Ruta: Dis-aggregated routing system over multi-cloud

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ABSTRACT
Over the years, the SDN evolution create multiple overlay technologies which is inefficient and hard to deploy end-to-end traffic engineering services, Ruta is designed as an unified encapsulation with Segment Routing, Crypto and NAT-Traversal capabilities over UDP.

Ruta could be deployed as a cloud native SDN platform globally over multi-cloud and integrated with each applications on transport layer, which provide nearly zero loss and almost less than 200ms latency to access anywhere in the world over internet.

CCS CONCEPTS
• Computer systems organization → Cloud computing. • Networks → Transport protocols. • Hardware → Networking hardware.

KEYWORDS
Routing, Overlay Network, Software Defined Network, Distributed Controllers

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1 INTRODUCTION
Software Defined Network and Cloud VPC evolution create multiple overlay technologies in last decade, the different implementation separate network into multiple domains. Meanwhile applications require simplicity for end-to-end traffic engineering and security policy enforcement, the domain-specific SDN design cause many overheads on both control and data plane.

Paper Organization: We introduce the challenges of overlay technologies used today and the motivation for Ruta project in Section 1. We present the control plane architecture in Section 2, data plane architecture in Section 3 and prototype system implementation and demonstrate multi-cloud deployment in Section 4. We conclude in Section 5.

1.1 Overlay Technologies
A packet from client to cloud require multiple times encapsulation and encryption/decryption which introduce significant latency and inter-working complexity on each boarder network devices.

A packet which send by a wireless client require location-agnostic vendors like Cisco [4] or juniper [8] implement overlay and group based policy for wireless converged campus network. Each vendor has private control-plane protocol(lisp [5], BGP-EVPN) and data-plane(vxlann-gbp [12] vxlann-gpe-gbp and lisp-gpe-gbp [7]). The campus network fabric policy design based on user-centric approach, thus group based policy tag only contain user or group identity.

When the packet arrive campus boarder, SDWAN Router will decap the packet and enable deep-packet inspection(DPI) for application aware routing or security policy enforcement, packet will be encap and encrypted in IPSec or DTLS with a transport VPN tag, then sent to remote on-prem datacenter or public cloud. In SDWAN domain policy design based on transport-centric approach. Most of the SDWAN implementations are based on point-to-point tunnel, thus the multi-hop traffic engineering may require multiple times encryption and decryption with multiple times policy lookup. Some of the service provider use MPLS-VPN, MPLS-Segment Routing or SRv6 as overlay to handle the traffic, MPLS require dedicated underlay and SRv6 require IPv6 link, and the SRv6 forwarding mechanism does not change the source address which may cause problems when unicast reverse path forwarding(uRPF) enabled, so most of them can not directly transport over internet. Even with segment routing over IP (RFC8663) may support MPLS-SR over IPv4 UDP, but the forwarding mechanism does not support NAT-Traversal.

When packet arrive on-prem datacenter, the network policy design based on application-centric approach, group based tag like Endpoint Group(EFG) in Cisco ACI architecture [3] identify application sever groups. The boarder gateway have to update the source and lookup the destination group id and set related VNID and group ID.

It’s more complex in public cloud, Virtual Private Cloud(VPC) are based on region and available zones, inter-VPC communication require complex routing and security group policy which requires VPC-Peer or Transit-VPC services. cloud-agnostic require more generic overlay network support, but different cloud provider may have different overlay terminology introduce significant workload for multi-cloud deployment.

1.2 Design principal
Inspired by cloud native approach, we design Ruta based on service-mesh architecture, we dis-aggregate routing service to distributed KV control-plane and micro-service based data-plane to provide unified encapsulation to meet each network domain’s requirement.
It could significantly reduce the inter-working complexity and provide flexible programming interface for applications.

However, Design dis-aggregated routing platform is not simply leverage distributed software architecture to build controller and data-plane, but it require more carefully trade-off on architecture level, because the system failure may cause network partitioning and lose availability. Based on CAP theorem [1], some design principals are shown as below.

Consistency is the must to have feature in traditional network, the destination-based forwarding requires all nodes have consistent forwarding table. Inconsistent forwarding table scenario may well-known as “Micro Loop” or “Black hole”.

Meanwhile, the traditional routing protocols are designed to serve destination based forwarding. No matter which routing protocol were used, it must implement a routing information database(RIB) and keep availability for data-plane calculate the forwarding information database(RIB). Most of the routing protocols soften the partition tolerance as a trade-off, for instance OSPF-area or BGP-Autonomous System are designed to hide topology and isolate failure.

At the same time, keeping availability may loss partition tolerance, many routing protocol need to deal with “brain-split” situation. Leader arbitration, split-horizon are designed to reduce the network partition impact, but it has side effect for the availability.

In the SDN Era, control-plane is centralized, many network devices need sequential consistency, and the DHCP like address assignment need strictly consistency. The controller implementation and placement under network partition becomes major challenge. For instance, recently facebook outage [14] indicate the controller availability is the root cause.

In summary, the consistency requirement and destination based forwarding is a kind of trade-off few decades ago. In the old days, the forwarding ASICs or Network Processors may have limited forwarding capabilities and the network has limited bandwidth to carry more information for source routing.

Can we soften the consistency requirement by introducing the source-routing or segment-routing(SR) and decouple the devices configuration?

Can we soften the availability requirement by using distributed path-compute on each forwarding adjacency when running into the headless mode?

These are the design principals for Ruta system, we implement an eventually consistency model to decouple the prefix announcement and path-computation process by using a location descriptor, then we leverage local cache mechanism for distributed path-computation during control-plane offline. We select ETCD as our control-plane and simplify all routing updates and decouple the policy related configurations in K-V pairs.

Ruta separate the consistency requirement by using distributed path-calculation and segment routing to decouple overlay route information and linkstate, linecard could use partially linkstate db for path calculation without global consistency requirement. In some large scale deployment, users could deploy multiple redis based service node for regional linkstate database and provide cache service for linecards.

Segment Routing(SR) with loop-free alternative provide better resilience under network partition, however it only support IPv6 or MPLS, even RFC8663 may support MPLS based SR over UDP, but it lack of programmability and NAT-traversal support. Meanwhile, as a cloud-native routing system, we need to use a pure user-space dataplane to bypass kernel overhead and simplify the programmability for application developers. SRv6 may require kernel support to add IPv6 Option header which is not friendly for application developers.

We develop a new data-plane protocol by using segment routing over UDP(SRoU). SRoU header can be integrated with QUIC to provide secure and reliable transport services. Many public cloud and many internet service still using IPv4 and deal with the SRv6 uRPF issue, we encode the original source address in SRoU, then we develop STUN services to resolve IPv4 NAT-Traversability problem.

2 CONTROL PLANE

Ruta control plane is heavily use the ETCD features like lease, distributed lock and transparent proxy. Each service node could be a proxy for others connect to ETCD. All communications to ETCD require TLS, RBAC could be added enhance system security.

2.1 Service Node Roles

Ruta define 5 roles of service node which is shown in Figure.1.

- **ETCD:** This node is running ETCD process to provide distributed K-V store services as Ruta control-plane. All Ruta node info, routing table, policy and link state are represent in K-V pairs.
- **Fabric:** This node type is used as an middle box to relay the SRoU packets. This node could be implemented by in DPDK based appliance, or offload packet processing on DPU or pure P4 based switch to provide high bandwidth forwarding capabilities. This node must enable link probe to other Fabric node and report link-state to K-V store.
- **Linecard:** This node fetch routing table and topology from ETCD and execute flexible algorithm to find available path and encode SRoU SID-list in each packet. Linecard node has various types to provide basic transport service or tightly integrate with applications. It could be physical SDWAN routing box, mobile vpn client, sidecar proxy, DPU or even a QUIC socket library integrated with applications.

![Figure 1: Ruta: Dis-aggregated routing architecture](image-url)
2.2 Node Registration
All service node must register to ETCD based on the following K-V pairs
- **Key:** "/node/<role>/<systemName>*/
  <role> is defined in section 2.1, <systemName> is a system wide unique value, just like traditional Router-ID, users could continue use router-id in this field, or use hostname string instead.
- **Value:** contains Site-Id, Location and SystemLabel
  **Site-ID:** This field is used for site level policy enforcement.
  **Location:** This field store the node latitude and longitude information. Linecard node could apply flexible geo-aware-routing or build random-graph to reduce computational complexity in large scale network.
  **SystemLabel:** This is 24bits field for Segment ID compression and MPLS interworking. Label assignment is implemented by distributed lock mechanism over ETCD, each node acquire the lock from ETCD then assign unique smallest Number as SystemLabel, and register it back to ETCD with SystemLabel field.

2.3 Service Locator(SLoC)
Each of service node has multiple interfaces, Ruta use Service Locator(SLoC) describe them.

| Field          | Usage                                                                 |
|----------------|-----------------------------------------------------------------------|
| Color          | This field is used for link level policy enforcement, user may defined it based on link type or coloring different links(same as color definition in SR-Policy). |
| Private IP&Port| The private IP address and UDP port used for Ruta service.            |
| Public IP&Port | The public IP address and UDP port used for Ruta service.             |
| Interface Name | optional field to store the local interface which initialize the SRoU session. |
| RX/TX BW       | max upstream/downstream bandwidth, used for calculate link utilization. |

Ruta may use the shorten format to distinguish interfaces.

$SLoC_{short} := <systemName>-<systemName>-<Private IP:Port>$

2.4 Service Hunting
After Node registration, service node must send Service Location Route for service discovery.
- **Key:** "/service/<role>/<systemName>*/
- **Value:** SLoC data structure will be used in this field.

Service Node could use prefix based fetch /service/<role> for service hunting. For instance, a new on-boarding device need STUN service, it may fetch /service/STUN as prefix from ETCD to hunt STUN server’s public ip address and port.

2.5 Link State
When Fabric node finished the on-boarding process, it must fetch the /service/lsdb to discover the LinkState Database node. it must use prefix based fetch /service/Fabric to discover other fabric nodes, then start full-mesh link state probe to others. In some large scale deployment, Fabric node could config a white-list to reduce full-mesh probe.

The probe result need to update in LSDB Redis DB, if system does not contain LSDB node, it must send to ETCD, Link State K-V pair is shown as below:
- **Key:** "/stats/linkstate/<SLoC_src> - <SLoC_dst>*/
- **Value:** Ruta Link state probe leverage the algorithm from Two-Way Active Measurement Protocol(RFC5357) [9], it could provide two-way delay, jitter, loss measurement, it will also report the link utilization and up/down status.

2.6 Service Route
Inspired by Locator/Identifier Separation Protocol(LISP), Ruta service route does not contain any explicit nexthop but just mapping the uniform resource identifier(URI) to SLoC. Ruta URI service route framework not only designed for packet routing service, but also support various of new services(eg. multi-cloud RPC, edge computing node).

For multi-cloud packet routing services, Ruta could carry EVVPN-Route as resource identifier.
- **Key:** "/route/<type>/<export RT>/<RD>/**
  Route Target(RT) and Route-Distinguisher(RD) usage are same as BGP-EVPN, RT mechanism could be implemented by watch "/route/<type>/<RT>/*" prefix.

EVPN route URI listed below:

| Type     | Key                                      |
|----------|------------------------------------------|
| EVVPN Type2 | /route/*/<export RT>/*<RD>/MAC/IP       |
| EVVPN Type5 | /route/*/<export RT>/*<RD>/IPPrefix/Mask |

Table 2: EVPN Route URI Format

- **Value:** just like BGP attributes, it has 3 mandatory field(SiteID, SystemName, PolicyTag). TLV based optional field extension will be used in the future.

2.7 Path Computation
Unlike traditional routing protocol, Ruta is used for overlay transportation. The path computation logic is more like google map
navigation, it could support various of algorithms to meet differ-
ence SLA. Meanwhile it does not require consistency of link-state
database which is very useful during network failure.

By default, the linecard will build destination SLoC list based
on EVPN routes, it will only use active link state probe for each
destination service node. If some of the route has SLA violation,
the linecard could use a fabric-node-list or randomly selected fab-
ric nodes to fetch the related link-state, and execute local path
computation.

Path Computation engine will generate a SLoC list for each
EVPN route. This list will be encoded in SRoU header.

2.8 Node Keepalive

Service Node keepalive leverage the ETCD lease function, When
a node failed to update lease time, the ETCD will automatic with-
draw the related information. Consider the controller availability
we implement 2 different lease time. The first lease time(60 120 sec-
onds) is used for service node keepalive. The second lease time(600
seconds 1200seconds) used for linkstate and service route.

2.9 Micro Segmentation

Endpoint Identity: Each of the endpoint may have it’s identity or
group policy tags, it could be updated by the following K-V pairs

Key: /identity/userid/device-id
Value: "group policy tags"

Group based policy: Each node may use the following K-V pairs
for group based micro-segmentation:

Key: /control/group/SRC_group/Dst_group
Value: "Action"|"SLoC list"

Route control: Network operator could update the control policy
to the entire system by using:

Key: /control/RT/SRC_MAC/SRC_IP/DST_MAC/DST_IP
Key: /control/RT/SRC_prefix/SRC_mask/DST_prefix/DST_mask
Value: "Action"|"SLoC list"

3 DATA PLANE

Ruta dataplane leverage the SRv6 programmable SRH concept,
but move the SRH after the UDP header, this new encapsula-
tion called SR over UDP(SRoU). It add explicit FlowID field for micro-
segmentation. Source IP address and port are added for NAT-Traversal.

Figure 2: SRoU Encapsulation

| IP Header | SRoU Header | Payload |
|-----------|-------------|---------|

3.1 SRoU Header

SRoU header defined as below:

- **magic number**: 1Byte field with ALL ZERO. it used to dis-
tinguish packet in QUIC socket mode.
- **SRoU Length**: 1Byte. The total byte length of a SRoU header.
- **FT**: 2bits, defined flowid type, 0x0 = 32bits, 0x1 = 64bits, 0x2
  = 96bits.
- **C**: C-bit, indicate the packet is encrypted.
- **F**: F-bit, indicate the packet encryption scope, 0x0 = SRoU
  header only , 0x1 = Full packet encryption.
- **T**: T-bit, indicate the packet need to send postcard telemetry
to controller.
- **Protocol-ID**: 8bits, defined the inner packet protocol, 0x0 =
  SRoU OAM, 0x1 = IPv4, 0x2 = IPv6
- **Source Address & Port**: length based on Protocol-ID. OAM
  message does not contain this field.
- **SLoC Type**: 8bits field, 0x0 Reserved, 0x1 indicate the SLoC
  length is 48bits(IPv4+UDP port), 0x2 reserved for interwork-
ing with SRv6 with length equal 128bits, 0x3 used for Com-
pressed Segment list.
- **SR Hdr Len**: R Header length, include the Header flags(4Bytes),
  Segment List and Optional TLV.
- **Last Entry**: contains the index(zero based), in the SLoC List,
  of the last element of the SLoC List.
- **Segments Left**: 8-bit unsigned integer. Number of route
  segments remaining, i.e., number of explicitly listed inter-
  mediate nodes still to be visited before reaching the final
  destination.
- **Segments List[0...n]**: SLoC store in each segment element.
- **Optional TLV**: 0x0 used for padding, 0x1 used for SR In-
  tegrity, 0x2 used for PathTelemetry.

3.2 SRoU OAM

SRoU OAM Message format defined as below:
3.3 Network programming

Same as SRv6 Network Programming [2], Ruta defined a virtual SLoC for network programming, IPv6 is same as RFC8986, Ruta under IPv4 based SLoC follows the following definition:

\[
\begin{array}{c|c}
| Args | Function |
\hline
11111111 & 32 & 47
\end{array}
\]

Figure 5: SLoC for network function

We implement End.DT2U and End.DT4 in our prototype to provide VPN services.

4 SYSTEM IMPLEMENTATION

We implement Ruta prototype in native golang with nearly 9000 loc, cross compile could support multiple platform(x86/arm based linux, mips and arm based OpenWRT). We also patch some codes to quic-go to support QUIC transport protocol over Ruta.

4.1 Datacenter Spine-leaf deployment

We deploy ruta with 2 linecard nodes as leaf ToR switch and 2 fabric nodes as spine, topology shown as below, demo code available in [11].

ETCD cluster could be deployed in multiple region to provide better resilience, each ruta node could be run as etcd proxy mode to help other nodes use in-band communication to register to ETCD cluster. For instance Spine_Fabric node could be etcd proxy for Linecard node in this deployment scenario.

Linecard may have multiple uplinks, it could be represented and encoded in different colors and UDP ports in SLoC. The following chart shows the information retrieve from ETCD. Linecard will learn the MAC and IP address information from host and announce EVPN-Type2 route in ETCD, type-5 route were learned by local configuration or route redistribution by other protocols.

FlexAlgo could be added in each linecard. In general case, H1->H2 communication could be encoded by Linecard1 with only one SLoC in SRoU Segment list, the interim Fabric just involved as basic IP forwarding function.

The total SRoU header length is 24Bytes which is equal to SRv6 SRH, but it has IPv4 underlay which is more efficient than SRv6. Compare with VXLAN, the SRoU flowID header could be used as application aware tag or group based policy header, it could easily support traffic-engineering, however VXLAN need to use multiple NSH header instead. For instance, when network congestion, the Linecard could add more SLoC in segment list for traffic engineering. Spine-A will invoke the SRoU stack to relay packet to Linecard_B.
4.2 Multi-cloud deployment

Real time collaboration (RTC) like Cisco Webex, Zoom and Microsoft Teams are widely used during COVID-19, but the internet directly connection performance does not meet the application’s requirement. Internet routing is based on BGP AS-PATH, congestion always observed between AS, can we build a pinhole between service providers without change any BGP routes? A multihoming ruta fabric node with SRoU encapsulation could easily implement packet relay between SP, meanwhile public cloud service providers always multi-homing with other traditional service providers and internet exchanges, deploy virtual machine on public cloud as Ruta fabric node could significantly improve RTC performance.

We need to emphasize multi-cloud deployment is useful, for instance, from Alicloud Frankfurt region to Alicloud Chengdu region, the directly internet connections over elastic IP over internet has 385 milliseconds latency, however if we relay it at Tencent Cloud guangzhou region will lower down the latency to 240 milliseconds.

Finally, we deploy 20 fabric nodes over multiple public cloud providers (Alicloud and Tencent) over the world, the result shows ruta could significantly reduce the latency and packet drop. It could provide nearly zero loss and almost less than 200ms latency to access anywhere in the world over internet with maximum 4 segments, full result available in [10].

| Field                  | Value                                                                 |
|------------------------|------------------------------------------------------------------------|
| IP Header              | src: client_ip dst: edge_fabric1’s ip                                   |
| SRoU Header            | magic number 0                                                          |
|                        | flowid 32bits service token assigned by edge_fabric1                   |
|                        | source address 0.0.0.0                                                 |
|                        | source port 0                                                           |
|                        | segment list[0] final server ip and port                               |
|                        | segment list[1] transit fabric node                                    |
| Inner Payload          | QUIC packet                                                            |

4.3 Native Socket

QUIC is a reliable and secured transport protocol in user-space, we implement SRoU function with quic-go to enhance the network programmability to provide traffic-engineering and multi-path forwarding capabilities over internet and directly traversal VPC.

In native socket mode, server may register to Ruta ETCD to provide application awareness, especially in K8s deployment case, Ruta ETCD could directly sync the server’s identity with K8s ETCD. Client does not required to register to ETCD, a simple DNS SRV record could be used to announce the edge_fabric and transit_fabric.

The client select edge fabric 1 could send the packet in the following format, consider the network security issue, Edge fabric1 could allocation some time based token for client, this token could be store in flowid field.

| Field   | Value                                                                 |
|---------|------------------------------------------------------------------------|
| Field   | Value                                                                 |
| IP Header | src: client_ip dst: edge_fabric1’s ip                                   |
| SRoU Header            | magic number 0                                                          |
|                        | flowid 32bits service token assigned by edge_fabric1                   |
|                        | source address 0.0.0.0                                                 |
|                        | source port 0                                                           |
|                        | segment list[0] final server ip and port                               |
|                        | segment list[1] transit fabric node                                    |
| Inner Payload          | QUIC packet                                                            |

Table 3: Service Locator(SLoC) Field
client may not require to connect to STUN server for public address discovery, it simply fill ZERO in the SRoU source address and port field. The first hop fabric node will help copy the underlay source address inside the SRoU header for NAT-Traversal. when the server receive the packet and find the UDP first 8 bits is ALLZERO, it will copy the internal SRoU header source address and port to Outer IP header and trim the SRoU to deliver the packet to application.

4.4 Transparency VPC

The native socket mode is not only support QUIC packets, but also support TCP and other UDP encapsulations.

Existing VPC design requires cloud service provider manage the overlay routing table which makes some challenges for network devices \[13\]. Many hybrid cloud solution require SDWAN or IPSec VPN as Gateway to bring traffic into the VPC, however it’s very hard to inter working with overlay VPC routing table with existing private network, meanwhile each cloud provider has private micro-segmentation polices design, that may introduce significant efforts for interworking.

Ruta provide a cloud-native based approach to resolve the challenges, by enable Ruta linecard at each VPC and provide Segment Routing capability on overlay makes the VPC more transparency and the cloud provider could significantly reduce the overlay routing control and offload service gateway to each host or dedicated DPU.

This dis-aggregation routing system could benefit edge cloud and hybrid cloud deployment in the future.

4.5 Large-scale deployment

Some massive scale cloud service provider could use Ruta as distributed SDN solution. An Ruta system(with multiple LC and Fabric) could be treated as an single Linecard with multiple SLoC to join another Ruta system. Or multiple Ruta System could leverage on BGP-EVPN to share routing information as same as Inter-AS Option C MPLS VPN.

5 CONCLUSION AND FUTURE WORK

Ruta is a dis-aggregated routing system based on cloud native approach, we develop a new K-V based control plane to decouple the configuration and management complexity and provide distributed deployment which perfectly resolve the centralized SDN controller challenge. Meanwhile we provide a Segment routing based transport layer, it provide nearly zero loss and almost less than 200ms latency to access anywhere in the world over internet. We also enable native socket support for endpoint enable QUIC multi-path capabilities, even more we simplify the cloud VPC deployment and provide transparency VPC to support hybrid-cloud deployment.

Ruta is a first step towards cloud native datapath, we believe it cloud be used in more scenarios like NetDAM \[6\] for HPC, new container network interface and cloud-agnostic RPC framework in the future. We are exploring to enable Ruta for P4 based switch and DPU offload, server-less computing and datastreaming processing cases in the future.

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