ZbSR: A Data Plane Security Model of SR-BE/TE based on Zero-Trust Architecture

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Article

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Abstract: Facing the untrusted threats of network elements and PKI/CA faced by SR-BE/TE(Segment Routing-BE/TE) data plane in the zero-trust network environment, firstly, this paper refines it into eight specific security issues. Secondly, an SR-BE/TE data plane security model ZbSR(ZTA-based SR) based on zero-trust architecture is proposed, which reconstructs the original SR control plane into a "trust-agent" two-layer plane based on 4 components of the controller, agent, cryptographic center and information base. On one hand, we distinguish between the two segment list generation modes and proposes corresponding data exchange security algorithms, by introducing north-south security verification based on identity authentication, trust evaluation, and key agreement before the terminal device establishes an east-west access connection, so reliable data exchange between terminal devices can be realized. On the other hand, for the network audit lacking SR-BE/TE, a network audit security algorithm based on solid authentication is proposed. By auditing the fields, behaviors, loops, labels, paths, and SIDs of messages, threats such as stream path tampering, SID tampering, DoS attacks, and loop attacks can be effectively detected. Finally, through the simulation test, the proposed model can provide security protection for the SR data plane with a 19.3% average incremental delay overhead for various threat scenarios.

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1. Introduction

Segment Routing (SR) was born out of MPLS, and it revolutionized MPLS by deleting LDP and RSVP label distribution protocols and adding source routing features, which significantly improved the simplicity of network co24ntrol and the ability of super-large-scale networking [1]. Because of its stateless, easy deployment, cross-domain, and other excellent features, SR fully embodies the new network development concept of "application-driven network". Now, it has been supported by OpenDaylight open source SDN controller and Linux system, which can strongly support the end-to-end traffic scheduling of IP network and programmable reconfiguration of the software-defined network [2] and become the key technology of SDN/NFV in the next step [3].

SR can be divided into SR-MPLS and SRv6[4] according to the data plane encapsulation method, and can also be divided into SR-BE(SR Best Effort) and SR-TE(SR Traffic Engineering) according to the implementation mode, in which the SR-BE mode determines the Segment list by the head node through the IGP shortest path; in SR-TE mode, the SDN controller or SR PCE sends the Segment list to the head-end node through PCEP, BGP, BGP-LS, XML, and NETCONF, or the head-end node can automatically generate the Segment list through ODN(On-Demand Next-hop) mechanism, or the operator can explicitly configure it through CLI, NETCONF, etc. The source routing characteristics of SR enable it to specify the key nodes of the traffic path at the head node, and guide the traffic

through any path based on the Segment ID (SID), which achieves a delicate balance between control granularity and control simplicity, but also brings new available conditions for attackers to accurately attack the specified links or devices in the domain. However, at present, the academic circles focus on the functional research of SR, such as principle analysis [5], protocol expansion [6], technology implementation [7], and system integration [8], the research on its security is insufficient, especially the systematic solutions to the threats such as message forgery, identity fraud and node failure faced by its data plane is less.

What aggravates the threat faced by SR is that the network environment is also accelerating the transition to weak trust and zero trust, and Zero-Trust Architecture (ZTA) emerges at the historic moment. This architecture focuses on replacing the default trust granted by traditional network boundary security models (such as firewall, NAT, VPN) through dynamic trust based on multi-factor authentication and fine-grained authorization, to change the security boundary form between the host and the object from fixed hardware to software definition, to fundamentally solve zero trust threats. The progressive nature of ZTA is mainly reflected in the following aspects: the network boundary security models grant long-term trust based on single verification, lacks the traffic inspection inside the boundary, and is challenging to resist threats such as traffic eavesdropping and loopback attacks; while ZTA grants temporary trust based on each verification, which changes the paradigm of trust granting, and implements the security policy of "binding users and devices as network agents, authenticating and granting trust based on network agents, and dynamically authorizing according to trust" [9], replacing fixed boundaries with dynamic identities, and blocking the lateral movement of attackers [10].

Focusing on providing the SR-BE/TE data plane security scheme for the zero-trust network environment, this paper applies ZTA to SR-BE/TE and proposes a data plane security model of SR-BE/TE based on ZTA: ZbSR (ZTA-based SR), which focuses on the security of data plane switching device. In this model, the original SR control plane is transformed into a trust plane and an agent plane based on four security components: controller, key center, agent, and information base. Aiming at the two untrusted functions of data exchange and network audit of SR-BE/TE data plane, two list acquisition modes, Segment list generated by switching device in SR-BE/TE and list issued by controller in SR-TE, are distinguished, and the corresponding data exchange security algorithms based on trust evaluation are proposed respectively, that is, before the data exchange in east-west direction data plane terminal device via routing device of SR-BE/TE, in the north-south direction, firstly, it carries out identity authentication based on device information comparison, trust evaluation based on recommendation trust reasoning, and key negotiation based on encryption and digital signature to support it to establish a trusted connection; besides, this paper proposes a network audit security algorithm based on strong authentication, which can detect the attack representations of different threats by auditing the fields, behaviors, loops, labels, paths and SID information of the messages in various directions. Through simulation test and analysis, the proposed model is helpful to deal with different threats faced by SR-BE/TE data plane.

In summary, the main contributions of this article are as follows:

(1) 8 kinds of SR-BE/TE data plane security problems facing zero-trust network environment are put forward, and the technical combination basis of SR and ZTA basic function models is summarized;

(2) a security model of SR-BE/TE data plane based on ZTA is designed and implemented. For the untrusted function of the SR data plane, two security algorithms of data exchange and network audit are proposed, and 4 sub-algorithms of identity authentication, trust evaluation, key agreement, and loop audit are proposed;

(3) the effectiveness of the proposed architecture is proved by cost analysis and simulation, and the shortcomings of high cost and lack of fault self-recovery ability are also found.

This paper mainly consists of 5 sections, among which, the second section summarizes and puts forward SR native security mechanism, primary routing security mechanism, SR-BE/TE data plane security problem for the zero-trust network environment, and basic function models of SR and ZTA. The third section expounds the architecture design, component functions, security algorithms, security overhead, and so on of the ZbSR model. In the fourth section, based on the EVE-NG simulation environment, the security performance and overhead of the ZbSR model and the other two types of SR function models are compared and tested. The fifth section summarizes the full text and looks forward to the following research.

2. Related works

At present, as there is no molding solution to the threats faced by SR in the zero-trust network environment, this section mainly summarizes 7 kinds of SR native security mechanisms and 6 kinds of existing mainstream routing security mechanisms, puts forward 8 kinds of SR-BE/TE data plane security problems for the zero-trust network environment, and analyzes the coupling basis of SR and ZTA basic function models.

2.1 SR native security mechanism and primary routing security mechanism

Literature [2][11] points out the native security mechanisms adopted by SR, summarized into 7 categories in this paper. As shown in Table 1, these security mechanisms can't cope with threats such as control plane message tampering, denial of service attack, topology based on devices in the domain, and label detection.

Table 1. SR native security mechanism

security mechanism	Implementation method	Threat against
Source routing	The head node of the flow encapsulates the label stack to specify the flow path.	Malicious drainage
Trust domain	Only the source route is used in the domain, and the source route information is cleared by setting the C-flag flag in SRH when the data packet leaves the domain.	Label leakage
Package validation	RFC8754 stipulates that the optional TLV object field of SRH in SRv6 message carries HMAC TLV.	SRv6 data message tampering
load leveling	Anycast-SID will balance the traffic from a single node to multiple nodes.	Single point failure
fault detect	Local trigger (such as bidirectional fault detection BFD), remote intra-domain trigger (IGP flooding), remote cross-domain trigger (updated by BGP-LS), end-to-end SR Policy survivability detection, explicit candidate path verification and dynamic candidate path recalculation.	-
failure recovery	TI-LFA node protection	-
Service hiding	Use the "mpls ip-ttl-propagation disable" command to hide the multi-hop MPLS network as a single-hop network, thus invalidating the traceroute command.	Traditional topology detection, inter-domain topology detection
	By binding the SR Policy of the specified domain to BSID, users outside the domain cannot obtain the topology within the domain based on the candidate path information.	

Literature [12-22] puts forward a variety of mainstream routing security mechanisms, summarized into 6 categories in this paper, as shown in Table 2. These mechanisms did not consider the label and source routing characteristics of the SR network, and could not directly migrate to the SR scene, nor did they consider and deal with the threats they faced as a whole, so their universality was limited.

Table 2. Main routing security mechanisms

Security mechanism	Examples
Identification inspection	StackPi algorithm for judging the security of forwarding path based on check stack identification [12]; SNAPP algorithm for verification by adding message integrity verification code (MIC) at sender and intermediate node [13]
Node verification	The ICING mechanism checks the received data packets by deploying authentication servers in each node of the network, but it brings high transmission overhead [14]; OSP algorithm grants a certificate between the source and the router, and the intermediate node verifies the data packet according to the certificate, which improves the inspection efficiency but increases the management overhead [15]. RPKI uses digital signature and

	certificate to authenticate routing source, which can effectively prevent route hijacking [16]; due to the limited deployment of RPKI infrastructure, Tomas and others put forward DISCO, which is based on distributed trust architecture to authenticate routing [17]
Trusted hardware	TrueNet mechanism deploys trusted computing module (TCB) in each node of the network, and determines malicious links through multi-node security information negotiation [18]
centralization of control	SDN architecture is usually adopted, such as VeriDP algorithm, which verifies whether the data is transmitted normally through control plane policy, thus improving the accuracy of network behavior detection [19]. DFL mechanism collects the verification information of nodes in the transmission path in a centralized way, but it is difficult to avoid a single point of failure [20]
collaborative filtering	RISP uses RPKI to protect the inter-domain communication of source address, and completes traffic filtering through the cooperation of server, alliance center and AS border router [21]
New technology	Using blockchain to build a distributed trust framework can be used for inter-domain routing protocol to realize IP address prefix authentication [22]

2.2. SR-BE/TE data plane security for zero-trust network environment

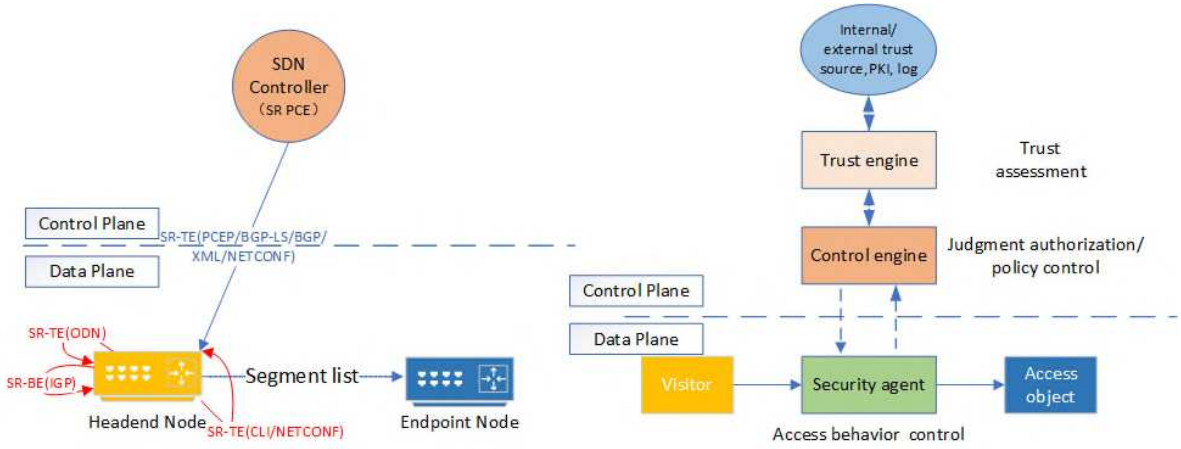
Based on the above analysis and the premise that "no user, device or application are trusted in the zero-trust environment", this paper defines the SR-BE/TE data plane security problem in the zero-trust network environment as threats of untrusted network element and PKI/CA, which is divided into 8 categories, as shown in Table 3. It can be seen that these problems can be attributed to the unreliable data exchange and network audit function of the SR-BE/TE data plane and the lack of relevant security mechanisms.

Table 3. SR security issues for zero-trust network environment

Security issue		Specific description	Major threats
Untrusted network element	Eavesdropping and replay	After the tag of source node and data packet is obtained by eavesdropping, the explicit path of downstream traffic of eavesdropping point will be obtained directly, and replay attack can be realized by replaying normal identity messages to access the network.	Confidentiality and Authenticability
	Message forgery	SR is usually only verified at domain boundary devices. By means of routing protocol flooding mechanism, forging control plane protocol messages, or modifying packet headers, it can change critical flow paths or occupy specific link bandwidth, create routing loops, drop traffic, intentionally report errors and other consequences, and destroy link load balance or block network communication.	Integrity
	Denial of service attack	According to the SR protocol, when the "segment left" field is non-zero, the router in the domain needs to send ICMP messages to the source address of the data packet. Attackers can use this to force SR nodes to generate and send a large number of ICMP messages, thus realizing DoS/DDoS attacks.	Usability
	Identity deception	Because all the nodes in the SR trust domain are under the unified control, it is usually impossible to implement identity deception in the domain, but the nodes outside the domain may access the SR network as nodes in the domain.	Confidentiality and controllability
	Intra-domain detection based on back door of device	By detecting and using the back door of network device, the tag information and data packet payload generated by control protocols such as OSPF for SR are obtained by grabbing packets or tampering with forwarding table entries, and the MPLS/IPv6 tag stack information in them is analyzed to obtain the node tags, link tags and topological relations of downstream device.	Controllability and confidentiality
	In-domain detection based on social	Log in to the device in SR domain without credit by means of social engineering such as cheating passwords, obtain the label and topology information stored by the device by	Controllability and confidentiality

	engineering attack	means of show command, CLI, SNMP and NETCONF with the help of device maintenance and management tools, and use the device as a sniffing springboard and OAM functions such as MPLS tracert and MPLS ping of SR-MPLS network. Construct attack messages with different label stacks and specific TTL to detect network topology, nodes and links hop by hop. In the network which multi-source manufacturers' devices using different control standards coexist, springboard detection is easier to succeed.	
	Failure of intra-domain node	Due to the lack of stable label release mechanism, modifying SRGB of SR router, assigning used labels to it or configuring MPLS label range will lead to service interruption, and the device needs to be restarted.	Usability
PKI/CA failure	Infrastructure failure	Attackers captured network security infrastructure such as PKI/CA through APT attacks, which led to the failure of traffic encryption in SR domain.	Confidentiality and Authenticability

2.3. Coupling foundation of SR and ZTA basic function model



(a)SR basic function model (b) ZTA basic function model

Figure 1. SR basic function model and ZTA basic function model

Figure 1(a) and (b) are the basic functional models of SR and ZTA, respectively, in which components with similar functions are identified with the same color. As shown by the red line and blue line in Figure 1(a), there are two generation modes of Segment list in SR basic function model: self-generation of network element and issuance of the controller; SDN controller, as its control engine, lacks the trust engine for managing trust and internal and external information sources, PKI, logs and other components for storing identity in ZTA model of Figure 1(b), which leads to its unreliable data exchange and network audit functions. Therefore, the two functional models have a certain coupling foundation, and the ZTA trust engine can be integrated into the SDN controller.

3. SR-BE/TE Security Model (ZbSR) Based on ZTA

Based on the above analysis, the ZbSR security model proposed in this paper is mainly composed of trust plane, agent plane, and data plane, as shown in Figure 2, in which the trust plane is composed of the controller (C), key center (K) and information base (D), which is connected to the data plane through agent plane, and whitelist access control is established between planes, which is responsible for centralized control, authentication and trust calculation of data plane devices, in which the controller is based on the expansion of the original SDN controller of SR architecture. The agent plane consists of agent (A) connected in series to each SR data plane device, responsible for providing se-

curity agency services such as encryption, auditing, and reporting. The data plane is composed of switching devices such as SR router (R) and terminal device such as host (H), which is responsible for generating data and transmitting traffic.

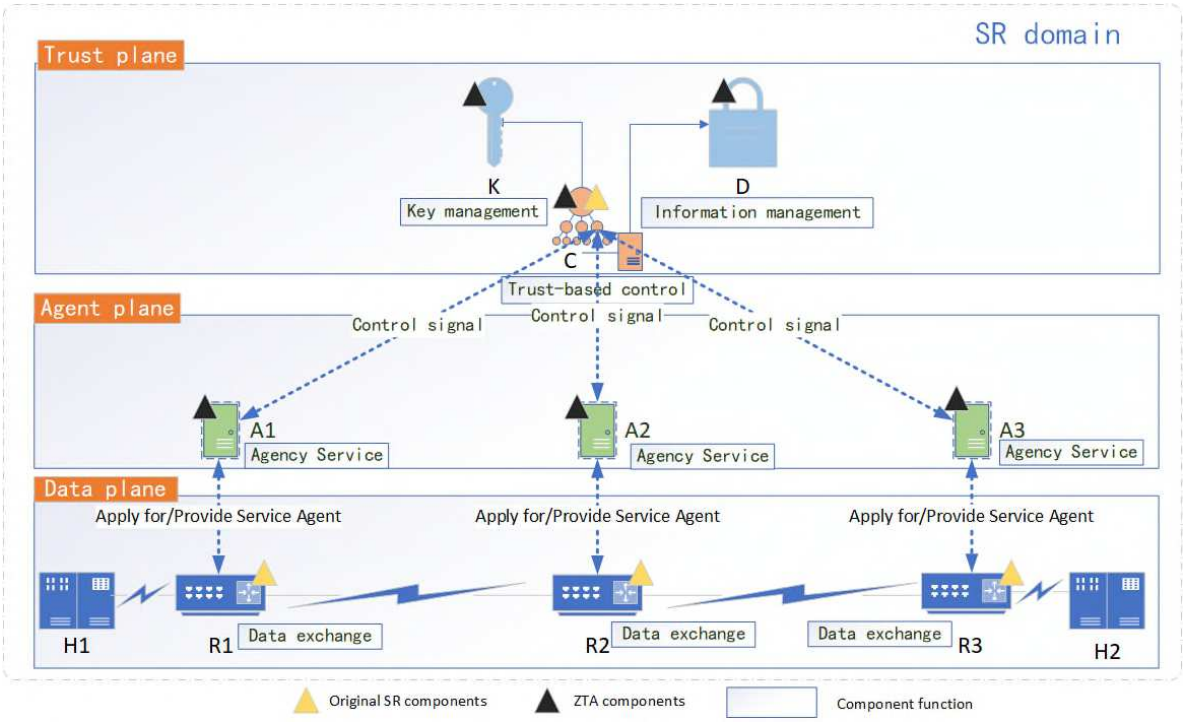


Figure 2. ZbSR security model

The ZSR model is modeled with symbols and definitions in Table 1.

3.1. ZbSR model component function and modeling

The function of the ZbSR model component is that the controller calls the key center (for managing keys) and the information base (for managing and storing identity information) to control the subordinate plane based on trust, and the agent provides security agency services for the data plane.

3.1.1 The controller (C)

The controller consists of the original SDN controller and the trust engine expansion module. It is responsible for realizing access control, path delivery, and other functions based on authentication and trust calculation.

(1) Segment list issuing

In SR-TE, a path is issued for the data plane by generating a Segment list, the Segment list *SL* is shown in formula (1).

$$SL = \left\{ SID_1, SID_2, SID_3, .., SID_i, \ldots, SID_j, \ldots, SID_n \right\} \quad (1)$$

(2) Authentication and authorization

Referring to the security design based on identity control access [24][25] in Software-Defined Perimeter (SDP) [23], the trust engine of the controller performs identity authentication and trust evaluation on the devices in the domain, and then implements the minimum authorization [26], and then the authentication and authorization results are handed over to the SDN controller, which issues control signaling. The access subject and object 5-tuple authorization information Credit is modeled as shown in formula (2), where *Smac* and *Dmac* represent the MAC addresses of the access device and the visited device respectively, *SID* and *pSID* represent the Prefix Node SID assigned by the access device and the visited device respectively, and *P* represents the access protocol.

$$\text{Cre}dit \overset{def}{=} \{\text{Smac} + Dm\text{ac}+SID + P + pSID\} \quad (2)$$

According to the ZTA concept, the authorization mode can be divided into centralized authorization and separate authorization. Centralized authorization means that after authentication and trust evaluation are carried out on the network-connected devices, the list of accessible devices and protocols is granted in a centralized way in the form of an authorization list. As shown in formula (3), the authorization list contains 6 types of information, among which, D^i, $Cert^i$, t_{Certi}, PK_{Di}, P and $K_{D(i)}$ respectively represent the accessible device i, the access certificate of device I, the lease period of the access certificate of device i, the public key of device i, the access protocol and Separate authorization means that device A needs to verify authorization every time it accesses device B through the new protocol. At this time, the authorization information is shown by formula (5), including the access certificate of device B, the lease period of the access certificate of device B, the public key of device B, the access protocol, and the traffic encryption key. Compared with centralized authorization, separate authorization not only achieves fine-grained control but also brings more overhead. Therefore, this paper sets two authorization modes that can be switched as needed.

$$List_A = \{D, Cert_A, t_{Cert_A}, PK, P, K_D^A\} \quad (3)$$

$$\begin{cases} D = \{D^1, D^2, D^3, ..., D^n\} \\ Cert_A = \{Cert_A^1, Cert_A^2, Cert_A^3, ..., Cert_A^n\} \\ t_{Cert_A} = \{t_{Cert_A^1}, t_{Cert_A^2}, t_{Cert_A^3}, ..., t_{Cert_A^n}\} \\ PK = \{PK_{D^1}, PK_{D^2}, PK_{D^3}, ..., PK_{D^n}\} \\ P = \{P_{D^1}, P_{D^2}, P_{D^3}, ..., P_{D^n}\} \\ K_D^A = \{K_D^A(1), K_D^A(2), K_D^A(3), ..., K_D^A(n)\} \end{cases} \quad (4)$$

$$List_A(B) = \{Cert_A^B, t_{Cert_A^B}, PK_B, P_B, K_D^A(B)\} \quad (5)$$

(3) Rules issuing

Before the SR source node starts streaming according to the Segment list, the controller issues security rules for preventing path tampering to the agents of each node in the list, detailed in section 3.2.2.

(4) Device control

The controller centrally controls all devices in the domain, centrally configures their Prefix-SID to prevent the attackers from tampering, and timely removes the failed devices from the list of available devices and recycles their SIDs; storing the suspected malicious device behavior found in the detection into the information base, disabling its access credentials and reporting to the network administrator when the negative feedback accumulation causes its trust to be lower than the threshold; provide the central working clock for each component of the system and provide a unified time reference.

(5) Keys scheduling

Through the agent plane of the controller, the key center is called to centrally distribute the traffic encryption key and other keys to the protocol peers that have been authorized successfully.

3.1.2 Key Center

The key center is used to centrally control the keys in the domain and prevent the potential safety hazard of key decentralized configuration [27]. It adopts the popular "symmetric password-asymmetric password" mixed encryption mechanism [28], in which the fast symmetric password is used for traffic encryption/decryption, and the slow asymmetric password is used for key exchange and signature verification; because ZTA doesn't trust public PKI/CA, the key center is used as the private CA in the domain to issue digital certificates to the terminal devices in the domain [29]. The managed keys include traffic encryption key K_D, key-encryption key KeK, its own public and private keys K_{pub} and K_{pri}, and the public and private keys R_{pub} and R_{pri} of each terminal device. All keys are replaced

regularly to prevent abuse. To simplify the configuration, duplicate keys can be configured for the nodes in an SR Anycast group. The use of all kinds of keys can be divided into 4 steps, as shown in Figure 3.

Step1 K preallocates the public and private keys for all terminal devices, sends them through C, deposits them in A, and replaces them regularly;

Step2 K allocates K_D and *KeK* as needed for data exchange between H_i and H_j, which is issued by C, stored in A, and replaced regularly;

Step3 A_i and A_j use the public and private keys of H_i and H_j to negotiate K_D and *KeK*;

Step4 H_i and H_j exchange data with K_D and *KeK*.

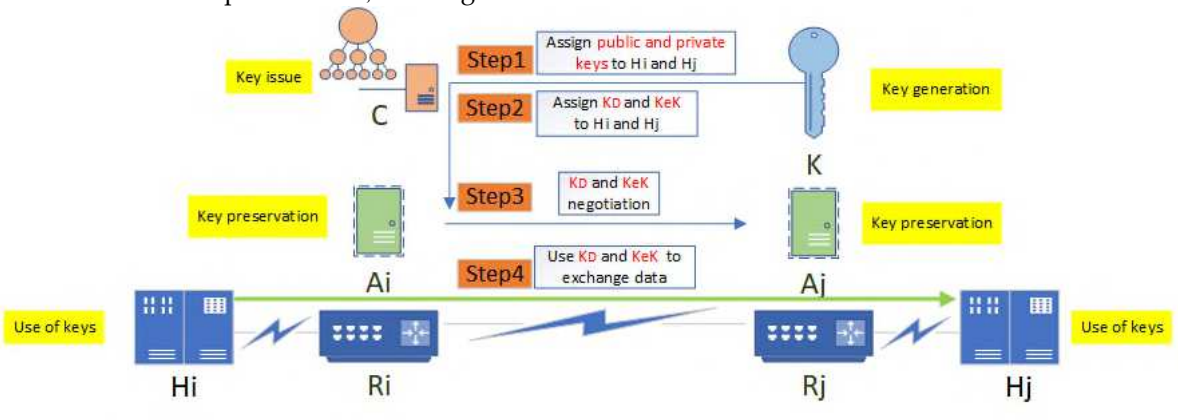


Figure 3. ZbSR key usage process

3.1.3 Information base

The information base is used to store and manage device authentication information and protocol authorization information. The device authentication information is related to authentication information of the device itself, such as username/password, SID, router-mac, etc. [30], which is determined by the formula (6), and the protocol authorization information is related to the protocol authorization. Such as *Whitelist* of connection, routing protocol type P_R, link Adjacency Adj_{ij}, port number *Interface*, peer IP address IP_p, etc., are determined by the formula (7), in which Adj_{ij} is determined by the adjacency matrix of link, as shown in formula (8), which describes the adjacency of device, with 1 indicating adjacency and 0 indicating non-adjacency; the Whitelist of connections is determined by the formula (9), which specifies all permitted connections in the domain, and the information in the information base is dynamically updated with the change of network devices.

$$I_a(i) \overset{def}{=} \{Uname + Upass + SID + Rmac\} \tag{6}$$

$$P_a(i,j) \overset{def}{=} \{Interface_i + Adj(i,j) + Whitelist + P_R + IP_j\} \tag{7}$$

$$Adjacency = \begin{pmatrix} Adj_{11} & \mathrm{K} & Adj_{1m} \\ \mathrm{M} & Adj_{ij} & \mathrm{M} \\ Adj_{m1} & \mathrm{L} & Adj_{mm} \end{pmatrix}, Adj_{ij} = (1,0) \tag{8}$$

$$Whitelist = \{(SID_i, SID_j), ..., (SID_i, A_k), ..., (A_k, C), ...\} \tag{9}$$

3.1.4 Agent

The agent is used to provide security agency service for data plane devices, and it is directly connected with each SR switching device [31]. There is no direct connection channel between agents, to prevent malicious nodes from bypassing trust plane supervision and direct communication. The agent mainly has 4 functions: key management, path report, log record, and behavior audit. Key management means that the agent provides key negotiation agent services for data plane devices; path report implies that after the SR head node generates the flow path, it needs to report the path to the controller through

the agent for decision-making; logging refers to recording the behavior log of SR switching device to trace the malicious behavior; behavior audit refers to auditing the behavior of data plane devices together with the controller according to the network audit security algorithm in Section 3.2.2.

3.2 Data exchange and network audit security algorithm of ZbSR model

To ensure the integrity, confidentiality, and availability of data in the SR domain, the ZSR model introduces five security mechanisms: packet authentication, data encryption, check and filtering, security audit, and trust renewal.

3.2.1 Data exchange security algorithm based on trust evaluation

To realize reliable east-west data exchange between switching devices, firstly, based on ZTA's security design of "first authentication, then connection", a UDP-based SPA (Single Packet Authorization) method is adopted to initiate pre-authentication to the trust plane, and the trust plane carries out the north-south security authentication based on identity authentication, trust evaluation, and key negotiation. Secondly, the terminal device realizes the encrypted traffic exchange by encrypting traffic with a key. Taking the separate authorization mode as an example, the simplified process of terminal H1 accessing H2 is shown in Figure 4, implemented in two modes: Segment list generation by the network element and Segment list distribution by the controller.

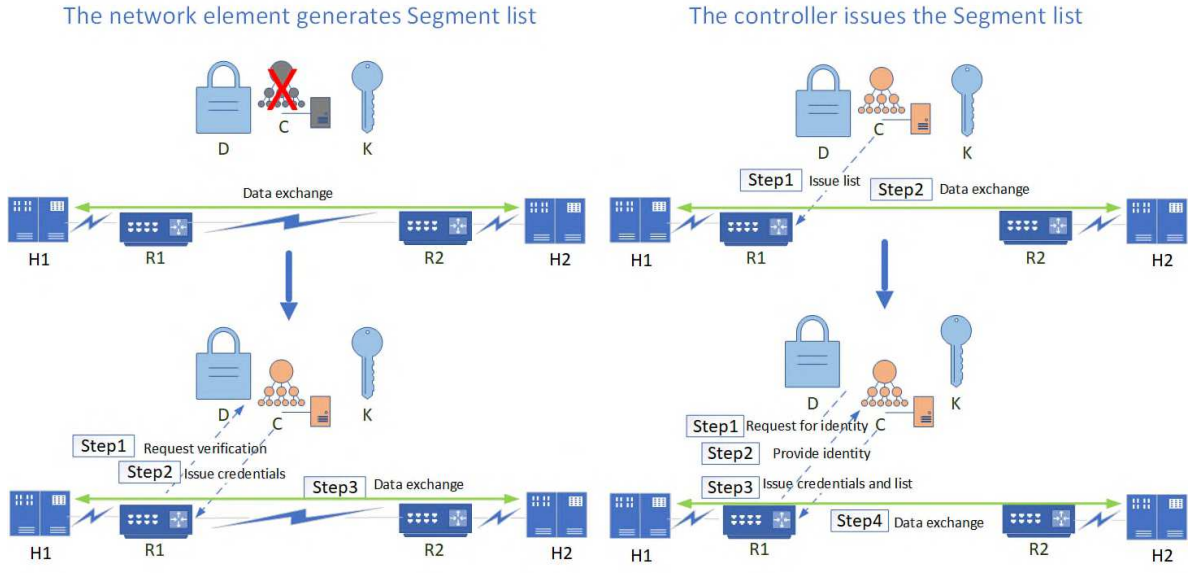


Figure 4. Simplified ZbSR access process

(1) Mode for the network element to generate Segment list

In this case, the data exchange process is shown in Figure 5, and the pseudo-code of the process is shown in Algorithm 1.

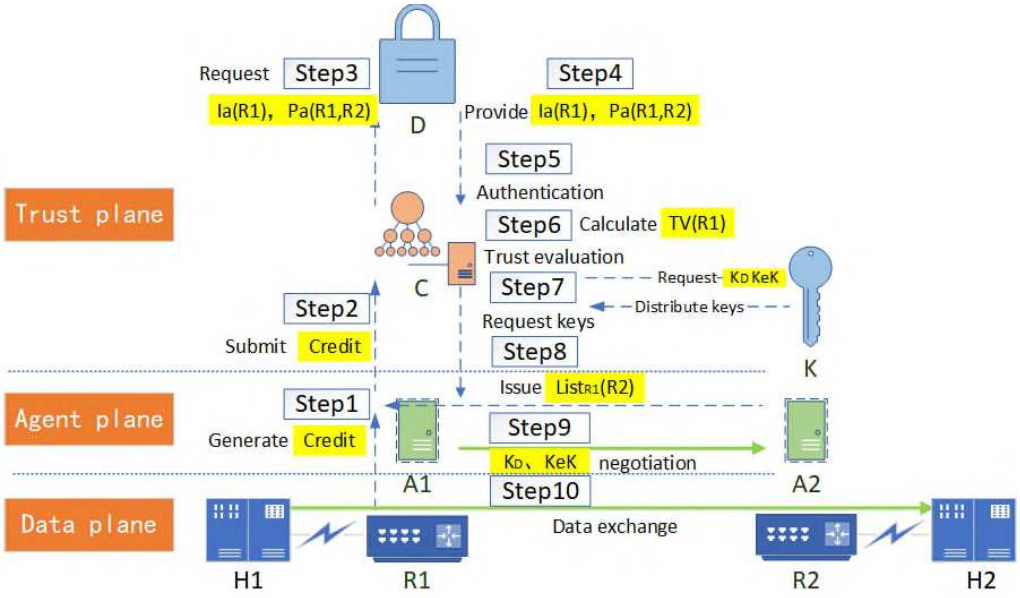


Figure 5. Data exchange process in the mode for the network element to generate Segment list

Algorithm1 data exchange security algorithm in the mode for the network element to generate Segment list

Input: MAC address *Smac* and Prefix Node SID *SID* of routing device R1,
MAC address *Dmac* and Prefix Node SID *pSID* of routing device R2,
Segment list *segment* generated by device R1, residual transmission flow from R1 to R2, trust threshold *Th*,
public key MP_{pub} and private key MP_{pri} of device H1, public key SP_{pub} and private key SP_{pri} of device H2

Output: the result of data exchange between terminal devices H1 and H2 (1: success; 0: fail)

1. Deploy IACL filtering policy for R1, and filter the access of out-of-domain nodes to the intra-domain segments according to source IP, destination IP, SRH, etc. //Prevent service theft.
2. Headend node R1 automatically generated *segment* and prepare to send data
3. A1 and A2 collect *Smac, Dmac, SID, pSID* of R1 and R2 respectively, and A1 combines above information with P to generate *Credit*
4. A1 submits *Credit* as SPA package load to C //A1 initiates single verification package to C
5. C applies for $I_a(R1), P_a(R1,R2)$ from D
6. D provides $I_a(R1), P_a(R1,R2)$ to C
7. C ***call*** $subalgorithm_{IA}$ according to Credit, $I_a(R1)$、$P_a(R1,R2)$ // Call for authentication sub-algorithm
8. ***if*** $subalgorithm_{IA}(R1, R2)=1$
9. ***then*** C ***call*** $subalgorithm_{TE}$ //Call for trust evaluation sub-algorithm
10. ***if*** $subalgorithm_{TE}(R1) \geq Th$
11. ***then*** C applies to K to allocate K_D and *KeK*
12. K allocates K_D and *KeK* for C
13. Establish a bidirectional encrypted connection between C and A1 //mTLS [32] can be adopted
14. C sends $List_{R1}(R2)$ to A1
15. A1 and A2 represent H1 and H2 respectively, and call $subalgorithm_{KN}$ // Call for key negotiation sub-algorithm
16. **if** $subalgorithm_{KN}(MP_{pub}, MP_{pri}, SP_{pub}, SP_{pri}, K_D, KeK)$ =1
17. ***while*** *flow*>0 ***do***
18. H1 and H2 use K_D and *KeK* to transport encrypted traffic
19. *flow=flow-*
20. ***end while***

21. ***output*** 0
22. ***end if***
23. ***output*** 1
24. ***else return*** 0
25. ***end if***
26. ***else return*** 0
27. ***end if***

(2) Mode for the controller to issue Segment list

In this case, the data exchange process is shown in Figure 6, and the pseudo-code of the process is shown in Algorithm 2.

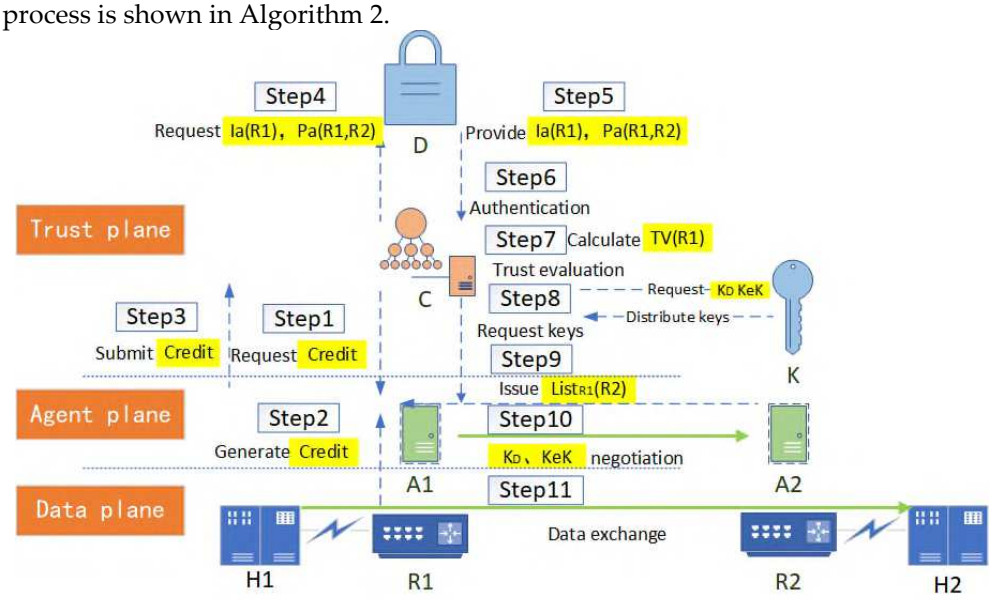


Figure 6. Data exchange process in the mode for the controller to issue Segment list

Algorithm2 data exchange security algorithm in the mode for the controller to issue Segment list

Input: MAC address *Smac* and Prefix Node SID *SID* of routing device R1,

MAC address *Dmac* and Prefix Node SID *pSID* of routing device R2,

Segment list *segment* generated by controller, residual transmission flow from R1 to R2, trust threshold *Th*,

public key MP_{pub} and private key MP_{pri} of device H_1, public key SP_{pub} and private key SP_{pri} of device H2

Output: the result of data exchange between terminal devices H_1 and H_2 (1: success; 0: fail)

1. C generated *segment* and prepare to send it to the headend node, then C ask the headend node R1 and the endpoint node R2 to upload their *Credit* //If there are intermediate nodes between R1 and R2, it is necessary to upload their macs and SIDs.
2. A1 and A2 collect the *Smac, Dmac, SID, pSID* of R1 and R2 respectively, and , and A1 combines above information with P to generate *Credit*
3. A1 submits *Credit* as SPA package load to C //The following is the same as algorithm 1.
4. …***call*** … $subalgorithm_{IA}$ **…**
5. …***call*** … $subalgorithm_{TE}$ **…**
6. …***call*** **…** $subalgorithm_{KN}$ **…**

The authentication sub-algorithm, trust evaluation sub-algorithm, and key negotiation sub-algorithm called by algorithms 1 and 2 are shown as $subalgorithm_{IA}$, *subalgo-*

rithm$_{TE}$, and *subalgorithm*$_{KN}$. In *subalgorithm*$_{TE}$, trust renewal can be implemented for temporary trust granted based on security metrics, but this scheme has not been implemented in this paper due to limited research energy.

subalgorithm$_{IA}$ authentication sub-algorithm

Input: *Credit* of devices Ri and Rj,

device authentication information $I_a(Ri)$, protocol authentication information $P_a(i,j)$, number of devices to be authenticated l

Output: device identity authentication result (1: true; 0: false)

1. ***while*** l>0 ***do***
2. C extracts macs from the *Credit* of Ri and Rj respectively, and records them as $Mac1_{Ri}$, $Mac1_{Rj}$
3. C extract SIDs and macs of Ri and Rj from$I_a(Ri)$, and record them as SID_i, SID_j, $Mac2_{Ri}$, $Mac2_{Rj}$
4. C extract Whitelist from $P_a(i,j)$
5. ***if*** $Mac1_{Ri} = Mac2_{Ri} \vee Mac1_{Rj} = Mac2_{Rj}$ // Compare the identity of devices Ri and Rj
6. ***if*** $(\mathrm{SID_i}, SID_j) \in Whitelist$ // Check whether the connection relationship between Ri and Rj belongs to the *whitelist*
7. ***then return*** 1
8. ***else return*** 0
9. ***end if***
10. ***else return*** 0
11. ***end if***
12. l=l-1
13. ***end while***

subalgorithm$_{TE}$ trust evaluation sub-algorithm

Input: device r, device set R^m, number of devices in device set m

Output: device trust value $TV(r)$

1. Initialize $TV(r)=0$, $TV(r)\in[-1,1]$ // $TV(r)=1$ means trust device r completely, while $TV(r)=-1$ means that don't trust device r completely
2. Set the evaluation set to $R_a = R - r$, the trust value of C to the evaluation node R_a^i is T_{C,R_a^i} , the threshold value of T_{C,R_a^i} is $Th(T_{C,R_a^i})$, which meeting $-1 \le T_{C,R_a^i} \le Th(T_{C,R_a^i}) \le 1$, $T_{C,R_a^i} = 1$ //The controller does not grant subjective trust to the switching device, but determines it according to the recommendation of other nodes; set the controller's initial trust value to all recommenders as 1.
3. ***while*** $0 < n \le \mathrm{m} - 1$ ***do*** //filter evaluation set
4. For the evaluation node R_a^i, calculate the probability that the monitored device r faithfully forwards packets and record it as $F_{R_a^i,r}$ //Take $F_{R_a^i,r}$ as the recommended trust value of R_a^i to r [33]
5. Calculate the current trust value of device r: $TV_{tem} = \sum_{i=1}^{n}(\frac{T_{C,R_a^i}}{\sum_{i=1}^{n} T_{C,R_a^i}} \times F_{R_a^i,r})$ //Get the instantaneous trust value of device r based on the current and previous recommendation values of all recommenders by weighted average
6. Calculate the difference $dv_{C,R_a^i} = |TV_{tem} - F_{R_a^i,l}|$ between the recommended trust value $F_{R_a^i,r}$ from R_a^i and current instantaneous trust value of r//This result can reflect the deviation degree between the given recommended opinion and the overall opinion, which is used as the basis for feedback on the trust degree of the recommender R_a^i based on

his recommendation

7. Set the threshold of the difference dv_{ir} to $Th(dv_{ir})$, and the reward and punishment factors are *rd* and *p* respectively, which meet the requirements $p > rd$
8. Calculate the trust value of C to the evaluation node $R_a^i : T_{C,R_a^i} = \begin{cases} T_{C,R_a^i} + rd, dv_{C,R_a^i} < Th(dv_{ir}) \\ T_{C,R_a^i} - p, dv_{C,R_a^i} \geq Th(dv_{ir}) \end{cases}$

//evaluate the trust of the evaluation node based on the recommendation feedback

9. ***if*** $T_{C,R_a^i} < Th(T_{C,R_a^i})$
10. ***then*** remove R_a^i form R_a *// When the recommender's trust level falls below the threshold, it will be removed out of the evaluation set*
11. ***end if***
12. ***end while***
13. Set the number of interactions between R_a^i and *r* to $n_{R_a^i,r}$
14. $TV(r) = \sum_{l=1}^{card(R_a)} \left(\frac{CR_{ir_l} \times n_{R_a^i,r}}{\sum_{l=1}^{n} CR_{ir_l} \times n_{R_a^i,r}} \times F_{\eta j} \right) \times e^{-1/card(R_a)}$ //Trust value of device *r* is the weighted average of the recommended values from the evaluation set, and the evaluation set size $card(R_a)$ and the number of interactions $n_{R_a^i,r}$ between the evaluation set elements and device *r* are used for optimization
15. ***output*** $TV(r)$

subalgorithmKN key agreement sub-algorithm

Input: public key MP_{pub} and private key MP_{pri} of H_i^k connected with device R_i, public key SP_{pub} and private key SP_{pri} of H_j^l connected with device R_j, data encryption key K_D, key encryption key KeK

Output: the result of key negotiation between H_i^k and H_j^l (1: completed; 0: failed)

1. A_i uses KeK to encrypt K_D: $C_{K_D} = E_{KeK}(K_D)$
2. A_i uses SP_{pub} to encrypt KeK : $C_{KeK} = E_{SP_{pub}^j}^{H_j^l}(KeK)$
3. A_i uses MP_{pri} to sign K_D : $D_{K_D} = D_{SP_{pri}^i}^{H_i^k}(K_D)$ [34]
4. A_i binds the above results to triple message *CCK (i, j)*, so that $CCK(i,j) \overset{def}{=} \{C_{K_D}, C_{KeK}, D_{K_D}\}$
5. A_i sends $CCK(H_i^k, H_j^l)$ to A_j via C
6. A_j receives $CCK(H_i^k, H_j^l)$
7. A_j uses SP_{pri} to decrypt C_{KeK} : $KeK = D_{SP_{pri}^j}^{H_j^l}(C_{KeK})$
8. A_j uses KeK to decrypt C_{K_D} : $K_D = D_{KeK}(C_{K_D})$
9. A_j uses MP_{pub} to authenticate signature D_{K_D} : $K_D' = E_{SP_{pub}^i}^{H_i^k}(D_{K_D})$
10. ***if*** $K_D = K_D'$
11. ***then*** H_i^k、H_j^l save K_D、KeK
12. ***else*** alerts the operator, ***return*** 0
13. ***return*** 1
14. ***end if***

3.2.2 Network audit security algorithm based on solid authentication

Due to the lack of audit mechanism for threat representation in SR network, a network security audit algorithm is proposed based on ZTA's strategy of solid verification of all behaviors in the domain. The pseudo-code of related process is shown in algorithm 3. The audit content includes the following 6 aspects.

(1) Field audit: audit whether the TTL value of the packet header is legal and whether the outbound traffic of the domain egress router has removed the SRH.

(2) Behavior audit: audit whether the rate of ICMP information generation reaches the threshold for enabling the ICMPv6 rate-limiting mechanism and whether the traffic which cannot find next-hop to be malicious.

(3) Loop audit: if the label stack only uses Prefix-SID, then directly determine whether there is a loop according to the following subalgorithmLP; if the label stack contains Adjacency-SID, restore the network topology according to the label stack, and then determine the loop according to subalgorithmLP.

(4) Label audit: audit the validity of SRGB labels, SRLB labels of specific border routers, and other external labels.

(5) Path audit: audit whether the flow path has been tampered with by malicious intermediate nodes. As shown in Figure 7, the controller issues a segment list {16007} to node 3, and according to the list, issues security rules to all intermediate nodes (node 5 at this time) along the path: the top label of the received packet from the interface from node 3 to node 5 should be 16007; otherwise, it is discarded.

(6) SID audit: audit whether the SID of a flow path node has been tampered with by malicious intra-domain nodes; it can be divided into two steps. As shown in Figure 8, the controller centrally configures the Prefix-SID, router-id of each device node, imports them into the information database in advance, and synchronizes them to each device node through LSA notifications. Each device node caches its own and other node SIDs to Label Manager (LM); in the first step, when each device node receives a new LSA notification, it will be audited and compared with the SID cached by the LM. It will be considered valid and received only if the matching is successful. If the matching fails, it will report an exception to the controller, then the controller determines whether there is an attack; the second step is to refer to LM and FIB (Forwarding Information dataBase) to audit whether the SID has been tampered with during streaming. If an unrecognized SID is found in the LM, it will be further matched in the information database. If the matching fails, it will be reported to the operator.

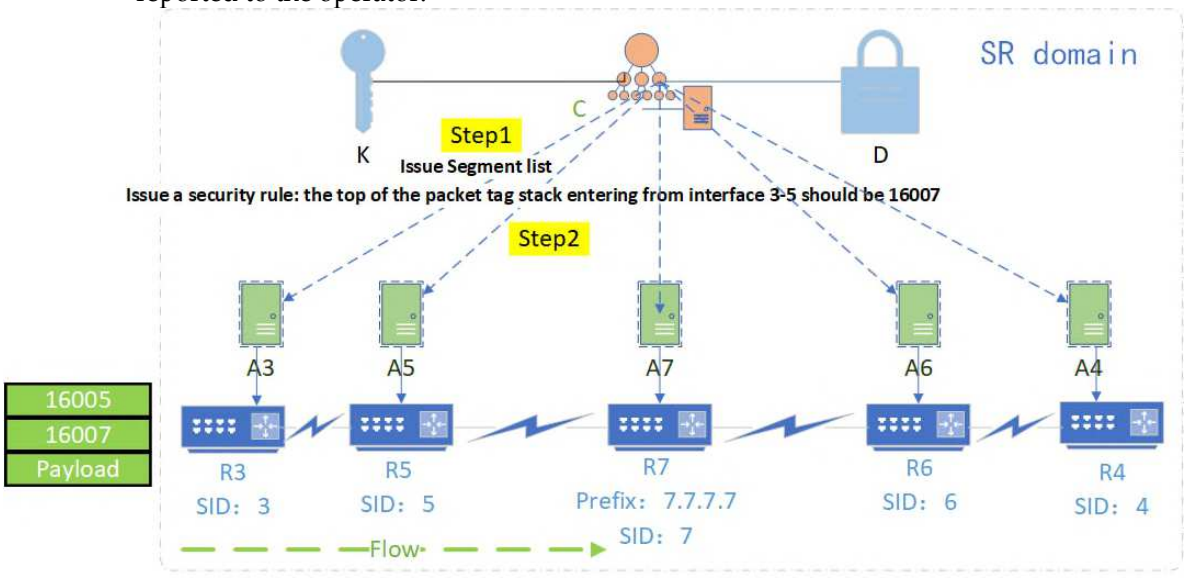


Figure 7. Schematic diagram of SR rule audit

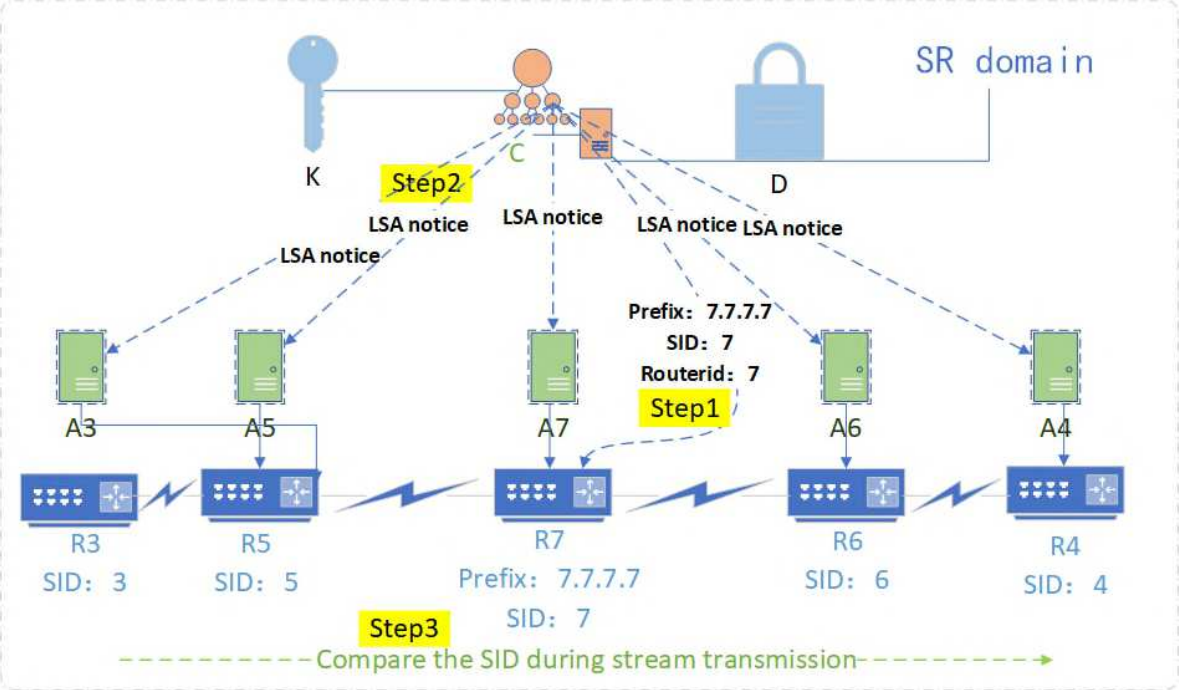


Figure 8. Schematic diagram of SR SID audit

Algorithm3 Network audit security algorithm based on strong authentication

Input: Topology $G = (V, L)$, number of nodes n, number of flows k,
Segment list $SL = \{SID_1, SID_2, SID_3, ..., SID_i, \ldots, SID_j, \ldots, SID_n\}$

Output: Safety audit results (1: passed; 0: failed)

1. Initialize variables j, t, v = 0//respectively represent the current ICMP message generation amount, time and ICMP message generation rate
2. Initialize T, V//Threshold of variables t, v
3. ***while*** $t \le T \vee v \le V$ ***do***// Within the requirements of streaming period and ICMP information rate range
4. j increments with each ICMP message generated
5. $v = \frac{j}{t}$
6. ***for*** $I = 1$ ***to*** M / // Traverse each agent
7. Initialize set $P, Q = \{\emptyset\}$//P，Q are used to store all the message headers and label stacks of the flows corresponding to each agent respectively
8. ***for*** $i = 1$ *to* K_i // For each data flow of the agent
9. Extract all headers in the data stream to P
10. ***if*** TTL field of headers are legal
11. Extract all tag stacks in the data stream to Q.
12. ***call*** $subalgorithm_{LP}$ // Call the loop audit sub-algorithm
13. ***if*** $subalgorithm_{LP}(SL) = 1$
14. *if* the order of the node labels in the label stack corresponds to the actual topology //Tag audit
15. ***if*** all intermediate nodes of flow comply with security rules and SIDs have not been tampered with //Path audit and SID audit
16. ***then*** start streaming
17. *if* the flow which reaches the node can find the corresponding tag // Behavior audit
18. Stream continues
19. ***else return*** 0 // Behavior audit failed
20. ***end if***
21. ***return*** 1
22. ***else return*** 0 //Path audit and SID audit failed
23. ***end if***

```
            else return 0 //Tag audit failed
            end if
          else return 0 // Loop audit failed
          end if
        else return 0 // Field audit failed
        end if
      end for
    end for // Field audit completed
  end while
  Discard packet// The packet timed out or ICMP rate exceeded the limit
  return 0
```

The *subalgorithm*$_{LP}$ called in algorithm 3 is as follows.

subalgorithm$_{LP}$ loop audit sub-algorithm

Input: Segment list $SL = \{SID_1, SID_2, SID_3, .., SID_i, \ldots, SID_j, \ldots, SID_n\}$

Output: Loop detection result (1: none; 0: exist)

1. Set the number of intermediate nodes between SID_i and SID_j to N_{ij}, and the set of intermediate nodes to $F^{N_{ij}}$
2. *for* $i = 1; i \le n; i++$
3. *for* $j = i; j \le n; j++$
4. *if* $SID_i \notin \{SID1, SID2, ..., SID_{i-1}\} \vee \{SID1, SID2, ..., SID_{i-1}\} \notin F^{N_{ij}}$ //Determine whether there are duplicate tags in SL, and the intermediate nodes between any two nodes R_i and R_j must not contain the nodes before R_i in the Segment list
5. *then output* 1
6. *else output* 0
7. *end if*
8. *end for*
9. *end for*

3.3 ZbSR model security overhead

According to different components, the security cost of the ZbSR model is divided into 6 parts, that is, controller cost, key center cost, information base cost, agent cost, encryption cost of terminal devices, and component synchronization cost. Because all kinds of security components run in parallel, in addition to the one-time hardware cost brought by the introduction of devices, the evaluation of system performance cost only needs to pay attention to the time delay item that has the most significant influence on streaming transmission. The related symbols and definitions are shown in Table 4.

Table 4. Definitions of symbols in the ZbSR model

symbol	definition
M	Number of agents
N	Number of device nodes
N_t	Number of nodes in communication
N_f	Flow quantity
N_f^i	Number of streams that agent i flows through
k1	Flow speed
k2	Constant
n_i	Number of message segments in each stream
μ	Key update period

The first is the controller overhead. If the performance allows, controller can be deployed single, and it can also be deployed multiple to realize load balancing and disaster

recovery. The cost is related to the number of devices N it controls, and the cost is associated with the number of streams N_f when it issues paths and rules. When authenticating, the cost is related to N; when controlling the device, it is only performed when the device leaves the network, or malicious device is generated, and the occurrence probability is small and can be ignored; when scheduling the key, it is only issued to the nodes in communication after the key is updated, so the computational complexity of the controller overhead is $O(N + N_f)$. The second is the key center overhead. There is only one set in the SR domain, and the cost mainly comes from its regularly key updating, and its computational complexity is $O(N_t \times \frac{k2}{\mu})$. The third is the information base overhead. In-domain devices cache commonly used verification information to the local agent, and the information base only needs to import information when the topology is established, verify information when new users access the network, and update the information when devices change, so the overhead is negligible compared with the controller. The fourth is the agent overhead. The agent is used in every streaming for key management, path reporting, and logging, which is related to N_f^i; in behavior audit, the time complexity of field audit is $\sum_1^{N_f}(k1 \times n_i)$: Behavior audit is triggered only when abnormal traffic occurs, and the overhead can be ignored. Other auditing functions are only related to the number of streams N_f^i, so the computational complexity of agent overhead is $O(\sum_1^{N_f}(k1 \times n_i) + \sum N_f^i)$, namely $O(\sum_1^{N_f}(k1 \times n_i) + N_f)$. The fifth is the encryption overhead of terminal devices. If hardware devices are used for encryption, the efficiency is high, so the time delay can be ignored. However, if software devices are used for encryption, it will take more time. The sixth is the component synchronization overhead. Usually, there is only one controller deployed in the domain, and the information between agents does not have to be identical, so only the key negotiation and authentication need to be synchronized. Here, the Raft state synchronization technology is implemented according to the flow information between devices, and the overhead is low and can be ignored. It can be seen that the security overhead of the ZbSR model is concentrated in 3 parts: controller, agent, and terminal device encryption.

4 Simulation test and analysis

4.1 Simulation Settings

OpenDaylight open-source controller is installed based on KVM virtual machine in EVE-NG 3.0.1-16 PRO, and its function is programmed to realize ZbSR controller. Dedicated Linux virtual machine is used as agent. Because it is challenging to build private CA, information base, and encryption hardware, and it is not the focus of research, this paper adopts a simplified design and uses virtual machines based on X.509 protocol and DES encryption software to simulate key center. Virtual machine simulation information base based on MySQL database. Due to the lack of mature and comparable SR security models, the ZbSR model is compared with the SR Baseline model and the MFRA model [35], among which the SR Baseline model has been introduced in section 2.3. In the MFRA model, the multi-fault quick recovery and avoidance mechanism based on SR pre-deployment link ring backup is mainly applied, and the configuration of test objects is shown in Table 5. There are 5 security tests and 1 overhead tests: control plane message tampering, data plane loop attack, identity deception, backdoor exploitation, and DoS attack. The simulation network topology is shown in Figure 9, in which the components of the Baseline model and MFRA model are shown by the red box in the figure, that is, they include the SR native network composed of 5 Cisco xrv9k routers and 1 OpenDaylight controller based on KVM; ZbSR model, based on KVM, additionally set an information base, an expansion controller and a key center, and each router is connected with another KVM virtual machine as an agent.

Table 5. Test object configuration

	ZbSR	Baseline	MFRA
Physical machine/virtual machine operating system	Ubuntu18.04/ Ubuntu16.04		
Physical machine CPU	Core i7-7700 3.6GHz		
Physical/virtual machine memory	32GB/2GB		
controller	OpenDaylight		
southbound interface	PCEP/NETCONF		
Data plane	MPLS		
Additional security mechanism	Data exchange security algorithm, network audit security algorithm	none	Backup, multi-failure recovery and re-failure avoidance

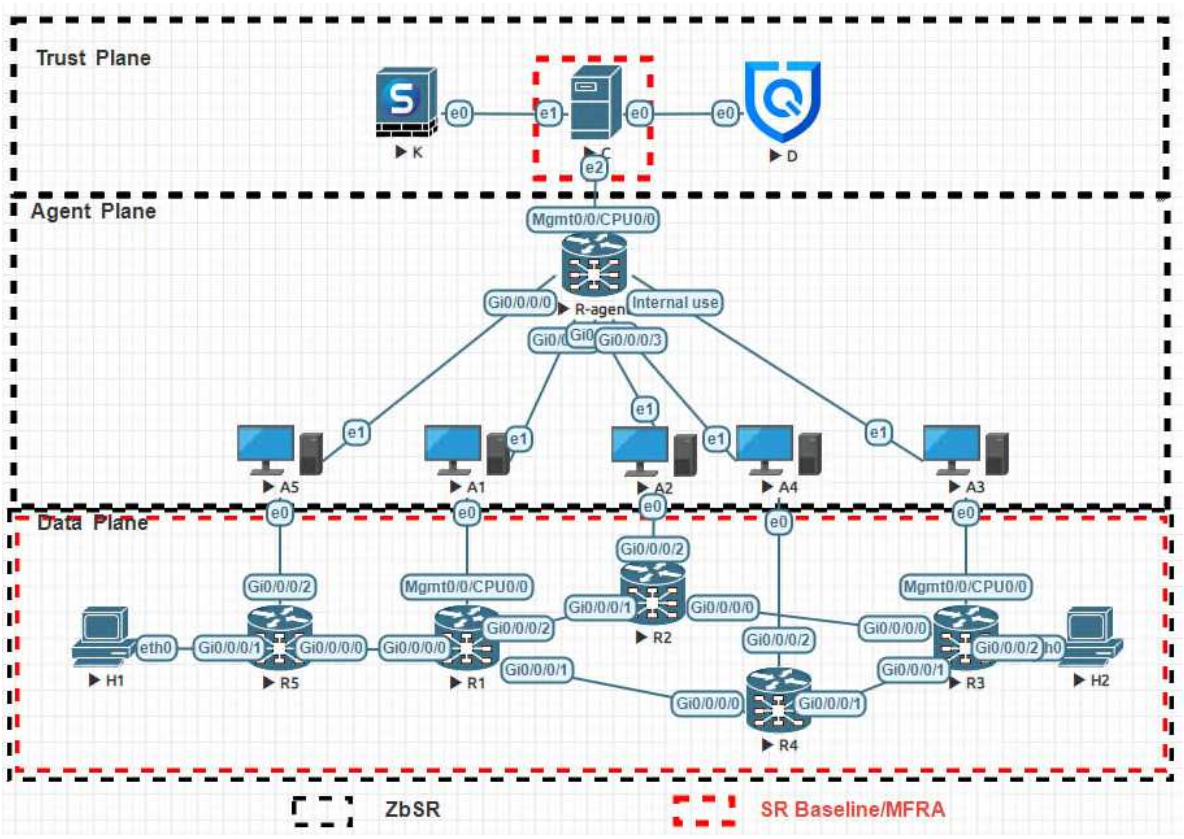


Figure 9. Simulation network topology

4.2 Safety performance test and analysis

4.2.1 Control plane message tampering

Configure the Loopback 0 address of the 2.2.2.2/32 for the R2 device, and assign it SID:16222. At this time, it is found that the next-hop corresponding to the tag 16222 in the source route on the R1 device points to R2 by grabbing the packet with the Wireshark tool, as shown in Figure 10. At this time, the attacker tampered with the control plane message using routing protocol flooding mechanism, etc., set the Loopback 0 address of R4 device to the same 2.2.2.2/32 as R2 and set the link cost value between R1 and R4 to half of the link cost value between R1 and R2. At this time, because the Baseline model use none additional security mechanisms, the MFRA model only takes effect after node and link failures are found. According to the SR mechanism, the next-hop corresponding to R1 selection label 16222 will prefer R4. As shown in Figure 11, the traffic path has been tampered, which may cause the traffic to enter the untrusted node and result in information

leakage. However, the ZbSR model rejected the tampering of the control plane message by using the security audit algorithm, and the traffic path was not tampered with, still as shown in Figure 10.

```
RP/0/RP0/CPU0:ios#show mpls forwarding prefix 2.2.2.2/32 detail
Tue Jan 19 03:13:48.354 UTC
Local  Outgoing    Prefix            Outgoing     Next Hop        Bytes
Label  Label       or ID             Interface                    Switched
------ ----------- ----------------- ------------ --------------- ------------
16222  Pop         SR Pfx (idx 222)  Gi0/0/0/0    10.1.1.2        320
     Updated: Jan 19 03:13:09.725
     Version: 696, Priority: 1
     Label Stack (Top -> Bottom): { Imp-Null }
     NHID: 0x0, Encap-ID: N/A, Path idx: 0, Backup path idx: 0, Weight: 0
     MAC/Encaps: 4/4, MTU: 1500
     Outgoing Interface: GigabitEthernet0/0/0/0 (ifhandle 0x01000018)
```

Figure 10. Original control plane message

```
RP/0/RP0/CPU0:ios#show mpls forwarding prefix 2.2.2.2/32 detail
Tue Jan 19 03:10:11.352 UTC
Local  Outgoing    Prefix            Outgoing     Next Hop        Bytes
Label  Label       or ID             Interface                    Switched
------ ----------- ----------------- ------------ --------------- ------------
16222  Pop         SR Pfx (idx 222)  Gi0/0/0/1    40.1.1.4        640
     Updated: Jan 19 03:07:03.111
     Version: 691, Priority: 1
     Label Stack (Top -> Bottom): { Imp-Null }
     NHID: 0x0, Encap-ID: N/A, Path idx: 0, Backup path idx: 0, Weight: 0
     MAC/Encaps: 4/4, MTU: 1500
     Outgoing Interface: GigabitEthernet0/0/0/1 (ifhandle 0x01000028)
```

Figure 11. Tampered control plane message

4.2.2 Data plane loop attack

By pressing the MPLS label stack {R1→R2→R3→R4→R1} into the head node to construct a loop attack packet, and capturing packets from R1~R4, the message flow of Figure 12 (a), (b), (c), (d) and (e) can be obtained in the Baseline model. It can be seen that the stream starts from R1 (the source IP is 1.1.1.1), and the MPLS labels from R1 to R4 pop up hop by hop. The MFRA model mainly realizes fast route recovery through data plane link backup and does not identify loop attacks as faults, consistent with Figure 12 corresponding to the Baseline model. However, the ZbSR model detects the loop attack through the loop audit algorithm, and the above attack consequences do not appear.

```
▸ Frame 363: 94 bytes on wire (752 bits), 94 bytes captured (752 bits) on interface 0
▸ Ethernet II, Src: 50:0c:00:05:00:05 (50:0c:00:05:00:05), Dst: 50:0c:00:01:00:05 (50:0c:00:01:00:05)
▸ MultiProtocol Label Switching Header, Label: 16222, Exp: 0, S: 0, TTL: 63
▸ MultiProtocol Label Switching Header, Label: 16333, Exp: 0, S: 0, TTL: 64
▸ MultiProtocol Label Switching Header, Label: 16444, Exp: 0, S: 0, TTL: 64
▸ MultiProtocol Label Switching Header, Label: 16111, Exp: 0, S: 1, TTL: 64
▸ Internet Protocol Version 4, Src: 172.18.3.91, Dst: 1.1.1.1
▸ Internet Control Message Protocol
```

(a) The message received by R1 pops up the 16111 label

```
▸ Frame 448: 90 bytes on wire (720 bits), 90 bytes captured (720 bits) on interface 0
▸ Ethernet II, Src: 50:0c:00:01:00:03 (50:0c:00:01:00:03), Dst: 50:0c:00:02:00:03 (50:0c:00:02:00:03)
▸ MultiProtocol Label Switching Header, Label: 16333, Exp: 0, S: 0, TTL: 62
▸ MultiProtocol Label Switching Header, Label: 16444, Exp: 0, S: 0, TTL: 64
▸ MultiProtocol Label Switching Header, Label: 16111, Exp: 0, S: 1, TTL: 64
▸ Internet Protocol Version 4, Src: 172.18.3.91, Dst: 1.1.1.1
▸ Internet Control Message Protocol
```

(b) The message received b) R2 pops up the 16222 label

```
▸ Frame 486: 86 bytes on wire (688 bits), 86 bytes captured (688 bits) on interface 0
▸ Ethernet II, Src: 50:0c:00:02:00:04 (50:0c:00:02:00:04), Dst: 50:0c:00:03:00:04 (50:0c:00:03:00:04)
▸ MultiProtocol Label Switching Header, Label: 16444, Exp: 0, S: 0, TTL: 61
▸ MultiProtocol Label Switching Header, Label: 16111, Exp: 0, S: 1, TTL: 64
▸ Internet Protocol Version 4, Src: 172.18.3.91, Dst: 1.1.1.1
▸ Internet Control Message Protocol
```

(c) The 16333 label pops up for the message received by R3

```
Frame 577: 82 bytes on wire (656 bits), 82 bytes captured (656 bits) on interface 0
Ethernet II, Src: 50:0c:00:03:00:03 (50:0c:00:03:00:03), Dst: 50:0c:00:04:00:03 (50:0c:00:04:00:03)
MultiProtocol Label Switching Header, Label: 16111, Exp: 0, S: 1, TTL: 60
Internet Protocol Version 4, Src: 172.18.3.91, Dst: 1.1.1.1
Internet Control Message Protocol
```

(d) The message received by R4 pops up the 16444 label

```
Frame 937: 78 bytes on wire (624 bits), 78 bytes captured (624 bits) on interface 0
Ethernet II, Src: 50:0c:00:04:00:04 (50:0c:00:04:00:04), Dst: 50:0c:00:01:00:04 (50:0c:00:01:00:04)
Internet Protocol Version 4, Src: 172.18.3.91, Dst: 1.1.1.1
Internet Control Message Protocol
```

(e) R1 receives the message that the MPLS label stack is empty

Figure 12. The process of jumping out MPLS labels from R1 to R4

4.2.3 Identity deception

To simulate the real network scene, the Iperf tool is used to inject the background traffic with the ratio of normal traffic to malicious traffic of 3: 1. Let the Smac and SID in the Credit information correspond to the mac and Prefix Node SID of R5, the pSID corresponds to the Prefix Node SID of R1, R2, and R3, the traffic with P as OSPF/ISIS is normal traffic, and the others are malicious traffic. The recall rate curve of malicious traffic (the probability of malicious traffic being detected and identified) can be obtained by statistics, as shown in Figure 13. It can be seen that the ZbSR model can better identify and prevent identity spoofing attacks based on traffic characteristics. In contrast, the Baseline model and MFRA model can filter a small amount of malicious traffic thanks to SR native security mechanism.

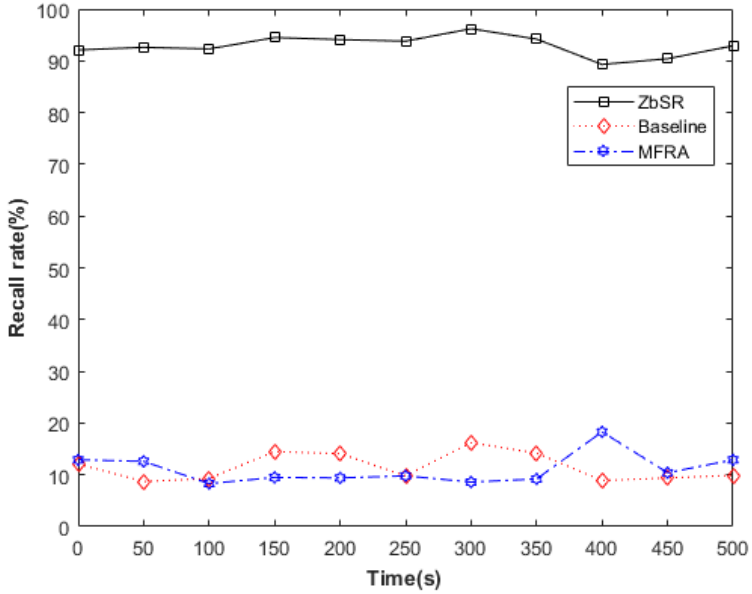


Figure 13. Comparison of malicious flow recall rates in the 3 models

4.2.4 Back door utilization

By querying the vulnerability inquiry platforms such as CVE, CVND, Seebug, etc., there are no open vulnerabilities of the Cisco XRV9k router, so the original vulnerabilities of other components and the preset test back door were used for testing, among which the real vulnerabilities were CVE-2014-5035 vulnerability of OpenDaylight and CVE-2021-22543 vulnerability of KVM. The preset back door is for a device to report its fault to the controller through telemetry protocol after receiving the specific OSPF protocol LSR message, and evaluate whether the test passed, fault recovery capability, and attack tolerance. The results are shown in Table 6. It can be seen that the Baseline model can neither recover from the attack nor tolerate the attack. The MFRA model based on backup links can only recover quickly from node failures, but not from the controller and virtual machine environment failures. ZbSR model can guarantee the continuous service of the network by

tolerating attacks and can identify the source of tracing attacks by security audit algorithm, but it takes a long time to recover the fault by the administrator.

Table 6. Comparison of the ability of 3 models to deal with back door utilization

	ZbSR			Baseline			MFRA		
	Attack passability	Recovery ability	Attack tolerance	Attack passability	Recovery ability	Attack tolerance	Attack passability	Recovery ability	Attack tolerance
OpenDaylight vulnerability	✓	✓, slower	✓	✓	×	×	✓	×	×
KVM vulnerability	✓	✓, slower	✓	✓	×	×	✓	×	×
OSPF preset backdoor	✓	✓, slower	✓	✓	×	×	✓	✓, faster	×

4.2.5 DOS attack

As shown in Figure 14, the horizontal axis is the network running time, and the vertical axis is the network processing capacity, which is measured by the retention rate of the source route generation rate (this value is 1 when the network is normal). DoS attack started at 20 seconds. It can be seen that after a brief decline in the processing capacity of the ZbSR model, the malicious traffic was filtered after the interface injected with malicious traffic was found by traffic audit, and the processing capacity gradually recovered. The processing ability of the Baseline model drops rapidly after malicious traffic is injected; in the MFRA model, the network processing capacity is temporarily restored because the backup link is enabled after the congested link is detected, but the backup link also quickly becomes congested.

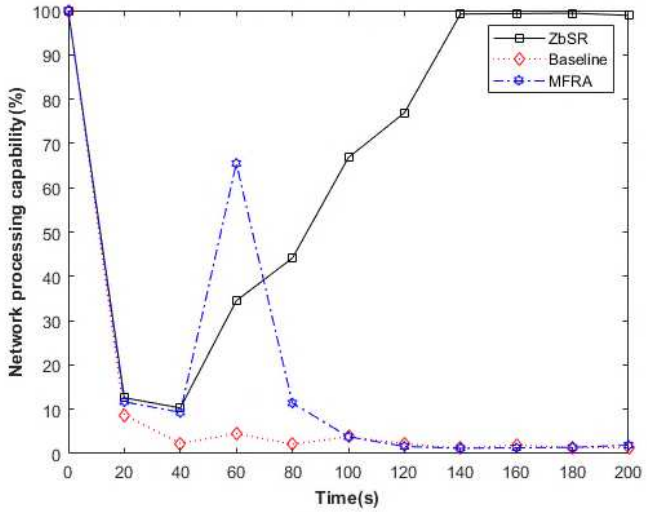


Figure 14. Comparison of the decline of the processing capacity of 3 models

4.3 Performance overhead test and analysis

The streaming transmission delay of the 3 models in the network with 5, 11, and 15 nodes is shown in Figure 15.

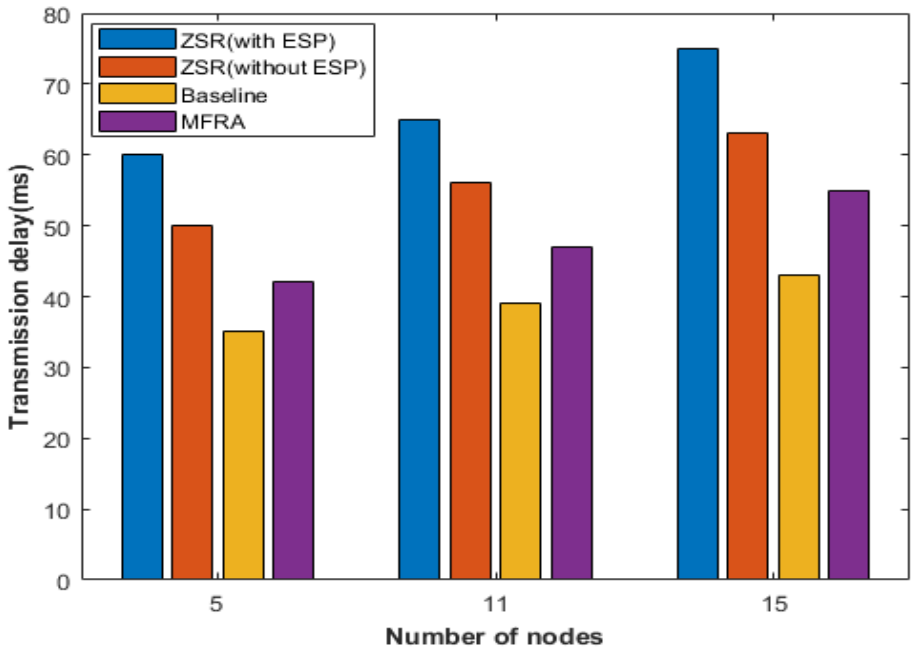


Figure 15. Comparison of streaming transmission delay of 3 models

It can be seen that when software encryption is not turned on (ZbSR (unencrypted)), compared with the Baseline model and the MFRA model, the time delay of the ZbSR model increases by 18.2%~22.7% (average incremental time delay is 19.3%) and 8.5%~12.3% (average incremental time delay is 10.4%), respectively, and the proportion of time delay increased compared with MFRA model decreases with the number of nodes. After software encryption is turned on (ZbSR (encrypted)), the delay of the ZbSR model is further improved, which is 37.4%~41.1% higher than that of encryption without it, which is consistent with the cost analysis in section 3.3. Considering that if the application layer of the SR network terminal device has a mature encryption mechanism, there is no need to enable the terminal device encryption of the ZbSR model, and the Baseline model and MFRA model will also significantly increase the delay after encryption is turned on, so the security cost of the ZbSR model is regarded as 19.3% of the average incremental delay compared with the Baseline model when encryption is not turned on. To reduce the security overhead of the model, we can consider introducing particular data encryption components to replace software encryption in the terminal device; besides, the ZbSR model should be configured on-demand to focus on auditing the backbone network nodes with a large degree of nodes or large flow.

5 Conclusion and future work

This article analyzes the untrustworthy security problems of network elements and PKI/CA in the zero-trust network environment of SR, and points out that it can be attributed to the untrustworthiness of SR data exchange and network audit functions, but there is no corresponding supporting security mechanism at present. Focusing on the application of ZTA in the SR-BE/TE network to improve its data plane security performance, this paper proposes a ZbSR data plane security model based on ZTA and the corresponding data exchange and network audit security algorithms. Through simulation test, the proposed model can provide various security protection for SR-BE/TE data plane, but also exposes its disadvantages of high-security cost and lack of automatic fault recovery capability. In the next step, we will focus on the hardware design of security components, the improvement of the trust evaluation algorithm for trust renewal, and the incremental network attack surface introduced by the model.

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