Dynamic Virtual Network Connectivity Services to Support C-RAN Backhauling

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Abstract—**Aiming at satisfying in a cost-effective manner the forecast traffic growth that future mobile networks will need to support, traditional distributed Radio Access Networks (RANs) are evolving towards centralized architectures. Specifically, the Cloud-RAN (C-RAN) architecture has shown that can alleviate to some extent the ever increasing Total Cost of Ownership in mobile networks. The current trend in C-RAN is to separate Remote Radio Heads (RRH) with radio frequency (RF) functions and Baseband Units (BBU) gathering baseband processing. This functional split allows keeping RF modules close to the antennas while placing BBUs at centralized locations so they can be shared among different sites and even be virtualized. However, some issues still need to be addressed in future mobile networks, especially due to the dynamicity of services and the strict constraints imposed by the interfaces needed. In fact, connectivity reconfiguration for X2 and S1 backhaul interfaces needs to be provided as an all-or-nothing request to enable mobile resources reconfiguration in a geographical area. In view of that, in this paper we propose dynamic Customer Virtual Network (CVN) reconfiguration to be supported in metro and core network segments. Such CVN requests must include Quality of Service constraints to ensure specific delay constraints, as well as bitrate guarantees to avoid service interruption. A mathematical formulation and a heuristic algorithm are presented for the CVN reconfiguration problem and exhaustive simulation results study its performance on realistic scenarios.**

Index Terms—**Customer Virtual Networks, C-RAN backhaul**

I. INTRODUCTION

FORECAST of mobile data traffic shows that it will reach up to 367 EBs per year by 2020 [1]. Such huge demand growth needs to be satisfied in a cost-effective manner, which imposes challenging requirements to future mobile networks. In consequence, next generation mobile networks are currently hot topic within the research community.

From the mobile side, huge efforts have been carried out to study architectures and techniques to increase capacity offered to users (see e.g., HetNets [2] and MIMO [3]). However, those solutions may result in higher interference and costs increments. To alleviate to some extent the ever increasing Total Cost of Ownership (TCO) in mobile networks (including both Capital Expenditures (CAPEX) and Operational Expenditures (OPEX)) while satisfying the expected cells'

demand growth, research work has focused on centralized Radio Access Network (RAN) architectures, including the Cloud RAN (C-RAN) concept [4]. In centralized RAN architectures, baseband processing is gathered in baseband units (BBU) and placed in central offices (CO) separated from Remote Radio Heads (RRH) with radio frequency (RF) functions, so they can be shared among different sites and even be virtualized to run in the form of virtual machines. A fronthaul network connects RRHs and BBUs and entails stringent requirements to support protocols such as the Common Public Radio Interface (CPRI) [5]. To connect BBUs to core COs (hosting the Mobility Management Entity – MME– or the serving Gateway –S-GW–) connections need also to be established over the so called backhaul network.

Benefits from shared BBU pools have been lately studied (see e.g., [4]). To support this, authors in [6] proposed the telecom cloud architecture focused on orchestrating cloud with heterogeneous access and core networks to maximize the performance in terms of throughput and latency while minimizing TCO. In addition, noticeable OPEX reduction can be obtained by dynamically reconfiguring the C-RAN mobile network to adapt it to the actual load [7].

Several works can be found in the literature where optical networks are proposed to support C-RAN architectures. In [8], the authors proposed using the Wavelength Division Multiplexing (WDM) technology in the access/aggregation network. Focusing on the same network segment, the authors in [9] proposed an energy-efficient WDM aggregation network and formally defined the BBU placement optimization problem as an Integer Linear Programming (ILP) model aiming at optimizing the aggregation network in terms of power consumption. The authors in [10] recently proposed an ILP model for optimal BBU hotel placement over WDM networks in centralized RAN.

Nonetheless, some issues need to be addressed to support the expected dynamicity in future mobile networks, specifically related to the wide range of services that those networks are expected to support. As a result, communication interfaces required in future RAN require very restrictive constraints, mainly in terms of capacity and delay, which transport networks need to satisfy. In fact, Service-specific parameters in Service Level Agreements (SLAs) become crucial to guarantee both the required Quality of Service (QoS) and a minimum bitrate guaranteed aiming at avoiding service interruption.

To provide service-specific network services, network virtualization techniques on Multiprotocol Label Switching (MPLS) or Optical Transport Network (OTN) multilayer networks can be considered. Network virtualization allows network operators to optimize their infrastructure and resources utilization while offering customer virtual networks (CVN) to, among others, mobile operators providing C-RAN services. The latter can manage their mobile infrastructure and resources using their own Software Defined Network (SDN) controller and request reconfiguring their virtual network to add or release capacity on-demand subject to some constraints, such as delay and bitrate guarantees. Note that since the network operator controls the network infrastructure, is aware of resource availability and is able to collect performance monitoring data, such as effective throughput and delay, and correlate them into QoS indicators.

To facilitate network resources virtualization, IETF is working on the Abstraction and Control of Transport Networks (ACTN) framework [11]. Moreover, ACTN is supported by the standardized Application-Based Network Operations (ABNO) architecture [12], which can accept on-demand connection requests via an ABNO controller. In addition, ABNO can be complemented with an Application Service Orchestrator (ASO) on top implementing a northbound interface aiming at facilitating applications' requests using their own semantic [13]. Based on the ACTN model, in our previous work in [14] we proposed using an ASO for providing on-demand reconfiguration of CVNs.

Several works can be found in the literature studying related topics (see e.g., [15]-[16]). Focused on scenarios requiring both virtual topology reconfiguration and additional service-related requirements, authors in [15] studied reconfiguration in scenarios requiring service resilience and security based on periodic pre-planning, whilst authors in [16] proposed to control virtual networks that adapt to traffic changes.

Since the requirements for C-RAN fronthaul and backhaul networks are different, differentiated approaches need to be considered. An important requirement to support C-RAN backhauling is that connectivity must be survivable by offering bitrate guarantees in case a failure affects the underlying network. Such bitrate guarantees can be based on recovery techniques such as 1:1 (or 1+1) *protection*, where two Shared Risk Link Group (SRLG) -disjoint paths are established [17]. Another option is *diversity*, where two SRLG-disjoint paths are set-up with a combined capacity to satisfy that requested and being the minimum path capacity equal to that to be guaranteed. It is worth noting that diversity, being supported by two paths, entails less capacity to be reserved compared to protection. Authors in [18] proposed using SRLG for protection in WDM networks with differentiated reliable requirements.

An important feature of C-RAN is the ability to reconfigure the resources in a geographical area to adapt the mobile network to the current load. In that regard, when a reconfiguration is decided, connectivity reconfiguration needs to be provided as an all-or-nothing request. In this paper, we focus on the backhaul network and propose dynamic CVN provisioning with quality constraints and bitrate guarantees to support such all-or-nothing connectivity requests. Specifically, the contribution is two-fold:

- Firstly, Section II defines the requirements to provide connectivity services supporting C-RAN backhauling and presents our proposal for CVN reconfiguration. Although the concept of CVN reconfiguration is general and can be applied considering different network technologies, in this work we assume that the underlying optical network is an Elastic Optical Network (EON) [19]. In addition, in view of the characteristics of backhaul interfaces, we propose specific bitrate guarantees options.

- In Section III, a Mixed Integer Linear Program (MILP) formulation is presented for the CVN reconfiguration problem considering diversity and protection to guarantee bitrate. In view of the complexity and the size of the problem, a heuristic algorithm is proposed to provide better trade-off between complexity and optimality.

The discussion is supported by the results in Section IV, including exhaustive simulation over realistic scenarios to study the performance of MPLS network approaches to support CVNs and the performance of CVNs to support C-RAN backhauling.

II. C-RAN REQUIREMENTS AND CVN SUPPORT

In this section, we first present the C-RAN scenario considered in this paper and summarize its requirements for the backhaul links. Finally, our proposal to provide CVN with QoS constraints and bitrate guarantees is described.

A. C-RAN Architecture Model

Recently, the functional splitting of RF and baseband processing into RRHs and BBUs, respectively, allows keeping the RF modules close to the antennas while placing BBUs at certain distant locations. RRH and BBU are usually connected using an optical fronthaul network to support CPRI [5], which requires huge capacity and strict delay constraints. Moreover, two interfaces are needed at the backhaul [20]: *i*) X2 interfaces are required between base stations of neighboring cells to assist handover and to support rapid co-ordination schemes; and *ii*) S1 interfaces between base stations and mobile core entities, such as MME or S-GW are also required. Connections supporting X2 or S1 interfaces are needed in the backhaul.

Finally, C-RAN assumes that virtualized BBU pools are hosted in different central locations and can be flexibly configured to serve RRHs [21]. This reconfiguration requires thus, from connectivity services provided by the underlying network supporting C-RAN backhauling.

Without loss of generality, in this paper we consider a reference scenario for future mobile networks based on C-RAN. A set of geographically distributed RRHs cover certain regions and virtualized BBU pools are hosted in COs in the

metro segment. Mobile core entities, MME and S-GW, are placed in the core network and their functions virtualized in a core CO. Aiming at satisfying the required capacity in different areas, we consider RRHs corresponding to Macro Base Stations (MBSs) and RRHs corresponding to small cells, which can be activated or deactivated for capacity management according to the traffic demand fluctuation at different hours. Let us assume that activation/deactivation of those RRHs can be done through the corresponding entity in charge of the control and management of the C-RAN. In addition, similarly as the cloud variant in [21] and as in [7], we consider that a given RRH can be served from different virtualized BBU pools along the time.

Moreover, handover and tight co-ordination schemes among active and neighboring RRHs need to be considered; thus, X2 interfaces between virtualized BBUs in BBU pools are required. It is worth noting that, due to strict delay limitations required in X2 interfaces, not all BBUs in BBU pools hosted in distant COs might be accessible among them. Finally, connections to support the S1 interface towards the core CO (hosting MME and S-GW entities) need also to be established over the backhaul network.

B. Backhaul requirements in C-RAN

According to scenarios similar to the above described, in [7] we tackled the problem of minimizing CAPEX costs to equip COs while satisfying demand at any time for all cells; CPRI, S1, and X2 interfaces requirements and limitations, such as capacity and maximum delay constraints, were considered. Focusing on the X2 and S1 interfaces, from the studies carried out in [7], we summarize a set of requirements that backhaul networks need to satisfy to support C-RAN:

a) S1 and X2 required capacity depends not only on the site configuration (technology adopted, MIMO, and spectrum width among others) but also on the load density, which varies with time. Moreover, although configurations such as 8x8 MIMO and 100 MHz spectrum width require about 3 Gb/s according to S1 peak rate, higher capacities will be required in future mobile networks, targeting at cell throughputs between 10 and 100 Gb/s.

b) From the C-RAN operator side, the required network topology in the backhaul can also vary with the time: during periods of low dense demand, when few RRHs are active to serve a given load, certain BBU pools may remain unused and no connections are required to support neither X2 nor S1 interfaces. On the contrary, during peak hours, more BBUs need to be allocated and connectivity increased to serve the load. As a result, when a reconfiguration is decided in a geographical area, connectivity reconfiguration for all the affected X2 and S1 backhaul interfaces needs to be provided as an all-or-nothing request. Fig. 1 shows an example with the virtual topology required from a C-RAN operator to satisfy backhaul connectivity requirements for X2 and S1 at two different hours of the day (5 am and 12 pm).

c) Delay constraints need to be considered in both interfaces, although they are especially restrictive in the X2 interface.

Currently, delays in the order of tens of milliseconds are allowed in S1 interfaces, whereas tight co-ordination schemes between base stations lead to maximum delays allowed in the order of hundreds of microseconds for the X2 interface (round-trip delay time under 1 ms).

d) Failures in links supporting connections in the backhaul would impact several sites simultaneously and interrupt service for a wide range of users. To avoid such service interruption, some kind of bitrate guarantees is needed for both, X2 and S1 interfaces.

Generally speaking, C-RAN and the transport network are independently operated. C-RAN operators can compute their RAN architecture reconfiguration dynamically (e.g., according to the load density), which in turn translates into a reconfiguration on the backhaul connections, in terms both of connectivity and capacity required. However, C-RAN operators are not aware of transport network resources. Therefore, once the C-RAN operator has computed its solution to reconfigure its RAN, it can request the new topology (and capacities) required in the backhaul to effectively implement the computed solution.

Finally, and although both, X2 and S1 interfaces belong to the backhaul network as seen from the C-RAN operator, from the point of view of the transport operator, X2 connectivity will be supported on metro/regional networks, whereas S1 will be supported on core national networks.

C. CVN Reconfiguration

In view that connectivity reconfiguration needs to be provided as an all-or-nothing request, we propose dynamic CVN reconfiguration based on the ACTN framework to be supported in metro and core networks. In brief, three key entities can be differentiated in the ACTN framework: customers, service providers and network providers. Customers can request on-demand connectivity between their end-points (EPs) to reconfigure their virtual topology. In the
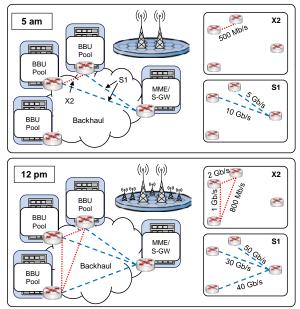

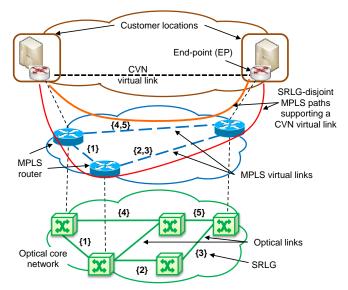Fig. 1. Example of CVN reconfiguration in C-RAN scenarios.

Fig. 2. MPLS over optical layered network to support CVNs.

Fig. 3. Proposed bitrate guarantees for X2 and S1 interfaces.

Fig. 4. Control and management architecture.

case of C-RAN, EPs are COs and mobile core entities. As stated in the introduction, we assume that CVN are provided on top of a multilayer MPLS network supported by an EON. Fig. 2 represents such 3-layered network. The following layers can be identified from top to bottom: *i*) the customer layer with CVNs connecting customer's EPs. Every CVN's link is supported by one or more MPLS paths; *ii*) the network operator's MPLS network layer consisting in a number of MPLS routers connected through virtual links (*vlink*) supported by optical connections; *iii*) the network operator's EON consisting of a number of optical nodes and optical links.

Although, this architecture can be deployed for single or multiple network operators providing connectivity services to a set of service operators, e.g., C-RAN operators, in this paper we restrict ourselves to the single network operator scenario for the sake of clarity. In such case, the network operator owns and controls the transport network infrastructure being thus, aware of resource availability and able to collect performance monitoring data, such as effective throughput and delay, and correlate them into QoS indicators. C-RAN operators own and control their mobile infrastructure and require virtual network services to connect EPs in geographically disperse locations; a C-RAN service orchestrator requiring on-demand connectivity between separated BBU pools (X2) or between BBU pools and the mobile core entities (S1) is assumed.

According to the described architecture and assumptions, C-RAN operators can request to the network operator CVN reconfiguration, including service-specific parameters for each vlink such as maximum end-to-end (e2e) delay between EPs or bitrate guarantees, in addition to the required capacity.

Regarding bitrate guarantees, the requested bitrate for X2 interfaces needs to be guaranteed in case of failures, so protection is strictly required. In contrast for S1, a reduction in the available bitrate would entail a reduction in users' data rate that can be acceptable for the C-RAN operator. Therefore, diversity can be considered for S1 interface, where a
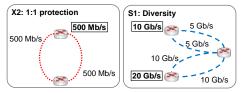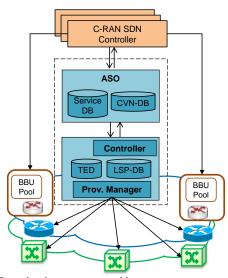
proportion (e.g., 50%) of the requested bitrate is guaranteed in case of a failure. This results in a better cost-effective solution compared to protection, considering also the difference in the required bitrate and the network segment that will support each of the interfaces. Fig. 3 illustrates the selected bitrate guarantees options. Note that both bitrate guarantees options are supported by the MPLS over optical network assumed; Fig. 2 shows a CVN vlink supported by two SRLG-disjoint MPLS paths, where one of them uses SRLGs {4, 5} and the other uses SRLGs {1, 2, 3}.

To control such layered network, the architecture in Fig. 4 is assumed, with C-RAN SDN controllers on top controlling each CVN and requesting their reconfiguration to the ASO. The ASO module maintains service-related databases; the CVN-DB describes the current state of each CVN in terms of EPs and CVN links, whereas the service DB includes, among other, SLA-related data. In contrast, ABNO maintains network-related databases, i.e., TED and LSP-DB and is in charge of the control of the transport network.

Next section, formally states the CVN reconfiguration with QoS constraints and bitrate guarantees (CUVINET) problem and presents a MILP formulation to model it. In view of its complexity and the short time in which it must be solved, a heuristic algorithm is eventually proposed.

III. THE CUVINET PROBLEM

A. Problem statement

The CUVINET problem can be formally stated as follows:

Given:
- a multilayer optical network represented by the graph

$G^O(N, L)$; being N the set of optical nodes and L the set optical of links;

- an MPLS network represented by a graph $G^V(V, E)$; being V the set of MPLS nodes and E the set of vlinks, where each vlink can be supported by several lightpaths.

- a set of customers C; each $c \in C$ manages its own CVN service, which topology is represented by a fully meshed graph $G_c(V_c, E_c)$; being V_c the set of EPs and E_c the set of CVN vlinks of c.

- a CVN service reconfiguration request coming from customer c that is represented by the tuple $\{B^r, Q^r, W^r\}$; where B^r is the capacity matrix of CVN vlinks between EPs, Q^r is the QoS matrix, and W^r is the matrix with CVN links capacity to be guaranteed. We assume that the number of SRLG-disjoint MPLS paths is restricted to two, thus the maximum guaranteed bitrate cannot exceed 50% of the total capacity in the case of diversity ($w^r \leq 0.5 * b^r$).

Output: the set of MPLS paths over G^V and lightpaths over G^O to be established to serve the CVN reconfiguration request.

Objective: minimize the cost of the used resources in both, the optical and the MPLS layer.

B. Mathematical model

As stated in the introduction, we assume that the optical network is based on EON. In that regard, we solve the Routing and Spectrum Allocation (RSA) following a link-path formulation based on the pre-computing frequency slots [22], [23]. Aiming at allowing distinct bitrate guarantees options, a parameter α is used to define whether diversity or protection is selected to support every CVN link.

Thus, the following sets and parameters have been defined.

N Set of optical nodes, index n.

L Set of optical links, index l.

P Set of optical routes, index p.

S Set of frequency slices, index s.

K Set of frequency slots, index k.

A Set of SRLG identifiers, index a.

β Capacity of lightpaths in Gb/s.

δ_{pl} 1 if route p uses optical link l; 0 otherwise.

δ_{ks} 1 if slot k uses slice s; 0 otherwise.

δ_{ls} 1 if slice s in link l is available; 0 otherwise.

δ_{la} 1 if optical link l is supported by SRLG a.

q_p Delay introduced by route p.

The following sets and parameters have been defined for the MPLS network:

V Set of MPLS routers, index v.

E^+ Augmented set of vlinks to connect every pair of MPLS routers, index e.

$E^+(v)$ Subset of E^+ with the vlinks incident to node v.

M Set of MPLS paths, index m.

$P(e)$ Subset of P with optical routes for MPLS vlink e.

δ_{me} Equal to 1 if MPLS path m uses MPLS vlink e; 0 otherwise.

δ_{ea} 1 if MPLS vlink e is supported by SRLG a.

φ_e Available capacity in vlink e; in Gb/s.

t_v Number of available transponders in MPLS node v.

q_V Delay introduced by MPLS routers.

q_e Delay introduced by MPLS vlink e; 0 for those vlinks not supported by any lightpath.

The following sets and parameters have been defined for CVN c requesting a reconfiguration:

V_c Set of CVN c nodes.

$E_c=D$ Set of CVN vlinks, index d.

$M(d)$ Subset of M with the MPLS paths for CVN link d.

b_d Requested capacity for CVN link d.

q_d Requested delay for CVN link d.

w_d Requested capacity to be guaranteed for CVN link d.

Finally, the additional parameters have been defined:

κ_e Cost per Mb/s from using MPLS vlink e.

κ_l Cost per Mb/s from using optical link l supporting a MPLS vlink.

α 1 if diversity is considered; 0 for protection.

The decision variables are:

h_e Continuous with the maximum delay of vlink e.

h_m Continuous with the maximum delay of MPLS path m.

r_{dm} Binary. 1 if MPLS path m is selected as the SRLG-disjoint MPLS path to guarantee w_d for CVN link d.

r_{dma} Binary. Equal to 1 if CVN link d is supported by SRLG-disjoint MPLS path m and SRLG a.

u_{de} Continuous, with the amount of flow in MPLS vlink e from CVN link d.

x_{ma} Binary. Equal to 1 if MPLS path m is supported by SRLG a.

y_{epk} Binary. Equal to 1 if MPLS vlink e uses optical route p and slot k.

z_{dm} Binary. Equal to 1 if CVN link d is supported by MPLS path m as primary path.

z_{dma} Binary. Equal to 1 if CVN link d is supported by primary path MPLS path m and SRLG a.

The MILP model for the CUVINET problem is as follows:

$$\text{Minimize} \quad \sum_{e \in E^+} \sum_{d \in D} \kappa_e \cdot u_{de} + \sum_{l \in L} \sum_{e \in E^+} \sum_{p \in P(e)} \sum_{k \in K} \kappa_l \cdot \delta_{pl} \cdot y_{epk} \quad (1)$$

subject to:

$$\sum_{m \in M(d)} z_{dm} = 1 \quad \forall d \in D \quad (2)$$

$$\sum_{m \in M(d)} r_{dm} = 1 \quad \forall d \in D \quad (3)$$

$$u_{de} = \sum_{m \in M(d)} \delta_{me} \cdot \left[(b_d - \alpha \cdot w_d) \cdot z_{dm} + (b_d - \alpha \cdot (b_d - w_d)) \cdot r_{dm} \right] \quad (4)$$
$$\forall e \in E^+, d \in D$$

$$\sum_{d \in D} u_{de} \leq \varphi_e + \beta \cdot \sum_{p \in P(e)} \sum_{k \in K} y_{epk} \quad \forall e \in E^+ \quad (5)$$

$$\sum_{e \in E^+} \sum_{p \in P(e)} \sum_{k \in K} \delta_{ks} \cdot \delta_{pl} \cdot y_{epk} \leq \delta_{ls} \quad \forall l \in L, s \in S \quad (6)$$

$$\sum_{e \in E^+(v)} \sum_{p \in P(e)} \sum_{k \in K} y_{epk} \leq t_v \quad \forall v \in V \quad (7)$$

$$h_e \geq q_e \quad \forall e \in E^+ \quad (8)$$

$$h_e \geq \sum_{k \in K} q_p \cdot y_{epk} \quad \forall e \in E^+, p \in P(e) \quad (9)$$

$$h_m = \sum_{e \in E^+} \delta_{me} \cdot (q_V + h_e) + q_V \quad \forall m \in M \quad (10)$$

$$q_d + (1 - z_{dm}) \cdot bigM \geq h_m \quad \forall d \in D, m \in M(d) \quad (11)$$

$$q_d + (1 - r_{dm}) \cdot bigM \geq h_m \quad \forall d \in D, m \in M(d) \quad (12)$$

$$\sum_{e \in E^+} \delta_{me} \cdot \left(\delta_{ea} + \sum_{p \in P(e)} \sum_{l \in L} \sum_{k \in K} \delta_{pl} \cdot \delta_{la} \cdot y_{epk} \right) \leq bigM \cdot x_{ma} \quad (13)$$
$$\forall m \in M, a \in A$$

$$z_{dma} + 1 \geq z_{dm} + x_{ma} \quad \forall d \in D, m \in M(d), a \in A \quad (14)$$

$$z_{dma} \leq z_{dm} \quad \forall d \in D, m \in M(d), a \in A \quad (15)$$

$$z_{dma} \leq x_{ma} \quad \forall d \in D, m \in M(d), a \in A \quad (16)$$

$$r_{dma} + 1 \geq r_{dm} + x_{ma} \quad \forall d \in D, m \in M(d), a \in A \quad (17)$$

$$r_{dma} \leq r_{dm} \quad \forall d \in D, m \in M(d), a \in A \quad (18)$$

$$r_{dma} \leq x_{ma} \quad \forall d \in D, m \in M(d), a \in A \quad (19)$$

$$\sum_{m \in M(d)} z_{dma} + \sum_{m \in M(d)} r_{dma} \leq 1 \quad \forall d \in D, a \in A \quad (20)$$

The objective function (1) minimizes the cost of using resources in MPLS vlinks and that of the optical resources to support new MPLS vlinks.

Constraints (2)-(7) deal with paths and lightpaths serving demands. Constraints (2) and (3) ensure that exactly two MPLS paths support each CVN link d disregarding whether diversity or protection is selected. Constraint (4) computes the amount of bitrate from a given demand that is conveyed through each vlink, which depends on the selected bitrate guarantees option. When diversity is considered (α=1) the disjoint path must meet the guaranteed bitrate, whereas in case of protection (α=0), the requested capacity must be ensured in both primary and disjoint paths. Constraint (5) ensures that

every vlink has enough aggregated capacity and forces new lightpath set-up if necessary. Constraint (6) guarantees that every frequency slot is used by one new lightpath at the most, provided it was unused. Constraint (7) limit the number of new lightpaths that are set-up to the number of available transponders.

Constraints (8)-(12) ensure the requested QoS. Constraints (8) and (9) compute the maximum delay of every vlink considering its current delay and the delay of every new lightpath supporting such link, respectively. Constraint (10) computes the delay of every MPLS path as the sum of the delay in every vlink and MPLS router it traverses. Constraints (11) and (12) guarantee that the delay of both primary and SRLG-disjoint paths do not exceed the requested delay for the CVN link they support; otherwise, the problem becomes unfeasible.

Finally, constraints (13)-(20) deal with SRLGs. Constraint (13) computes SRLG support for every MPLS path. Constraints (14)-(16) guarantee that a CVN vlink using a primary MPLS path is assigned to the SRLG supporting that path. Specifically, these constraints compute z_{dma} as the product between z_{dm} and x_{ma} variables by means of linear equations. Similarly, constraints (17)-(19) computes that product for the SRLG-disjoint path of every CVN vlink. Constraint (20) ensures that the primary path and the SRLG-disjoint path are not supported by any common SRLG for every demand.

The CUVINET problem is *NP-hard* since simpler multilayer network problems have been proved to be *NP-hard* (e.g., [24]). Regarding problem size, the number of variables is $O(|D| \cdot |M| \cdot |A| + |D| \cdot |V|^2 + |V|^2 \cdot |P| \cdot |K|)$ and the number of constraints is $O(|D| \cdot |M| \cdot |A| + |V|^2 \cdot (|D| + |P|) + |L| \cdot |S|)$. Considering a realistic scenario on a network like those in the next section, the number of variables is in the order of 10^6 and the number of constraints in the order of 10^5, which makes the above MILP model unsolvable within the times required for serving on-demand CVN reconfiguration requests, even using state-of-the-art computer hardware and the latest commercially available solvers, as it will be shown in Section IV. As a result, a heuristic algorithm is needed aiming at providing near optimal solutions in realistic scenarios.

C. Heuristic Algorithm

To solve the CUVINET problem, we propose the randomized algorithm in Table I [22]. The algorithm runs a number of iterations (line 2 in Table I), where at every iteration the set of requested CVN links (demands) is randomly sorted and served sequentially in the resulting order (lines 3-14). At the end of each iteration the obtained solution is compared against the best solution obtained so far and, in case the latter is improved, it is updated (lines 15-16). The best solution is eventually returned (line 17).

The algorithm updates first those CVN links with unchanged or decreased requirements to release resources that can be reused afterwards (lines 4-6 in Table I). The rest of the CVN links are de-allocated from G_c and added to the set D (lines 7-9). The set D is randomly sorted (line 10) and every CVN link is then set up (lines 11-14) using the *setupCVNLink*

TABLE I ALGORITHM FOR THE CUVINET PROBLEM

INPUT: $G_c(V_c, E_c)$, B^r, Q^r, W^r, α, *maxIter*
OUTPUT: Ω

```
1:   BestSol ← Ø
2:   for 1..maxIter do
3:       D ← E_c, Sol ← Ø
4:       for each e ∈ E_c do
5:           if B^r(e) ≤ B(e) and Q^r(e) ≤ Q(e) and W^r(e) ≤ W(e) then
6:               update (e, B^r(e), Q^r(e), W^r(e))
7:           else
8:               dealloc (e, G_c)
9:               D ← D \ {e}
10:      shuffle (D)
11:      for each d ∈ D do
12:          Ω ← setupCVNLink (d, B^r(d), Q^r(d), W^r(d), G_c, α)
13:          if Ω = Ø then break
14:          Sol ← Sol ∪ { Ω }
15:      if BestSol = Ø OR Sol.fitness > BestSol.fitness then
16:          BestSol ← Sol
17:  return BestSol
```

TABLE II *setupCVNLink* ALGORITHM

INPUT: d, b, q, w, G_c, α
OUTPUT: Ω

```
1:   Ω ← Ø
2:   if α = 0 then b_p = b; b_s = b
3:   else b_p = b-w; b_s = w
4:   R ← findPath(d, b_p, q)
5:   if R = Ø then
6:       Ω ← Ω ∪ setupMPLSLinks (d, b_p, q)
7:       R ← findPath(d, b_p, q)
8:       if R = Ø then return Ø
9:   Ω ← Ω ∪ allocate(G^V, d, R, b_p)
10:  S ← findDisjointPath (d, q, R, b_s)
11:  if S = Ø then
12:      Ω ← Ω ∪ setupDisjointMPLSLinks (d, b_s, q, R)
13:      S ← findDisjointPath (d, q, R, b_s)
14:      if S = Ø then
15:          deallocate(Ω)
16:          return Ø
17:  Ω ← Ω ∪ allocate(G^V, d, S, b_s)
18:  return Ω
```

algorithm described in Table II. The *setupCVNLink* algorithm returns the set Ω with the MPLS paths and lightpaths to be established. Note that, if one of the CVN links cannot be updated, then the complete CVN reconfiguration request is blocked (line 13).

The *setupCVNLink* algorithm (Table II), starts computing the capacity to be assigned to each MPLS path supporting the CVN link depending on the considered bitrate guarantees option. In the case that protection is selected, *b* is the bitrate to be carried by both, the primary and the disjoint path; otherwise, the required capacity for CVN links is split (lines 2-3). Then, function *findPath* finds an MPLS path *R* with capacity b_p in G^V for the primary path to guarantee the requested QoS *q* (line 4). In the case that no path is found, the algorithm tries to increase capacity in G^V so as to serve *d* by adding new MPLS vlinks and another try is performed. If no path is found, CVN link *d* cannot be served (lines 5-8). Otherwise, the primary path is allocated in G^V (line 9). Next, the algorithm calls function *findDisjointPath* to find a MPLS path *S* guaranteeing SRLG-disjointness with *R*, as well as meeting capacity and delay requirements (line 10). In case that no disjoint path is found in G^V, a similar procedure as the one described for the primary path is followed to increase its capacity G^V (lines 11-16). The set Ω with the MPLS paths and lightpaths to be established is eventually returned (line 18)

IV. ILLUSTRATIVE NUMERICAL RESULTS

In this section, we first evaluate the proposed heuristic algorithm and then, we use it to study CVNs from both, the network operator and the C-RAN operator view point. From the network operator's viewpoint, we evaluate two alternative MPLS network approaches to support CVN services for different kind of customer, which includes, but it is not limited to, C-RAN operators. From the C-RAN operator's view point, we evaluate the performance of CVNs to support C-RAN backhauling.

A. Network scenario

We use the realistic network topologies depicted in Fig. 5,

representing the Telefonica's Spanish network topology (TEL) and Orange's French network topology (FR).

The management architecture including customer (e.g., C-RAN) controllers, ASO (running the heuristic algorithm described in section III), and ABNO were developed in C++ and integrated in an ad-hoc event driven simulator based on OMNET++. A set of customers (e.g., C-RAN operators) require CVN reconfiguration and send CVN reconfiguration requests to ASO according to an exponential distribution with mean 1 hour following the traffic profiles in [4]. A CVN reconfiguration request is accepted provided that all the requested CVN link's capacity, QoS constraints and bitrate to be guaranteed is served; otherwise the request is blocked.

Regarding the optical layer, fiber links with spectrum width equal to 2 THz are considered; the spectral granularity was set to 6.25 GHz. An MPLS router is co-located with every optical node and connected to it through 100 Gb/s bandwidth-variable transponders (BVT) using 37.5 GHz [25]. Note that MPLS vlinks are supported by lightpaths on the optical layer and CUVINET creates and releases them to serve the actual load.

B. Heuristic algorithm validation

In order to validate the proposed heuristic algorithm, we compared its performance against solving the MILP formulation in terms of quality of obtained solutions and solving time. Several instances of an X2 connectivity service reconfiguration among a number of COs distributed over the TEL topology were generated and solved with both MILP and heuristic methods using an Intel(R) Core(TM) i7-4790K CPU @4.00GHz machine with 4GB RAM running Linux.

The results showed that solving the MILP formulation took up to 40 minutes for instances of the size considered in the following studies (i.e., 5 COs). As for the proposed heuristic algorithm, it reached the optimum in less than 500 ms, which validates the proposed heuristic algorithm as a scalable method for solving the CUVINET problem. In consequence, we use the proposed heuristic for the studies in this section.

C. Approaches to support CVNs from the network viewpoint

The performance from the network operator's viewpoint is studied considering two incremental approaches: *i*) a *static* MPLS network approach in which the MPLS virtual network is pre-planned beforehand; and *ii*) a MPLS *dynamic* approach allowing MPLS network reconfiguration.

Regarding customers, two differentiated services have been considered: one requiring regional five-EP CVN topologies during office hours and 50% bandwidth guaranteed; the other requiring nation-wide CVN topologies during off-peak periods. EPs are connected to the closest MPLS router. The maximum delay allowed between EPs is 10 ms. CVN reconfiguration requests arrive during service-defined periods, where the capacity requested between EPs is randomly chosen in the range [1-10] Gb/s. The offered load is related to the number of customers being served.

For evaluation purposes, a MPLS virtual network topology was pre-planned targeting at providing the same performance than that of the MPLS dynamic approach at 1% of service blocking probability (normalized load 0.85). Each point in the results is the average of 10 runs with more than 10,000 CVN reconfiguration requests entailing capacity increment of at least on one CVN link.

Fig. 6a focuses on QoS on the TEL network topology. As shown, the MPLS preplanning approach provides the best QoS for both average and maximum delay. As for the dynamic approach, it provides QoS which increases with the load but always under the specified maximum; on-average delay, however is comparable to that of the static approach. Next, Fig. 6b concentrates on the total number of BVTs to equip on the TEL network topology. As observed, the required number of BVTs increases with the load in the dynamic approaches, in contrast to the static one. CAPEX savings as high as 16% for 1% service blocking probability are shown. Similar results were obtained for the FR network topology.

The above clearly show that dynamic MPLS-over-optical networks provide noticeable benefits to the network operator to support CVNs.

D. Performance of CVN to support C-RAN backhauling

Let us now evaluate the performance of CVNs to support C-RAN backhauling. Because of their different capacities, QoS and bitrate guarantees requirements, we assume that specif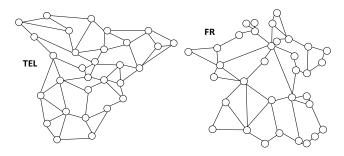ic CVNs are requested for X2 and S1 connectivity. The performance of CVNs supporting the X2 interface is studied in terms of delay and the affected connections in the event of a failure in an optical link, comparing the case that no bitrate guarantees are requested (referred to as *no guarantees*) against with bitrate guarantees considering 1:1 protection (referred to as *protection*). Regarding CVNs supporting the S1 interface, performance in terms of service blocking probability and affected connections in the event of a failure is compared for no bitrate guarantees and 50% bitrate guarantees considering diversity (referred to as *diversity*).

The network topologies in Fig. 5 are used here for both, metro and core segments. However, to capture real distances (and delays), the network diameter is scaled down to about 50 km when those topologies are used for the metro segment.

To evaluate the performance in failure scenarios, the network was loaded and the traffic generation was stopped at noon peak hour (12 p.m.). Then, we simulated that a failure occurs for each optical links in the route of MPLS paths supporting CVN vlinks and computed the CVN vlinks affected.

Finally, each point in the results is the average of 10 runs with more than 10,000 CVN reconfiguration requests entailing capacity increment of at least on one CVN link.

C-RAN CVN provisioning to support X2

To represent X2 CVN scenarios, we consider a set of 5 COs geographically distributed, hosting virtualized BBU pools and connected to the network through packet nodes. The number of X2 CVNs ranges from 10 to 90 for TEL and from 55 to 75 for FR topologies resulting the maximum values of CVNs in 1% of service blocking probability when protection is considered. The capacity of each link is in the range 200 Mb/s and 5 Gb/s according to a uniform distribution. X2 CVNs are full mesh topologies, where the probability that a X2 connection between 2 specific COs is required depends on the hour of the day, being higher during daytime hours and lower during night hours thus, representing the flexible assignment between RRHs and BBUs along the day to a different number of COs [7]. Regarding delay constraints, we limited the maximum e2e delay to 0.5 ms for X2 interfaces; note however, that per-CVN link values can be specified in the CVN reconfiguration request, e.g., to satisfy more restrictive delay constraints.
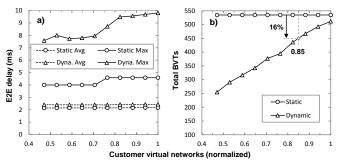

Fig. 6. End-to-end delay (a) and total number of BVTs (b) vs. number of CVNs (normalized).
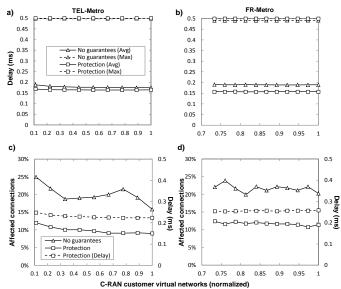

Fig. 5. Network topologies considered in this paper.

Fig. 7. Delay and affected connections vs. number of X2 CVNs.

Fig. 8. Service blocking and affected connections vs. number of S1 CVNs.

TABLE III. AVERAGE LENGTH (KM) OF MPLS PATHS SUPPORTING X2

	TEL-Metro (# CVN normalized)				
	0.2	**0.4**	**0.6**	**0.8**	**1.0**
No guarantees	36.2	35.3	35.2	35.0	34.9
Working path	33.0	32.8	32.7	32.7	32.9
Prot. path	47.7	45.9	45.1	44.7	44.8
	FR-Metro (# CVN normalized)				
	0.8	**0.85**	**0.90**	**0.95**	**1.0**
No guarantees	38.0	37.9	37.8	37.8	37.9
Working path	31.4	31.4	31.4	31.4	31.4
Prot. path	51.2	51.3	50.8	51.3	51.7

Fig. 7 illustrates the results obtained for the two topologies, each with its own COs placement. Fig. 7a and Fig. 7b show the average and maximum delay values for TEL and FR, respectively. Delay limit is never exceeded, being maximum values close to 0.5 ms. Interestingly, if we focus on the average values, the protection approach results in slightly lower times than when no bitrate guarantees are considered. The reasoning behind this is that a large number of MPLS vlinks are established to support SRGL-disjoint MPLS paths aiming at guaranteeing the whole capacity. In contrast, fewer MPLS vlinks need to be established under the no guarantees approach thus, reducing the number of routes.

Although using protection resulted in slightly lower delays, the cost in terms of number of transponders needed increases on average 81% for the TEL and 110% for the FR topologies, respectively, compared to no guarantees approach. Regarding failures, it is worth noting that when a failure affects the working path of a connection supported by 1:1 protection, the delay of the protected path is considered.

Table III summarizes representative values for the length of MPLS paths. Note that when protection is applied, only values for the working path are considered. As it can be seen in Fig. 7c and Fig. 7d, the affected connections when protection is required (about 10% for TEL and 12% for FR) is lower than when no guarantees are requested (20% for TEL and 22% for FR). When protection is used, larger routes will be considered
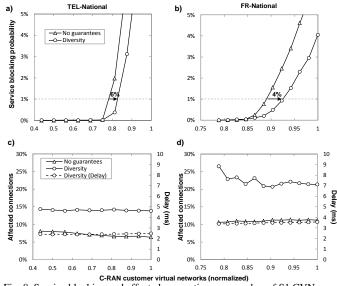
when a failure affects a connection, according to values shown in Table III thus, increasing average delay (without exceeding the 0.5ms limit) as shown in Fig. 7c and Fig. 7d. In contrast, when no guarantees are requested, service supported by the affected connections will be disrupted thus, impacting several cells simultaneously.

C-RAN CVN provisioning to support S1

Differently from X2, S1 connections require higher capacities but less restrictive delay constraints. To reproduce S1 scenarios as described in Section II, we consider regions, each containing 1 or more sets of COs (each set of COs with 3 to 5 COs) to create star topologies. A set of C-RAN operators manage their own CVNs and require connectivity to support S1 interfaces between COs and a centralized CO hosting mobile core entities. To represent the asymmetric traffic related to S1, the capacity required from COs to the central location is about 1/3 of the capacity required from the central location to COs, which varies following a uniform distribution between 5 and 50 Gb/s. Moreover, a given CO requires connectivity or not with a certain probability, depending on the hour of the day; fewer connections are required during night hours than during working hours. In addition, we consider that the maximum allowed e2e delay is 10 ms.

Aiming at providing solid conclusions for a wide range of scenarios a lower number of C-RAN operators but CVNs requiring a large number of connections were considered for the TEL network, whereas the opposite situation was explored in FR (large number of C-RAN operators with smaller CVNs).

Plots in Fig. 8a and Fig. 8b show the service blocking probability for the TEL and FR topologies, respectively. In the evaluated scenarios, the performance of the diversity approach slightly improves that of the approach without bitrate guarantees. The rationale behind that is that under the diversity approach two disjoint paths with 50% capacity (50% of bitrate to be guaranteed has been considered) are used, in contrast to the single path used when no guarantees is requested.

When failures are considered (Fig. 8c and Fig. 8d), the percentage of affected connections is higher when bitrate guarantees are required, since two MPLS paths are considered to support every single CVN vlink. Notwithstanding the available capacity is reduced in affected connections, service will not be interrupted when diversity is implemented. This is in contrast to service disruption in the case that no bitrate guarantees are requested. Additionally, Fig. 8c and Fig. 8d illustrate connections' average delay when diversity is considered.

V. CONCLUSIONS

Dynamic customer virtual topology services have been proposed to support C-RAN backhauling (X2 and S1 interfaces). Customers (i.e., C-RAN operators) request their CVNs to be reconfigured while taking into account delay constraints imposed by the interfaces and guaranteeing bitrate. To that end, a MILP formulation was presented for the CVN reconfiguration problem, named as CUVINET. In view of the complexity and the size of the problem, a heuristic algorithm was proposed providing better trade-off between complexity and optimality.

The performance of the proposed CUVINET heuristic to adapt the underlying MPLS virtual network by creating and releasing MPLS vlinks has been demonstrated though simulation; delay was kept under the limit while the amount of BVTs to be equip in the network was noticeable reduced when the the MPLS network was dynamically managed with respect to the static MPLS alternative.

Next, exhaustive simulations were carried out in scenarios focusing on the X2 interface, where bitrate guarantees are implemented using protection 1:1, and on the S1 interface, where guarantees are implemented considering diversity. Results showed that using 1:1 protection for X2 backhauling to avoid service interruption, slightly increases the average delay in the connections in scenarios with failures. Regarding S1 backhauling, diversity was considered to guarantee 50% of the requested bitrate in case of a single link failure thus, avoiding service disruption. In addition, benefits from using more than one path to support a CVN link were observed in the scenarios evaluated, which resulted in the fact that the CVNs supported was slightly increased for a given blocking probability.

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