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NVGRE: Network Virtualization using Generic Routing Encapsulation

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Abstract

We describe a framework for policy-based, software controlled network virtualization to support multitenancy in public and private clouds using Generic Routing Encapsulation (GRE). The framework outlined in this document can be used by cloud hosters, enterprise data centers and enables seamless migration of workloads between public and private clouds. This document is focused on the data plane aspects of the NVGRE framework.

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1. Introduction

Conventional data center network designs cater to largely static workloads and cause fragmentation of network and server capacity [VL2, COST-CCR]. The key concepts described in this document are motivated by earlier work [VL2], although the specific approach described here is significantly different from the one outlined in the paper. There are several issues that limit dynamic allocation and consolidation of capacity. Layer-2 networks use Rapid Spanning Tree Protocol (RSTP) which is designed to eliminate loops by blocking redundant paths. These eliminated paths translate to wasted capacity and a highly oversubscribed network. There are alternative approaches such as TRILL that address this problem [TRILL].

The network utilization inefficiencies are exacerbated by network fragmentation due to the use of VLANs for broadcast isolation. VLANs are used for traffic management and also as the mechanism for providing security and performance isolation among services belonging to different tenants. The Layer-2 network is carved into smaller sized subnets typically one subnet per VLAN, with VLAN tags configured on all the Layer-2 switches connected to server racks that run a given tenant's services. The current VLAN limits theoretically allow for 4K such subnets to be created. The size of the broadcast domain is typically restricted due to the overhead of broadcast traffic (e.g., ARP). The 4K VLAN limit is no longer sufficient in a shared infrastructure servicing multiple tenants.

Data center operators must be able to achieve high utilization of server and network capacity. In order to achieve efficiency it should be possible to assign workloads that operate in a single Layer-2 network to any server in any rack in the network. It should also be possible to migrate workloads to any server anywhere in the network while retaining the workload's addresses. This can be achieved today by stretching VLANs however when workloads migrate the network needs to be reconfigured which is typically error prone.

By decoupling the workload's location on the LAN from its network address, the network administrator configures the network once and not every time a service migrates. This decoupling enables any server to become part of any server resource pool.

The following are key design objectives for next generation data centers: a) location independent addressing, b) the ability to a scale the number of logical Layer-2/Layer-3 networks irrespective of the underlying physical topology or the number of concurrent VLANs, c) preserving Layer-2 semantics for services and allowing them to retain their addresses as they move within and across data centers, and d) providing broadcast isolation as workloads move around without burdening the network control plane.

2. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC-2119 [RFC2119].

In this document, these words will appear with that interpretation only when in ALL CAPS. Lower case uses of these words are not to be interpreted as carrying RFC-2119 significance.

3. Network Virtualization using GRE

Network virtualization involves creating virtual Layer 2 and/or Layer 3 topologies on top of an arbitrary physical Layer 2/Layer 3 network. Connectivity in the virtual topology is provided by tunneling Ethernet frames in IP over the physical network. Virtual broadcast domains are realized as multicast distribution trees. The multicast distribution trees are analogous to the VLAN broadcast domains. A virtual Layer 2 network can span multiple physical subnets. Support for bi-directional IP unicast and multicast connectivity is the only expectation from the underlying physical network. If the operator chooses to support broadcast and multicast traffic in the virtual topology the physical topology must support IP multicast. The physical network, for example, can be a conventional hierarchical 3-tier network, a full bisection bandwidth Clos network or a large Layer 2 network with or without TRILL support.

Every virtual Layer-2 network is associated with a 24 bit Tenant Network Identifier (TNI). A 24 bit TNI allows up to 16 million logical networks in the same management domain in contrast to only 4K achievable with VLANs. Each TNI represents a virtual Layer-2 broadcast domain and routes can be configured for communication

between virtual subnets. The TNI can be crafted in such a way that it uniquely identifies a specific tenant's subnet. The TNI is carried in an outer header allowing unique identification of the tenant's virtual subnet to various devices in the network.

GRE is a proposed IETF standard [RFC 2784, RFC 2890] and provides a way for encapsulating an arbitrary protocol over IP. The tunneling mechanism itself is designed to be stateless although for this specific implementation there may be some soft state to handle issues such as IP fragmentation as explained in later sections. The GRE header provides space to carry TNI information in each packet. The TNI information in each packet can be used to build multi-tenancy aware tools for traffic analysis, traffic inspection, and monitoring.

The following sections detail the packet format for network virtualization, describe the functions of a NVGRE endpoint, illustrate typical traffic flow both within and across data centers, and discuss address, policy management and deployment considerations.

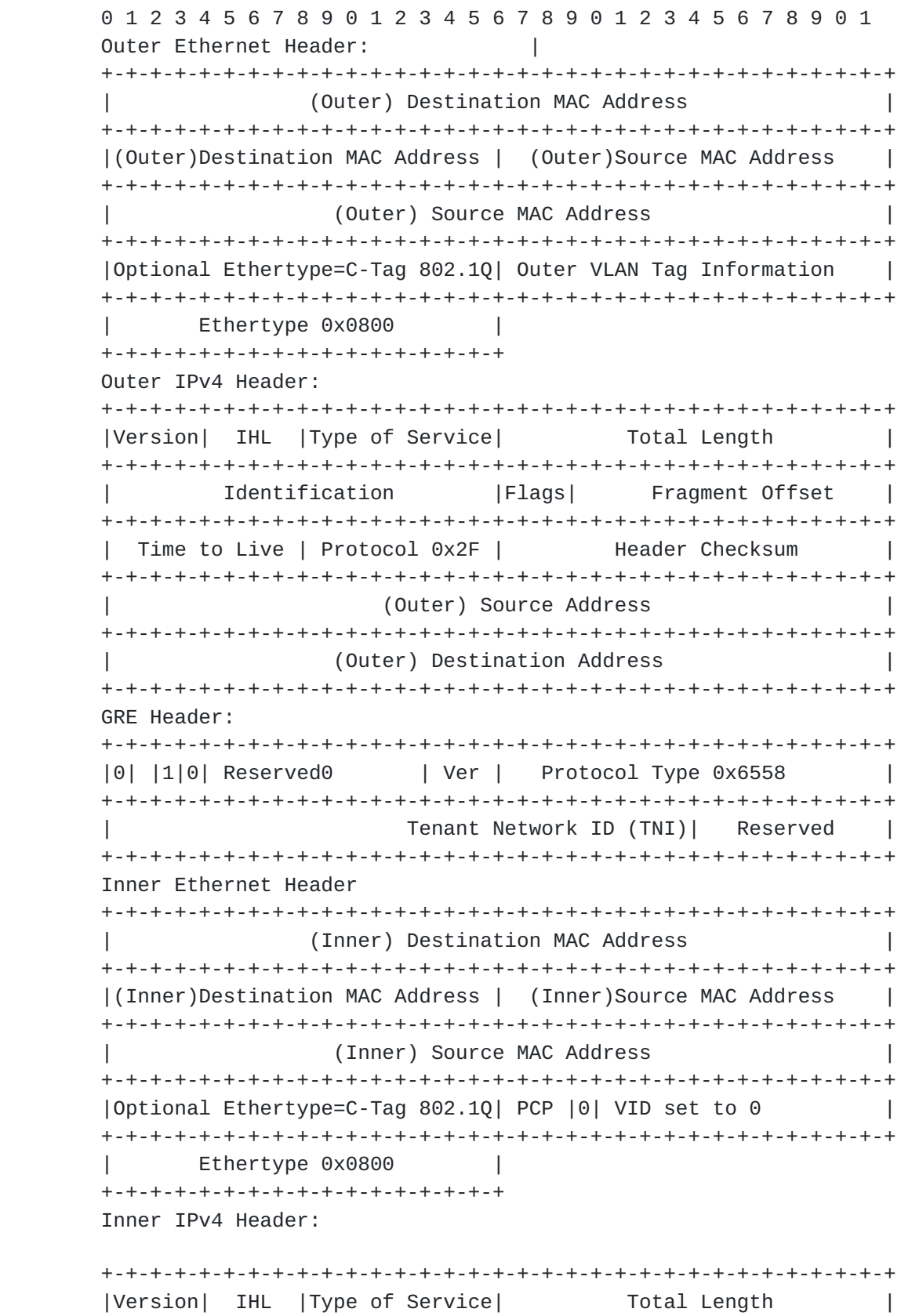
3.1. NVGRE Endpoint

NVGRE endpoints are gateways between the virtual and the physical networks. Any physical server or network device can be a NVGRE endpoint. One common deployment is for the endpoint to be part of a hypervisor. The primary function of this endpoint is to encapsulate/decapsulate Ethernet data frames to and from the GRE tunnel, ensure Layer-2 semantics, and apply isolation policy scoped on TNI. The endpoint can optionally participate in routing and function as a gateway in the virtual subnet space. To encapsulate an Ethernet frame, the endpoint needs to know location information for the destination address in the frame. The way to obtain this information is not covered in this document and will be covered in a different draft. Any number of techniques can be used in the control plane to configure, discover and distribute the policy information. For the rest of this document we assume that the location information including TNI is readily available to the NVGRE endpoint.

3.2. Network virtualization frame format

GRE encapsulation as specified in RFC 2784 and RFC 2890 is used for communication between NVGRE endpoints. The Key extension to GRE

specified in RFC 2890 is used to carry the TNI. The packet format for Layer-2 encapsulation in GRE is shown in Figure 1.


0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
Outer Ethernet Header:
(Outer) Destination MAC Address
(Outer)Destination MAC Address
(Outer)Source MAC Address
(Outer) Source MAC Address
Optional Ethertype=C-Tag 802.1Q
Outer VLAN Tag Information
Ethertype 0x0800
Outer IPv4 Header:
Version
IHL
Type of Service
Total Length
Identification
Flags
Fragment Offset
Time to Live
Protocol 0x2F
Header Checksum
(Outer) Source Address
(Outer) Destination Address
GRE Header:
0
1
0
Reserved0
Ver
Protocol Type 0x6558
Tenant Network ID (TNI)
Reserved
Inner Ethernet Header
(Inner) Destination MAC Address
(Inner)Destination MAC Address
(Inner)Source MAC Address
(Inner) Source MAC Address
Optional Ethertype=C-Tag 802.1Q
PCP
VID set to 0
Ethertype 0x0800
Inner IPv4 Header:
Version
IHL
Type of Service
Total Length

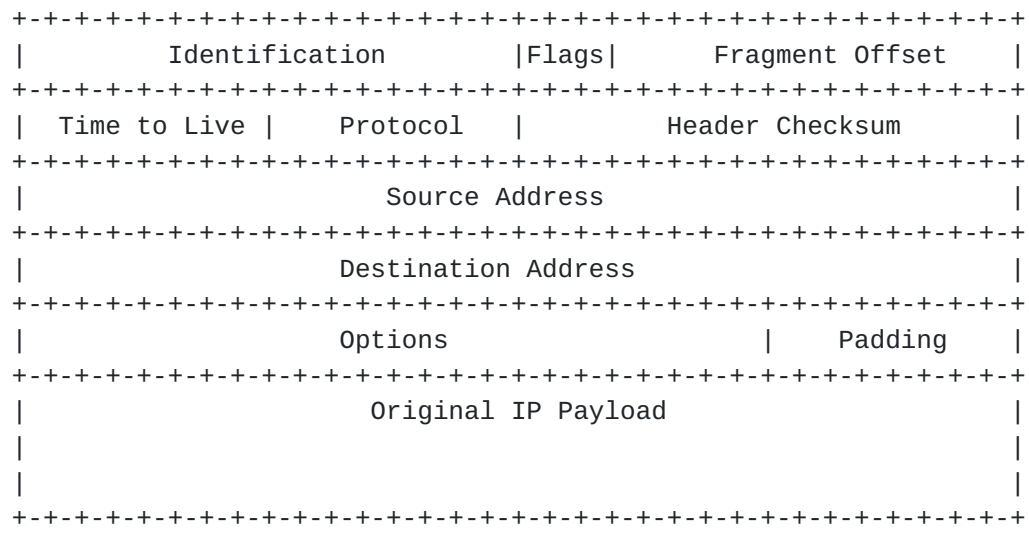


Figure 1 GRE Encapsulation Frame Format

O The inner Ethernet frame comprises of an inner Ethernet header followed by the inner IP header, followed by the IP payload. The inner frame could be any Ethernet data frame not just IP. Note that the inner Ethernet frame's FCS is not encapsulated.

0 Traffic may go through multiple NV-GRE gateways and no assumptions can be made about the VLAN ID space. NVGRE endpoint MUST set the VID in 802.1Q VLAN tags, if present, to zero before encapsulating the frame in a GRE header. If a VLAN-tagged frame arrives encapsulated in NV-GRE with VID not set to zero, then the decapsulating device SHOULD drop the frame.

0 For illustrative purposes IPv4 headers are shown as the inner IP headers but IPv6 headers may be used. Henceforth the IP address contained in the inner frame is referred to as the Customer Address (CA).

O The Key field in the GRE header is used to carry the Tenant Network Identifier. Key field is 32 bits long of which the lower 24 bits are used for TNI. The Key Present (bit 2 in the GRE header) is always set to 1.

0 The upper 8 bits of the Key field are reserved for use by NVGRE endpoints and are not part of the TNI space. NVGRE endpoints MUST set this value to zero.

0 NVGRE endpoint MUST set C and S bits in the GRE header to zero.

O The protocol type field in the GRE header is set to 0x6558 (transparent Ethernet bridging) [ETHTYPES].

O Outer IP header: Both IPv4 and IPv6 can be used as the delivery protocol for GRE. The IPv4 header is shown for illustrative purposes. Henceforth the IP address in the outer frame is referred to as the Provider Address (PA). There can be one or more PA address associated with the NVGRE endpoint, with policy controlling the choice of PA to use for a given CA.

O The source Ethernet address in the outer frame is set to the MAC address associated with the NVGRE endpoint. The destination Ethernet address is set to the MAC address of the nexthop IP address for the destination PA. The destination endpoint may or may not be on the same physical subnet. The outer VLAN tag information is optional and can be used for traffic management and broadcast scalability.

3.3. Broadcast and Multicast Traffic

The following discussion applies if the network operator chooses to support broadcast and multicast traffic. Each virtual subnet is assigned an administratively scoped multicast address to carry broadcast and multicast traffic. All traffic originating from within a TNI is encapsulated and sent to the assigned multicast address. As an example, the addresses can be derived from a administratively scoped multicast address as specified in RFC 2365 for IPv4 (organization Local Scope 239.192.0.0/14), or an Organization-Local scope multicast address for IPv6 as specified in RFC 4291. This provides a wide range of address choices. Purely from an efficiency standpoint for every multicast address that a tenant uses the network operator may configure a corresponding multicast address in the PA space. To support broadcast and multicast traffic in the virtual topology the physical topology must support IP multicast. Depending on the hardware capabilities of the physical network devices multiple virtual broadcast domains may be assigned the same physical IP multicast address. For interoperability reasons, a future version of this draft will specify a standard way to map TNI to IP multicast address.

3.4. Unicast Traffic

The NVGRE endpoint encapsulates a Layer-2 packet in GRE using the source PA associated with the endpoint with the destination PA corresponding to the location of the destination endpoint. As outlined earlier there can be one or more PAs associated with an endpoint and policy will control which ones get used for communication. The encapsulated GRE packet is bridged and routed

normally by the physical network to the destination. Bridging uses the outer Ethernet encapsulation for scope on the LAN. The only assumption is bi-directional IP connectivity from the underlying physical network. On the destination the NVGRE endpoint decapsulates the GRE packet to recover the original Layer-2 frame. Traffic flows similarly on the reverse path.

3.5. IP Fragmentation

RFC 2003 section 5.1 specifies mechanisms for handling fragmentation when encapsulating IP within IP. The subset of mechanisms NVGRE selects are intended to ensure that NVGRE encapsulated frames are not fragmented after encapsulation en-route to the destination NVGRE endpoint, and that traffic sources can leverage Path MTU discovery. A future version of this draft will clarify the details around setting the DF bit on the outer IP header as well as maintaining per destination NVGRE endpoint MTU soft state so that ICMP Datagram Too Big messages can be exploited. Fragmentation behavior when tunneling non-IP Ethernet frames in GRE will also be specified in a future version.

3.6. Address/Policy Management & Routing

Address acquisition is beyond the scope of this document and can be obtained statically, dynamically or using stateless address auto-configuration. CA and PA space can be either IPv4 or IPv6. In fact the address families don't have to match, for example, CA can be IPv4 while PA is IPv6 and vice versa. The isolation policies MUST be explicitly configured in the NVGRE endpoint. A typical policy table entry consists of CA, MAC address, TNI and optionally, the specific PA if more than one PA is associated with the NVGRE endpoint. If there are multiple virtual subnets, explicit routing information MUST be configured along with a default gateway for cross-subnet communication. Routing between virtual subnets can be optionally handled by the NVGRE endpoint acting as a gateway. If broadcast/multicast support is required the NVGRE endpoints MUST participate in IGMP/MLD for all subscribed multicast groups.

3.7. Cross-subnet, Cross-premise Communication

One application of this framework is that it provides a seamless path for enterprises looking to expand their virtual machine hosting capabilities into public clouds. Enterprises can bring their entire IP subnet(s) and isolation policies, thus making the transition to or from the cloud simpler. It is possible to move portions of a IP subnet to the cloud however that requires additional configuration on the enterprise network and is not discussed in this document.

Enterprises can continue to use existing communications models like site-to-site VPN to secure their traffic.

A VPN gateway is used to establish a secure site-to-site tunnel over the Internet and all the enterprise services running in virtual machines in the cloud use the VPN gateway to communicate back to the enterprise. For simplicity we use a VPN GW configured as a VM shown in Figure 2 to illustrate cross-subnet, cross-premise communication.

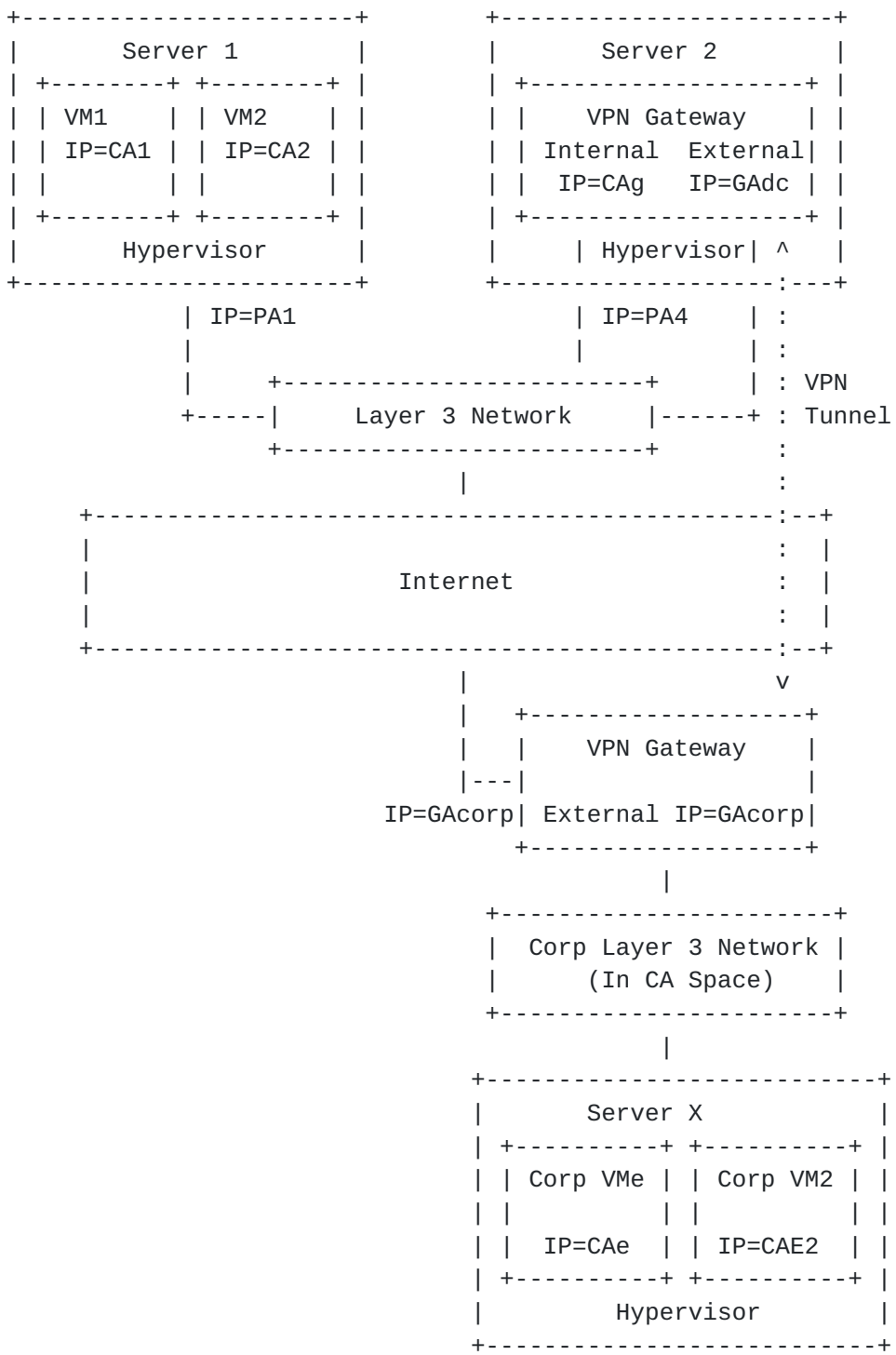


Figure 2 Cross-Subnet, Cross-Premise Communication

The flow here is similar to the unicast traffic flow between VMs, the key difference in this case the packet needs to be sent to a VPN

gateway before it gets forwarded to the destination. As part of routing configuration in the CA space, a VPN gateway is provisioned per-tenant for communication back to the enterprise. The example illustrates an outbound connection between VM1 inside the datacenter and VMe inside the enterprise network. The outbound packet from CA1 to CAe when it hits the hypervisor on Server 1 matches the default gateway rule as CAe is not part of the tenant virtual network in the datacenter. The packet is encapsulated and sent to the PA of tenant VPN gateway (PA4) running as a VM on Server 2. The packet is decapsulated on Server 2 and delivered to the VM gateway. The gateway in turn validates and sends the packet on the site-to-site tunnel back to the enterprise network. As the communication here is external to the datacenter the PA address for the VPN tunnel is globally routable. The outer header of this packet is sourced from GAdc destined to GAcorp. This packet is routed through the internet to the enterprise VPN gateway which is the other end of the site-to-site tunnel at which point the VPN decapsulates the packet and sends it inside the enterprise where the CAe is routable on the network. The reverse path is similar once the packet hits the enterprise VPN gateway.

3.8. Internet Connectivity

To enable connectivity to the Internet, an Internet gateway is needed that bridges the virtualized CA space to the public Internet address space. The gateway performs translation between the virtualized world and the Internet, for example, the NVGRE endpoint can be part of a load balancer or a NAT. Section 4 has more discussions around building GRE gateways.

3.9. Manageability

There are several protocols that can manage and distribute policy; however this document does not recommend any one mechanism. Implementations SHOULD choose a mechanism that meets their scale requirements.

4. Deployment Considerations

One example of a typical deployment consists of virtualized servers deployed across multiple racks connected by one or more layers of Layer-2 switches which in turn may be connected to a layer 3 routing domain. Even though routing in the physical infrastructure will work without any modification with GRE, devices that perform specialized processing in the network need to be able to parse GRE to get access to tenant specific information. Devices that understand and parse the TNI can provide rich multi-tenancy aware services inside the

data center. As outlined earlier it is imperative to exploit multiple paths inside the network through techniques such as Equal Cost Multipath (ECMP). The Key field may provide additional entropy to the switches to exploit path diversity inside the network. One such example could be to use the upper 8 bits of the Key field to add flow based entropy and tag all the packets from a flow with an entropy label. A diverse ecosystem play is expected to emerge as more and more devices become multitenancy aware. In the interim, without requiring any hardware upgrades, there are alternatives to exploit path diversity with GRE by associating multiple PAs with NVGRE endpoints with policy controlling the choice of PA to be used.

It is expected that communication can span multiple data centers and also cross the virtual to physical boundary. Typical scenarios that require virtual-to-physical communication includes access to storage and databases. Scenarios demanding lossless Ethernet functionality may not be amenable to NVGRE as traffic is carried over an IP network. NVGRE endpoints mediate between the network virtualized and non-network virtualized environments. This functionality can be incorporated into Top of Rack switches, storage appliances, load balancers, routers etc. or built as a stand-alone appliance.

It is imperative to consider the impact of any solution on host performance. Today's server operating systems employ sophisticated acceleration techniques such as checksum offload, Large Send Offload (LSO), Receive Segment Coalescing (RSC), Receive Side Scaling (RSS), Virtual Machine Queue (VMQ) etc. These technologies should become GRE aware. IPsec Security Associations (SA) can be offloaded to the NIC so that computationally expensive cryptographic operations are performed at line rate in the NIC hardware. These SAs are based on the IP addresses of the endpoints. As each packet on the wire gets translated, the NVGRE endpoint SHOULD intercept the offload requests and do the appropriate address translation. This will ensure that IPsec continues to be usable with network virtualization while taking advantage of hardware offload capabilities for improved performance.

4.1. Network Scalability with GRE

One of the key benefits of using GRE is the IP address scalability and in turn MAC address table scalability that can be achieved. NVGRE endpoint can use one PA to represent multiple CAs. This lowers the burden on the MAC address table sizes at the Top of Rack switches. One obvious benefit is in the context of server virtualization which has increased the demands on the network infrastructure. By embedding a NVGRE endpoint in a hypervisor it is possible to scale significantly. This framework allows for location

information to be preconfigured inside a NVGRE endpoint allowing broadcast ARP traffic to be proxied locally. This approach can scale to large sized virtual subnets. These virtual subnets can be spread across multiple layer-3 physical subnets. It allows workloads to be moved around without imposing a huge burden on the network control plane. By eliminating most broadcast traffic and converting others to multicast the routers and switches can function more efficiently by building efficient multicast trees. By using server and network capacity efficiently it is possible to drive down the cost of building and managing data centers.

5. Security Considerations

This proposal extends the Layer-2 subnet across the data center and increases the scope for spoofing attacks. Mitigations of such attacks are possible with authentication/encryption using IPsec or any other IP based mechanism. The control plane for policy distribution is expected to be secured by using any of the existing security protocols. Further management traffic can be isolated in a separate subnet/VLAN.

6. IANA Considerations

None.

7. References

7.1. Normative References

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8. Acknowledgments

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