Progressive Hybrid Greyfield Wireless Access Virtualization with Leveraged Combining of Cloud, Fog, and Legacy RANs

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***Abstract*—In this paper, we develop a new dynamic utility for wireless access virtualization (WAV) optimization embodying highly-dimensional time-varying multi-criteria metrics (i.e., CAPEX and OPEX costs, QoS or QoE, multi-tier and/or multi-RAT HetNets, etc.) that gauge the best deployment and viability scenarios of cloud (C)- and fog (F)-RANs within legacy networks. Exploiting the powerful tool of graph theory, we devise a progressive greyfield WAV strategy that optimizes our dynamic utility through an efficient combination of C- and F-RANs. This strategy is able to readjust very quickly to any changes in existing or new constraints as they evolve or occur in time, respectively. The resulting optimized hybrid RAN deployment outperforms both the greenfield and the pre-planed greyfield "turnkey" WAV strategies.**

***Index Terms*—Wireless access virtualization, radio access network (RAN), cloud-RAN (C-RAN), fog-RAN (F-RAN), hybrid-RAN (H-RAN), dynamic utility, progressive deployment, graph theory.**

I. Introduction

Wireless access virtualization (WAV) emerges as a promising solution that enables sufficient flexibility and elasticity to cope at low cost with the unprecedented data rates and traffic demand envisioned in 5G networks [1]-[4]. Indeed, in a virtual topology, independent virtual networks (VN)s are built on a one or more physical network substrates in which the VNs are isolated and transparent to each other. Each VN's resources could be then scaled up or down according to its traffic demand, thereby resulting not only in an enhanced perceived quality-of-service (QoS), but also in an efficient use of the available resources.

Significant research endeavors have been devoted to virtualizing the wireless access at different layers. [5] and [6] have focused on spectrum virtualization while [7] and [8] have studied the virtualization of different radio access technologies (RAT)s. [9]-[14] have investigated the integration of cloud computing into the radio access networks (RAN)s. In these cloud-RANs (C-RAN)s, a central computing unit (CCU) is connected to a large number of randomly deployed remote radio heads (RRHs). Since the latter are usually much closer to the user equipments (UE)s than the traditional base stations (BS)s, dramatic performance improvements both in spectral and power efficiencies may be achieved. Furthermore, pooling the network resources into a CCU not only allows an efficient use of the latter, but also paves the way towards the use of power-efficient centralized large-scale signal processing techniques aiming to enhance the UEs QoS. A C-RAN offers also an important cost gain due to its low-cost RRHs and the fact that it does not require any dimensioning of the traditional BSs' resources based on individual peak loads. Nevertheless, despite its benefits, the C-RAN technology is limited by its high latency mainly due to the often large distances between the RRHs and CCU and their time-delay constrained connections [9].

In order to overcome such drawbacks, a locally virtual network (LVN) was introduced, for the first time, in [15] as an alternative solution to C-RAN that capitalizes, in contrast to the latter, on the locally available resources at the vicinity of each access point (AP). LVN is actually nothing but a costly migration of cloud computing to the network edges (i.e., APs) to substantially reduce the latency and offer user-centric services [15] [16]. It is for this reason that Cisco coined it when introducing it shortly later as fog-RAN (F-RAN), widely adopted since by the research community. Due to its advantages, F-RAN has attracted intense research interest both from academia and industry [17]-[22]. [20] compared the C- and F-RAN technologies and identified the major challenges and open issues that should be coped with to ensure their successful rollout. [16] analyzed the cost and throughput performances of these technologies and proposed a new hybrid-RAN (H-RAN) framework that combines both C- and F-RANs while [21] investigated the benefits of cooperation among the latter within H-RAN. [22] developed a new software defined architecture for H-RANs and proved its feasibility.

All the above works and references therein have agreed that F-RANs will not completely substitute C-

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RANs. They will rather act in complementarity with one another in order to provide the sufficient flexibility and elasticity required to cope with the unprecedented data rates and traffic demand envisioned in 5G networks. Contributions have so far addressed many issues all related to the co-existence between C- and F-RANs. But to the best of our knowledge, none of them provided insights on how, where, and in which proportions these technologies would be deployed in future virtualized 5G networks, well except [16]. However, the latter considered only greenfield (i.e., does not integrate legacy RAN) and non-progressive hybrid deployment scenarios that are relatively more suitable for new VNO (VN operator) players. But such ”turnkey” or ”one-shot” virtualization of all network areas simultaneously is totally unrealistic and unsuitable for existing operators. In contrast to greenfield WAV, the progressive deployment of C- and F-RANs within legacy RANs that accounts for their inevitable coexistence and viability periods is undoubtedly much more compelling. Nevertheless, any progressive greyfield (i.e., integrates legacy RAN) strategy must be carefully implemented to optimize both network performance and deployment cost.

This work is the first to develop optimized progressive greyfield WAV deployment strategies that integrate both C- and F-RAN frameworks in legacy RANs based on a new dynamic utility embodying highly-dimensional time-varying multi-criteria metrics (i.e., CAPEX and OPEX costs, QoS or QoE, multi-tier and/or multi-RAT HetNets, etc.). Exploiting the powerful tool of graph theory, this strategy is able to readjust very quickly to any changes in existing or new constraints as they evolve or occur in time, respectively. The resulting optimized hybrid RAN deployment outperforms both the greenfield and the pre-planed greyfield ”turnkey” WAV strategies.

The rest of this paper is organized as follows. The considered WAV frameworks are detailed in Section II. Section III discusses the challenges of progressive WAV. Our novel WAV strategy is proposed in Section IV and its advantages are highlighted in Section V. Section VI verifies its efficiency through computer simulations. Concluding remarks are given in Section VII.

II. WAV FRAMEWORKS

In this work, we consider two WAV frameworks: i) cloud RAN (C-RAN) where the network resources (i.e., computational, storage, etc.) are centralized to provide on-demand processing, delay-aware storage, as well as high ubiquitous network capacity; and ii) fog RAN (F-RAN) that moves the computation tasks to the networks edge to offer customized user-centric services.

A. Cloud-RAN (C-RAN)

As illustrated in Fig 1, in C-RAN, all network resources are pooled in a CCU located in a centralized site and connected through fiber to a large number of randomly deployed RRHs. In contrast to traditional RANs, this cloud-based virtualization or remotely-virtualized network (RVN) as called in [16] dynamically adapts the allocated resources to the user equipments (UE)s and QoS requirements, providing thereby sufficient flexibility and elasticity to cope with the mobile data deluge foreseen in future 5G systems. Furthermore, a C-RAN may achieve dramatic performance improvements in both spectral and power efficiencies due to the likely short distances between UEs and RRHs. As the latter are much less expensive than traditional BSs and do not require any resource dimensioning based on individual peak loads, such a framework allows also important cost gains. It can be shown that the required number of macro-RRHs is given by [16]

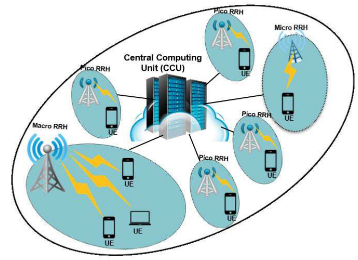


Fig. 1. C-RAN framework.

$$N_r^m = n_{op} \max\left(\frac{d_{cpc}^2}{\pi d_m^2}, (\nu_m(\mu_m A_{cpc})R_{mu})/R_m\right), \quad (1)$$

where n_{op} is the number of operators, d_{ccu} and A_{ccu} are the CCU size and coverage area, respectively, and μ_m, ν_m, R_{mu}, and R_m are the user density, the HetNet coefficient (i.e., the ratio of macro, micro and pico cells), the average macro user data rate, and the data rate capacity of a macro-RRH, respectively. Similarly, the number of micro-RRHs and pico-RRHs are given by

$$N_r^{mi} = (\nu_{mi}(\mu_{mi} A_{cpc})R_{miu})/R_{mi}, \quad (2)$$

and

$$N_r^{p} = (\nu_{p}(\mu_{p} A_{cpc})R_{pu})/R_{p}, \quad (3)$$

respectively.

It was shown in [16] that C-RAN provides important cost gains with respect to traditional RANs but requires high-bandwidth and low-latency connections between the CCU and its remote RRHs. In practice, such connections are unfortunately capacity and time-delay constrained and, hence, may significantly deteriorate the average network throughput [9] [16] [20]. This has motivated the development of the next framework.

B. Fog-RAN (F-RAN)

As illustrated in Fig. 2, in F-RAN or locally-virtualized network (LVN) as called in [16], a number of co-located access points (AP)s dynamically share their hardware and radio resources to better serve the UEs. These fog-APs (F-AP)s form then a virtual-AP (V-AP) close to the UEs that takes over the execution of all their required computational tasks, thereby allowing real-time low-latency constrained services which are practically infeasible in a C-RAN. Fig. 3 illustrates the block diagram of such V-AP where a fog-Orchestrator is responsible of the F-APs' resources pooling and sharing. It also slices the obtained pool into several virtual instances associated with different VNOs. More or less resources are then allocated to a VN according to its current traffic demand and the service level agreement (SLA) between its corresponding VNO and the infrastructure provider (InP). It is noteworthy that a V-AP may support multiple RATs (e.g., WiFi, OFDMA-based 4G systems, etc.) and serve UEs belonging to different VNOs using one or some if not all of its RATs. In such a multi-operator context, this V-AP (or the F-APs which compose it) may be substituted by a single physical entity called super BS (SBS) in [16], thereby leading to a new centralized flavor of F-RAN (CF-RAN). Actually, the latter is appealing due to: i) the economies of scale resulting from building a single entity that combines the distributed F-APs resources in a unique site; ii) the reduced latency from achieving processing locally very close to UEs, in contrast to C-RAN. Accordingly, by allowing the management of different VNOs from a single physical entity, CF-RAN not only translates the essence of virtualization but also moves it even closer to the UEs. In what follows, we consider, for the sole sake of simplicity, that both CF-RAN and its distributed counterpart already commonly known as F-RAN, and coined here as DF-RAN, have the same dimensioning and achieve the same performance in terms of cost and QoS. And again for simplicity, we will refer to both of them as F-RAN. The findings of ongoing in-depth performance comparisons between these two LVN frameworks will be disclosed in a future work. Assuming

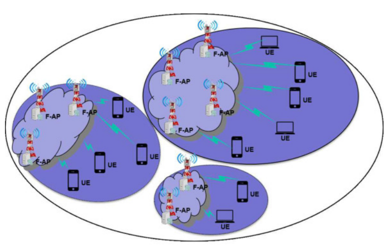


Fig. 2. F-RAN framework.

n_{op} VNOs in an area A and n_{sl} slices per V-AP, it could be easily shown that the required number of V-APs in this area is given by

$$N_{vap} = \frac{n_{op}}{n_{sl}} \max\left(\frac{A}{\pi d_{vap}^2}, \frac{N_{ue} R_{ue}}{R_{vap}}\right), \tag{4}$$

where R_{vap} is the data rate capacity per V-AP, R_{ue} is the average data rate demand per UE, N_{ue} is the average number of active UEs, and d_{vap} is coverage radius of the VAP. The latter may actually be macro-, micro-, or pico-AP depending on d_{vap}.

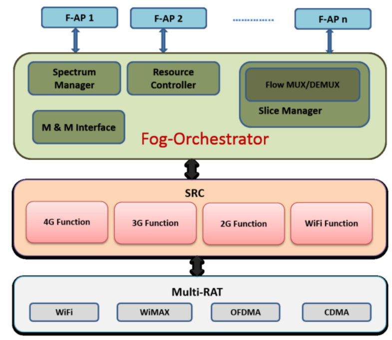


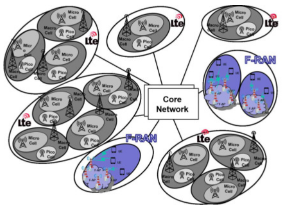
Fig. 3. Block diagram of V-AP.

It was shown in [16] that F-RAN (i.e., LVN) provides higher QoS than C-RAN (i.e., RVN) which is penalized by its high latency. However, it is more expensive than the latter due to the additional hardware required at the F-APs to ensure the management of their combined resources. It is this QoS/cost tradeoff that has motivated the design of a hybrid-RAN (H-RAN), called hybrid VN (HVN) in [16], which combines both aforementioned frameworks and capitalizes on the benefits of both local and remote virtualizations (i.e., higher QoS and lower cost, respectively). In the sequel, we provide insights on how to deploy progressively such H-RAN within existing traditional networks and in what proportions of C- and F-RANs and when so as to optimize both performance and cost criteria.

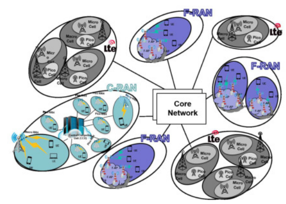
III. Progressive WAV deployment challenge

As illustrated in Fig. 4, any traditional network may be seen as a set of subnetworks located in subareas with often different subscriber densities. Let c_d be the duration of each virtualization cycle during which a maximum budget c_b could be spent by the InP. If c_b is unrealistically large, the greenfield "turnkey" approach may be adopted to simultaneously (i.e., during one cycle) virtualize all the network subareas as has been done in [16]. However, in practice, WAV will be always governed by budget constraints and its return on investment and, hence, must be achieved progressively during a number of cycles. A viability period between the traditional and virtualized RANs is then unavoidable and must be taken into account to optimize the overall system performance. In order to progressively virtualize the network of our concern, we need to know, at each virtualization cycle, which subareas to virtualize and also which WAV frameworks to adopt during each virtualization cycle.

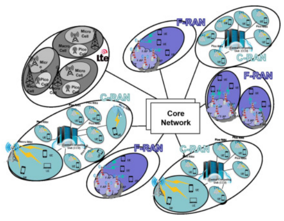
Fig. 4 shows an example of a progressive deployment scenario of C-RANs (i.e., RVN) and F-RANs (i.e., LVN) that consists of four cycles:



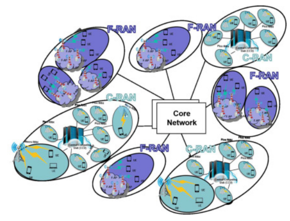
(a) 1st virtualization cycle



(b) 2nd virtualization cycle



(c) 3rd virtualization cycle



(d) 4th virtualization cycle

Fig. 4. Progressive WAV deployment challenge.

1) Virtualizing two subareas using F-RAN;
2) Virtualizing two subareas using different WAV frameworks: F-RAN and C-RAN;
3) Virtualizing two subareas using C-RAN; and
4) Virtualizing only one subarea using F-RAN.

Obviously such a scenario is far from optimal but gives an unambiguous idea on how daunting and challenging is progressive deployment, more so when the numbers of network subdivisions and WAV frameworks are large. In such a case, huge possibilities exist, making the selection of the proper subarea/framework pairs at each cycle extremely tedious. Yet if not carried out properly at any given cycle, it may hamper the viability of the different RANs and, hence, degrade both the network performance and cost. Additional virtualization dimensions that certainly complicate this task are the multi-tier cell/BS/TP types. Actually, one could also virtualize different BS types belonging to the same subarea using different frameworks (e.g. macro-BSs with F-RAN and micro-BSs with C-RAN). This results in an extremely heterogenous yet more efficient WAV architecture along exponentially increased possibilities at each cycle, making the selection of the progressive deployment road-map even more complex. Defining a new dynamic (i.e., time-varying) WAV utility embodying multi-dimensional heterogenous metrics (i.e., CAPEX and OPEX costs, QoS or QoE, etc.) is undoubtedly another challenge that needs to be addressed. Choices of which subareas or/and BS types to virtualize and which frameworks to adopt at each cycle must actually be made to optimize the latter.

IV. Proposed progressive WAV strategy

Several techniques may be used to solve this multi-dimensional optimization such as graph theory, hidden Markov models (HMMs), time alignment techniques, artificial intelligence (AI), and machine learning (ML).

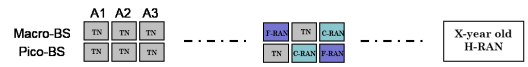


Fig. 5. Initial, intermediate, and final graph states.

Due to its simplicity, we propose to exploit in what follows the efficient tool of graph theory to devise a new optimized greyfield WAV strategy which makes at each cycle the proper decision on which subareas or/and BS types to virtualize and which frameworks to adopt.

To this end, we need to identify the different states (i.e., vertices) of our graph as well as a unique source (i.e., initial state) and a unique destination (i.e., final state). For the sole sake of simplicity, let us first consider a traditional network with three subareas A_1, A_2, and A_3. We also consider that only macro-BSs and pico-BSs exist in the latter. In such a case, each state within our graph may be seen as six substates where each one corresponds to the macro- or pico-BSs of a particular subarea. As any virtual network will be deployed over an existing traditional architecture, all the substates of the initial state must obviously be set to "Traditional Network (TN)". For instance, at the initial state, the substate corresponding to the macro-BSs of the subarea A_1 is set to "TN" since before virtualization these BSs are part of TN. As far as the intermediate state is concerned, its substate corresponding to BS-type of area $A_i, i = 1, \ldots, 3$ is set to "F-RAN" or "C-RAN" if the latter is virtualized and to "TN" otherwise. An example of an intermediate state is shown in Fig. 5 where only the macro-BSs of A_1 and pico-BSs of A_2 are virtualized using F and C-RANs, respectively, whereas both BS types of A_3 are virtualized using a permutation of the latter, respectively.

Now, let us turn our attention to the final state. At the end of the virtualization period, any BS-type of any area could be virtualized with either F-RAN or C-RAN which results in several possible final states. Since a unique final state is required for any graph, we choose the one stemming from an x-year old fully-virtualized network.. Besides solving the unique final state issue, we will show in what follows that the latter allows also accounting for the cost and QoS of this fully-virtualized network when optimizing the progressive WAV deployment.

After identifying the initial, final and intermediate states, we need to compute the graph-state transition cost to be able to optimize the progressive WAV deployment. To this end, one must first design a new WAV metric that quantifies the virtualization impacts in terms of both QoS and cost as well as the InP virtualization policies (i.e., tradeoff between these performance measures).

A. *New WAV metric: graph-state transitions cost*

The graph-state transition cost should satisfy the following requirement: i) memoryless (i.e., independent of the previous states and transitions) ii) specific to each pair of "departure" and "arrival" states. In this work, we propose to use the following graph-state transition cost:

$$U_{i\to j} = \underbrace{\left(\frac{(1+\delta)C_{max} - C_{i\to j}}{(1+\delta)C_{max}}\right)^{w_c}}_{\text{Cost gain}} \times \underbrace{\left(\frac{T_i}{T_{max}}\right)^{(1-w_c)}}_{\text{QoS gain}}, \tag{5}$$

where $U_{i\to j}$ denotes the utility or the transition cost between the i-th and j-th states consisting of two gains: cost and QoS, $C_{i\to j}$ is the required virtualization cost to make a transition between these two states, C_{max} is the maximum virtualization cost that could be incurred during a transition in our graph, δ is a strictly positive overestimation safety-margin factor aiming to avoid the zero-utility case when $C_{i\to j} = C_{max}$, T_i and T_{max} are the average user throughputs provided by the network configuration in the i-th state and the maximum throughput, respectively, and w_c is the cost weight that governs the QoS/cost tradeoff to mirror the InP virtualization policies. In order to derive $C_{i\to j}$, we propose to exploit the cumulated discounted cash flow (DCF) which is a very commonly used valuation method to estimate the attractiveness of an investment opportunity. Assuming a discount rate d, $C_{i\to j}$ could be expressed as

$$C_{i\to j} = C_{capex,i\to j} + \sum_{y=0}^{c_d-1} \frac{C^y_{opex,i}}{(1+d)^y}, \tag{6}$$

where $C_{capex,i\to j}$ is the CAPEX relative to the new substates virtualized at the j-th state and $C^y_{opex,i}$ is the OPEX of all the substates within the i-th state. For example, assuming that there is a direct link between the initial and intermediate states in Fig. 5, the virtualization cost incurred between these states is nothing but the CAPEX relative to virtualizing the macro-BSs of A_1 and pico-BSs of A_2 as well as all the BSs in A_3 plus the OPEX of TN.

Let us now take a closer look at $U_{i\to j}$. An in-depth inspection of (5) reveals that it is a dynamic (i.e., time-varying) utility that mirrors the cost/QoS balance during the virtualization period. It may then integrate any changes in constraints and/or parameters as they evolve or happen in time. To ensure an optimal cost/QoS balance while accounting for time-varying constraints and parameters during all the virtualization period, we need to find the proper path (i.e., a number of consecutive states from the initial to final ones) that maximizes the total utility given by

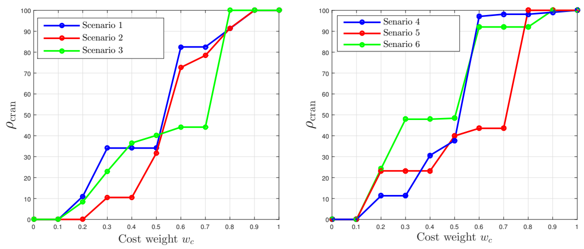
$$U^{Total} = \prod U_{i\to j}. \tag{7}$$

This is nothing but the shortest/longest path problem that could be easily and efficiently solved using any existing algorithm in the literature such as Dijkstra, BellmanFord, FloydWarshall, and Viterbi algorithms. It is noteworthy that the so-obtained WAV strategy readily adapts, through the utility in (7), to all predictable changes in constraints and parameters. Should unpredictable changes happen, our proposed strategy could also handle them by easily re-optimizing what is left from the deployment path based on any new constraints as they occur. All these will be further verified through simulations in Section VI.

V. Advantages of the proposed WAV strategy

We summarize below the advantages of the proposed progressive WAV deployment optimization strategy:

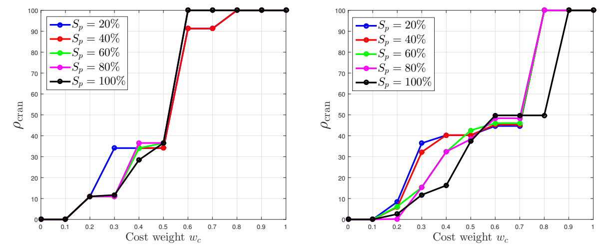
- **Optimality**: guarantees the overall optimal network performance according to the InP virtualization policies. It also provides the optimal portions of F- and C-RANs within the fully-virtualized H-RAN. Please note that F-RAN and C-RAN frameworks are only taken as examples. The proposed strategy may actually be exploited to optimize the deployment of any other WAV frameworks.
- **Low complexity**: exploits a simple graph model where the optimum path may be found using any low-cost shortest/longest path algorithm available in the open literature.
- **Flexibility**: may handle more or less deployment subareas with different characteristics (i.e., UE/BS density, BS type, etc.), thereby mirroring the real-world heterogeneity of the deployment area. For instance, small ultra-dense subareas may be assumed to emulate hotspots while larger areas with lower UE density may be adopted for a classic urban environment.
- **Adaptive**: adapts to area densities, their HetNet configurations, cost weight, etc. Indeed, we will show in Section VI that any variation in one of these parameter values may result in a completely different optimal deployment strategy and, hence, a different fully virtualized network with different allocations of C- and F-RANs.
- **Operator-friendly**: may integrate time-varying budget constraints and cost weights in order to comply with the operators' policies and investment plans as well as the actual and projected market conditions. It may also integrate subscriber growth-rate projections to provide the best fit with the operators needs, thereby optimizing the return on investment.
- **Increasingly-heterogeneous multi-dimensionality**: able to handle at low-cost multi-dimensional optimization problems that are increasingly heterogeneous (greenfield/greyfield sub-areas, multi-tier cell/BS/TP/ types, multi-RAT, multi-operator, etc.). This is actually a very important feature that makes optimized deployment scenarios well-adapted to real-world environments.
- **Scalability**: besides cost and QoS, it may easily incorporate other optimization criteria (power cost,



(a) Scenarios 1, 2 and 3

(b) Scenarios 4, 5 and 6

Fig. 7. ρ_{cran} in [%] vs. w_c for different scenarios.



(a) Scenario 1

(b) Scenario 3

Fig. 8. ρ_{cran} in [%] vs. w_c for different S_p values.

degree of human exposure to RF, green power ratio, etc.) by simply adapting the proposed WAV metric.

TABLE I
CONSIDERED SCENARIOS

Scenario	$A_{i=1,2,3}$[km^2]	λ_1	λ_2	λ_3
1	100	10^2	10^3	10^3
2	100	10^3	10^3	10^3
3	100	10^4	10^3	10^3
4	100	10^2	10^3	10^2
5	100	10^2	10^4	10^2
6	100	10^2	10^3	10^4

VI. SIMULATION RESULTS

This section provides numerical results aiming to verify the efficiency of the proposed progressive WAV deployment strategy. In all simulations, we consider that the network is divided in three subareas A_1 A_2 and A_3 of 100 km^2 each. We also consider that only macro-BSs and pico-BSs exist in the latter. Furthermore, we assume that $n_{op} = 3$, $c_d = 5$ years, and c_b allows to virtualize at most two subsections during each cycle. The considered scenarios are listed in Table I where λ_i is the A_i's density. Please note here that we exploit the cost and throughput expressions developed in [16] and the Dijkstra's shortest path algorithm to find the optimal path.

Fig. 6 illustrates the optimal deployment road-map for different w_c values and different subarea densities. For $w_c = 0$ (Fig. 6(a)) and $w_c = 1$ (Fig. 6(c)), the whole network is virtualized using either F-RAN or C-RAN only, respectively. This is hardly surprising since either the QoS or cost is entirely favored against the other, respectively. Recall that F-RAN provides better QoS than C-RAN while the latter is much less expensive. In the most general cases, however, the optimal progressive deployment road-map and its F-/C-RAN allocations depend both on w_c and the subareas densities. This very suitable feature as it allows the InP to adapt its deployment solutions to not only its business plans but also to the number of subscribers its VNO customers serve. Please note that our progressive WAV deployment strategy may also easily handle time-varying cost weights and densities.

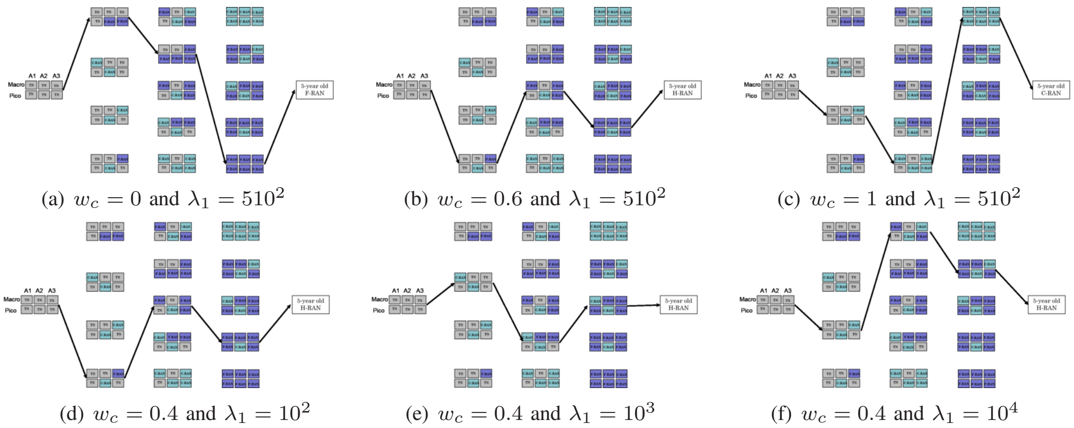
Figs. 7 plots the network percentage that exploits C-RAN ρ_{cran} versus w_c for different scenarios. As expected, ρ_{cran} increases with w_c. More weight is given to cost when the latter increases and, hence, to the less expensive C-RAN WAV framework. Indeed, for low w_c values (i.e., $w_c \leq 0.2$), the network is mainly F-RAN (i.e., at most 20% of the network is C-RAN). Whereas for high w_c values (i.e., $w_c \geq 0.8$), at least 80% of the network is C-RAN. Furthermore, we see that ρ_{cran} varies with each scenario, thereby validating once again the adaptive nature of the proposed solution.

Fig. 8 plots ρ_{cran} versus w_c for different subscriber growth-rate projection values S_p. The latter is involved each virtualization cycle. For low w_c values, ρ_{cran} decreases with S_p whereas it decreases with the latter for large w_c values. This is hardly surprising since $S_p \neq 0$ translates in continuously and increasingly denser subareas that directly affect the optimal progressive WAV deployment road-map as already observed in Fig. 6. This results proves that our strategy may handle practical time-varying parameters, thereby allowing the InP to optimize its virtualization based on its projected subscriber growth-rate or even available budget.

Fig. 9 compares the total utility function U^{Total} achieved by the proposed optimal progressive WAV deployment strategy against two "turnkey" strategies: the green-field [16] and a non-optimized progressive WAV. The latter is actually a "pre-planned" deployment consisting of virtualizing all macro-BSs then all pico-BSs of the whole network during the first and second virtualization cycles, respectively. Despite being progressive, this arbitrary "pre-planned" approach is far from being optimal. As far as green-field deployment is concerned, it achieves much weaker utility (i.e., in terms of both performance and cost criteria) than the proposed strategy. This proves unequivocally its very high efficiency and very large and strong benefits.

VII. CONCLUSION

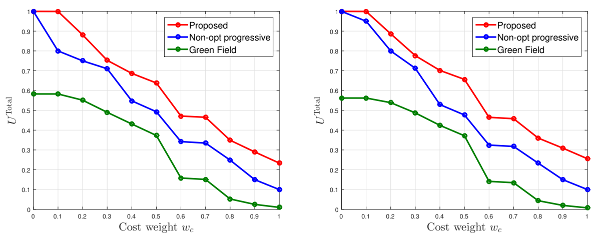
This paper developed optimized progressive greyfield WAV deployment strategies that integrate both C- and F-RAN frameworks in legacy RANs based on a new dynamic utility embodying highly-dimensional time-varying multi-criteria metrics (i.e., CAPEX and OPEX



(a) $w_c = 0$ and $\lambda_1 = 510^2$ (b) $w_c = 0.6$ and $\lambda_1 = 510^2$ (c) $w_c = 1$ and $\lambda_1 = 510^2$

(d) $w_c = 0.4$ and $\lambda_1 = 10^2$ (e) $w_c = 0.4$ and $\lambda_1 = 10^3$ (f) $w_c = 0.4$ and $\lambda_1 = 10^4$

Fig. 6. Optimal progressive WAV deployment road-map for different w_c and λ_1 values when $\lambda_2 = \lambda_3 = 10^3$.



(a) Scenario 1 (b) Scenario 3

Fig. 9. U^{Total} vs. w_c achieved by the proposed and two "turnkey" strategies (the greenfield [16] and a non-optimized pre-planned progressive WAV).

Costs, QoS or QoE, multi-tier and/or multi-RAT HetNets, etc.). Exploiting the powerful tool of graph theory, this strategy is able to readjust very quickly to any changes in existing or new constraints as they evolve or occur in time, respectively. The resulting optimized hybrid RAN deployment outperform both the greenfield and the pre-planed greyfield "turnkey" WAV strategies.

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