ACHIEVING SECURE SERVICE SHARING OVER IP NETWORKS

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Abstract: No matter how many and how comprehensive the services a network can provide, in order to satisfy the diverse requirement of services, networks should share services among themselves. For secure service sharing on IP networks, the authenticity of users and the scalability of participating networks are always two major issues among others. Service Network Graph (SNG) was proposed to address the problems of cross network authentication and scalability, which usually occur in a dynamic aggregations of heterogeneous networks.

Our SNG approach is based on *Authentication Propagation* and *Service Paths*. Authentication Propagation is a process of relaying authentication results from the authenticating network to the service providing network. Within an SNG, networks delegate authentication duties to some other networks which gather all authentication and service information and return the authentication result to the user. A Service Path is designed to hold all the authentication delegation information from the user's home network to the service providing network. An example of Service Path in a network, N_x, looks like: $< F : /N_x/N_y/N_z/S_z/Service_z >:< 4 >$ where the second field, $/N_x/N_y/N_z/S_z/Service_z$, stands for the $NetworkPath$ of a service, $Service_z$, which is provided by a server S_z, in a network N_z. We can work out the routes for the authentication and service information from the $NetworkPath$ as (1) from N_x to N_y if it does not end at N_x; (2) from N_y to N_z if it does not originate from N_z; (3) from N_z to N_y if it does not end at N_x; and (4) from N_y to N_x if it does not originate from N_x.

These routes can be represented in the 4-tuples form: $(< Net_{ori} >, < Net_{from} >, < Net_{to} >, < Net_{dest} >)$ To differentiate route (2) and route (4), $<Net_{ori}>$ is used. Route (1) can be expressed as $(Net_x, Net_x, Net_y, Net_z)$ using the 4-tuple notation. Obviously, it is not efficient to extract the routes from incoming Service Paths each and every time. Besides, the *NetworkPath* field may contain a substantial number of networks. Hence reusing the routes could improve the efficiency. The 4-tuple notation facilitates the reuse of routing information.

In this paper, we devise a 4-tuple (ATR tuple) representation of authentication and service information routes. The ATR tuple representation is shown to be an alternative representation of SNG other than the graphical representation. We also explore how the ATR tuple representation can be applied to facilitate the authentication propagation process. A set of experiments on network simulator, OMNeT++, have been carried out to illustrate the application of SNG with ATR tuples to IP networks. The preliminary simulation results show that the ATR tuple representation greatly simplifies the implementation of the SNG authentication routing algorithm, and secure service sharing can be achieved as well.

Key words: Service Network Graph, service sharing, authentication delegation, authentication propagation, service path, routing tuple.

1 Introduction

A network has limited resources and can provide only a limited number of services. Administrative constraints also limit the categories of service available to users. Users may request services that are beyond the domain of service for the network and can only be honored with shared services provided by other networks. To share a service, authenticity of users and scalability of participating networks are two major issues related to security.

Service sharing involves cross network authentication. For security and privacy reasons, authentication servers keep their authentication information repository private. Further more, different networks always use different authentication schemes. One set of authentication information can hardly fulfill the requirements of all authentication schemes.

To enable cross network authentication, an AS needs to have access to the rightful authentication information or entrust other AS to perform the authentication task. Administration and maintenance of a global repository of authentication information render such repository not practical. Besides sharing of the authentication information may breach the privacy of users.

Alternatives to a global repository of authentication information include the use of X.509 [1] digital certificates and the establishment of *trust* [2, 3, 4]. Both approaches require all participants involved in the authentication process to accept a single or a group of third parties. The use of X.509 digital certificates in cross network authentication requires a commonly trusted Certification Authority which binds the user identity with the public key in an X.509 digital certificate and all authentication servers must trust the certificates issued by the Certificate Authority. In other words, all of them have to adopt the use of X.509 digital certificates as their authentication scheme and trust the same Certificate Authority in performing the duty of binding user identities and the corresponding public keys before cross network authentication is possible. In addition, they have to agree on a common set of policies regarding the validity and revocation of X.509 digital certificates [5, 6]. In particular, an authentication server prescribes a list of trust agents which are authorized to issue trust tokens [7, 8, 9, 10]. The aggregated result of a number of trust tokens is used to determine the authenticity and possible authorization of the user [11]. The authentication server then distributes the authentication duty to the prescribed trust agents while making its own final authentication decision. A common set of overlapped trust agents is required for cross network authentication. i

Service Network Graph (SNG) [12, 13, 14] is a new way to handle cross network authentication, which enables service sharing among dynamic aggregation of autonomous networks. The authentication duty of the authentication server, AS_s, in the service providing network, N_s, is delegated to the authentication server, AS_h, of the home network, N_h, of an individual user. N_h and AS_h are referred to as the delegatee network and delegatee AS while N_s and AS_s are the delegator network and delegator AS. The delegator AS_h performs authentication, bundles the result, a session key and the Service Path into an authentication token ($AToken$), and passes the $AToken$ to the server via AS_s. The server accepts the authentication result from the delegatee AS_h the same way as that from the delegator AS_s and appends the necessary service information to the $AToken$ which is handed back to the user via AS_s and AS_h. With authentication delegation, a server can authenticate any user from a delegatee network and users from a delegatee network can access shared services provided by delegator networks. Participating networks of an SNG can maintain their own authentication schemes, keep their own private authentication information repository private and still can perform cross network authentication. They can join or detach from SNG while maintaining their autonomy.

When $AToken$ is routed from a home network to a service providing network, routing information for the AToken can be extracted from the $NetworkPath$ information in the

Service Path which is part of the $AToken$. In practice, the token routing information can be reused and more readily available if each AS can keep its own set of $AToken$ routing information. To facilitate routing of $ATokens$, we propose to use a 4-tuple representation for storing the token routing information (ATR tuple). We formulated the ATR tuples in such a way that they can be used to hold routes for forward or backward ATR routing. Each AS is required to hold only the ATR tuples related to itself.

The rest of the paper is structured as follows: Section 2 is an overview of SNG. In particular, Authentication Delegation, Service Paths and Authentication Propagation are briefly explained. In Section 3 we investigate the routing of $ATokens$ and the ATR tuple representation. An example of deriving the ATR tuples from an SNG is also given. Lastly, we apply the ATR tuple representation in Section 4 in an implementation of SNG over IP networks. A set of experiments was carried out using ATR tuple implementation of the SNG and network simulator OMNeT++. The paper is ended with a conclusion and future works.

2 Overview of Service Network Graph

SNG is based on Service Paths, Authentication Delegation and Authentication Propagation. They are summarized in the sections below.

2.1 Authentication Delegation

In SNG, network N_x can extend its services by *attaching* to another network, say N_y. On the other hand, network N_y shares it services by *delegating* its authentication duty to an *attached* network say N_x. Hence a network can extend its service by attaching to another network as an authentication delegatee network and share its services as an authentication delegator network. A delegatee network can also be a delegator network as shown in Figure 1. N_4 is the delegator network of N_1 and is also the delegatee network of N_2. N_1 and N_3 are both delegator and delegatee network of each other.

A network delegates its authentication authority to another network when its authentication server (AS) generates and shares an Authentication Token key (ATK) with the delegatee network AS. It also informs the delegatee network AS of the services it provides, locally or shared from other networks in the form of Service Paths detailed in section 2.2. Local services are directly shared with the delegatee network and tagged with *free* or *restricted* to control further delegation. Shared services with *free* authentication delegation can further be shared indirectly with other delegatee networks.

When U_x requests a service provided by N_y, AS_x in home network (N_x) of U_x authenticates U_x on behalf of N_y. If the authentication is successful, AS_x generates a session key for the service request. The Service Path, session key and authentication result are bundled together to form an $AToken$.

2.2 Service Paths

When referring to a service, we have to specify from where we can access the service. As a service can be provided by different servers in more than one network, we have to specify the *network path* for the service. Other important attributes for services are the service cost and whether the service can be further shared or not. If a shared service can be shared with other networks, it is a *free* authentication delegation and a *restricted* authentication delegation means that the service should not be shared with other networks. So a typical Service Path looks like:

$< F : ./S_1/Sv_4 >:< 4 >$
means service Sv_4 provided by local server S_1 with cost 4 units
is a service shared with *free* authentication delegation
and can be shared with other networks.
Authentication Propagation path is local authentication only.

$< R : /N_1/N_4/N_2/S_2/Sv_{123} >:< 25 >$
means service Sv_123 provided by server S_2 in N_2 with cost 25 units
is a service shared with *restricted* authentication delegation
and should not share with other networks.
Authentication Propagation path is $N_1 \Longrightarrow N_4 \Longrightarrow N_2$.

The Service Listing server (SLS) of a network provides a complete and updated list of services available including local and shared services.

2.3 Authentication Propagation

In order to explain Authentication Propagation, we will refer to Figure 2 assuming each network has an AS, a server S, a user U and a Service Listing server SLS with the appropriate subscript to denote the network they belong to. We use P_{xy} to denote a service path in which service y is provided by network x. The SNG depicted in Figure 2 has four participating networks. N_1 is attached to N_4 as indicated by the single headed arrow while N_1 and N_3 are attached to one another as indicated by the double headed arrow.

The Authentication Token propagation path is represented by dotted lines as shown in Figure 2.

We will use:

$Send\ (< from >, < to >, < msg >)$
to mean $< from >$ send a message $< msg >$ to $< to >$

$Encrypt\ (< msg >, < key >)$
to mean message $< msg >$ is encrypted with $< key >$

A service request starts with a user, say U_1 asks for a Service List from SLS_1.

$$Send(< U_1 >, < SLS_1 >, < \text{“}RequestforServiceList\text{”} >)$$
$$Send(< SLS_1 >, < U_1 >, < P_{1a}, P_{1b}, P_{2a}, P_{2b} >)$$

U_1 makes his choice, say P_{2a} and sends his authentication information along with P_2a to the AS_1.

$$Send(< U_1 >, < AS_1 >, < P_{2a}, \text{"}AuthenInfo\text{”} >)$$

When U_1 is authenticated, AS_1 generates a session key K_{1u} for the service request. The session key is bundled with other authentication information and the Service Path as an authentication token. The authentication token is propagated to AS_4 and finally reached AS_2. Note that ATK_{4a} is the ATK between AS_1 and AS_4, and ATK_{2a} is the ATK between AS_4 and AS_2,

$$Send(< AS_1 >, < AS_4 >, < P_{2a}, Encrypt(< K_{1u} >, < ATK_{4a} >) >)$$
$$Send(< AS_4 >, < AS_2 >, < P_{2a}, Encrypt(< K_{1u} >, < ATK_{2a} >) >)$$

AS_2 then passes the session key to the service providing server which returns the service information to AS_2. The messages are encrypted with the server key K_{2s}.

$$Send(< AS_2 >, < S_2 >, < P_{2a}, Encrypt(< K_{1u} >, < K_{2s} >) >)$$
$$Send(< S_2 >, < AS_2 >, < P_{2a}, Encrypt(< \text{“}ServiceInfo\text{”} >, < K_{2s} >) >)$$

The service information follows a reversed path specified in P_{2a} and arrives at AS_1.

$$Send(< AS_2 >, < AS_4 >, < P_{2a}, Encrypt(< \text{“}ServiceInfo\text{”} >, < ATK_{2a} >) >)$$
$$Send(< AS_4 >, < AS_1 >, < P_{2a}, Encrypt(< \text{“}ServiceInfo\text{”} >, < ATK_{4a} >) >)$$

The authentication propagation process is completed when AS_1 passes the service information and the session key K_{1u} to U_1.

$$Send(< AS_1 >, < U_1 >, < P_{2a}, K_{1u}, \text{“}ServiceInfo\text{”} >)$$

U_1 can now communicate with S_2 and can access service directly. Note that the security of passing authentication information and session key from AS_1 to U_1 depends on the authentication and session key generation schemes adopted. One appropriate candidate is Dynamic Password and the associated key exchange scheme [15] which performs authentication and session key generation at the same time.

AS of a network in SNG holds a service list from which it will derive the forward and backward routes for the ATokens. In the next section, we will discuss how to represent the AToken routes in an SNG to optimized the performance for Authentication Token routing.

3 Service Network Graph Representation

The Service Network Graph is a logical representation of the authentication delegation relationships. A graphical representation is best suited for a human administrator. In practice, we must represent the service network graph in a form which best suits our purpose - routing of the authentication tokens and optimizing the Service paths.

To understand how an SNG can be represented using AToken routes, we will start with the routing mechanism of Authentication Tokens.

3.1 Authentication Token Routing

A Service Path itself provides enough information to route the Authentication Token to the destination. As an example, in Figure 2, consider a service path:

$$< F : /N_3/N_1/N_4/S_4/Sv_4 >:< 2 > \tag{1}$$

When AS_1 gets this service path, it will parse the NetworkPath field of the service path to get the routing information. As AS_1 is located in N_1, it will forward the AToken to N_4 if the AToken comes from N_3 or to N_3 if the AToken comes from N_4.

Since the AToken routing information can be reused for other service requests with the same service path, extracting the forward and backward AToken routing information with each and every AToken is not efficient. At the same time, the NetworkPath field of a service path may contain substantial number of networks. Hence storing the AToken routing information for reuse improves performance.

3.2 Tuple Representation

To reuse any AToken routing information, we must store the necessary information to determine the appropriate route. Referring to the SNG shown in Figure 2, consider the pair of Service Paths:

$$< F : /N_2/N_1/N_4/S_4/Sv_4 >:< 4 > \tag{2}$$

$$< F : /N_2/N_1/N_3/S_3/Sv_3 >:< 4 > \quad (3)$$

Service path 2 tells AS_1 to forward the AToken to N_4 while service path 3 instructs AS_1 to forward the AToken to N_3. The two AToken routes are different and the choice depends on the destination network which are N_4 and N_3. Note that the destination network may not be the same as the network an AToken is routed to. For instance, $< F : /N_2/N_1/N_3/N_5/S_5/Sv_5 >:< 4 >$ informs AS_1 to forward the AToken to N_3 and the destination network is N_5. Both service path uses the same backward AToken route: pass AToken from N_1 to N_2.

Consider another pair of Service Paths:

$$< F : /N_2/N_1/N_4/S_4/Sv_4 >:< 4 > \quad (4)$$

$$< F : /N_3/N_1/N_4/S_4/Sv_4 >:< 4 > \quad (5)$$

Both Service Paths informs AS_1 to forward the ATokens to N_4. Service path 4 tells AS_1 to route the AToken to N_2 while service path 5 instructs AS_1 to route the AToken to N_3 when the ATokens return from N_4. Again, the two AToken routes are different and can be distinguished one from another by looking at the origin network.

Hence to hold the necessary information for AToken routing, we use 4-tuples (ATR tuples) to hold not only the network an AToken comes from (N_{from}) and goes to (N_{to}), but also the origin network (N_{ori}) and destination network (N_{dest}):

$$(< N_{ori} >, < N_{from} >, < N_{to} >, < N_{dest} >)$$

We now derive ATR tuples when from an SNG and explain how an SNG follows from an ATR representation. The graphical representation and the ATR tuple representation are shown to be equivalent.

3.3 Deriving ATR Tuples from an SNG

As discussed in Section 2, the following rules are used for building up an SNG:

SNG Building Rule 1 When network N_1 attaches to network N_2 in an SNG, N_2 will pass its service list to N_1, assuming all services have free authentication delegation.

SNG Building Rule 2 When network N_1 attaches to network N_2 in an SNG, it will pass the service list it gets from N_2 to all its delegatee networks. And in so doing, all delegatee networks can access all local or shared services provided by N_2.

SNG Building Rule 3 When a network N_1 receives a Service Path from its delegator network N_2 in an SNG, N_1 will pass the AToken routes (ATR tuples) it worked out from the Service Path back to the appropriate delegator networks.

We will build an SNG such as the one shown in Figure 2. Suppose the SNG was built in the following five stages of attachment:

1. N_4 attaches to N_2.
2. N_2 attaches to N_1.
3. N_1 attaches to N_4.
4. N_3 attaches to N_1.
5. N_1 attaches to N_3.

For the sake of clarity, we assume a uniform cost of 2 for all services.

Stage 1 N_4 attaches to N_2.

At the very start, N_4 attaches to N_2. After the attachment process, it has acquired the Service Path: $< F : N_4/N_2/S_2/Sv_2 >:< 2 >$. The forward and backward ATR tuples are worked out: (N_4, N_4, N_2, N_2), (N_4, N_2, N_4, N_2) restively. The backward ATR tuple is sent back to N_2. The ATR tuples derived are shown in Table 1

Stage 2 N_2 attaches to N_1. When N_2 attaches to N_1, it will acquire the Service Path: $< F : N_2/N_1/S_1/Sv_1 >:< 2 >$. N_2 extracts the forward ATR tuple (N_2, N_2, N_1, N_1) and backward ATR tuple (N_2, N_1, N_2, N_1) which is sent to N_1.

At the same time, N_2 has to inform N_4 of the newly acquired Service Path and N_4 will add a corresponding Service Path to its service list: $< F : N_4/N_2/N_1/S_1/Sv_1 >:< 2 >$. The forward and backward ATR tuples extracted by N_4 from the newly acquired Service Path are listed in Table 2. Note that a network keeps only those ATR tuples that are useful to them. An ATR tuple is useful only to the network which has the same name as the attribute $< Net_{from} >$ in the tuple. Hence N_1 will keep the second and last ATR tuples while N_2 will keep the first, fourth and fifth ATR tuples in Table 2.

Stage 3 N_1 attaches to N_4. N_1 acquires service paths $< F : N_1/N_4/S_4/Sv_4 >:< 2 >$, $< F : N_1/N_4/N_2/S_2/Sv_24 >:< 2 >$ from N_4. N_1 will pass the newly acquired service paths to N_2 but N_2 will have only one additional service paths $< F : N_2/N_1/N_4/S_4/Sv_4 >:< 2 >$ as $< F : N_2/N_1/N_4/N_2/S_2/Sv_2 >:< 2 >$ is referring to a local service. No new service path is acquired by N_4 as the services will then have a looping Network Path like $N_4/N_2/N_1/N_4/N_2/S_2/Sv_2 >:< 2 >$.

N_1 and N_2 will follow the same steps as discussed in Stage 2 to build up the ATR tuples as shown in Table 3.

Stage 4 N_3 attaches to N_1. N_3 acquires, from N_1 service paths $< F : N_3/N_1/S_1/Sv_1 >:< 2 >$, $< F : N_3/N_1/N_4/S_4/Sv_4 >:< 2 >$, $< F : N_3/N_1/N_4/N_2/S_2/Sv_24 >:< 2 >$. ATR tuples are generated similar to the process in previous stages and listed in Table 4.

Stage 5 N_1 attaches to N_3. This time, N_1, N_2 and N_4 will all have new Service Paths: $< F : N_1/N_3/S_3/Sv_3 >:< 2 >$, $< F : N_2/N_1/N_3/S_3/Sv_3 >:< 2 >$ and $< F : N_4/N_2/N_1/N_3/S_3/Sv_3 >:< 2 >$ respectively. The ATR tuples are listed in Table 5

We can easily verify that the ATR tuples indeed represent all the necessary AToken routing information. Our next step is to demonstrate how ATR tuples can be used to build up a graphical representation of an SNG.

3.4 Graphical Representation of SNG from ATR Tuples

We notice that in any ATR tuple, if the $(< Net_{from} >, < Net_{to} >)$ attribute pair matches with the attribute pair $(< Net_{ori} >, < Net_{dest} >)$ in a forward route, network Net_{ori} is attached to network Net_{dest}. To build up a graphical representation of an SNG, we need to have all the direct authentication delegation relationships. Other indirect authentication delegation relationships can be used to verify the result.

From the set of ATR tuples derived in Section 3.3, we collect all distinct ATR tuples that have the match attribute pairs in Table 6. Note that the last action ends up with a double headed arrow. The final SNG may have a different look from the SNG in Figure 1, but they have the same authentication delegation relationships and in which case, we consider them as two valid graphical representations of the same SNG. In next section, we will explore how to implement SNG over IP networks using network simulator OMNeT++.

4 Application of SNG over IP networks

To illustrate how SNG can be applied to the secure service sharing over IP networks, we design a few IP networks and simulate the SNG shown in Figure 2 using network simulator OMNeT++.

The simulation network was set up with the following assumptions:

- Each network has one $AuthenticationServer(AS)$, one $ServiceListingServer(SLS)$, one $Server(S)$ and one $User(U)$.
- Each server (network) provides one type of services.
- A service request originates from user U_1 of network N_1.
- SNG configuration is shown in Figure 2.

In the simulations, the messages used carry five parameters: *server*, *start*, *stop*, *src*, *dest*. These five parameters are used to hold the information required for AToken forward and backward routing.

The ATR tuples from Section 3.3 are hard coded in the OMNeT++ module for AS. We code all tuples in one module used for all AS. In practice, only the tuples required for each AS need to included in the implementation of each AS.

The simulated events are

1. A local service request for Sv_1 provided by S_1 in N_1 from U_1.
2. A directly shared service request for Sv_4 provided by S_4 in N_4 from U_1. The Authentication Token has to propagate from AS_1 to AS_4
3. An indirectly shared service request for Sv_2 provided by S_2 in N_2 from U_1. The service is provided by S_2 in N_2. N_2 shares the service with N_4. On the other hand, N_4 shares all services it provides, including shared service Sv_2, with N_1. Hence users from N_1 can access *indirected* shared service Sv_2. The Authentication Token now has to propagate from AS_1 to AS_2 via AS_4.

4.1 Local Service Request

User requesting a local service is the simplest case in SNG. It does not matter if the network is part of an SNG or not as it does not involve any Authentication Token routing. Figure 3(a) shows the basic operation of a local service request. A local service request starts with a request for a service list from the Service Listing Server SLS_1. The user U_1 then choose a service, sends the corresponding Service Path $< F : ./S_1/Sv_1 >:< 2 >$ and authentication information to the Authentication Server AS_1. AS_1 generates a session key and send it to Server S_1. S_1 replies AS_1 with the information for Sv_1. AS_1 will relay the information for Sv_1 and the session key to user U_1. Note that AS_1 does not need any ATR tuple for authentication Token routing.

A screen capture of simulation output window is shown in Figure 3(b).

4.2 Shared Service Request - Direct Sharing

For shared services, there are two cases - direct sharing and indirect sharing. Direct sharing is the case when you access local services of a delegator network. Indirect sharing is the case when you access shared services of a delegator network. Indirect sharing is possible when the authentication delegation is not restricted. For simplicity of discussion, we assume that all delegations are free and all shared services can be further shared with other networks when they attach to a network in an SNG. Figure 4(a) shows an SNG with N_1 attached to N_4. U_1 initiated a service list request to SLS_1. This time, he chooses a service offered by S_4. A screen capture of simulation output window is shown in Figure 4(b).

4.3 Shared Service Request - Indirect Sharing

When a network N_1 shares its services with another network N_2, N_2 may further share the services to other networks attached to it. These type of sharing is an example of indirect sharing. Figure 5(a) shows an SNG with N_4 attached to N_2. When N_1 attaches to N_4, all shared services from N_2 is indirectly shared with N_1 also. A screen capture of simulation output window is shown in Figure 5(b). Note that the main difference in the three cases is the Authentication Propagation process. In local service access, there is no Authentication Propagation. For direct sharing of services, Authentication Propagation is just single hop traffic and indirect sharing of services involves multi-hops Authentication Propagation.

Although extra message passing are involved in the Authentication Propagation process, after authentication, the user communicates directly with the server. The traffic overhead is minimized this way.

5 Conclusion

Service sharing is one of the desired features of networks. Cross network authentication is the key to the success of service sharing. The dynamic nature of the networks participating in service sharing adds more constraints to plausible solutions. In this paper, we proposed the ATR tuples to represent the routing information of ATokens. We have demonstrated how to derive those Tuples from an SNG and have established a graphical representation of an SNG from the ATR tuples. We also applied the Tuple representation in the implementation of SNG over IP networks and illustrated the case with an OMNeT++ simulation. In the future, we will focus on optimizing the Service paths and establishing an optimal local view of an SNG. Authorization for SNG is another important research topic in the future.

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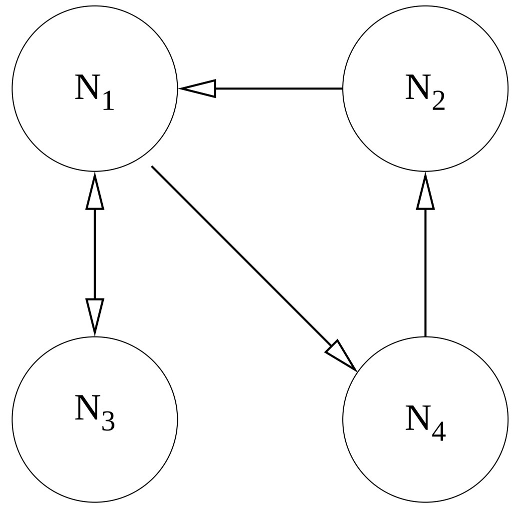


Figure 1: A Service Graph

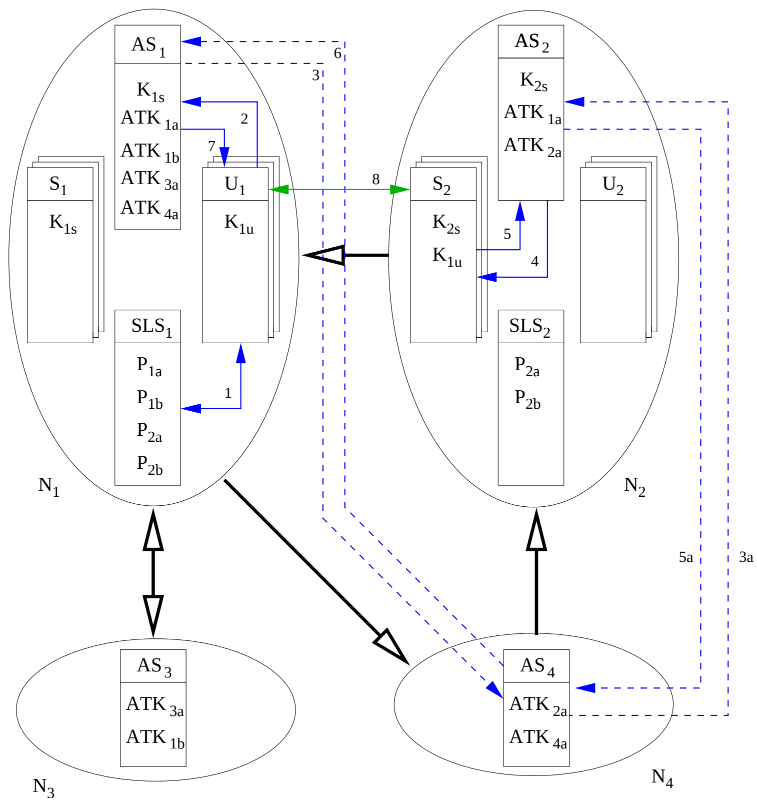


Figure 2: User requesting a shared service

Service Path	In	ATR tuple	Direction	Sent to
$< F : N_4/N_2/S_2/Sv_2 >:< 2 >$	N_4	(N_4, N_4, N_2, N_2)	forward	N_4
		(N_4, N_2, N_4, N_2)	backward	N_2

Table 1: ATR tuples derived in Stage 1

Service Path	in	ATR tuple	Direction	Sent to
$< F : N_2/N_1/S_1/Sv_1 >:< 2 >$	N_2	(N_2, N_2, N_1, N_1)	forward	N_2
		(N_2, N_1, N_2, N_1)	backward	N_1
$< F : N_4/N_2/N_1/S_1/Sv_1 >:< 2 >$	N_4	(N_4, N_4, N_2, N_1)	forward	N_4
		(N_4, N_2, N_4, N_1)	backward	N_2
		(N_4, N_2, N_1, N_1)	forward	N_2
		(N_4, N_1, N_2, N_1)	backward	N_1

Table 2: ATR tuples derived in Stage 2

Service Path	In	ATR tuple	Direction	Sent to
$< F : N_1/N_4/S_4/Sv_4 >:< 2 >$	N_1	(N_1, N_1, N_4, N_4)	forward	N_1
		(N_1, N_4, N_1, N_4)	backward	N_4
$< F : N_1/N_4/N_2/S_2/Sv_2 >:< 2 >$	N_1	(N_1, N_1, N_4, N_2)	forward	N_1
		(N_1, N_4, N_1, N_2)	backward	N_4
		(N_1, N_4, N_2, N_2)	forward	N_4
		(N_1, N_2, N_4, N_2)	backward	N_2
$< F : N_2/N_1/N_4/S_4/Sv_4 >:< 2 >$	N_2	(N_2, N_2, N_1, N_4)	forward	N_2
		(N_2, N_1, N_2, N_4)	backward	N_1
		(N_2, N_1, N_4, N_4)	forward	N_1
		(N_2, N_4, N_1, N_4)	backward	N_4

Table 3: ATR tuples derived in Stage 3

Service Path	in	ATR tuple	Direction	Sent to
$< F : N_3/N_1/S_1/Sv_1 >:< 2 >$	N_3	(N_3, N_3, N_1, N_1)	forward	N_3
		(N_3, N_1, N_3, N_1)	backward	N_1
$< F : N_3/N_1/N_4/S_4/Sv_4 >:< 2 >$	N_3	(N_3, N_3, N_1, N_4)	forward	N_3
		(N_3, N_1, N_3, N_4)	backward	N_1
		(N_3, N_1, N_4, N_4)	forward	N_1
		(N_3, N_4, N_1, N_4)	backward	N_4
$< F : N_3/N_1/N_4/N_2/S_2/Sv_2 >:< 2 >$	N_3	(N_3, N_3, N_1, N_2)	forward	N_3
		(N_3, N_1, N_3, N_2)	backward	N_1
		(N_3, N_1, N_4, N_2)	forward	N_1
		(N_3, N_4, N_1, N_2)	backward	N_4
		(N_3, N_4, N_2, N_2)	forward	N_4
		(N_3, N_2, N_4, N_2)	backward	N_2

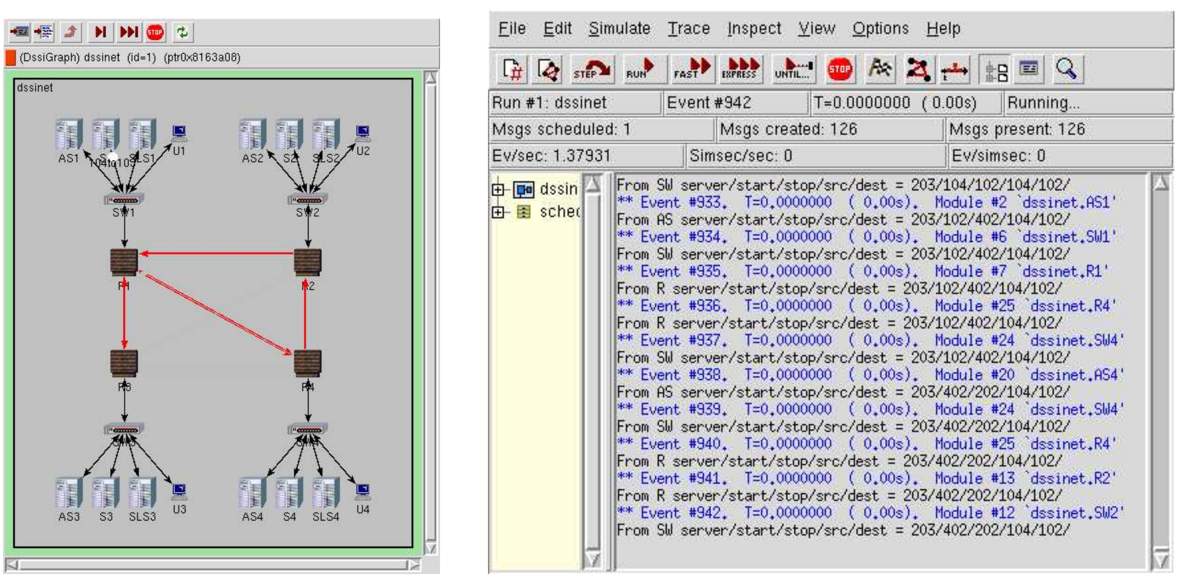
Table 4: ATR tuples derived in Stage 4

Service Path	in	ATR tuple	Direction	Sent to
$< F : N_1/N_3/S_3/Sv_3 >:< 2 >$	N_1	(N_1, N_1, N_3, N_3)	forward	N_1
		(N_1, N_3, N_1, N_3)	backward	N_3
$< F : N_2/N_1/N_3/S_3/Sv_3 >:< 2 >$	N_2	(N_2, N_2, N_1, N_3)	forward	N_2
		(N_2, N_1, N_2, N_3)	backward	N_1
		(N_2, N_1, N_3, N_3)	forward	N_1
		(N_2, N_3, N_1, N_3)	backward	N_3
$< F : N_4/N_2/N_1/N_3/S_3/Sv_3 >:< 2 >$	N_4	(N_4, N_4, N_2, N_3)	forward	N_4
		(N_4, N_2, N_4, N_3)	backward	N_2
		(N_4, N_2, N_1, N_3)	forward	N_2
		(N_4, N_1, N_2, N_3)	backward	N_1
		(N_4, N_1, N_3, N_3)	forward	N_1
		(N_4, N_3, N_1, N_3)	backward	N_3

Table 5: ATR tuples derived in Stage 5

ATR Tuple	Action
(N_4, N_4, N_2, N_2)	Draw N_4. Draw N_2. Draw an arrow from N_4 to N_2
(N_2, N_2, N_1, N_1)	Draw N_1. Draw an arrow from N_2 to N_1
(N_1, N_1, N_4, N_4)	Draw an arrow from N_1 to N_4
(N_3, N_3, N_1, N_1)	Draw N_3. Draw an arrow from N_3 to N_1
(N_1, N_1, N_3, N_3)	Draw an arrow from N_3 to N_1

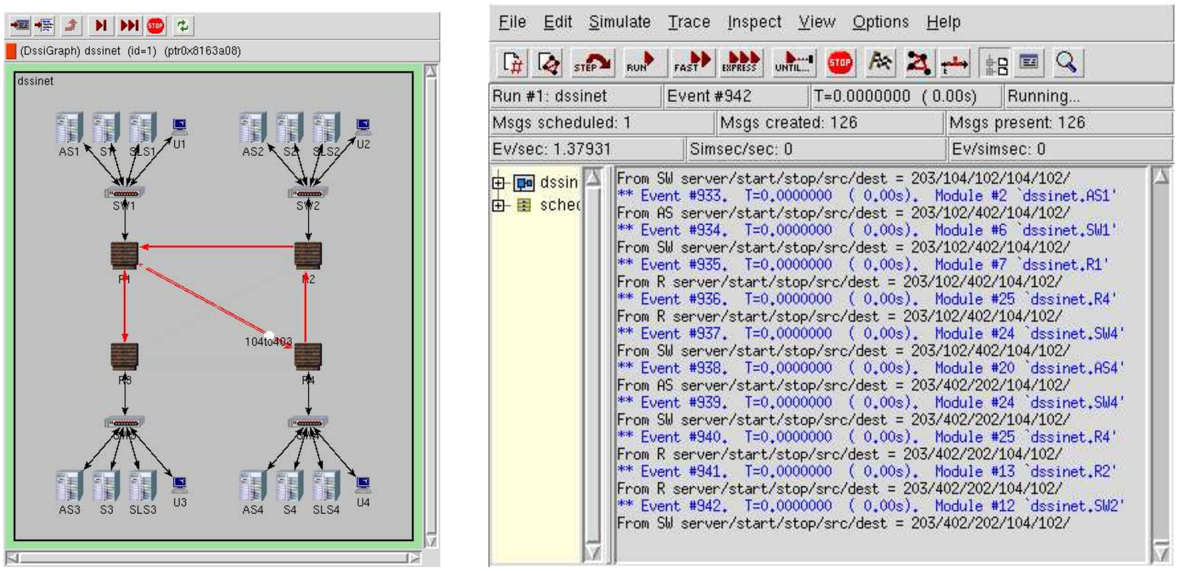
Table 6: ATR tuples and the corresponding graphical representation



(a) Simulation network configuration

(b) Simulation output

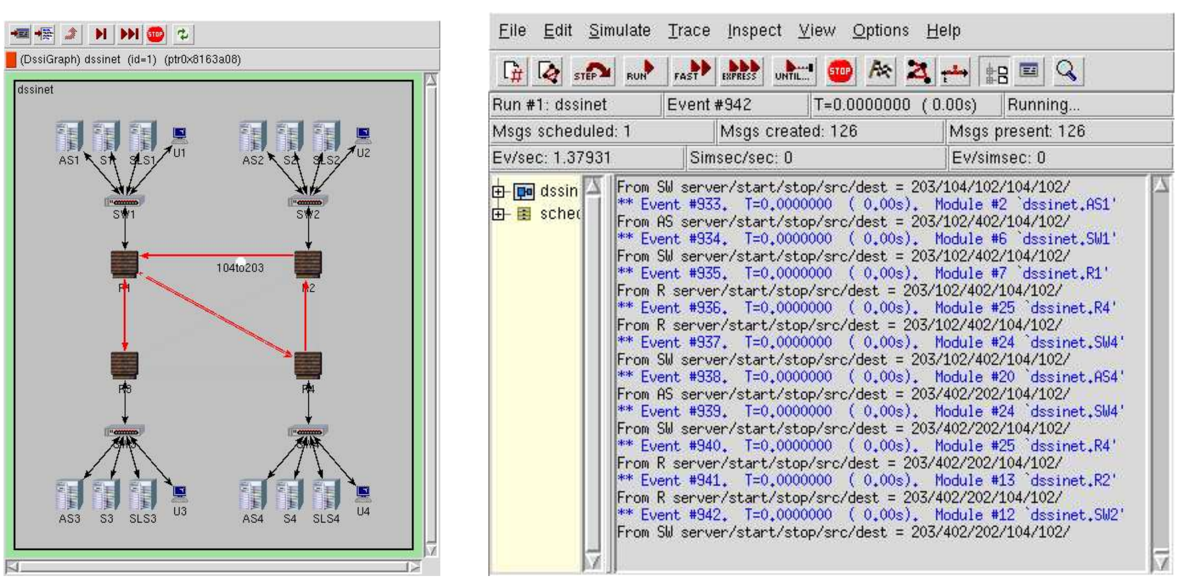
Figure 3: Local service request



(a) Simulation network configuration

(b) Simulation output

Figure 4: Directly shared service request



(a) Simulation network configuration

(b) Simulation output

Figure 5: Directly shared service request