SD-WAN Integration with Network-Compute Fabric for Programmable Interconnection CEC in 6G Networks

Razvan Mihai*, Marius Iordache*, Catalin Brezeanu*, Ioana Dragus†
Adlen Ksentini‡, and Akram Boutouchent‡
*Orange Romania, Romania
†Realworld Eastern Europe, Romania
‡Eurecom, France
Email: {razvan.mihai, marius.iordache, catalin.brezeanu}@orange.com;
ioana.dragus@realworld-systems.com; {adlen.ksentini, akram.boutouchent}@eurecom.fr

***Abstract*—SD-WAN is an integrating component of the Network Compute Fabric (NCF) concept, that implements the network transport pool of resources with dynamic management and orchestration, as flexible and programmable framework for interconnecting the continuum PoPs. SD-WAN and NCF are enabling dynamic control of transport resources, with adaptation of flexible services and changes on demand, using closed-loop and automation. Traffic can be manipulated or rerouted for better performance and SLAs, innovation being the SD-WAN through the controller capabilities. The North Bound Interfaces(NBIs) is the abstract point of interaction between the SD-WAN controller and the upper layer NCF. The programmable SD-WAN enables transport automation and permits the deployment and scaling of computing workloads, implementing the dynamically adjustment of conectivity in response to computes data exchange requirements. 6G SD-WAN enables the dynamic links between compute edges, to scale the CEC infrastructure while maintaining the QoS. This innovative approach empowers interconnected computing through programmable infrastructures.**

***Index Terms*—6G networks, orchestration, automation, control & management, closed-loop, AI/ML, SD-WAN**

I. Introduction

The telecommunications industry is under rapid transformation that is driven by increasingly complex network services. 5G brought significant architectural [4] modifications through virtualization technologies (NFV/SDN) [1] and network cutting capabilities, substantially increasing operational complexity. In response, industry initiatives like ETSI ZSM [7], [10] aim to create fully automated, self-managing networks [9], while Intent-Based Networking (IBN) simplified operations. In addition, Artificial Intelligence (AI) and Machine Learning (ML) are evolving to support future 6G architectures [11], positioned as a fundamental component in the 6G AI native architecture. This native AI approach is the shift from reactive to programmable AI/ML automation, enabling features like intelligence at all network levels, distributed data frameworks, and autonomous operations. In this case, AI as a Service is improving sustainability, coverage, security, and network resiliency. This transformation requires a complete redesign of service management and orchestration for 6G networks. The traditional management approaches are inadequate for the new AI native environments, which require a more comprehensive AI/ML model lifecycle management and distributed AI workload orchestration. New architectures must extend beyond conventional management frameworks to incorporate AI operations and advanced analytics. 6G Intent-Based Networking will provide the necessary abstraction layer, while intent-driven management will be essential for managing complexity and to ensure the optimization of resources. The new model will open the door for new enabling innovative business models. SD-WAN technology will play a crucial role in 6G transport

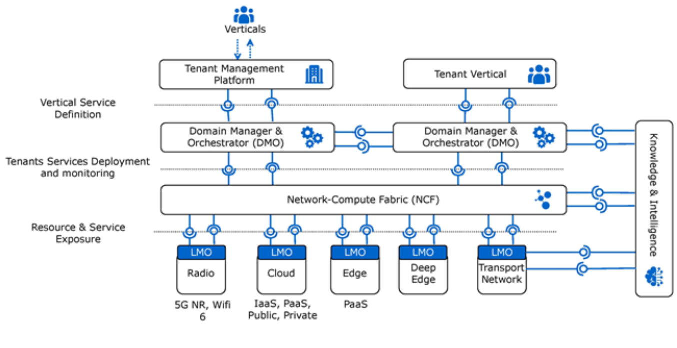

Fig. 1. 6G-INTENSE High-Level Architecture

networks, 6G-INTENSE proposes a beyond-MANO approach for Compute Inter-Connection (CIC), fully adopting the SD-WAN paradigm and Layer-7 overlays as a scalable solution that can be easily extended towards a distributed Cloud-Edge Continuum with multiple owners. In 6G-INTENESE, see Fig.1 the SD-WAN controller is part of the Network-Compute Fabric [6] [3] abstraction, aiming to offer (programmability in order to allow the Network-Compute Fabric, enforcing QoS to guarantee SLA of some services, such as low-latency, high bandwidth, and low-loss rate and Resiliency support, by being able to select different routes for the same service.

II. Architectural Framework for CEC Interconnection

Software-Defined Wide Area Network (SD-WAN) [2] technology is evolving significantly as networks transition toward 6G. The current state and evolution path of SD-WAN has emerged as a key technology for Compute Inter-Connection (CIC), Fig.2, moving beyond the limitations of traditional WAN Infrastructure Manager approaches used in MANO frameworks. 6G-INTENSE aims to introduce network programmability at the WAN level with SD-WAN adopted as a key technology. However, while an SDN controller performs device-level configurations, an SD-WAN controller can create overlay networks on top of heterogeneous underlay networks abstracted as "SD-WAN Edges", with varying degrees of programmability, reliability and cost. This hierarchical scheme is much more scalable and puts the burden of network abstraction on the underlay networks (or Regions) that expose unified Open APIs towards the DMO. Each PoP runs an SD-WAN edge which is under the control of the intent-driven SD-WAN controller to perform application-based QoS and security policy enforcement, application forwarding over one or more WAN connections, and QoS performance measurements over each WAN to determine WAN path selection. The 6G-INTENSE leverages SD-WAN actuation (through the Network-Compute Fabric) integrated with the Cognitive Intent Handler to offer API-first onboarding and self-configuration of a new PoP and automated creation and (re-)configuration of overlays.

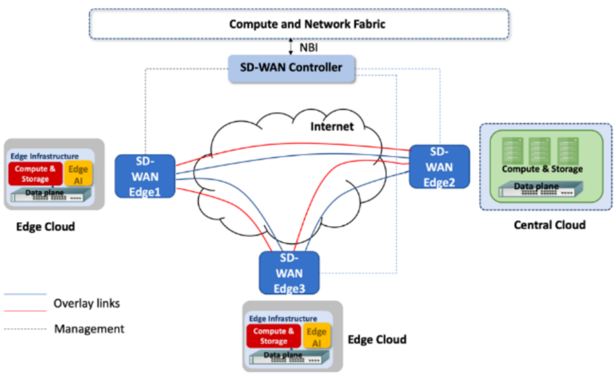

Fig. 2. CEC Interconnection using a programmable SD-WAN overlay

The proposed intent-driven SD-WAN mechanisms will represent an important breakthrough idea to facilitate autonomous inter-connectivity of CEC resource pools via programmable WAN links in place of the rigid WIM system of MANO. The SD-WAN transport domain is part of the orchestration continuum, facilitated by the Network-Compute fabric and innovative AI Native Toolkit. SD-WAN adopted as a scalable solution that can be easily extended toward a distributed Cloud-Edge Continuum with multiple stakeholders, with several key advancement in 6G SD-WAN:

- **Layer-7 Overlay Approach**: SD-WAN is being implemented as a Layer-7 overlay solution, which doesn't require full authorization to configure networking devices.
- **Integration with Network-Compute Fabric**: SD-WAN controllers are becoming part of the Network-Compute Fabric abstraction, offering programmability to specify QoS levels and resiliency.
- **Intent-Driven Programmability**: The 6G-INTENSE project proposes intent-driven SD-WAN mechanisms to facilitate autonomous inter-connectivity of Cloud-Edge Continuum (CEC) resource pools.
- **Enhanced QoS Capabilities**: SD-WAN in 6G is being designed to enforce QoS to guarantee SLA for services.
- **Improved Resiliency**: Advanced SD-WAN implementations can select different routes for the same service, enhancing network resilience.

III. 6G SD-WAN Technical implementation

The NCF is the layer of the 6G-INTENSE architecture that is tasked with abstracting and managing diverse resource providers across heterogeneous infrastructure domains. It operates as the bridge between service-level orchestration (handled by DMOs) and the technological domains managed by LMOs, enabling intelligent and intent-driven allocation and optimization of compute, network, and sensing resources throughout the CEC.

The innovative SD-WAN technology is capable of enabling the network orchestration between PoPs, and the integration with the NCF resources transport pool. Based on the monitoring capabilities (QoS, Performance), the SD-WAN is capable of dynamically controlling the resources, flexible services adaptation and on-demand changes, using closed-loop automation. The innovation is supported by the SD-WAN controller capabilities, the NBIs acting as an abstract point of interaction between the SD-WAN controller and the QoS monitoring capabilities. It's integration within the NCF enables abstracting and managing these different transport network resources, as for the instantiation we leverage an open source controller and SD-WAN edge [5].

In 6G-INTENSE, see Fig 3, the SD-WAN Controller provides a comprehensive Representational State Transfer (REST) API structure, enabling management and orchestration of Software-Defined Wide Area Network services. The northbound interface allows the creation, configuration, monitoring, and management of network overlays across distributed edge devices. It is supporting key capabilities, for Overlay Network Management, Edge Device Configuration, Service Access Control, Traffic Classification and Performance/QoS Monitoring. This is done through a programatic interface, for NCF, that will manage and controll of SD-WAN [8]. The service QoS class association at the orchestration layer is passed to the SD-WAN controller, which converts it into policy rules for traffic identification and routing. Matching rules based on parameters such as IP addresses, ports, or protocols are generated and pushed to SD-WAN edges that constitute the lower or data-plane layer of the architecture and are deployed at each POP to classify traffic flows and apply routing policies accordingly.

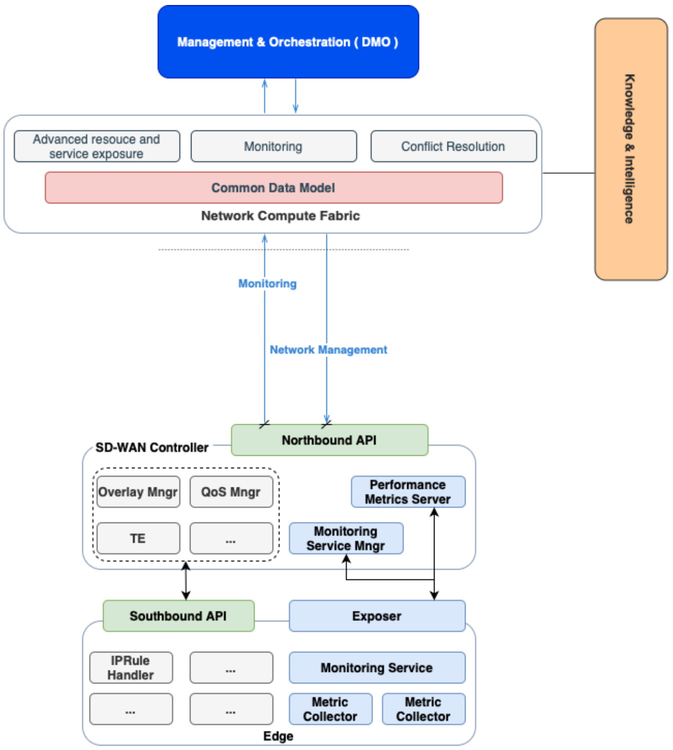

Fig. 3. SD-WAN NCF High-Level Architecture

The control plane, or the SD-WAN controller, interprets the requirements received from the orchestration layer and maintains the real-time configuration of the SD-WAN edge instances. When the NCF observes SLA violations, such as exceeding latency for a given service, it can instruct the controller to reassign the affected service traffic flow to another overlay with better performance. This rerouting can be reactive, based on real-time metrics collected by the controller, or proactive if driven by embedded AI modules.

The SD-WAN controller acts as the transport network domain, abstracting and exposing capabilities and service models to the NCF via the NBI, enabling control over the distributed WAN infrastructure. Its primary function is to translate the abstract network requests received from the NCF into configurations to be enforced at the edges. These configurations include tunnel establishment, routing logic, traffic classification rules, and telemetry activation. The SD-WAN Northbound Interface (NBI) is the abstract point of interaction between the NCF and the Transport Network LMO or the SD-WAN controller. It enables configuration and monitoring of overlay networks, as well as the enforcement of service-specific routing configurations.

SD-WAN Controller API enables the NCF to monitor the network performance (QoS Monitoring) and, based on analytics, to implement closed-loop control mechanisms and provide services traffic engineering. This dynamic interaction is essential for ensuring optimal service delivery and automated adaptation to changing network conditions. The Technical capabilities of SD-WAN enables the Controller in order to ensure the QoS Monitoring, service performance, and TE, as based on the features, the monitoring is applied end-to-end to the overlay tunnels, and measurements can be used by the NCF upper layer

Conclusions

The integration of SD-WAN with NCF represents a significant advancement in the evolution toward 6G networks. SD-WAN serves as a critical component within the Network-Compute Fabric, as it is enabling programmable interconnection of Cloud-Edge Continuum resources across distributed environments. Its implementation offers enhanced flexibility, improved QoS enforcement, and resilience through intelligent path selection. The intent-driven SD-WAN mechanisms proposed in the 6G-INTENSE facilitate autonomous interconnectivity of CEC resource via programmable WAN.

The technical implementation showcases how the SD-WAN controller enables the NCF to monitor network performance, implement closed-loop control mechanisms, and provide service traffic engineering. This innovation will play an increasingly important role in meeting unprecedented performance requirements by enabling programmable transport automation and dynamic adjustment of connectivity in response to compute data exchange requirements.

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