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Cost-Effective Migration towards C-RAN with Optimal Fronthaul Design

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Abstract—Centralized Radio Access Network (C-RAN) has been recently proposed to increase network capacity, reduce energy consumption, and improve scalability. However, C-RAN requires an extensive modification to the current infrastructure, which results in a considerable deployment cost. In this paper, we conduct a techno-economic study to evaluate the migration cost of C-RAN, and we propose a methodology for cost and energy efficient C-RAN deployment. We exploit the concept of total cost of ownership, defined as the sum of capital and operational expenditures. We formulate a Digital Unit (DU) pool placement optimization problem as Mixed Integer Linear Programming (MILP), which minimizes the total cost of ownership. We compare the total cost of ownership of C-RAN to that of the existing infrastructure, under different deployment scenarios such as greenfield and brownfield deployment of fiber and DU pool, and different cell sizes. The results show that the optical infrastructure plays a determinant role in the migration cost of C-RAN. If greenfield fiber is assumed, the migration cost cannot be compensated in a reasonable amount of time. If brownfield fiber is assumed, the migration cost is considerably reduced, and a more feasible C-RAN deployment is achieved.

I. INTRODUCTION

Radio Access Networks (RANs) are facing a rapid increase in traffic demand, due to the increasing number of devices connected to the network, and to the higher quality of service requested by the users. Network operators must be able to provide the required capacity to fulfill such demand. C-RAN has been recently proposed as a promising architecture to increase network capacity, while improving energy efficiency, and providing scalability [1]. In a traditional RAN, the components constituting the base station are located at the cell site, and are divided into a radio unit for the transmission and reception of radio signals, and a digital unit for the baseband signal processing. The main idea of C-RAN is to centralize the digital units in a shared location responsible for coordinated signal processing and management, which is called DU pool, while keeping the radio units at the cell sites. Such centralization allows to share maintenance costs and energy consumption among several digital units. A low latency aggregation network is used to transport the baseband signals between the radio units and the digital units. This aggregation network is referred to as fronthaul, in opposition to the traditional backhaul which connects the digital units to the network backbone [2]. Despite the attractive advantages, the deployment of C-RAN brings considerable challenges for the operators. The fronthaul constraint, which must guarantee

a certain latency, the infrastructure deployment, and the pool placement, are among the main challenges to focus on.

Researchers have already addressed some of these challenges. Authors in [3] present an overview of the fronthaul requirements, and propose architectures and transmission technologies for next generation optical access networks. Authors in [4] address the fronthaul constraint problem by proposing many solutions, such as signal compression and quantization, coordinated signal processing, and radio resource allocation optimization. The pool placement optimization problem is addressed by several authors. Authors in [5] propose an energy efficient aggregation network and a pool placement optimization problem, to minimize the total aggregation infrastructure power. While authors in [6] define an energy efficient optimization problem to perform load balancing and resource sharing, by dynamically assigning a virtual base station to each cell. Authors in [7] propose an optimization problem to determine the configuration of each DU pool, which minimizes the deployment cost.

In this paper, we focus on the evaluation of the migration cost of C-RAN from today's Distributed Radio Access Network (D-RAN). To do so, we determine the total cost of C-RAN, and we define a DU pool placement optimization problem to minimize such cost. The total cost of C-RAN is modeled by adopting the concept of Total Cost of Ownership (TCO), which is defined as the sum of build-out costs, i.e. Capital Expenditures (CapEx), and operation and maintenance costs plus electric bills, i.e. Operational Expenditures (OpEx). The TCO of C-RAN is compared over time to that of traditional D-RAN, which we assume only includes OpEx, as it is already deployed. This analysis is intended to understand the migration cost of C-RAN, and the amount of time needed to compensate for such cost, under different cost assumptions.

The main contributions of this paper are: (i) the formulation of a TCO model to identify the migration cost of C-RAN; (ii) the formalization of a DU pool placement optimization problem to minimize the TCO, using Mixed Integer Linear Programming (MILP). In our model, we merge deployment cost and energy consumption into a single quantity, while related work has only considered the energy consumption [5] [6], or the deployment cost [7]. With our framework, one can optimally design C-RAN and make an informed decision regarding the migration from the existing architecture.

The remainder of this paper is organized as follows. Sec-

tion II presents the network architecture and the TCO model. The DU pool placement optimization problem is presented in Section III. Section IV presents the simulation results, while the conclusions are discussed in Section V.

II. NETWORK ARCHITECTURE AND TCO MODEL

In this section, we describe the network architecture under analysis, and we present the TCO model. First, we identify the components needed to implement C-RAN, which affect the TCO and, consequently, the optimization problem. Then, we present D-RAN architecture, used as main comparison term for C-RAN. Power consumption models for the two aforementioned architectures are defined. These models are necessary for the formulation of the TCO model at the end of this section.

A. C-RAN Architecture

In this paper, C-RAN fronthaul is assumed to be a Time Wavelength Division Multiplexing (TWDM) Passive Optical Network (PON). This means that both wavelength and time division multiplexing are performed at different network layers, to exploit the bandwidth efficiency of WDM with the cost efficiency of TDM. We assume two aggregation levels in the fronthaul. The first aggregation level is composed of passive splitters, while the second aggregation level is composed of Arrayed Wavelength Grating (AWG) filters. The radio units access the first aggregation level in time division, and the second aggregation level in wavelength division. The TWDM PON fronthaul architecture is illustrated in Figure 1.

Figure 1. TWDM PON fronthaul architecture.

The two main components are the Optical Network Unit (ONU), located at the cell site, and the Optical Line Terminal (OLT), located at the pool site. These components perform electrical to optical signal conversion and vice versa. The OLT considered in this architecture provides single line rates of 10 Gbps, and it is composed of a wavelength division multiplexer, and a Line Card (LC) for each digital unit. Common Public Radio Interface (CPRI) standard sets a constraint on the round trip time between radio units and digital units, in order to achieve seamless baseband signal transmission. This constraint translates in a maximum ONU-OLT distance between 20 and 40 km [1]. Splitting ratios of both AWG filters and splitters must be defined. We denote N and M as the AWG and splitter splitting ratio, respectively. In the definition of splitting ratios, we must consider the line rate constraint imposed by the CPRI standard. For a system where radio units are provided with LTE

coverage of 3 sectors with 20 MHz bandwidth and 2x2 MIMO configuration, the minimum line rate must be set to 2.4576 Gbps [8]. Thus, a maximum number of four CPRI flows can be transmitted in a 10 Gbps link, which leads to $M_{max} = 4$. We assume that a fiber can achieve a maximum rate of 80 Gbps, i.e., the number of wavelengths per fiber in the TWDM PON is at maximum $N_{max} = 8$ [9].

In the proposed system model, other assumptions are made on the deployment of the optical fronthaul, which significantly affect the TCO model:

- 1) Greenfield vs brownfield deployment of fiber. In the greenfield case, existing D-RAN with microwave backhaul is assumed. Therefore, the optical infrastructure must be deployed through digging and rollout operations. In the brownfield case, existing D-RAN with fiber backhaul is assumed, hence the optical infrastructure is already partially deployed. We reduce the fiber digging and rollout costs by a scaling factor α .
- 2) Greenfield vs brownfield deployment of DU pools. In the greenfield case, we assume that the pools can be installed in any location of the network. This allows to choose the optimal locations to minimize the TCO, and to realize high capacity pools, which can host several OLTs with capacity $N = N_{max}$. However, this approach does not allow to exploit existing facilities, therefore build-out costs must be afforded. In the brownfield case, we assume that the pools are realized by upgrading the existing base station facilities, to have zero build-out costs. This approach might not enable to select optimal locations, since we can only exploit the existing locations. Furthermore, we constrain the pool capacity to the size of the existing facility, therefore we assume that each pool can host only one OLT with capacity $N = \frac{N_{max}}{2}$.

B. D-RAN Architecture

D-RAN architecture is assumed to have either microwave or optical backhaul. We will benchmark our work with respect to both types of infrastructure. The microwave backhaul is composed of microwave links connecting the cell sites to the Central Office (CO) through aggregation nodes, namely microwave hubs [10]. We assume that each hub is composed of four sectors, and each sector supports up to six cell sites, with a maximum capacity of 1.2 Gbps per sector. Furthermore, we assume that the CO supports a maximum of 96 microwave links. The optical backhaul is assumed to be TWDM PON, as in the case of C-RAN architecture.

C. Power Consumption Model

According to the deployed architecture, i.e. C-RAN, microwave D-RAN, and optical D-RAN, we derive different power models, as follows.

1) C-RAN: The power consumption of C-RAN is defined as the sum of three components, namely the base station power consumption P_{bs} , the ONU power consumption P_{onu} , and the DU pool power consumption P_{pool} . It is expressed as

$$P_{cran} = N_{bs}(P_{bs} + P_{onu}) + N_{pool}P_{pool}, \quad (1)$$

where N_{bs} denotes the number of base stations, and N_{pool} the number of DU pools. The base station power consumption P_{bs} is defined as

$$P_{bs} = N_{tx}(P_o + \Delta p P_{out}), \quad (2)$$

where N_{tx} denotes the number of transmitters per base station, P_o the power consumption of the base station calculated at minimum transmitted power, Δp the slope of the load dependent power consumption, and P_{max} the power consumption of the base station calculated at maximum transmitted power [11]. The DU pool power consumption is defined as

$$P_{pool} = N_{du}(P_{proc} + P_{olt}) + P_{cool}, \quad (3)$$

where N_{du} denotes the number of digital units per pool, P_{proc} the processing power consumption of each digital unit, P_{olt} the power consumption of each OLT module, and P_{cool} the power consumption of the air cooling unit.

2) *Optical D-RAN*: The power consumption of optical D-RAN is defined as

$$P_{od} = N_{bs}(P_{bs} + P_{proc} + P_{cool} + P_{onu} + P_{olt}). \quad (4)$$

Every base station has dedicated processing and air cooling units, and the OLT modules in the CO are not shared among several radio units.

3) *Microwave D-RAN*: The power consumption of microwave D-RAN is defined as the sum of three components, namely the power consumption at the cell site, the aggregation node power consumption P_{ag} , and the backhaul link power consumption P_{bhl} , as in [10]. It is expressed as

$$P_{md} = N_{bs}(P_{bs} + P_{proc} + P_{cool}) + P_{ag} + P_{bhl}. \quad (5)$$

The aggregation node power consumption is defined as

$$P_{ag} = \alpha P_{m,ag} + \frac{N_{bhl} R_{bs}}{C_{ag}} (1 - \alpha) P_{m,ag} + N_{dl} P_{dl} + N_{ul} P_{ul}, \quad (6)$$

where $P_{m,ag}$ denotes the maximum power supplied to the aggregation node, α the percentage of $P_{m,ag}$ consumed in idle mode, N_{bhl} the number of backhaul links, R_{bs} the maximum backhaul load offered by each base station, assumed to be 0.05 Gbps, and C_{ag} the capacity of the aggregation node, assumed to be 3.6 Gbps [10]. While N_{dl} denotes the number of downlink interfaces in the aggregation node, P_{dl} the power consumed in downlink, N_{ul} the number of uplink interfaces in the aggregation node, and P_{ul} the power consumed in uplink. The backhaul link power consumption is defined as

$$P_{bhl} = P_{o,bhl} + \frac{R_{bs}}{C_{bhl}} P_{m,bhl}, \quad (7)$$

where $P_{o,bhl}$ and $P_{m,bhl}$ denote the backhaul link power consumption at minimum and maximum transmitted power, respectively, while C_{bhl} denotes the maximum capacity of the backhaul link, assumed to be 1.2 Gbps [10]. Table I reports the power values of the aforementioned parameters.

Table I
POWER CONSUMPTION PARAMETERS

Parameter	Value [W]	Source
P_o	53	[12]
Δp	3.1	[12]
P_{out}	6.3	[12]
P_{proc}	100	[6]
P_{cool}	500	[6]
P_{onu}	3.4	[13]
P_{olt}	20	[13]
α	0.6	[10]
$P_{m,ag}$	57	[10]
P_{ul}	2	[10]
P_{dl}	1	[10]
$P_{o,bhl}$	97	[10]
$P_{m,bhl}$	37	[10]

D. TCO Model

According to the deployed architecture, i.e. C-RAN, microwave D-RAN, and optical D-RAN, we derive different TCO models, as follows.

1) *C-RAN*: The TCO of C-RAN is expressed as the sum of CapEx and OpEx. The CapEx is defined as the sum of pool build-out, equipment, fiber digging and rollout costs. The build-out costs are not included in the brownfield pool case. The OpEx is defined as the sum of operation and maintenance costs, pool site rent, fiber lease, and electric bills. Cost values for CapEx and OpEx (electric bills excluded) are reported in Table II. The electric bills are derived from the power model by assuming 1€ per 1 Watt consumed.

2) *Optical D-RAN*: The TCO of optical D-RAN includes only OpEx, hence operation and maintenance cost, cell site rent, fiber lease, and electric bills. The cost values coincide with the ones of C-RAN reported in Table II, where it is assumed that the cell site and pool site rent are identical.

3) *Microwave D-RAN*: Similarly to optical D-RAN, the TCO of microwave D-RAN includes only OpEx, hence operation and maintenance costs, cell site rent, spectrum fee, and electric bills. Cost values are reported in Table III.

Table II
CAPEX AND OPEX OF C-RAN

Component	Parameter	Cost [k€]	Source
DU pool build-out	C_{build}	75	[10]
Equipment:			
– ONU	C_{onu}	0.25	[10]
– Passive splitter	C_{split}	0.1	[10]
– AWG	C_{awg}	0.25	[9]
– OLT access module	C_{oltm}	6.5	[10]
– OLT shelf	C_{olts}	35	[10]
Fiber digging per km	C_{dig}	60	[14]
Fiber rollout per km	C_{rol}	3.8	[10]
Annual operation and maintenance	C_{oem}	10% of equipment	[10]
Annual DU pool rent	C_{rent}	8	[10]
Annual fiber lease	C_{lease}	3	[10]

III. DU POOL PLACEMENT OPTIMIZATION PROBLEM

In this section, the DU pool placement optimization problem is presented. Given a set of radio units, the goal is to find the

Table III
OPEX OF MICROWAVE D-RAN

Component	Cost [k€]	Source
Microwave link	0.4	[10]
Microwave hub site, 24 ports	0.8	[10]
10 Gbit Ethernet Switch, 24 ports	0.18	[10]
Annual cell site rent	8	[10]
Annual spectrum fee per MHz and link	0.06	[10]

optimal number and location of pools, digital units, and splitters, such that all the radio units are connected to a pool and the TCO is minimized. For simplicity, the AWGs are assumed to be located in the same locations as the pools, hence they are not included in the optimization problem. The pool is considered as a shared location where the digital units are stacked on each other, according to the model presented in [15]. The digital units coincide with the processing units residing at the cell site in a traditional distributed topology. The problem is modeled as an MILP problem, and it is formulated as follows:

Given: set of radio units and digital units; candidate locations of pools and splitters; capacity of pools, digital units, AWGs and splitters; maximum distance allowed between pools, splitters and radio units; cost and energy consumption values.

Find: optimal locations of pools, digital units, and splitters; connections between pools, splitters, and radio units.

Objective: minimize the TCO.

Below, the input parameters, decision variables, objective function and constraints are listed.

A. Input Parameters

C : set of pools

D : set of digital units

S : set of splitters

I : set of radio units

Q : $C \times S$ distance matrix whose element q_{cs} denotes the distance from pool c to splitter s

P : $S \times I$ distance matrix whose element p_{si} denotes the distance from splitter s to radio unit i

D_1 : maximum distance between pool and splitter

D_2 : maximum distance between splitter and radio unit

C_{pool} : capacity of the pool in terms of digital units

C_w : capacity of the splitter in terms of radio units

B : a very large positive number, to enforce the integrality constraint of the decision variables

B. Decision Variables

$x_c = 1$ if pool c is active (binary)

$y_d = 1$ if digital unit d is active (binary)

$n_s = 1$ if splitter s is active (binary)

$w_{cd} = 1$ if digital unit d is connected to pool c (binary)

$l_{cds} = 1$ if splitter s is connected to digital unit d and pool c (binary)

$m_{cdsi} = 1$ if radio unit i is connected to splitter s , digital unit d and pool c (binary)

C. Objective Function

The objective is the minimization of the TCO, expressed as

$$\begin{aligned} \min \Big\{ & \sum_{c \in C} x_c C_{build} + L_f (C_{dig} + C_{rol}) \\ & + N_{bs} C_{onu} + N_{split} C_{split} + N_{awg} C_{awg} \\ & + N_{olts} C_{olts} + N_{oltm} C_{oltm} \\ & + C_{oem} + \sum_{c \in C} x_c C_{rent} + C_{lease} \\ & + N_{bs} (P_{bs} + P_{onu}) + \sum_{c \in C} x_c P_{pool} \Big\}. \end{aligned} \quad (8)$$

The first line of Equation 8 denotes the total build-out costs and fiber costs, respectively. The build-out costs are zero for brownfield pool deployment. The term L_f denotes the total fiber length, i.e. the sum of the total length between pools and splitters, and between splitters and radio units, expressed as

$$L_f = \sum_{c \in C} \sum_{d \in D} \sum_{s \in S} q_{cs} l_{cds} + \sum_{c \in C} \sum_{d \in D} \sum_{s \in S} \sum_{i \in I} p_{si} m_{cdsi}. \quad (9)$$

The second and third lines of Equation 8 denote the equipment costs. The fourth line denotes operation and maintenance costs, pool site rent, and fiber lease, respectively. The fifth line denotes the electric bills from the power consumption. The terms N_{split} , N_{awg} , N_{olts} , and N_{oltm} denote the total number of splitters, AWGs, OLT shelves and OLT modules, respectively.

D. Constraints

Distance constraints:

$$q_{cs} l_{cds} \leq D_1 \quad \forall c \in C, \forall d \in D, \forall s \in S \quad (10)$$

$$p_{si} m_{cdsi} \leq D_2 \quad \forall c \in C, \forall d \in D, \forall s \in S, \forall i \in I \quad (11)$$

Capacity constraints:

$$\sum_{d \in D} w_{cd} \leq C_{pool} \quad \forall c \in C \quad (12)$$

$$\sum_{c \in C} \sum_{d \in D} \sum_{i \in I} m_{cdsi} \leq C_w \quad \forall s \in S \quad (13)$$

Unicity constraints:

$$\sum_{c \in C} w_{cd} \leq 1 \quad \forall d \in D \quad (14)$$

$$\sum_{c \in C} \sum_{s \in S} l_{cds} \leq 1 \quad \forall d \in D \quad (15)$$

$$\sum_{c \in C} \sum_{d \in D} l_{cds} \leq 1 \quad \forall s \in S \quad (16)$$

$$\sum_{c \in C} \sum_{d \in D} \sum_{s \in S} m_{cdsi} = 1 \quad \forall i \in I \quad (17)$$

Activity constraints:

$$B x_c \geq \sum_{d \in D} w_{cd} \quad \forall c \in C \quad (18)$$

$$x_c \leq \sum_{d \in D} w_{cd} \quad \forall c \in C \quad (19)$$

$$B y_d \geq \sum_{c \in C} \sum_{s \in S} l_{cds} \quad \forall d \in D \quad (20)$$

$$y_d \leq \sum_{c \in C} \sum_{s \in S} l_{cds} \quad \forall d \in D \quad (21)$$

$$B n_s \geq \sum_{c \in C} \sum_{d \in D} \sum_{i \in I} m_{cdsi} \quad \forall s \in S \quad (22)$$

$$n_s \leq \sum_{c \in C} \sum_{d \in D} \sum_{i \in I} m_{cdsi} \quad \forall s \in S \quad (23)$$

Connection constraints:

$$B w_{cd} \geq \sum_{s \in S} l_{cds} \quad \forall c \in C, \forall d \in D \quad (24)$$

$$w_{cd} \leq \sum_{s \in S} l_{cds} \quad \forall c \in C, \forall d \in D \quad (25)$$

$$B l_{cds} \geq \sum_{i \in I} m_{cdsi} \quad \forall c \in C, \forall d \in D, \forall s \in S \quad (26)$$

$$l_{cds} \leq \sum_{i \in I} m_{cdsi} \quad \forall c \in C, \forall d \in D, \forall s \in S \quad (27)$$

Constraint (10) limits the maximum distance between pools and splitters, while Constraint (11) limits the maximum distance between splitters and radio units. These distances are set to satisfy the CPRI constraint. Constraint (12) and Constraint (13) limit the maximum number of digital units that a pool can host, and the maximum number of radio units that a splitter can serve, respectively. Constraints (14) and (15) enforce each digital unit to be associated to exactly one pool and one splitter, respectively. Constraint (16) enforces each active splitter to be associated to exactly one digital unit, while Constraint (17) enforces each radio unit to be connected to exactly one splitter. Constraints (18) and (19) ensure the selection of a pool, if there is at least one digital unit connected to it. Similarly, Constraints (20) and (21) ensure the activity of a digital unit, if there is at least one splitter connected to it. Constraints (22) and (23) ensure the placement of a splitter, if there is at least one radio unit connected to it. Constraints (24) and (25) enforce the connection between a pool and a digital unit, if there is a splitter connected to both. Finally, Constraints (26) and (27) enforce the connection between a pool, a digital unit, and a splitter, if there is a radio unit connected to all of them.

IV. CASE STUDY AND SIMULATION RESULTS

In this section, we solve the DU pool optimization problem for a given set of radio units. We compare the resulting TCO with that of D-RAN, to evaluate the migration cost of C-RAN. Then we compare TCO minimization (minTCO) to power minimization (minPOW), by solving the problem for two different objective functions: TCO and electric bills. By doing so, we understand whether an energy efficient solution can also

be cost efficient, and vice versa. Finally, we solve the TCO optimization problem for different cell sizes, to understand the impact of different deployment scenarios on the migration cost of C-RAN. Common parameters are $D_1 = 20$ km and $D_2 = 2$ km. We assume that a pool can host a maximum of 48 digital units for the greenfield pool case, and a maximum of 4 digital units for the brownfield pool case. The optimization problem is solved by using IBM ILOG CPLEX Optimization Studio.

A. Migration Cost of C-RAN

We consider a network of 25 cells with 0.5 km intersite distance. We solve the optimization problem with TCO minimization, and we compare the TCO of C-RAN and D-RAN over a time span T , which is computed by adopting the concept of Net Present Value (NPV), expressed as

$$NPV = \sum_{t=1}^T \frac{TCO_t}{(1+b)^t}, \quad (28)$$

where b denotes 10% bank interest rate. We compare greenfield and brownfield fiber deployment. The latter assumes that a part of the optical infrastructure is already deployed, and we model this by multiplying the fiber costs by a factor α , which is defined between 0.25 and 1. The case $\alpha = 1$ corresponds to greenfield fiber deployment.

Figure 2 and Figure 3 show the TCO of C-RAN and D-RAN over time, with TCO minimization, for greenfield and brownfield pool deployment, respectively. We observe that, when greenfield fiber deployment is assumed, approximately 10 and 12 years are required to compensate for the investment cost of C-RAN, for greenfield pool deployment. While approximately 8 and 10 years are required for brownfield pool deployment. However, the requirement becomes less stringent when brownfield fiber deployment is assumed. Specifically, it drops down to approximately two years when $\alpha = 0.25$. We conclude that the optical infrastructure plays a determinant role in the migration process from D-RAN to C-RAN.

Figure 2. TCO of C-RAN and D-RAN over the years, with TCO minimization, for greenfield pool deployment.

Figure 3. TCO of C-RAN and D-RAN over the years, with TCO minimization, for brownfield pool deployment.

Figure 4. TCO and electric bills of C-RAN, (M) Microwave D-RAN, and (O) Optical D-RAN, for both minTCO and minPOW, (g) greenfield pool and (b) brownfield pool deployment, with greenfield fiber deployment.

Figure 4 shows the breakdown of TCO and electric bills for C-RAN and D-RAN, for minTCO and minPOW, when greenfield fiber deployment is considered. In terms of electric bills, C-RAN is much more efficient than D-RAN, as stated in previous studies. However, the TCO of C-RAN is higher due to the CapEx. In terms of TCO, minPOW shows an increase of 104% and 128% with respect to minTCO, when greenfield and brownfield pool scenarios are assumed, respectively. This is because minPOW minimizes the power consumption by minimizing the number of pools, which results in longer fiber links, hence higher fiber costs. While minTCO takes both number of pools and fiber links into account, resulting in a more optimal solution in term of TCO. Hence we conclude that minPOW does not provide a TCO efficient solution. Concerning the electric bills, minPOW shows a power saving of 7% and 25% with respect to minTCO, when greenfield and brownfield pool scenarios are assumed, respectively. Hence we conclude that minTCO provides an energy efficient solution.

Figure 5. TCO and electric bills of C-RAN, (M) Microwave D-RAN, and (O) Optical D-RAN, for both minTCO and minPOW, (g) greenfield pool and (b) brownfield pool deployment, with brownfield fiber deployment ($\alpha = 0.1$).

Figure 5 shows the breakdown of TCO and electric bills for C-RAN and D-RAN, for TCO and power minimization, when brownfield fiber deployment is considered, with $\alpha = 0.1$. In this case, fiber costs are comparable to build-out and equipment costs. Therefore TCO minimization and power minimization behave in a similar way. Specifically, build-out costs, equipment costs, OpEx and electric bills coincide for both objective functions, since the number of selected pools is the same for both objective functions. Fiber costs are higher for power minimization, because power minimization does not optimize the connections between pools, splitters, and radio units, as they do not affect the objective function.

B. Impact of Cell Size

We assume a fixed network area of 3 km² where macrocells, microcells, or picocells are deployed. We consider two macrocells with intersite distance of 2 km, six microcells with intersite distance of 1 km, and 24 picocells with intersite distance of 0.4 km. With the introduction of different cell types, the power consumption model must be adapted, and in particular the base station power consumption, which varies depending on the cell type. Numerical values are reported in Table IV [12].

Table IV
POWER CONSUMPTION OF MACROCELLS, MICROCELLS, AND PICOCELLS.

Base station type	P_o	Δp	P_{out}
Macrocells	118.7	2.66	40
Microcells	53	3.1	6.3
Picocells	6.8	4	0.13

Figure 6 shows the TCO of C-RAN and D-RAN over time, with TCO minimization and greenfield fiber deployment, for macrocells, microcells, and picocells. For macrocells deployment, D-RAN always outperforms C-RAN in terms of TCO. For microcells deployment, a period of 14 and 20

Figure 6. TCO of C-RAN and D-RAN over the years, with TCO minimization and greenfield fiber deployment, for (a) macrocells, (b) microcells, and (c) picocells.

years is required to compensate for the migration cost of C-RAN, for brownfield and greenfield pool, respectively. For picocells deployment, this period is reduced to approximately 5 years. We conclude that, in densely deployed scenarios as the case of picocells, C-RAN provides superior scalability and cost efficiency with respect to D-RAN, in a long term perspective. While the migration cost of C-RAN results harder to compensate for less densely deployed scenarios, where D-RAN represents a more feasible solution.

V. CONCLUSIONS

In this paper, we have performed a migration cost analysis and proposed a cost efficient DU pool placement, by minimizing the TCO. Considering the TCO as objective function has allowed us to take both investment, maintenance and energy consumption costs into account, hence to identify a complete set of costs to be afforded in order to deploy C-RAN. Based on our assumptions in terms of cell density and employed optical technology, the simulation results show that the optical infrastructure plays a determinant role in the migration from D-RAN to C-RAN. If it is assumed that the optical infrastructure is not currently deployed, a period of approximately 10 years is needed to compensate for the migration cost of C-RAN. If it is assumed that the optical infrastructure is already partially deployed, as in the case of optical D-RAN, then the migration cost of C-RAN can be considerably reduced. The analysis of the cell size impact highlights the superior scalability of C-RAN compared to D-RAN, when densely deployed scenarios are considered.

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