Dynamic IP Pool Chunk Allocation for 5G Packet Core

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Abstract

For any mobile device to connect to the 4G/5G packet core infrastructure, it needs an IP address along with other information such as Domain Name Server (DNS), service type requested and accepted, and so on. Often, the user equipment does not get connected to network due to lack of available IP addresses and other network resources. 5G packet core architecture is based on 3GPP disaggregated architecture, based on Control and User Plane Separation (CUPS) [1]. IN CUPS architecture, IP address pool allocation is done by control plane (CP), whereas the actual IP address is conveyed per session by control plane to the user plane (UP). The user plane then provides data network connectivity to the subscriber by appropriately advertising the IP address subnets toward the data network.

This paper addresses one of biggest problems of dynamically managing the IP pool, which is subdivided into smaller address ranges that are referred to as IP chunks; this is done by the control plane. The control plane in question could be a 4G PGW-c (Packet Data Network [PDN] gateway) or a 5G SMF (Session Management Function). We have defined an algorithm that aims to allocate IP address in a ramped up or ramped down manner, to ensure fair usage of pools allocated. The algorithms can handle any corner cases such as resource constraints, congestion and race conditions, and so on.

Introduction

Service providers are rapidly transforming their mobile networks from 4G to 5G to provide new services and capabilities for superior user experience. They are deploying 5G based on two technologies, such as 5G NSA and SA, which can inter-operate with their existing 4G mobile services.

5G architecture is based on disaggregation and separation of control and user traffic. Control traffic refers to signaling, authentication, and managing subscriber sessions. User traffic refers to actual data transmission between server and client or peer-to-peer, where 5G mobile service can take the role of client, server or peer, and so on.

5G user plane function (UPF or UP) usually is deployed at network edge using an architecture based on Multi-Access Edge Computing [2] to provide latency, bandwidth, and edge-specific services. With edge computing, the control and user planes typically are separated physically and geographically. With CUPS architecture, user planes could be spawned up dynamically to meet architecture requirements. Typically, this is done by leveraging intelligent automation and configuration tools.

5G control plane is usually deployed at a central location because it does not need strict latency and it needs integration to backend services, such as authentication, policy and network slice managements, charging and billing, and so on. In 5G, this control plane is referred as Session Management Function (SMF).

The relation between control plane and user plane generally is referred to as N:M; this means one control plane can manage many user planes. Also, given user planes can be attached to more than one control plane for resiliency and redundancy. The control plane manages a set of user planes; thus, it has a complete view of the number of user planes currently deployed and managed.

One main function of the control plane is the allocation of IP pool chunk, which is a small set of IP addresses subnets. The centralized control plane typically assigns unique IP pools to the various user planes. A user plane typically receives dynamic IP addresses allocated by the SMF to UE, and it reports the status of IP pool chunk usage to SMF.

This paper addresses the challenges faced by management of IP pool chuck in CUPS architecture. The algorithms and strategy proposed in this paper can help optimize the IP pool chunk allocation procedure in SMF, so resources are utilized efficiently.

Existing IP Pool Management in 4G - CUPS

Before we delve into details of IP pool management in 4G, let us review the network elements that participate in this process. In 4G CUPS. the monolithic Serving Gateway (SGW) [3] and PDN Gateway (PGW) [4] are split functionally into control and user plane functions. Figure 1 denotes this separation.

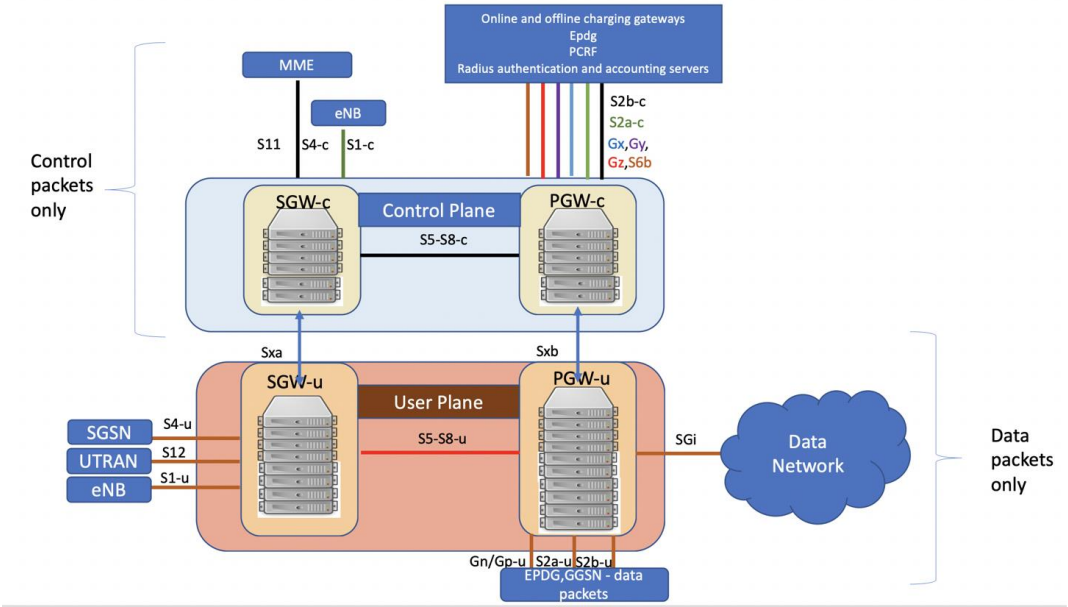

Figure 1- Control and User Plan Separation in 4G

The SGW serves as the local mobility anchor for inter-eNodeB handover and mobility between 3GPP networks and is communicated over GTP-c with MME and PGW for session establishment and modification. This functionality is retained in the control plane, SGW also forwards and routes packets to and from the eNodeB and PGW. This functionality is moved to the user plane in the CUPS architecture.

The PGW, known as the Packet Data Network Gateway, acts as the policy and charging enforcement function. It manages QoS and provides deep-packet inspection and lawful intercept. Most important, it is responsible for assigning the IP address to the User Equipment (UE). While the deep packet inspection and actual traffic steering has moved to the PGW-UP (user plane), it is controlled by the PGW-CP (control plane). Hence, the IP address allocation—the primary subject of this paper—is retained on the control plane.

With the existing CUPS architecture [5], the PGW-CP has all the IP Pool configurations in PDN/IP context. In compliance with 3GPP standards, the PGW-UP registers with PGW-CP via the Sx Association Request/Response procedure.

During the registration process, the PGW-CP looks for all configured Access Point Names (APNs) that are being served by the particular UP, and the associated Pool configuration in each APN. The CP allocates some of the IP chunk resources to a particular UP and sends over the Sx Association Update Request/Response procedure. This information is sent to PDN/IP context instance at UP.

After UP registration is successful, the PDN/IP instance initiates sending IP chunk resource information to the UP from the Pool. This IP chunk resource information is sent to the UP on Proprietary/Custom IE on Sx Association Update Request/Response message. The PDN/IP instance at UP announces the BGP routes, on per-chunk basis, which is received from the CP. Each UP that is registered with the CP is identified using “Peer ID” and the Node ID.

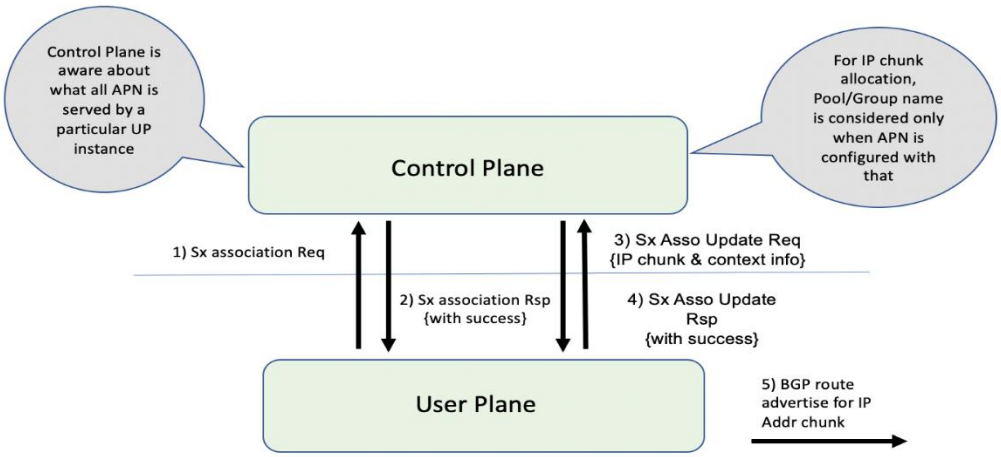

Figure 2- Existing IP Chunk Allocation Procedures by CP

Existing IP Resource Replenishment/Withdrawal Procedure in 4G CUPS

Currently, the CP allocates IP resources to UP as needed. Thus, it supports replenishment and withdrawal procedures for IP chunk resources.

Based on the CP's threshold logic, it monitors usage of IP resources in each UP on a pool-level basis. If overall IP chunk usage of the UP crosses a certain threshold, the CP sends additional IP chunk resources to the UP.

If certain IP chunks in the UP are not utilized and are idle for a certain duration, the CP withdraws those IP chunk resources from the respective UPs. This duration is configurable using the idle timer CLI command.

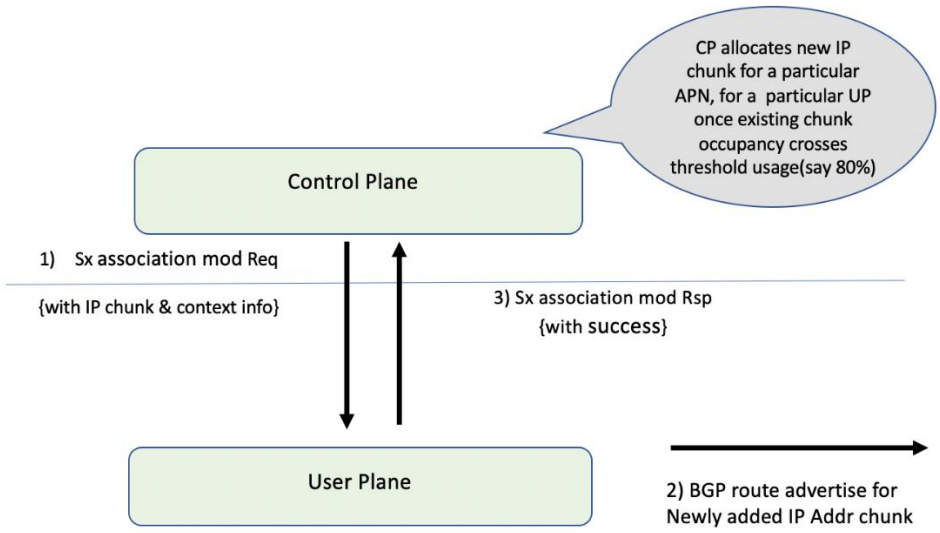

Figure 3 - IP Chunk Replenishment by CP

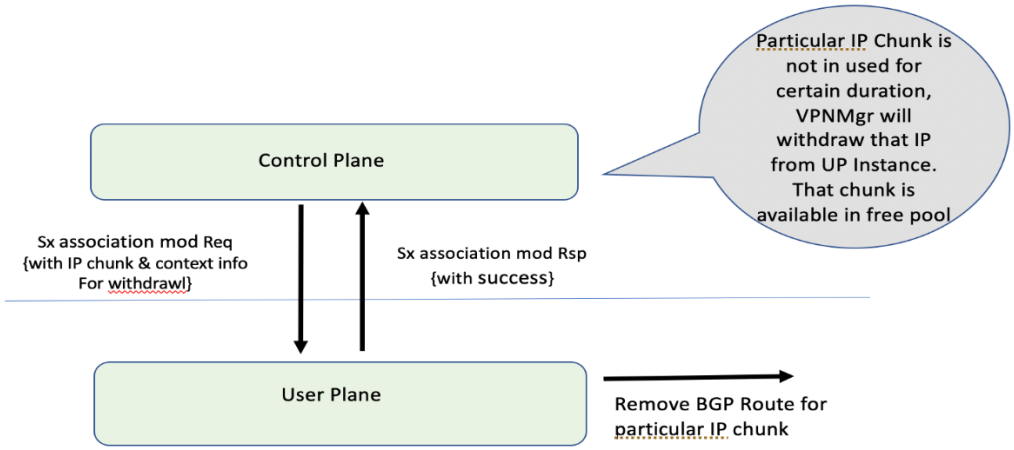

Figure 4 - IP Chunk Resource Withdrawal (Unused/Idle Chunk) by CP

Current IP Address Allocation and Replenishment in 5G

In the 5G SA deployment model, the control and user plane separation is natively built in. The node responsible for most of the PGW-c functionalities in 5G is called the Session Management Function (SMF) [6]. It responsible for session establishment, modification, and release, including the tunnel between the user plane function (UPF) [7] and the access network (AN).

SMF configures traffic steering at the UPF to route traffic to the corresponding Data Network (DN). It controls and synchronizes the charging data collection at the UPF, among others. It also handles user element IP address allocation and management.

IP Address Management (IPAM) [8] is a technique for tracking and managing IP addresses of a network. A part of the SMF, IPAM is one of the core components of the subscriber management system. It provides all the functionalities necessary for working with the cloud-native subscriber management system. It also acts as a generic IP address management system for different network functions such as the SMF, Policy Control Function (PCF), and so on.

The IPAM system includes the following functionalities to serve the cloud native and CUPS architecture:

- **Centralized IP resource management:** Based on the needs of the Internet Service Provider (ISP), the Control Plane (CP) is deployed either on a single (centralized) cluster or multiple (distributed) clusters. For multiple cluster deployments, the IPAM automatically manages the single IP address space across the multiple CPs that are deployed in the distributed environment.
- **IP address-range reservation per user-plane:** For subscribers connecting to the Internet core, the User Plane (UP) provides the physical connectivity. The UP uses the summary routes to advertise subscriber routes to the Internet core. For CPs that are managing multiple UPs, the CP reserves a converged IP subnet to the UPs. In such a scenario, the IPAM splits the available address space into smaller address ranges and assigns it to different UPs.
- **IP address assignment from pre-reserved address-ranges:** When subscribers request an IP address, the IPAM assigns addresses from the pre-reserved address range of their respective UP.

IPAM uses the following sub-modules for the cloud-native subscriber management system:

- **IPAM Server:** This module manages the complete list of pools and address-space configurations. It splits

the configured address ranges into smaller address ranges statically or dynamically, to distribute them to IPAM cache modules. The IPAM Server is deployed as a centralized entity to serve a group of cloud-native clusters. It also can be an integrated entity within a single cluster.

- **IPAM Cache:** This module receives the free address ranges from the IPAM Server and allocates the individual IP addresses to the IPAM clients. Usually, the IPAM Cache is deployed in a distributed mode running within each cluster to communicate with the co-located or remotely located IPAM server. The IPAM Cache also handles address-range reservation per UP and pool threshold monitoring. The IPAM Server and Cache modules can run as an integrated mode.
- **IPAM Client:** This module handles the request and release of an individual IP address from the IPAM Cache for each IP managed end device. The IPAM Client is tightly coupled with a respective network function.

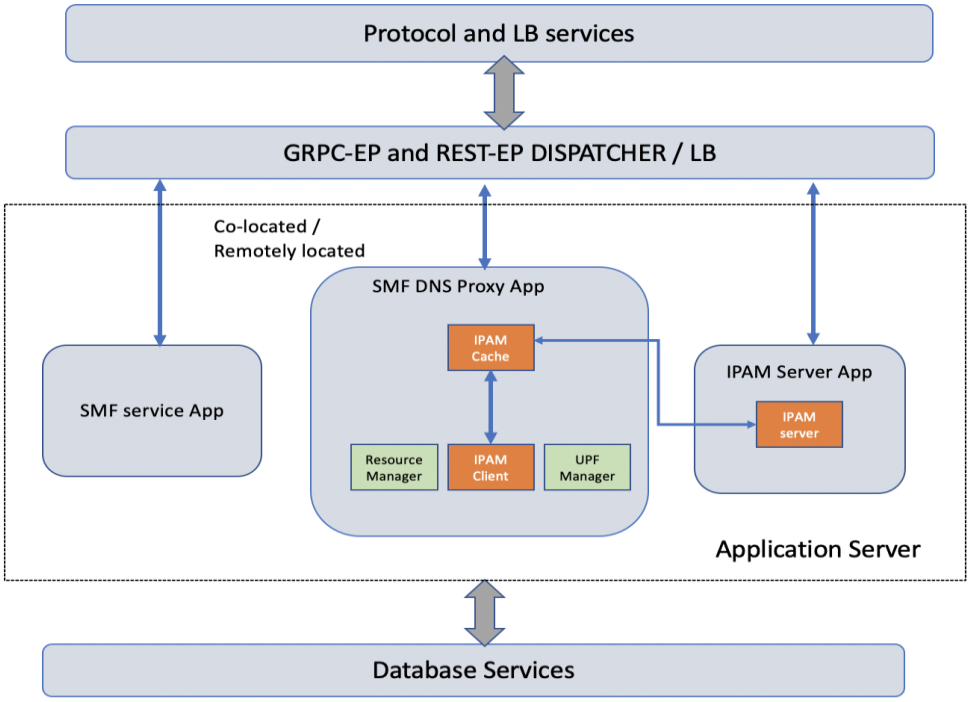

Figure 5 – IP Address Management in Session Management Function (SMF)

- **SMF Node Manager Application:** The SMF Node Manager Application takes care of the UPF, ID resource, and IP address management. It integrates the IPAM Cache and Client modules. The UPF Manager uses the IPAM Client module for address-range-reservation per UPF.
- **SMF Service Application:** The SMF Service Application provides PDU session services. During session establishment and termination, the IP addresses are requested and released back. The SMF Service Application invokes the IPC to RMGR in Node Manager, which receives (free) the IP from the IPAM module.
- **IPAM Server Application:** Based on the deployment model, the IPAM Server Application can run as an independent microservice, as a part of the same cluster or in a remote cluster. For standalone deployments, IPAM Servers are an integral part of the IPAM Cache.

The following call flow depicts the integration of the IPAM in the SMF.

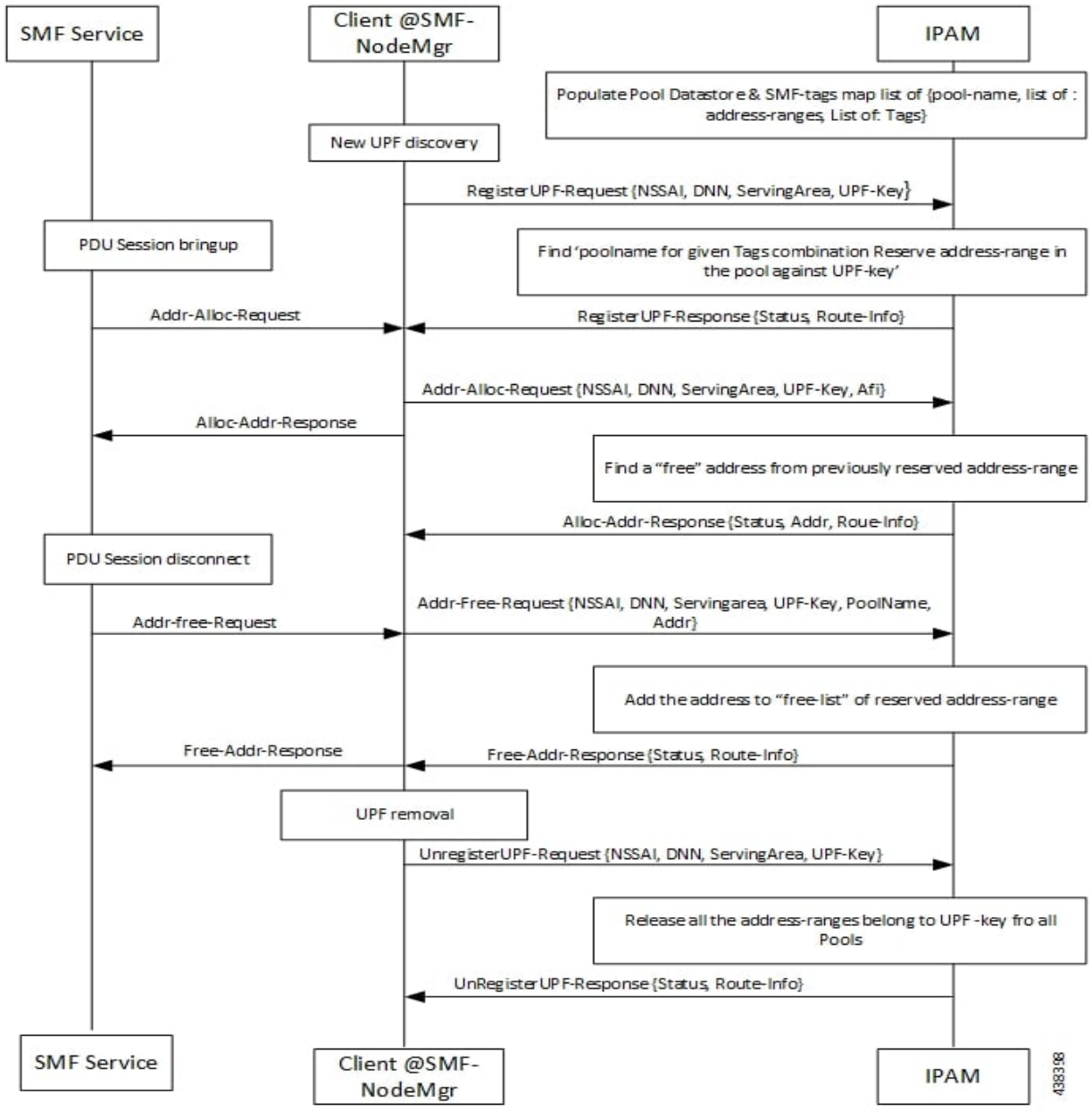

Figure 6 - IP Address Allocation Flow in SMF [9]

Limitations of Existing IP Pool Management Procedure

A centralized CP is responsible for IP pool allocation to each of these UP groups. The current Cisco® implementation of CPs does not support an adaptive approach to IP pool chunk size allocation.

All UPs in the pool are given the same size of IP pool chunk by means of static configuration in the CP (UP selection can be based on APN/DDN or TAI, and so on). When a new UP is added, it is allocated a similar pool chunk size as the other associated UPs. This is acceptable when there is an availability of pools chunks. However, if a condition exists in which the pools in CP are close to being exhausted—even if a new UP is allocated to reduce the load—CP would not be able to assign chunks. This is because it may not have an available chunk large enough to allocate to that UP; hence, the UP would be unable to share the load.

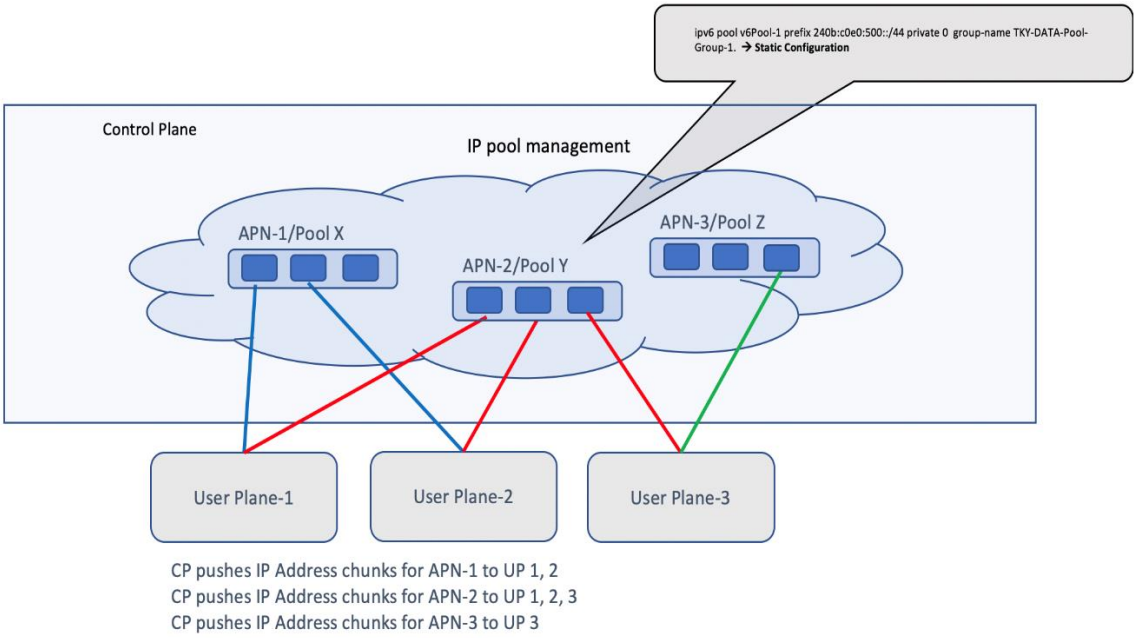

Figure 7 - Overall IP Pool Management by CP

Typically, All UPs in the same user plan group are given the same size of IP pool chunk by means of static configuration in the CP. When a new UP is added, it is allocated a similar pool chunk size as the other associated UPs.

Because the chunk size is constant, there is a possibility that CP shall not allocate IP chunks to a UP on request because of pool exhaustion on the CP. This can lead to a call-drop situation. Also, in case a new UP is added to the group, there can be a situation where there no chunks are available on the CP to allocate it to the request from the new UP. See the following figure for details.

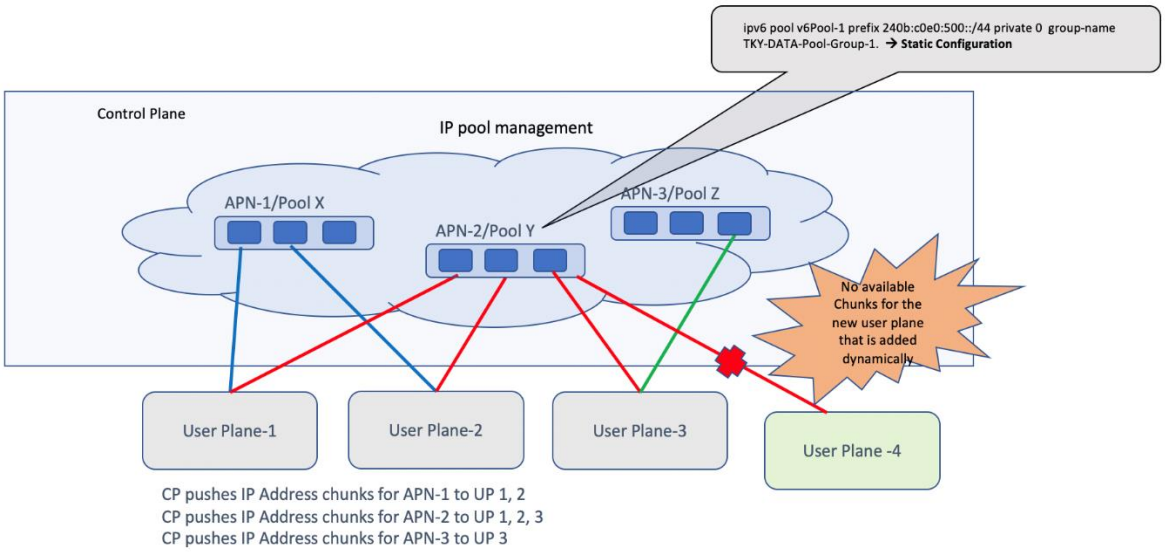

Figure 8- IP Chunk Allocation Failure when a New UP is Introduced in Load Conditions CP

Though the situation looks like a total congestion situation, it is possible to accommodate more users by optimizing the allocated chunk size to the existing UPs. The other UPs have many unused IPs/IP chunks that can be reused here.

Currently, Cisco CUPS and other competitors' architectures support only fixed-size "IP pool chunk". We need an adaptive pool chunk allocation algorithm in the control plane, which enables CPs to assess the current usage of IP pools and allocate adaptively, in a ramp-up or ramp-down manner, to cater to dynamic IP pool allocation requests.

We are working with Cisco CUPS customers (such as Rakuten, PLDT, T-Mobile, KDDI, Verizon), and this solution is applicable to everyone. It enables service providers deploying CUPS to dynamically monitor, re-calculate, and assign "IP chunks" that are aligned with user plane growth. This solution can be deployed for both 4G and 5G CUPS architectures.

Dynamic IP Chunk Allocation

Many service providers have experienced service loss and drop in KPIs due to non-availability of IP chunks in CUPS. The IP pool is a finite resource and needs to be used efficiently between all UPs. This new algorithm enables the CP to be able to allocate IP chunks to the associated Ups, even in high-usage conditions, by dynamically adapting the chunk size from the available pool—thereby ensuring that enough (smaller) chunks are available for service continuity. We propose a new algorithm to dynamically monitor "IP chunk usage" by using the following parameters:

1. **chunkCount:** Initial number of IP chunks configured
2. **chunkSize:** Initial chuck size configured
3. **chunkRecalcutionThreshold:** Used to recalculate chunk size based on the available free chunks in CP
4. **chunkResizeThreshold:** (0-100) % - Used for chunkRecalcutionThreshold
5. **chunkDelta:** Padding factor to avoid frequent recalculation (avoid flip flops)
6. **adaptiveChunkSizeAuditTime:** Audit interval for recalculation

This algorithm can be implemented with software changes in SMF. The algorithm is broadly classified into following wo steps

1. **Adaptive IP Chunk Size Ramp Down**
2. **Adaptive IP Chunk Size Ramp up**

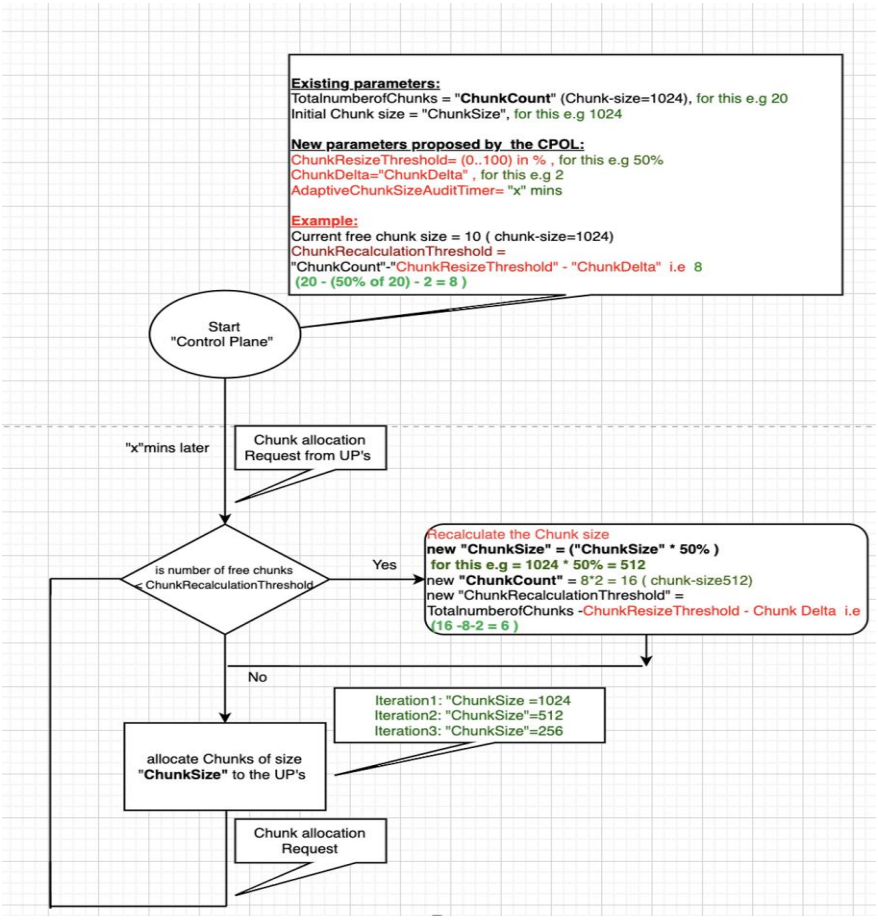

Figure 9 - Adaptive IP Chunk Size Ramp Down

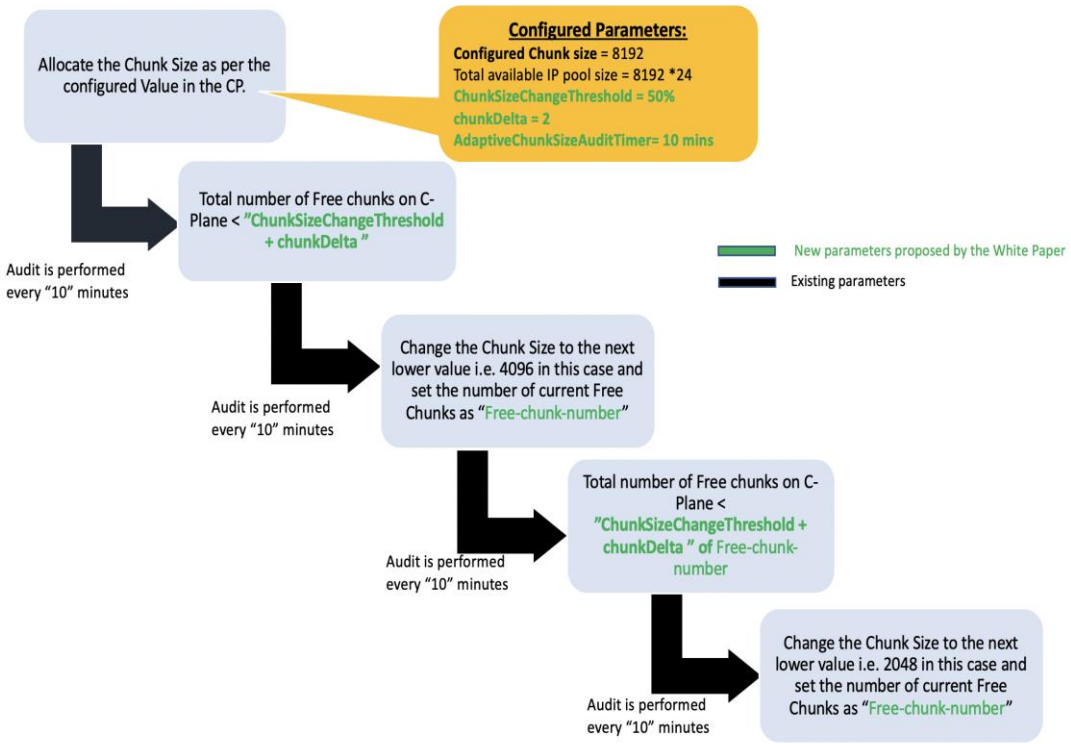

Figure 10 - Adaptive IP Chunk Size Ramp Down steps

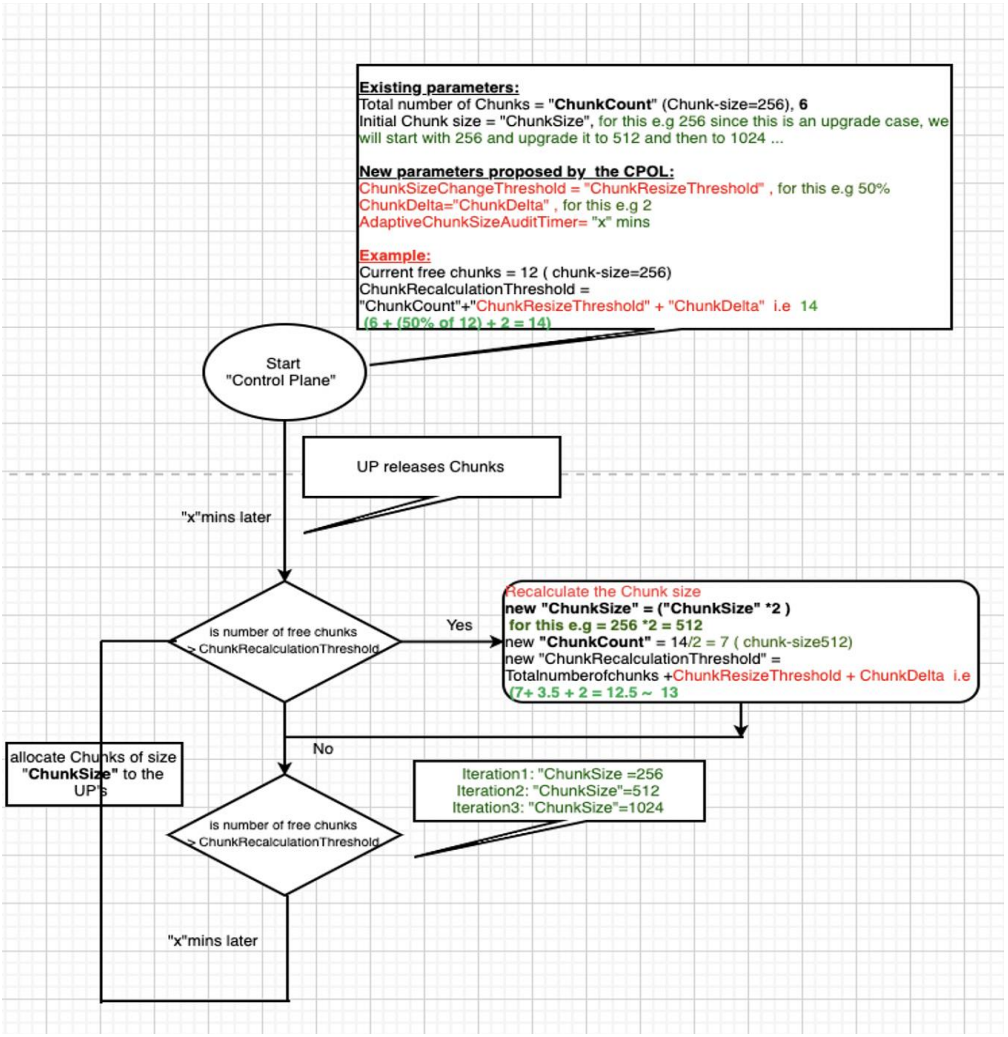

Figure 11 - Adaptive IP Chunk Size Ramp Up

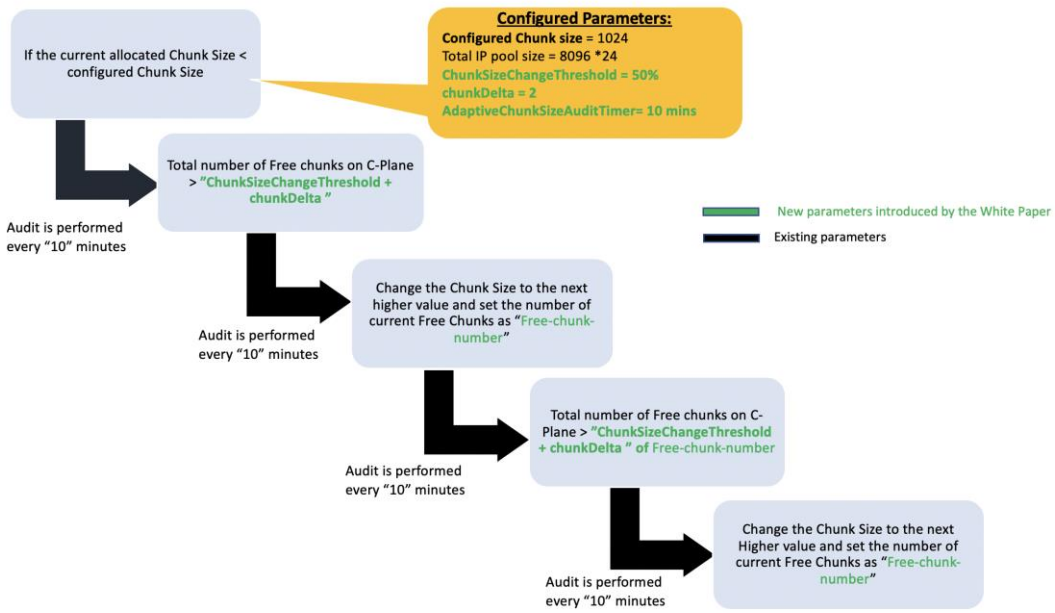

Figure 12 - Adaptive Chunk Size Calculator Algorithm for Upgrade Case

The above algorithms, once implemented in 5G Packet core using CUPS, will solve the problem arising due to limitation of resources and any mismatch. This requires enhancements to control messages on Sx interface however this can be deployed in a multi-vendor environment where the control plane and user plane are remotely located and belong to different vendors.

Summary

The IP pool allocation and dynamic management has been biggest challenge faced by mobile operators globally. This issue has caused several network and service disruptions because of mismatch of IP pool chunks between control and user plane network functions. This paper is not just describing the problems, but it provides solutions which can be deployed easily.

References

[1] 3GPP CUPS Architecture Specification

[2] ETSI Architecture for Multi-access Edge Computing

[3] Cisco Serving Gateway Admin Guide

[4] Cisco Packet Data Network Gateway Admin Guide

[5] Cisco User Plane Function Admin Guide

[6] Cisco Session Management Function Admin Guide

[7] Cisco User Plane NF

[8] IP Address Management (IPAM) Architecture

[9] Cisco IPAM Call Flow

Glossary of Terms

AMF	Access and Mobility Management Function
CN	Cloud-Native
CU	Centralized Unit
CUPS	Control and User Plane Separation
DCI	Datacenter Interconnect
DU	Distributed Unit
eNB	e NodeB
EPC	Evolved Packet Core
EVPN	Ethernet Virtual Private Network
gNB	g NodeB
IMS	IP Multimedia Subsystem
MEC	Multi-access Edge Compute
NFVI	Network Function Virtualization Infrastructure
NSA	Non-Standalone
SA	Standalone
SDN	Software Defined Networking
SMF	Session Management Function
SP	Service Provider
SR	Segment Routing
URLLC	Ultra Reliable Low Latency Communications
UPF	User Plane Function
(V)NF	(Virtualized) Network Function

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