is desirable, or where channel security is required. A querying node (Q-node) can choose to refresh the message routing state by resending a GIST-Query. Local policy can determine whether it is necessary to maintain a messaging association (e.g., a node may choose to keep it open if there are sessions still in place, which might generate messages that would use it). If no MA exists between a Q-node and the responding node (R-node), and the Q-node desires to run over C-mode, it will send a Query with a stack proposal and stack configuration data to negotiate (on the desired C-mode transport protocol, e.g., TCP, TCP+TLS) with the R-Node during the discovery phase (see Fig. 3(a)); TCP three-way handshake is required to setup MA.



a) C-mode MRS+MA setup

b) D-mode or C-mode (MA exists) MRS setup

Fig. 3. GIST session setup

A detailed GIST protocol description can be found in [25] and its corresponding state machine operations are described in [30].

### C. GIST Security

Security mechanisms for GIST try to provide the following properties:

1) Authentication of the two neighboring protocol peers;
2) Security association establishment to provide integrity, confidentiality and replay protection for signaling messages exchanged between these entities;
3) Denial of service protection;
4) Some security protection for the discovery mechanism.

It is difficult to design a new security protocol to address all these issues. Existing security protocols (such as TLS or IKEv2/IPsec) already provide a number of these features, such as properties 1), 2) and 3), but at the cost of considerable setup latency. The establishment of a secure channel between signaling peers to protect all signaling messages (which can belong to any signaling session), is recommended. This in turn limits the per-session security association setup cost in C-mode. When the GIST discovery mechanism is used to address only the peer that supports the desired NSLP (e.g., QoS NSLP), then GIST establishes a messaging association with the next (QoS) NLSP node, if C-mode is desired and available.

Authorization at the GIST layer aims to ensure that a GIST R-node only establishes communication with a legitimate GIST Initiator. It is even more difficult to ensure that the GIST Initiator sends signaling messages to the "right" GIST peer (which supports a specific NSLP); this requires authorization information to be provided along with the authentication and key exchange process (e.g., as part of the authorization certificate). These aspects are described in [31].

Relaxing assumptions regarding the desired protection against man-in-the-middle adversaries might often be required and desired. Furthermore, in most cases it is difficult for GIST to make an authorization decision without consulting the NSLP layer.

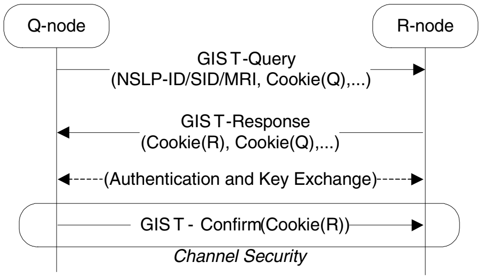

Q-node
R-node
GIST-Query
(NSLP-ID/SID/MRI, Cookie(Q),...)
GIST-Response
(Cookie(R), Cookie(Q),...)
(Authentication and Key Exchange)
GIST - Confirm(Cookie(R))
Channel Security

Fig. 4. Protection of the GIST discovery procedure

In order to deal with adversaries that redirect signaling messages, the cookie mechanism has been integrated into the discovery exchange. This mechanism (see Fig. 4) can be illustrated as follows. The cookies provided by the querying and responding node (Cookie(Q) and Cookie(R)), e.g., 256-bit cryptographically random nonces, are used to prevent DoS attacks. This is similar to those used by other protocols (e.g., SCTP or IKEv2). Cookie(Q) is included in the GIST-Response message to prevent off-path adversaries from flooding the querying node with bogus responses. The initiator uses this cookie to match a request with a pending response. Once a security association has been established, Cookie(R) is transmitted from the querying node to the responding node. This allows the responder to verify that it has actually participated in the discovery exchange, binding the discovery procedure to the subsequent exchange. The authentication and key exchange process in Fig. 4 is described in the GIST specification but the exact cookie data is not yet defined.

## III. Protocol Overhead

Every signaling protocol imposes some overhead in the form of number and size of control messages, which is indicative of the total bandwidth consumed by the signaling protocol and must be processed in signaling-aware nodes. In this section we discuss the sources and quantities of protocol overhead in GIST as opposed to RSVP. For convenience we consider the primary signaling messages used for state setup and maintenance: GIST-Query, Response, Confirm and GIST-Data in comparison with RSVP-Path and RSVP-Resv; RSVP/GIST Error, MAHello and RSVP PathTear/ResvTear messages are omitted here for simplicity.

The detailed sources of overhead (including message and memory overhead) in each of the layers of a GIST protocol structure (based on the latest draft version of [25]) are given in the Appendix, in comparison to RSVP. Table I summarizes the overall message overhead for involved message types.

With this information we are able to analyze the overhead of the two signaling protocols, GIST and RSVP. On the one hand, layering in GIST makes it possible to provide the general functionalities required for signaling transport, namely,

- Error control: GIST makes the "channel" more reliable (by reuse of reliable transport protocols);
- Flow control: GIST avoids flooding slower peer by signaling message flow control,
- Fragmentation: Dividing large data chunks into smaller pieces, and subsequent reassembly (e.g., TCP MSS fragmentation/reassembly for large sizes of NSLP payload),
- Multiplexing: Allow multiple sessions to share a single message association between adjacent peers,
- Connection setup: Handshaking with peer (e.g., by TCP three-way handshake).

More importantly, GIST provides richer security support, which makes it easier to support mobility and allows high modularity to allow any signaling applications with a comparable requirement for state repository.

On the other hand, layering and more functionality support increase message and memory overhead. For example, if C-mode is desired, there are at least two possibilities for GIST session setup with minimal security support (i.e., only cookie mechanism is used):

1) There is no TCP connection. This requires a GIST-Query(with stack proposal)/(TCP-SYN/TCP-SYNACK) /Response/Confirm process, which in turn imposes 176+44+44+220+188=672 bytes message overhead, in addition to the memory overhead for a new TCB/TCBI state [55], [56], a new GIST message routing state and a new GIST message association state.
2) Message association already exists. This requires a GIST-Query(no stack proposal)/Response/Confirm process, which imposes 144+188+188=520 bytes message overhead, in addition to update of TCB/TCBI state and a new GIST message routing state.

Thus, for signaling session setup, GIST C-mode requires 4 (or 3, when MA already exists; same applies below respectively) messages, totally 672 (or 520) bytes overhead, for the scenario where no TCP connection exists (or MA exists).

With GIST D-mode, no connection setup is required, but three-way handshake in GIST layer is still needed, imposing 144+176+136=456 bytes message overhead, in addition to the creation of per-session GIST MRS and update of per-peer MA+TCP connection state.

With RSVP, on the other hand, every session setup requires a Path+Resv pair 52+72=124 bytes (for Controlled-Load Service) / 52+108=160 bytes (for Guaranteed Service) message overhead, in addition to creating a new PSB and a new RSB.

For convenience we assume a (QoS) NSLP payload is the same as RSVP, e.g., Controlled-Load Service Flowspec of size 36 bytes, omitting the QoS NSLP header. According to this "example" NSLP is limited to 25% (or less, for the session initialization phase) of the whole GIST-Data message in an IP environment, and most of the protocol overhead result from the lower levels of the protocol stack.

This comparison demonstrates that GIST's rich functionality, modularity, security, and mobility support is also accompanied by certain costs. Indeed, similar to other general-purpose protocols, GIST does have its disadvantage of higher protocol overhead in terms of large messages, more message exchanges, additional parsing and processing. However, as we will show in Section IV-C, with some appropriate implementation considerations and optimizations, it is possible to reach a signaling performance in terms of maximal number of supported sessions, CPU and memory consumption in steady state comparable to existing RSVP implementations. Furthermore, it should also be noted that in many scenarios signaling application payloads are rather large (which can easily exceed normal link MTU), e.g., certificates and active programming packets, where the transport capability of GIST becomes of greater use and the relative GIST protocol overhead becomes much less. In addition, concepts of staged timers [12], [32] and state compression [33] can also be considered.

## IV. Implementation and Performance Evaluation

In this section, we evaluate the quantitative performance of a GIST implementation through benchmarks, and show its performance is roughly comparable to KOM RSVP [11], and scales well with the number of signaling sessions.

TABLE I

OVERHEAD BY PROTOCOL LAYER (IN BYTES)

| Message type\Protocol layer | IP layer | Transport layer | GIST layer | Overall overhead |
|---|---|---|---|---|
| GIST-Query (no stack proposal) | 24 (IPv4), 48 (IPv6) | 8 | 112 (IPv4), 152 (IPv6) | 144 (IPv4), 208 (IPv6) |
| GIST-Query (with stack proposal) | 24 (IPv4), 48 (IPv6) | 8 | 144 (IPv4), 184 (IPv6) | 176 (IPv4), 240 (IPv6) |
| GIST-Response (D-mode) | 20 (IPv4), 40 (IPv6) | 8 | 148 (IPv4), 188 (IPv6) | 176 (IPv4), 236 (IPv6) |
| GIST-Response (C-mode, no stack proposal) | 20 (IPv4), 40 (IPv6) | 20 | 148 (IPv4), 152 (IPv6) | 188 (IPv4), 212 (IPv6) |
| GIST-Response (C-mode, with stack proposal) | 20 (IPv4), 40 (IPv6) | 20 | 180 (IPv4), 184 (IPv6) | 220 (IPv4), 244 (IPv6) |
| GIST-Confirm (D-mode) | 20 (IPv4), 40 (IPv6) | 8 | 108 (IPv4), 148 (IPv6) | 136 (IPv4), 196 (IPv6) |
| GIST-Confirm (C-mode) | 20 (IPv4), 40 (IPv6) | 20 | 108 (IPv4), 148 (IPv6) | 188 (IPv4), 208 (IPv6) |
| GIST-Data (D-mode) | 20 (IPv4), 40 (IPv6) | 8 | 72 (IPv4), 116 (IPv6) | 100 (IPv4), 164 (IPv6) |
| GIST-Data (C-mode) | 20 (IPv4), 40 (IPv6) | 20 | 72 (IPv4), 116 (IPv6) | 112 (IPv4), 176 (IPv6) |
| (TCP-SYN/SYN+ACK) | 20 (IPv4), 40 (IPv6) | 24 | – | 44 (IPv4), 64 (IPv6) |
| (TCP-ACK) | 20 (IPv4), 40 (IPv6) | 20 | – | 40 (IPv4), 60 (IPv6) |
| RSVP-Path | 24 (IPv4), 48 (IPv6) | 0 | – | 52 (IPv4), 76 (IPv6) |
| RSVP-Resv (Guaranteed Service) | 20 (IPv4), 40 (IPv6) | 0 | – | 108 (IPv4), 144 (IPv6) |
| RSVP-Resv (Controlled-Load Service) | 20 (IPv4), 40 (IPv6) | 0 | – | 72 (IPv4), 108 (IPv6) |

### A. Implementation Overview

We have implemented the GIST protocol in C++, using Linux 2.6 kernel. Our implementation is fully conformant to the GIST protocol and its API (currently, support draft version 08 [25], except for some open issues like NAT, tunneling and detailed mobility support). We have developed a benchmarking NSLP application ("Ping") [34] for testing purposes. The implementation consists of about 6900 lines of code in total, which comprises about 1300 lines for the core program, 2000 lines for state machines, 700 lines for state management, 1400 lines for message parsing and processing, and 1500 lines for the GIST-NSLP API. The code is publicly available in [35].

The implementation architecture is shown in Fig. 5. It is currently based on a single process approach using a main event loop based on XORP [36] library, which is used to implement socket maintenance and callbacks as well as timer callbacks. This design has no additional overhead for maintaining and synchronizing multiple threads, which results in a high throughput and a rather simple implementation.

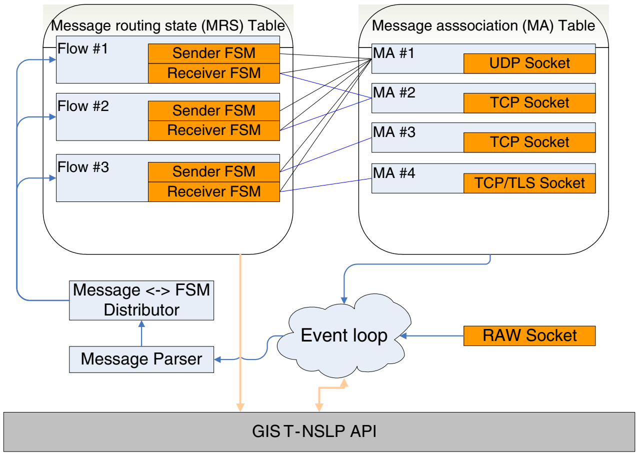


Fig. 5. Implementation Architecture

Besides the event loop, a key component in GIST implementation is state management. In order to support tens of thousands of signaling sessions efficiently, we used a hash table to manage the MRSs, associated with linked lists to resolve conflicts. A standard lookup takes constant time, however in the worst case, all table entries would be compared to find a given MRS.

To search the MRS table, one needs to know the associated key information, namely the session ID, the NSLP ID and message routing information (MRI). This is nevertheless subject to some limitations, e.g., it is not possible to search for all MRSs using a specific MRI. Such a search feature may be useful to find MRSs that are affected by a detected link failure. A possible solution is to maintain specialized hash tables for link failures, which would allow for quick searches. However, this approach would add maintenance overhead to every MRS table (which usually comprise a number of tables) operation.

In addition to managing MRSs, a GIST implementation has to manage MAs for C-mode operations. If two peers already have an MA and a new session is being established on the same path, the MA should be reused to minimize resource usage. This feature implies that there should be a way to search the MA table for an MA that can be reused for a certain session. Our implementation uses a second hash table to accomplish that goal. The upstream peer information (PI) serves as the key information. The UDP socket is treated as a "virtual" MA for the convenience of unifying the socket interface module.

Another important component of the GIST implementation is the finite state machine (FSM) to maintain states for each session. We implemented the GIST FSMs [30] based on a combination of the XORP timer class and an FSM framework that was originally written for the Linux ISDN device driver [37]. Every MRS is associated with two FSMs, one for the upstream peer and another one for the downstream peer. There is no need for a global table of FSMs, because every MRS provides pointers to the associated FSMs. In addition, every MA has a list of FSMs which it is associated with, so that the state machines can be informed e.g., when a loss of connectivity with its current peer takes place.

### B. Testbed Setup and Tools

The performance experiments were carried out on 6 low-end PCs running Linux 2.6.8.1. They are equipped with the following hardware:

- Via Eden CPU 533 MHz
- 3 Realtek 100 Mbps NICs
- 256 MB SDRAM PC 133
- 20 GB HDD

Fig. 6 depicts how we connected the nodes for our experiments. $N_1$ and/or $N_2$ was used as the sending host(s) – NI(s), while $N_3$, $N_4$ or $N_5$ were the flow destination(s) – NR(s). In addition to the benchmarking tool "Ping", we have also developed an Ethereal GIST dissector [38] for monitoring the GIST messages.

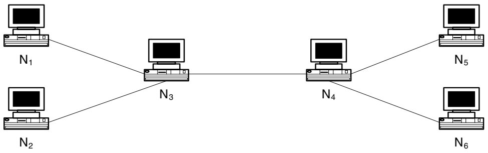


Fig. 6. Testbed Setup

The Ping tool is a light-weight NSLP protocol that sends so-called Ping messages through a GIST aware network. The traversed nodes insert a timestamp and information about the local node (i.e., the IP address). When the message reaches its destination host, it is redirected upstream and traverses the network back to the original sender.

We use this tool in our experiments to model the scenario of a real NSLP application without introducing unnecessary overhead. Our main goal was to measure the maximal number of sessions a backbone router can maintain. In addition, the tool was intentionally designed to involve other aspects a real NSLP application would likely require, including:

- GIST layer session lookup;
- GIST layer session refreshes;
- Communication between GIST and the NSLP layer;
- NSLP layer message processing.

In order to accomplish these goals, we disallow both maintaining timers for the NSLP application and storing NSLP layer state, but allow the sending node to send a Ping message for each session every 30 seconds in order to simulate NSLP behavior (this message can be regarded as a refresh message in the NSLP layer). As a result, we were able to use this tool to study the GIST performance and scalability. It is expected that a real NSLP application would have additional overhead (including timers, parsing and state management, all in NSLP layer), resulting in some worse results in terms of round trip times and maximal number of sessions that can be maintained at a time.

A simple PHP script measures the CPU and memory utilization every second using the proc-filesystem entries, in the same fashion as the popular *top* program. After completing the test, the script uses the debugging component of the GIST implementation to fetch internal statistical information like the average number of entries in the used hash table buckets.

To calculate the round trip times (RTTs), the information contained in every Ping message is saved on the sender and after the test is completed the collected timestamps are used to calculate the round trip times.

### C. Performance Study

*1) Scalability in Number of Sessions:* As signaling protocols maintain and manage soft state in network nodes, the most critical performance metric for GIST is the upper limit on the number of sessions a GIST node can maintain. Additionally, we would like to evaluate how the CPU load and memory consumption scale with an increasing number of concurrent sessions. Other parameters like average RTTs were collected too. We performed three experiments for this test.

In the first experiment, we used $N_1$ as the NI and $N_3$ as the NR, and let the NI first established a configured number of sessions and then emulated refreshes for all of them and measured performance of $N_3$. The refresh intervals for NSLP and GIST MRS were set 30 and 180 seconds, respectively.

The results are shown in Fig. 7-9. The first observation is that the increase in CPU load and memory consumption is nearly linear. The consumption of CPU time reached 70% (C-mode) – 71% (D-mode) of the whole system when serving 60,000 sessions at a same time in our test.

The second observation is that the RTTs were very small (4.8-5.2ms) before the session number reaches 50,000, increase to 56.2ms when serving 55,000 sessions, then increase rapidly afterwards, reaching 7.0 seconds when serving 60,000 flows, indicating approaching the exhaustion of system resources (memory/CPU/interface) in network nodes.

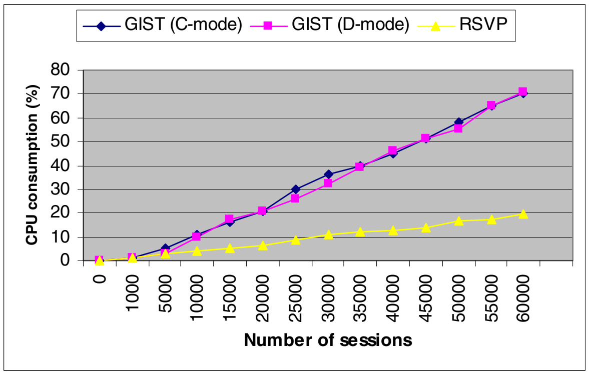


Fig. 7. Effect of different session number on CPU consumption

In the next experiment, we studied the case where two senders ($N_1$ and $N_2$), one intermediate node ($N_3$), and one receiver ($N_4$) were involved. NSLP refresh interval was 30 seconds, and GIST refresh rate was 180 seconds. We let each of senders serves 30,000 sessions, so receiver had to handle 60,000 sessions. The measured RTT turned out to be about 5.5ms. This confirms that the bottleneck for RTT in the tests above is the sender and not the receiver.

Based on these observations, we obtain a rough estimation of the upper limit of the supported session number in a GIST

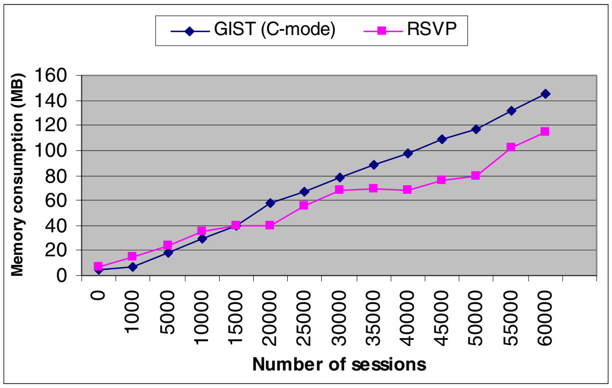


Fig. 8. Effect of different session number on memory consumption

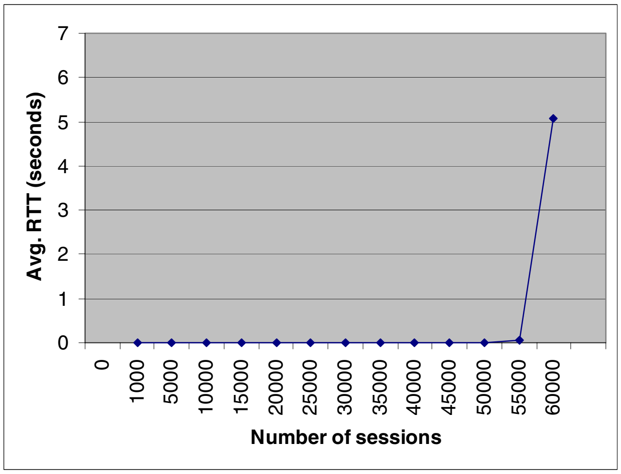


Fig. 9. Effect of different session number on average RTT

node, which is at least 60,000. This may be improved by introducing a thread pool based architecture, which is planned as a next step for the implementation and other optimizations, such as the ones suggested in Section IV-D.

Another experiment we performed was to measure the approximate processing time (i.e. the time difference from incoming to outgoing message) required for a GIST message in an intermediate node. Taking both the $N_1$ and $N_2$ as the flow receiver and using ethereal dissector, we performed tests for 20,000 and 60,000 simutaneous GIST sessions in steady state, respectively.

In the light traffic cases (20,000 sessions), the results show that the average processing time for GIST-Query and Response messages was very small, about 0.25 ms, whereas a GIST-Data (carrying Ping NSLP) message took the average processing time of 1.1 ms. This is conformant to the RTT results obtained in Section IV-C.1.

In the second set (the more heavy-load traffic case), the processing time for Query/Response increased to 0.9 ms, whereas for a GIST-Data message it increased to 20 ms. This confirms our observation in the first experiment, namely when entering the heavy load traffic range, RTT is starting to be much larger than the ligh traffic case.

We also did performance tests of a recent RSVP implementation, the KOM RSVP engine [11] in the same testbed and PC hardwares. The results are also shown in Fig. 7-9 and we could conclude that we obtained roughly comparable results. After fine tuning of the environment for running KOM RSVP[2], we observed that KOM RSVP grows slower for CPU consumption with session number increases: when serving 60,000 simultaneous sessions, KOM RSVP just needed about 20% of CPU time, in comparison with 70%. This difference demonstrates certain properties of implementation-specific design and the testing environment, for example: 1) the use of XORP timer turned out to consume 50% of the overall CPU usage in our GIST implementation, while the fuzzy timer approach allowed KOM RSVP to manage timers more efficiently [11], 2) in order to reach high signaling loads, we did not change anything to the system environment, while KOM RSVP has to be deliverably tuned by disabling other network applications. On the other hand, the required memory for KOM RSVP was found to be rather similar to that for GIST: it was just 20% less than GIST C-mode when both serving for 60,000 simultaneous sessions; for small numbers of sessions (less than 15,000), it required even more memory than our GIST implementation. This is due to our introduction of optimizations (see Section IV-D).

With further optimization of the GIST implementation we anticipate the performance result will be closer to KOM RSVP.

*2) Analysis of Session Setup Time:* When GIST is used in a real application (not just a Ping client), a critical metric is the time required to finish the first signaling round trip (e.g., a QoS reservation). This involves the GIST 3-way handshake for every hop-to-hop connection that is performed sequentially, which could result in a rather long initial setup delay. Our measurements show that this delay was between 3ms and 5ms for D-mode or C-mode scenarios when an existing message association can be reused. The number of sessions for this measurement ranged between 15,000 to 25,000.

*3) Impact of GIST Message Routing State Refreshes:* The main responsibility of GIST is to manage the MRSs and MAs which are used in delivering NSLP messages from one peer to another, where both states are soft states. We study the effect of MRS state refreshes since MA state refreshes by periodically GIST-Hello messages are not necessary if there are some active signaling messages between the peer pair.

We chose 30 seconds as NSLP refresh interval and ran tests under different refresh intervals for an overall number of 15000 GIST sessions between $N_1$ and $N_3$, all links operating on C-mode.

The measured CPU load in $N_3$ are summarized in Table II.

This indicates a small refresh interval at GIST level only introduces CPU load. Given the reliability properties of C-mode, a relatively long refresh interval (e.g., 180 sec) at

[2] In our tests it turned out KOM RSVP could not support more than 10,000 sessions without closing other network applications

TABLE II

IMPACT OF GIST MESSAGE ROUTING STATE REFRESH INTERVAL ON CPU LOAD

| Refresh interval (sec) | % of CPU load used by GIST |
|---|---|
| 30 | 56% |
| 60 | 47% |
| 90 | 43% |
| 120 | 42% |
| 150 | 41% |
| 180 | 40% |
| 210 | 40% |

GIST level for MRS maintenance which impose limited CPU overhead should be enough, especially where route changes are not frequently experienced.

We performed some more tests where all the 6 nodes in the testbed were involved, and the results demonstrated similarly. A stably low CPU load in intermediate nodes was observed when the GIST MRS refresh interval was set about 180 sec (also the reason why we selected this value as default refresh interval in other tests).

*4) Per-routine Processing Time:* In order to study the bottlenecks of the implementation, we performed profiling for each individual routines in the GIST code, using the *gprof* tool. Table III shows the profiling results for each routine's contributions to the overall system processing. It reveals that the XORP library consumes over half of the total running time, mostly for managing XORP timer facilities. The reason is that XORP uses a sorted heap to structure the timers – a more detailed profile shows that maintaining this heap consumes up to 38 percent of the overall runtime of our implementation. This is due to the fact that, while adding and removing a heap element imposes a time complexity of *O(*$\log(n)$*)*, the heapify algorithm costs *O(*$n\log(n)$*)*, where $n$ is the total number of timers.

TABLE III

RUNTIME PROFILES OF THE IMPLEMENTATION

| Code component | % of total running time |
|---|---|
| 1. XORP | 53% |
| 1.1 XORP timer | 42% |
| 1.2 XORP socket container | 10% |
| 2. Receiving incoming message | 8% |
| 2.1 Receiving and distribution to FSM | 4% |
| 2.2 Message parsing | 4% |
| 3. Message composing and internal reading | 17% |
| 4. Hash tables (MRS and MA) | 8% |
| 5. Finite state maschine | 7% |
| 6. NSLP level processing (ping) | 1% |
| 7. Miscellaneous | 6% |

In the next step we plan to switch from using XORP for maintaining timers to implementing the more efficient concept of *timer wheels* based on [39] (which is also used by the KOM RSVP implementation [11]). In such a timer wheel individual timers are maintained in a hierarchical container. The upper layer consists of slots and inside the slots a sorted list of timers is maintained. The access complexity in a normal heap is *O(*$\log(n)$*)*, where $n$ is the overall number of timers. Sorting timers in the slots is comparable to a hash table and so the access complexity when using a timer wheel is *O(*$\log(m)$*)* where $m$ is the (varying) number of timers in a slot. If a reasonable number of slots is used, the reduction in access complexity can be eminent.

*5) C-mode versus D-mode:* GIST is capable of operating in both C-mode and D-mode. so that the difference in CPU load between both modes of operation is of interest. We implemented C-mode in both TCP and TLS/TCP but the evaluation here focuses on using TCP as transport.

Fig. 7 shows the CPU load for a different number of maintained sessions in C-mode and D-mode. From this figure we can conclude that the CPU load does not make much difference from each other.

Given that TCP offers a number of transport features desired for signaling protocols, as outlined in Section III, the above result suggests that C-mode should be used as much as possible instead of D-mode for GIST message transport.

### *D. Performance Optimizations*

During the performance experiments we introduced several optimization techniques and thus were able to significantly reduce the CPU load of our implementation. The first optimization was to reduce data copying between processing routines. When designing an object oriented implementation, the tendency is to design every class with its own copy of the data to ensure integrity. Network protocol implementations, however, cannot afford to waste CPU and memory resources. As a result, ideally there should be just one copy of every incoming and outgoing packet and all code parts should use pointers to the part they want to use. The zero-copy approach, which was not yet fully implemented in our code, reduced CPU load by about 20 percent.

Another performance bottleneck was found to be a poor design of the implemented hash table – initially we used the standard hash function, where 1 byte array as the hash key and dense size in rehash turned out to be very computation consuming. The hash function used now is still simple but efficient: The key is treated as a 4-bytes array and the hash value is the sum of the values in the array reduced modulo the hash table size. Let $k_1$, $k_2$, …, $k_n$ be the values of the integer array and $p$ be the hash table size. Then the (current) hash function is given by:

$$hash(k) = (k_1 + k_2 + \ldots + k_n)\ mod\ p$$

This results in a possible output range of values from 0 to $2^{32}-1$. The original hash function based on an array of 1 byte values, in contrast, results in a very limited range of output values, because all the $k_i$ are just in the range of 0 to 255 and a typical number of bytes is 16, resulting the range of the hash function was 0 to 4080. This means that a huge part of a large hash table was never used and so the distribution along the range was not uniform.

The hash table is rehashed with a higher hash table size whenever the load factor exceeds a certain limit (i.e., 0.5). The load factor is given by:

$$load\ factor = \frac{stored\ elements}{hash\ table\ size}$$

Originally, the list of supported hash table size was dense, which resulted in the need to rehash very often. The solution was to rapidly increase hash table sizes exponentially (i.e. the hash table size is more than doubled from one value to the next) to quickly achieve the necessary size while minimizing rehashing turns, which turned out very effective.

By optimizing the hash table, the average number of items in one hash table bucket was reduced by one magnitude and the overall GIST performance increased by approximately 20 percent.

The most important optimizations discussed above were also accompanied by less significant changes. Some functions were called several million times within a few minutes of operation, which resulted in a large amount of overhead. Using the *inline* statement to integrate the function body directly into the calling code reduced this overhead and the performance gain was up to 10 percent of overall performance. In current implementation, some small code optimizations, reducing readability but improving performance, were carried out in frequently used code sections.

These optimizations cut CPU load by half by incorporating the well-known principle of zero-copy and optimizing central data structures and frequently used code parts. As already mentioned in the above subsections, further optimizations in memory and timer management and introduction of thread pooling ought to contribute to more promising results.

## V. Related Work

Over the last decade, various issues for signaling in the Internet, especially for QoS resource reservation, have been widely investigated, They have ranged from soft state modeling [40], [41], scalability enhancements (e.g., by reservation aggregation and more efficient refreshes) [13], [42]–[44], to complexity [14]–[16], [20] and applicability [45]–[47], and have used either a server-based or a router-based approach to simplify or extend RSVP (even under other protocol names). For example, currently there are 31 RFCs with the word "RSVP" in their titles, while the index of Internet drafts lists 16 documents with "RSVP" in their titles. A server-based approach relies on centralized entities (known as "bandwidth brokers") to perform admission control, while the router-based approach installs packet filters either on a per-flow or aggregated basis in a hop-by-hop way. Although there has been much focus on modularity for specific QoS or multicast models (e.g., [48]), generic signaling support has acquired little focus. Furthermore, the dominant way of using the Router Alert Option and coupling discovery with discovery have lead to a number of security and complexity problems [20], [49].

Recently, several authors have addressed modular design, using either an RSVP-based or a CASP-based approach. In RSVP-based approaches, RSVP has been extended using an extra reliable mechanism [46] and general signaling support. This approach removes the QoS- and multicast-specific processing burden from the original RSVP, and has the advantage of better compatibility with existing protocol and implementations. Nonetheless, issues concerning security, congestion control and fragmentation of signaling messages may be more complex. No simple solution is available and RSVP still has to deal with these issues, since RSVP encapsulates its messages using raw IP or UDP, and couples PATH signaling with next-hop discovery. Variations of the RSVP-based approach have been described in [22], [50]. The latter proposal suggests a decomposite system where a signaling message is just sent to next CASP hop (discovered by some next-hop discovery mechanism) using an existing transport protocol which provides capabilities such as fragmentation, congestion control, and easier security when desired. Both proposals, however, leave the actual mechanism undefined. The present GIST design has followed many ideas of the CASP-based approach and reuse RSVP concepts whereever possible [25]. Nonetheless, the tradeoff between performance, security, complexity and modularity is still an issue in both approaches. Fault recovery, especially in dealing with rerouting [51] remains one major concern in the layered architecture.

These studies have been accompanied by some works on performance evaluation, in particular with RSVP. For example, Chiueh *et al.* [10] reported an empirical study of RSVP, which measured performance of a Cisco RSVP-capable router, including RSVP control packet latencies (under loaded and unloaded cases) and throughput impact delivered for QoS objectives. Pan *et al.* [14], [32], [52] extensively studied processing performance and scalability issues of RSVP and possible protocol improvements. Karsten *et al.* [11] implemented a user-level RSVP protocol engine (which allows multi-threading processing) in Linux C++, evaluated its performance to find out the upper limits of the reservation requests and profiled the system for different parts of protocol operations.

After we developed an open source CASP implementation and evaluated its running properties [53], the present paper elaborates the overhead study and performance results of the evolved IETF GIST protocol through a detailed evaluation. To our knowledge, the work presented in this paper is the first empirical study of the GIST protocol.

## VI. Conclusions

This paper presented the overhead, implementation and performance study of GIST, a generic IP signaling protocol being developed by the IETF. In contrast to traditional methods, GIST provides a modular architecture to support any application application (NSLP) requesting signaling services, and reduces complexity by relying on existing security and transport protocols for achieving signaling functionalities. The modularity design of the GIST implementation provides a flexible way for state management, message processing, and any type of application-specific signaling purposes. The result is improved extensibility, security, and transport properties at the cost of additional overhead. The implementation performed efficiently when serving a number of sessions (at least 60,000) and the profiling shows the detailed processing and round-trip times for different numbers of signaling sessions. C-mode is concluded to be preferred to D-mode.

The focus of this paper has been on GIST properties, such as protocol overhead, scalability and other performance issues. Composing signaling application protocols (NSLPs) and its effect on overhead and performance will certainly pose imminent concerns once the overall system has materialized, which will also effect its deployment. We will in turn study to what degree these optimizations will improve performance. In addition, a number of issues were encountered when investigating the GIST protocol, which went beyond the scope of this study. It is clear to say, however, that further study will be necessary with respect to a more sophisticated network topology, as well as the interaction with underlying transport and security protocols (effects of applying IPsec/TLS and different TCP variants in particular). It should be noted that some improvements in the GIST specification are currently underway to enhance more flexible and applicable signaling transport support and security concerns. In addition, studies are being carried out on other issues connected with GIST/NSIS, such as mobility support [25], [54], fault handling and route change, as well as the QoS and NAT/Firewall NSLPs under standardization [27], [28], and a comprehensive performance evaluation of the NSIS protocol stack in comparison with RSVP.

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## APPENDIX – SOURCES OF PROTOCOL OVERHEAD IN GIST (IN COMPARISON WITH RSVP

Here we give the details on how each of the layers of GIST and RSVP protocol structures contributes to their overall protocol overhead.

*1) IP:* Every RSVP or GIST message needs an IPv4 or IPv6 header, which is 20 bytes or 40 bytes without options, routing, fragmentation and security headers. For GIST-Query or RSVP-Path messages, the IP layer requires additional 4 bytes (for IPv4) or 8 bytes (for IPv6) in order to accommodate the IP Router Alert Option.

*2) Transport Layer:* GIST-Query messages are encapsulated using UDP, thus the transport layer overhead is 8 bytes. Other GIST messages can use either D-mode (UDP) or C-mode (TCP by default), resulting in a default transport layer overhead of 8 bytes (UDP header) or 20 bytes (a minimal TCP header). Note that C-mode messages in GIST require additional transport layer messages to accomplish the transport functionality, such as connection setup and reliability. Under normal circumstances (e.g., no loss, non-congested, no fragmentation), a TCP connection setup requires an additional TCP SYN, a SYN+ACK message and a TCP ACK message, whereas each GIST-layer message exchange needs an underlying TCP ACK message. SYN or SYN+ACK messages carry an MSS option (4 bytes) in addition to the normal TCP header, thus their overall overhead is 24 bytes plus IP header. The overhead of TCP ACK is 20 bytes plus IP header.

By default, RSVP messages are encapsulated directly using IP, so normally there is no transport layer overhead in RSVP. (Note the use of UDP for RSVP signaling is not discussed here.)

*3) GIST:* The GIST layer overhead can differ from one GIST message type to another, from one NSLP to another. It also relies on the used lengths of query-cookie and response-cookie as well as peer identity (PI, part of the NLI – the network layer information) and message routing method (MRM, used for managing message routing state) [25]. In our work we choose 36 bytes as the length for both query-cookie and response-cooke objects. We use the peer's IP address as the PI, thus a PI object length is 8 bytes (for IPv4) or 20 bytes (for IPv6). Among the optional fields of a basic path-coupled MRM, we choose to use only destination port (2 byte) for IPv4 and only flow label (3 bytes) for IPv6, which is suggested for usage by some other protocols as well, e.g., [7], [23]. All the mandatory fields are used in below discussions.

GIST-Query message comprises a common header (8 bytes), an MRM object (24 bytes for IPv4, 52 bytes for IPv6), a session ID object (20 bytes), a query-cookie object (36 bytes) and a network layer information object (24 bytes for IPv4, 36 for IPv6). For a node desiring C-mode operation, the Querying node's stack proposal object (12 bytes) and stack configuration data object (20 bytes) are also added. Therefore, the overall GIST layer overhead of a GIST-Query message is as follows:

$8 + 24 + 20 + 36 + 24(+12 + 20) = 112(+32,$ if stack proposal exists) bytes for IPv4, and

$8+52+20+36+36(+12+20) = 152(+32,$ if stack proposal exists) bytes for IPv6.

A GIST-Response message echos the query cookie and stack proposal objects, and additionally adds a response cookie object (36 bytes) to the received query message. Thus, the overall GIST layer overhead of a GIST-Response (C-mode) is 148 (+32 with stack proposal) bytes for IPv4 and 188 (+32 with stack proposal) bytes for IPv6.

A GIST-Confirm message differs from a GIST-Query in that it contains a response cookie object instead of a query cookie object (but of the same length), and removes the attached stack configuration data, besides the NSLP payload. Therefore, the overall GIST layer overhead of a GIST-Confirm is the same as Query.

A GIST-Data message comprises a common header, MRM, session ID and network layer information objects, excluding NSLP payload. GIST-Data message overhead is then as follows:

$8+24+20+20 = 72$ bytes for IPv4, and

$8+52+20+36 = 116$ bytes for IPv6.

*4) RSVP:* A minimal RSVP-Path message contains the IP layer (with overhead of 24 bytes for IPv4, 48 bytes for IPv6 including router alert option), common RSVP header (8 bytes), a session object (12 bytes for IPv4 and 24 bytes for IPv6), a RSVP_HOP object (12 bytes for IPv4, 24 bytes for IPv6), a TIMES_Values object (8 bytes), and a SENDER_TSpec (12 bytes [8]). Therefore, a minimal overhead for RSVP-Path is as follows:

$24+8+12+12+8+12 = 76$ bytes for IPv4, and

$48+8+24+24+8+12 = 122$ bytes for IPv6.

A minimal RSVP-Resv message contains the IP header, common RSVP header, a session object, a RSVP_HOP object, a TIMES_Values and a STYLE object (8 bytes). According to [7], it must at least also carry a Filter_Spec object for FF and SE styles (of 12 bytes length for IPv4, or of 24 bytes length for IPv6), a FlowSpec object for FF, WF and SE styles (of 48 bytes length for GS, the Guaranteed Service, or of 12 bytes length for CLS, the Controlled Load Service [8]), and a SCOPE object for WF style (of $4m$+4 bytes length for $m$ IPv4 source addresses, or of $16n$+4 bytes length for $n$ IPv6 source addresses). This indicates that a minimal unicast (i.e., FF style) RSVP-Resv message imposes the following overhead:

$8+12+12+8+8+12+48_{GS}(12_{CLS}) = 108_{GS}(72_{CLS})$ bytes for IPv4, and

$8+24+24+8+8+24+48_{GS}(12_{CLS}) = 144_{GS}(108_{CLS})$ bytes for IPv6.

*5) Memory Consumption:* Different from stateless protocols (e.g., IP and UDP), TCP, GIST layer and RSVP layer introduces memory requirements to store their layer-specific states, besides their protocol engine repository. As the exact presentation of these states is not part of the standards and may differ from one implementation/computer architecture to another, we estimate them below and validate them in the evaluation (see Section IV-C).

In the TCP layer, each TCP connection maintains a data structure for its state (TCP Control Block or TCB) [55], which includes a combination of parameters, such as connection state, current round-trip time estimates, congestion control information, and process information. A TCB connection state can vary in size between 256 bytes or less and more than 1 kilobytes. In GIST, TCP connections are recommended to be shared across signaling sessions between the same GIST pairs, where TCP Control Block Interdependence (TCBI) [56] or Congestion Manager [57] may be used in order to reduce connection state size, e.g., up to 512 bytes. Use of such multiplexing techniques allows a rather low memory consumption for per-peer GIST state management.

The GIST layer in D-mode maintains a per-session state, namely the message routing state. A minimum MRS state entry contains MRI (e.g., 1-byte method identifier for "path-coupled", and 10-byte 5-tuple flow ID for IPv4 or 35-bytes 3-tuple flow ID for IPv6 comprising flow label, flow sender's address, flow receiver's address), 16-byte session ID, 1-byte NSLP ID, response direction (e.g., flow sender's address, 4 bytes for IPv4 and 16 bytes for IPv6) and query direction (e.g., flow receiver's address). This indicates that such an MRS entry is 36 bytes (IPv4) or 85 bytes (IPv6) in size, in addition to a validity timer.

In addition to the per-session state MRS (same as in D-mode), GIST layer in C-mode also maintains a per-peer state MA, which includes the GIST messages pending transmission (the number can be zero) and MA active timer, which is rather small in size when serving for a number of MRS sessions.

In contrast, each RSVP node maintains a per-session Path State Block (PSB) and a Resv State Block (RSB) [58], each with a validity timer and refresh interval. A minimum PSB includes information about session (8 bytes for IPv4 and 20 bytes for IPv6), Sender_Template (8 bytes for IPv4 and 20 bytes for IPv6), Sender_Tspec (12 bytes), previous hop's IP address (4 bytes for IPv4, 16 bytes for IPv6) and logical interface handle (4 bytes), remaining IP TTL (1 byte), and several flags (assuming 1 byte), in total 38 bytes for IPv4 and 74 bytes for IPv6. A minimum RSB includes session (8 bytes for IPv4 and 20 bytes for IPv6), next hop IP address, Filter_Spec (12 bytes for IPv4 and 24 bytes for IPv6), style (4 bytes), and Flowspec (36 bytes for CLS), in total 64 bytes for IPv4 and 90 bytes for IPv6. This represents 82 bytes for IPv4 and 164 bytes for IPv6 in overall RSB and PSB excluding management overhead and timers. This conclusion (i.e., slightly higher than GIST memory consumption) does not appear surprising, since unlike GIST states, RSVP states also include IntServ parameters.