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CALCULATION OF THE TOTAL COST OF OWNERSHIP OF 5G NETWORK FOR DIFFERENT TYPES OF ARCHITECTURE: DISTRIBUTED RAN, CENTRALIZED RAN AND OPEN RAN

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A B S T R A C T

Due to introduction of the 5G NR standard, an estimation of the total cost of ownership for 5G networks is required, as well as expenses optimization. This paper provides a comparative analysis of the total cost of ownership for 5G networks of various architectures. Various deployment scenarios for D-RAN (Distributed RAN), C-RAN (Centralized RAN) and Open RAN of the radio access network provided by this standard are considered. The results of the work were obtained using mathematical modeling in the Matlab environment.

1. INTRODUCTION

Currently, the new 5G NR (5 Generation New Radio, 5th generation) mobile communication standard is being actively implemented around the world. Transition to the standard will accelerate development of information and communication services, so this process requires close attention. The implementation of 5G networks is an expensive and labor-intensive process, and for mobile operators, the optimization of deployment costs is the most important and primary task at this stage. To solve the problem of cost optimization, it is necessary to consider various architectures and approaches to the implementation of 5G NR networks. The basic architecture - D-RAN (Distributed Radio Access Network, distributed radio access network) implies the location of the radio module RU and computing modules DU and CU directly on the site. In the case of C-RAN (Centralized Radio Access Network, centralized radio access network), the computing modules DU and CU are located in the data center. V-RAN (Virtualized Radio Access Network, virtualized radio access network) allows you to virtualize the operations performed by the CU and DU, and perform them on general-purpose servers. The new radio access network architecture: Open RAN (Open Radio Access Network, open radio access network), as well as V-RAN, allows you to virtualize operations performed in CU and DU modules using general-purpose servers, while software and computers are disaggregated, as well as Fronthaul and Midhaul

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interfaces become open 3GPP (2017). Besides, the new standard supports several scenarios for sharing the computational load between network modules. In LTE (Long-Term Evolution, 4G) networks, there was only one option to split RU (radio module) and BBU (digital processing unit), the so-called Split 8: RU consisted of an ADC / DAC and an amplifying path, and all computational operations were performed in the BBU. With the advent of fifth generation networks and the division of the BBU module into DU (Distributed Unit, distributed module) and CU (Centralized Unit, centralized module), it became possible to flexibly share the computing load between modules. Thus, varying the number of operations performed in a particular module, it is possible to control the bandwidth requirements of the Fronthaul interfaces (interface between RU and DU) and Midhaul interfaces (interface between DU and CU) as well as the cost of RU, DU and CU.

The choice of presented architectures and computing operations split option determines the amount of capital and operating expenditures of deployment, which is an important issue for operators who need to optimize costs. The purpose of this work is comparative analysis of the 5G networks deploying cost using various architectures: D-RAN, C-RAN and Open RAN.

A number of works by foreign authorsare devoted to the topic of 5G NR networks deployment. An analysis of these works showed that they do not justify the choice of D-RAN, C-RAN, or Open RAN architectures. The complexity of models is estimated using integer linear programming (ILP, Integer Linear Programming) in 5G-RON (5G radio-optical network) scenarios (Klinkowski, 2018) An analysis of the scalability of the ILP simulation is carried out. The expenses optimization is considered with the usage of C-RAN virtualization by the integer linear programming method (Masoudi, Lisi, & Cavdar, 2020). The analysis of the cost structure for the deployment of the C-RAN network is carried out, and the costs are also optimized taking into consideration the Fronthaul interface expense (Yeganeh & Vaezpour, 2016). (Tonini, Raffaelli, Wosinska, & Monti, 2019) presents a hybrid solution for Fronthaul C-RAN links based on optical fibers and Free Space Optics (FSO, Free Space Optics) to increase the flexibility of Fronthaul links and minimize deployment costs. The papers (Colman-Meixner, Figueiredo, Fiorani, Tornatore, & Mukherjee, 2016), (Neji, Chendeb, Chabbouh, Agoulmine, & Ben Rejeb, 2017) and (Ramantas et al., 2018) describe the methods of 5G NR network virtualization. Paper (Ramantas et al., 2018) details the development of a 5G platform based on the C-RAN architecture with a fully virtualized radio access network (RAN) and optical/wireless Fronthaul. The authors Neji O. et al. (2017) describe their experience of virtualizing OpenAirInterface (OAI) software components to facilitate rapid deployment of an emulated 5G network. The OpenAirInterface Software Alliance (OSA) is a non-profit consortium that develops open source software and hardware for the network core, access network, and cellular user equipment, specifically the 5G NR stack. The authors Colman-Meixner, Figueiredo, Fiorani, Tornatore, & Mukherjee (2016) consider a BBU layout based on the cloud access network (ACN) concept. ACN consists of virtualized BBUs hosted in urban cloud data centers. The paper also proposes three approaches to ACN redundancy. The reviewed list of works describes methods for cost estimation and cost optimization, but they do not provide a comprehensive analysis, considering the use of various radio access network architectures and separation options during deployment. Our work calculates capital and operating costs for a period of 10 years, when deploying a 5G network, considering various architectures of the radio access network and many other factors.

2. BASE STATION ARCHITECTURE

In this section, we will consider the features of radio access network architectures: D-RAN, C-RAN, V-RAN and Open RAN.

In the D-RAN architecture, all base station equipment resides at the site. RUs are located at the top of the mast near the antennas, while DUs and CUs are located in a cabinet close to the mast itself, Figure 1 explains the equipment layout typical for the D-RAN case.

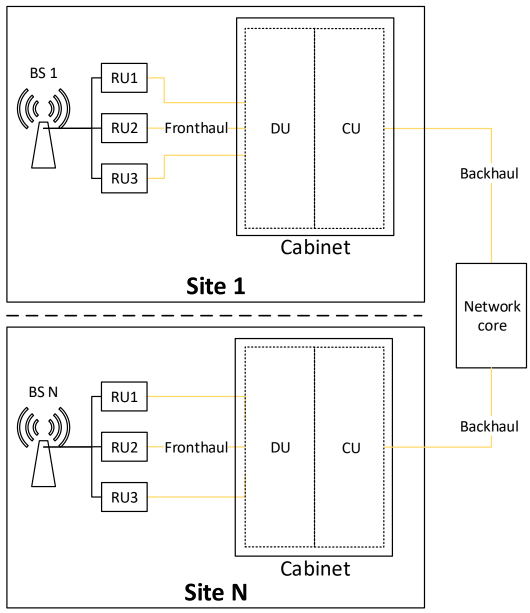

Figure 1. Location of base station equipment for D-RAN architecture

In the case of D-RAN, the hardware is proprietary and the software is inextricably linked to the computing hardware.

The main difference between C-RAN and D-RAN is that in C-RAN architecture the DU and CU units are no longer located at the base station site, but are moved to separate data processing centers (DPCs). Figure 2 explains the layout of the base station equipment for the C-RAN architecture.

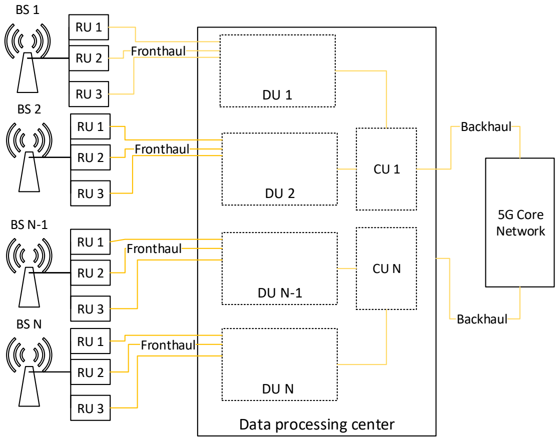

Figure 2. Location of base station equipment for C-RAN architecture

There are two cases of equipment separation: the first is when DU and CU are taken out to the data center, the second is when only CU is taken out. It is expected that the computing resource of the DU and CU can be used more efficiently in this way. The reason for this should be the distribution of computing power between the DUs. So, for example, having two base stations, one of which is loaded by 80%, and the second by 10%, the DU of the second base station can be turned off, and the computing load can be redirected to the DU of the first base station. This results in energy savings. Also, one of the important factors in reducing TCO is that it is much easier and cheaper to adjust the climatic conditions in the data center than adjusting the climatic conditions in each office at each of the sites.

With the advent of V-RAN, it became possible to implement the functions of computing equipment using a general-purpose server. One of the main advantages of this method is that there is no longer a need for specialized hardware, and the entire computing load can be performed on standard servers. Figure 3 shows the base station equipment layout for the V-RAN architecture.

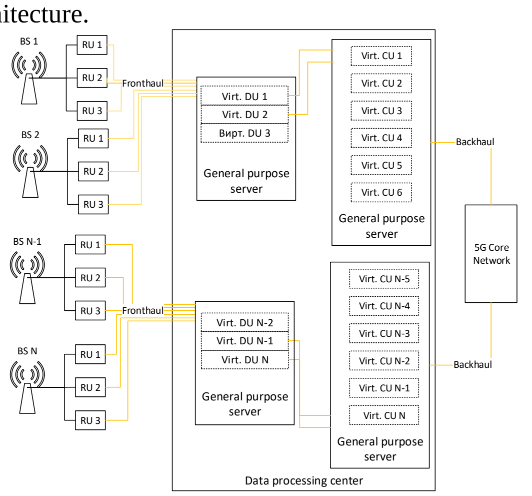

Figure 3. Location of base station equipment for V-RAN architecture

The benefits of virtualization are as follows:

- Use of less equipment;
- Increased flexibility;
- Ability to increase and scale the load with less effort relative to D-RAN and C-RAN;
- Allows scaling of resources depending on the changing needs of the network.

These benefits indicate that the use of V-RAN can simplify the deployment and scaling of the network, as well as reduce its total cost of ownership.

Thus, to deploy a network, there is no need to purchase proprietary equipment for the implementation of DU and CU, it is enough to install a public server and purchase software that implements their functionality. This solution will both reduce the cost of this equipment and simplify network deployment. However, in V-RAN, the interfaces between RUs and DUs, and between DUs and CUs remain closed Common Public Radio Interface (CPRI) (Interface Specification V7.0, 2015), which makes equipment from different manufacturers incompatible and forces the operator to purchase a complete set of equipment from one supplier. This reduces competition in the manufacturer's market and leads to an increase in the cost of equipment.
With the adoption of the 5G NR standard, the load on the Fronthaul interface will increase significantly due to the use of Massive MIMO multi-antenna systems. In this regard, the standards for separation of functions between RUs and DUs have been introduced in the 3GPP standard. Standardizing these separations and interfaces should result in equipment being interchangeable and the market more competitive. Changing the requirements for the distributed block DU also changes the requirements for the functionality of the RU and the communication line between the DU and RU - Fronthaul. The most interesting of these options is option 7, for which the Open RAN standard describes sub-options: 7.2, in particular 7.2a and 7.2b.

The Open RAN architecture is similar to the V-RAN architecture, except that Open RAN implies the opening of all interfaces between RUs, DUs, and CUs. In this case, all equipment and software from different manufacturers becomes compatible, which will lead to a reduction in the cost of implementing a base station due to a more competitive market.

The purpose of introducing options for separating functions between RUs and DUs is to reduce the bandwidth requirements of interfaces (K.V. Savenko, E.V. Rogozhnikov, S.A. Novichkov, & D.V. Lakontsev, 2022), which will facilitate their implementation and, ultimately, reduce the cost. Figure 4 shows a graphical representation of the division of computing operations between RU and DU on the Split 8, Split 7.1, Split 7.2, Split 7.3 options.

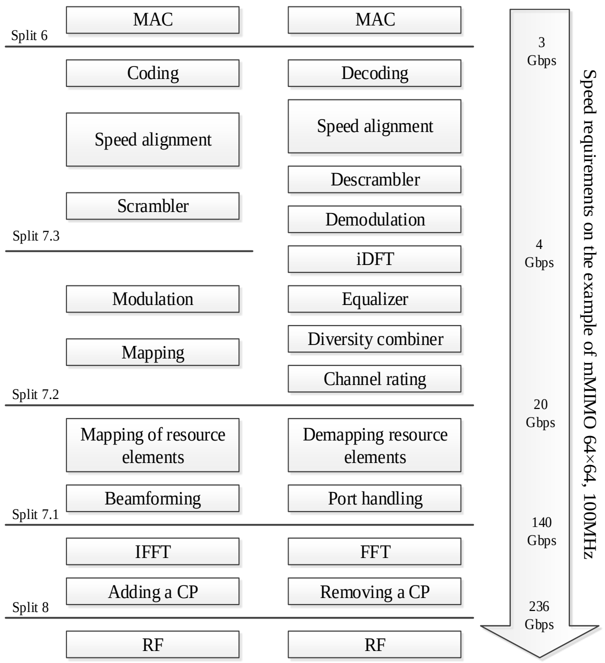

Figure 4. Split options of RU and DU

3. CALCULATION OF TOTAL COST FOR 5G NETWORK

This section presents a methodology for calculating the total cost of ownership (TCO, Total Cost Ownership) when an operator deploys a fifth-generation communication network. Total Cost of Ownership is a value that reflects the total cost of the target costs that the owner must bear from the moment of taking possession until the moment he leaves the possession and fully fulfills his obligations associated with ownership. The TCO calculation includes capital expenditures and operating expenses.

The calculation of the total cost of ownership includes capital (CAPEX, Capital Expenditure) and operating (OPEX, Operational Expenditure) costs and takes the following form:

$$TCO = CAPEX + OPEX. \quad (1)$$

The following is a TCO calculation for various radio access network architectures.

3.1 Capital and operating expenses for 5G Distributed RAN architecture

When a network operator deploys a fifth-generation network using a Distributed RAN architecture, the main capital costs will include the cost of sites, the cost of optics, and the cost of equipment replacement. Thus, the capital cost for D-RAN 5G will be calculated according to the formula:

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$$CAPEX_{D-RAN}^{5G} = N_{site} \cdot (C_{hard}^{site} + C_{CW}) + C_{optic} + C_{replace}, \quad (2)$$

where N_{site} – number of sites;

C_{site} – the cost of installing a site is calculated by the formula:

$$C_{hard}^{site} = C_{DU/CU} + N_{RU} \cdot C_{RU} + C_{mast} + C_{cool} + C_{fronthaul}, \quad (3)$$

where $C_{DU/CU}$ – the cost of DU/CU equipment, which is the sum of the cost of DU and CU – C_{DU} and C_{CU}, calculated as $C_{DU/CU} = C_{DU} + 1/2 C_{CU}$;

C_{optic} – optical fiber cost;

C_{CW} – CW costs (commissioning works) are calculated as:

$$C_{CW} = 0.2 \cdot (N_{RU} \cdot C_{RU} + C_{DU/CU} + C_{fronthaul}), \quad (4)$$

N_{RU} – number of RU modules;

C_{RU} – cost of RU modules;

C_{mast} – the cost of installing mast on the site;

C_{cool} – cooling plant cost;

$C_{fronthaul}$ – the cost of the Fronthaul interface board; $C_{replace}$ – the cost of replacing equipment in 7-8 years. It is determined by the period for which the technological obsolescence of equipment occurs, which entails its complete replacement. The lifetime of the equipment is about 10 years for a macro cell and 5 years for a micro cell (Rendon Schneir et al., 2019), after which it is necessary to replace the RU, DU/CU modules, the CPRI board and cooling. In our model, we assume an equipment replacement period of 7 years. These costs are calculated as:

$$C_{replace} = N_{site} \cdot (N_{RU} \cdot C_{RU} + C_{DU/CU} + C_{fronthaul} + C_{CW}), \quad (5)$$

The cost of laying an optical fiber C_{optic} is calculated by the formula:

$$C_{optic} = L_{optic} \cdot C_{rol} + (L_{summ}^{front}/3 + L_{summ}^{mid} + L_{summ}^{back}) \cdot C_{dig}, \quad (6)$$

where L_{optic} – the total length of the optical fiber, calculated as:

$$L_{optic} = L_{summ}^{front} + L_{summ}^{mid} + L_{summ}^{back}, \quad (7)$$

C_{rol} – cost of rolling out a kilometer of fiber optic line;

L_{summ}^{front} – total length of Fronthaul line;

L_{summ}^{mid} – total length of Midhaul line;

L_{summ}^{back} – total length of the Backhaul line;

C_{dig} – cost of digging a kilometer of trench.

Let's calculate the operating costs of OPEX for the Distributed RAN architecture. OPEX calculation is carried out for one year. This calculation includes the cost of electricity, operation and maintenance costs, the cost of maintaining optical fiber and renting sites for base stations, the cost of wages for employees and the calculation of the costs of maintaining and deploying the network.

$$OPEX^{5G}_{D-RAN} = C_{W/h} \cdot P + N_{site} \cdot (C^{site}_{rent} + \\ + C_{update}) + C_{OEM} + C_{wages}, \quad (8)$$

where $C_{W/h}$ – cost per W·h;

P – total power consumption;

C^{site}_{rent} – site rental cost;

C_{update} – cost of updating the software. The cost of updating the software of specialized equipment is equal to the cost of its acquisition. When purchasing specialized equipment, its cost consists of the cost of computing equipment and the cost of software. Usually, the distribution of these amounts is correlated as 70% - the cost of computing equipment and 30% - the cost of software. Accordingly, the software update is calculated as 30% of the cost of the equipment:

$$C_{update} = 0.3 \cdot (C_{RU} + N_{RU} + C_{DU/CU}), \quad (9)$$

C_{OEM} – annual operation and maintenance;

C_{wages} – annual salary of employees, calculated as:

$$C_{wages} = 12 \cdot wage \cdot N_{staff}, \quad (10)$$

where $wage$ – salary per employee per month;

N_{staff} – number of employees, 1 employee for every 500 sites, but a minimum of 1.

The total power consumption P is 60% (based on network congestion during the day) of the power consumption of each site P_{site}, multiplied by the number of sites, considering the hours in a year:

$$P = 0.6 \cdot (N_{site} \cdot P_{site} \cdot N_{hour/year}), \quad (11)$$

where $N_{hour/year}$ – number of hours per year.

The total power consumed by a site P_{site}, is calculated using the formula (12):

$$P_{site} = N_{RU} \cdot P_{RU} + P_{DU/CU} + P_{cool}, \quad (12)$$

where

P_{RU} – power consumption per RU module;

$P_{DU/CU}$ – power consumption per DU/CU;

P_{cool} – power consumption per cooling plant.

Annual operating and maintenance costs are calculated as a percentage of the cost of all the equipment used:

$$C_{OEM} = C_{percent} \cdot (N_{site} \cdot (N_{RU} \cdot C_{RU} + C_{cool} + \\ + C_{DU/CU} + C_{fronthaul})) + L_{optic} * C^{sevice}_{optic}, \quad (13)$$

where C^{sevice}_{optic} – cost of annual maintenance of one kilometer of optical fiber;

where $C_{percent}$ – percentage pledged for operation and maintenance, equal to 10% of the total cost of equipment. However, after the warranty period has expired, operating and maintenance costs may increase exponentially. This is due to the fact that the manufacturer providing goods and services, due to the lack of competition in the market, completely controls pricing.

3.2 Capital and operating expenses for 5G Centralized RAN architecture

Consider the case of calculating capital and operating costs when moving DU and CU modules to a data processing center (C-RAN architecture), when there is only a mast with antennas and radio modules on the site, and all computing power is moved to the data center. The block diagram of C-RAN for 5G network with DU and CU separation is shown earlier in Figure 2. Since the block allocation structure has changed, the TCO calculation model will also change. In particular, the costs for the construction of a mini data center for the removal of equipment will be added. (Pirogova, Grekoul, & Poklonov, 2016) the approximate cost of 1 sq. m. m for different levels of reliability of the data center, as well as the recalculation of the cost of the data center per rack. The CAPEX calculation formula for the C-RAN case will be as follows:

$$CAPEX^{5G}_{C-RAN} = N_{DPC} \cdot (C_{DPC} + C^{DPC}_{hard} + \\ + C^{DPC}_{CW}) + N_{site} \cdot (C^{C-RAN}_{site} + C^{site}_{CW}) + \\ + C_{optic} + C_{replace}, \quad (14)$$

where N_{DPC} – number of required datacenters, calculated as:

$$N_{DPC} = \frac{N_{site}}{N^{DPC}_{BS}}, \quad (15)$$

where N^{DPC}_{BS} – number of base stations served by one data center;

C_{DPC} – the cost of building a data center is calculated as:

$$C_{DPC} = C^{Tier}_{rack} \cdot N_{rack} \quad (16)$$

where C^{Tier}_{rack} – the cost of building a data center in terms of one rack for the desired level of reliability;

N_{rack} – required number of racks.

Considering the fact that part of the equipment is taken out to the data center, the cost of this equipment is not considered when calculating the cost of the site, but is considered in the cost of equipment installed in one data center – C_{hard}^{DPC}, the calculation is performed as follows:

$$C_{hard}^{DPC} = TC_{DU}^{DPC} + TC_{CU}^{DPC} + C_{cool}, \quad (17)$$

where TC_{DU}^{DPC} – the total cost of DUs installed in one data center is calculated as:

$$T_{DU}^{DPC} = N_{DU}^{DPC} \cdot (C_{DU} + C_{fronthaul}), \quad (18)$$

where N_{DU}^{DPC} – number of DUs in one data center, calculated as $N_{BS}^{DPC} \cdot N_{RU}/4$,

where N_{BS}^{DPC} – number of base stations within a radius of 15 km from the data center, and the denominator of the coefficient $N_{RU}/4$ – number of RUs served by one DU;

C_{DU} – cost of a DU module;

TC_{CU}^{DPC} – the total cost of CUs installed in one data center is calculated as:

$$TC_{CU}^{DPC} = N_{CU}^{DPC} \cdot C_{DU} \quad (19)$$

where N_{CU}^{DPC} – number of CUs in one data center, calculated as $N_{DU}^{DPC}/2$, where the denominator is the number of DUs processed by one CU;

C_{CU} – cost of a CU module;

C_{CW}^{DPC} – the cost of commissioning in one data center is 25% of the total cost of DU and CU:

$$C_{CW}^{DPC} = 0.25 \cdot (TC_{DU}^{DPC} + TC_{CU}^{DPC}), \quad (20)$$

The site has only a mast and radio modules, so only 3 quantities are involved in the calculation of capital costs for sites: N_{RU} – the number of RU modules per site, C_{RU} – the cost of one radio module, C_{mast} – the cost of installing a mast. Thus, the cost of a C-RAN site is calculated as:

$$C_{site}^{C-RAN} = N_{RU} \cdot C_{RU} + C_{mast}, \quad (21)$$

C_{CW}^{site} – cost of commission works for one site, calculated as 20% of the cost of all RU modules:

$$C_{CW}^{site} = 0.2 \cdot (N_{RU} \cdot C_{RU}), \quad (22)$$

The calculation of operating expenses will also undergo changes:

$$OPEX_{C-RAN}^{5G} = C_{W/h} \cdot P + N_{site} \cdot C_{rent}^{site} + N_{DPC} \cdot C_{rent}^{DPC} + C_{OEM} + C_{wages} + C_{update}, \quad (23)$$

where C_{rent}^{site} – base station site rental cost;

C_{rent}^{DPC} – DPCs site rental cost;

C_{update} – the cost of annual software updates, which is estimated at 30% of the cost of equipment:

$$C_{update} = 0.3 \cdot (N_{site} \cdot N_{RU} \cdot C_{RU} + N_{DPC} \cdot (C_{hard}^{DPC} - C_{cool})), \quad (24)$$

As in the case of D-RAN, equipment becomes obsolete and will need to be completely replaced after 7 years:

$$C_{replace} = N_{DPC} \cdot (C_{hard}^{DPC} - C_{cool} + C_{CW}^{DPC}) + N_{site} \cdot (N_{RU} \cdot C_{RU} + C_{CW}^{site}), \quad (25)$$

Since only radio modules remain on the site, the calculation of the power consumed by the site – P_{site}, is taking the following form:

$$P_{site} = N_{RU} \cdot P_{RU}, \quad (26)$$

It is also necessary to calculate the power consumed by the equipment on the side of the DPC. This power is calculated by the formula:

$$P_{DPC} = N_{DU}^{DPC} \cdot P_{DU} + N_{CU}^{DPC} \cdot P_{CU} + P_{cool}, \quad (27)$$

The total power consumption P is 60% of the power consumption of all sites P_{site} and DPCs P_{DPC}, multiplied by the number of hours per year:

$$P = 0.6 \cdot (N_{site} \cdot P_{site} + N_{DPC} \cdot P_{DPC}) \cdot N_{year/hour}, \quad (28)$$

Operation and maintenance costs are calculated using the formula:

$$C_{OEM} = C_{percent} \cdot (N_{site} \cdot (N_{RU} \cdot C_{RU}) + N_{DPC} \cdot C_{hard}^{DPC}) + L_{optic} * C_{optic}^{sevice}, \quad (29)$$

3.3 Capital and operating expenses for 5G Open RAN architecture

Let's calculate the capital and operating costs when deploying a fifth-generation network using the Open RAN architecture. Open RAN implies virtualization of DU and CU functions using general purpose servers, as well as open Fronthaul and Midhaul interfaces. For the calculation, we will use the split option 7.2. The Split 7.2 option involves performing Fourier transforms, adding/removing a cyclic prefix, mapping resource elements, and operations related to beamforming in the radio module. This will reduce the bandwidth requirements of the fronthaul interface, which significantly reduces the complexity of its implementation, but at the same time the radio module becomes more complex and the distributed module is simplified. In this case, the cost of the radio module will increase, but the cost of the distributed module will decrease.

The calculation of capital and operating costs will change, since instead of a one-time replacement of equipment, it is assumed here, a 2-stage replacement of equipment and the purchase of software. The formulas for calculating some components of the total costs will also change. In the case of Open RAN, the need to replace equipment arises twice: after 5 years, it is necessary to replace the server hardware, and after 7-8 years, the RU modules.

Capital costs are calculated by the formula:

$$CAPEX_{O-RAN}^{5G} = N_{DPC} \cdot (C_{DPC} + C_{hard}^{DPC} + C_{CW}^{DPC}) + N_{site} \cdot (C_{site}^{O-RAN} + C_{CW}^{site}) + C_{optic} + C_{soft} + C_{replace}^{serv} + C_{replace}^{RU}, \quad (30)$$

where, $C_{replace}^{serv}$ – replacement of server hardware after 5 years and is calculated as:

$$C_{replace}^{serv} = N_{DPC} * (C_{hard}^{DPC} - C_{cool} + C_{CW}^{DPC}), \quad (31)$$

$C_{replace}^{RU}$ – replacement of RU modules after 7 years and is calculated as:

$$C_{replace}^{RU} = N_{site} * (N_{RU} * C_{RU} + C_{CW}^{DPC}), \quad (32)$$

In this case, the calculation of the cost of commissioning in one data center will change:

$$C_{CW}^{DPC} = 0.25 \cdot (TC_{DU}^{DPC} / N_{DU}^{serv} + TC_{CU}^{DPC} / N_{CU}^{serv}), \quad (33)$$

where, N_{DU}^{serv} – number of DUs per server;

N_{CU}^{serv} – number of CUs per server;

The cost of purchasing the software will be calculated according to the formula:

$$C_{soft} = N_{site} \cdot N_{RU} \cdot C_{soft}^{RU} + N_{DPC} \cdot (N_{DU}^{DPC} \cdot C_{soft}^{DU} + N_{CU}^{DPC} \cdot C_{soft}^{CU}), \quad (34)$$

where,

C_{soft}^{RU} – cost of software per RU;

C_{soft}^{DU} – cost of software per DU;

C_{soft}^{CU} – cost of software per CU.

The calculation of OPEX is carried out according to the following formula according to the formula:

$$OPEX_{O-RAN}^{5G} = C_{W/h} \cdot P + N_{site} \cdot C_{rent}^{site} + N_{DPC} \cdot C_{rent}^{DPC} + C_{OEM} + C_{wages} + C_{update}, \quad (35)$$

where, C_{update} - cost of annual software updates, which is 30% of the cost of the software:

$$C_{update} = 0.3 \cdot C_{soft} \quad (36)$$

4. CALCULATION AND COMPARATIVE ANALYSIS

Using the equations described in Chapter 3, we calculate and compare capital, operating, and total cost of ownership for various 5G deployment architectures: D-RAN, C-RAN, and Open RAN over a 10-year period. The parameters used for the calculation are shown in Table 1.

Table 1. Parameters used in calculations

Name	Symbol	Value		
		D-RAN	C-RAN	Open RAN
Number of sites, pcs.	N_{site}	100	100	100
Number of RUs per site, pcs.	N_{RU}	3	3	3
Fronthaul optical line length, km	L_{front}	0,01	1	1
Number of DU/CU modules, pcs	$N_{DU/CU}$	N_{site}		
Number of DU modules, pcs.	N_{DU}		$3N_{site}/4$	$3N_{site}/4$
Number of CU modules, pcs.	N_{CU}		$1/2\, N_{DU}$	$1/2\, N_{DU}$
Cost of DU/CU per unit, t.USD	$C_{DU/CU}$	6		
DU cost per unit, t.USD	C_{DU}		3	3
CU cost per unit, t.USD	C_{CU}		5	4
The cost of the cooling unit on the site, t.USD	C_{cool}	1,5	5	5
Cost of RU per unit, t.USD	C_{RU}	2	2	4
Erection of the mast on the site, t.USD	C_{mast}	15	15	15
Rent of a platform for a website, t.USD per year	C_{rent}^{site}	5	5	5
Rent of a site for a data center, t.USDper year	C_{rent}^{DPC}		5	5
Annual maintenance of optical fiber, t.USD/km	C_{optic}^{sevice}	0,05	0,05	0,05

Salary of one employee per month, t.USD	$wage$	2,7	2,5	2,5
Number of employees	N_{staff}	1	1	1
The cost of building a DPC per rack, USD	C_{rack}^{Tier}		34,852	34,852
Number of racks in the data center, pcs	N_{rack}		1	1
Power consumption RU, Wh	P_{RU}	500	500	700
Power consumption DU/CU, Wh	$P_{DU/CU}$	400		
Power consumption DU, Wh	P_{DU}		400	400
Power consumption CU, Wh	P_{CU}		400	400
Power consumption of the cooling unit, W/h	P_{cool}	500	2000	2000
Cost of one Wh, USD	$C_{W/h}$	0,000673	0,000673	0,000673
The cost of 1 km of trench digging	C_{dig}	3	3	3
The cost of rolling 1 km optical fiber, t.USD	C_{rol}	1	1	1
Cost of fronthaul interface board, t.USD	$C_{fronthaul}$	2,5	2,5	0,150
Software cost, t.USD per module	C_{soft}^{RU}			0,2
	C_{soft}^{DU}			0,4
	C_{soft}^{CU}			0,4

As a result of the calculation, the dependences shown in Figures 5-13 were obtained. The following designations are used in the figures.

CAPEX: INTERF. BOARD - cost of interface boards, COOL - cost of a cooling unit, OPTIC - cost of an optical cable, MAST - cost of a mast for base stations, REPLACE - cost of equipment replacement, SOFT - cost of software, DPC BUILDING - cost of building a data center, CW - cost of commissioning works, DU/CU – cost of DU/CU modules, DU – cost of DU modules, CU – cost of CU modules, RU – cost of RU modules.
OPEX: DU/CU ENERGY - DU/CU energy bill, DU ENERGY - DU bill, CU ENERGY - CU bill, RU ENERGY - RU bill, COOL ENERGY - chiller bill, RENT - site rental, OEM - costs for maintenance, WAGES is the salary of employees, SOFT UPDATE is the cost of software updates.

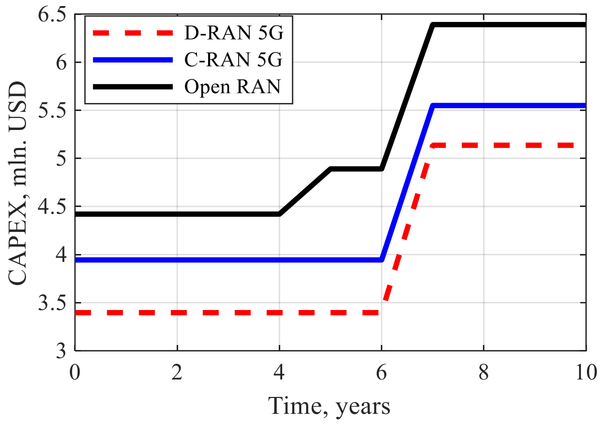

Figure 5. CAPEX versus time

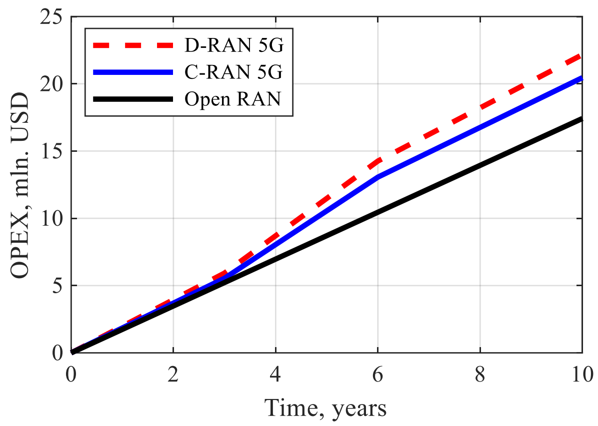

Figure 6. OPEX versus time

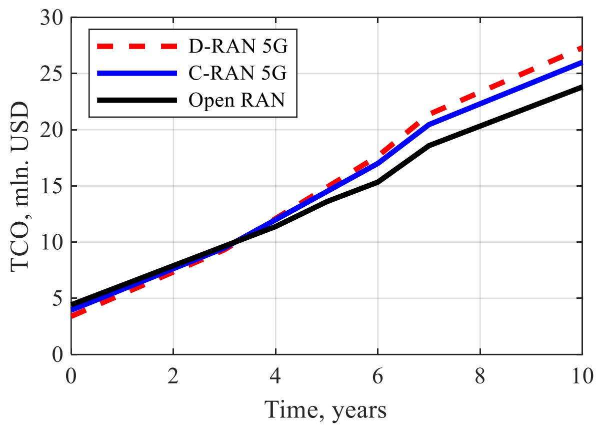

Figure 7. TCO versus time

RAN, and Open RAN is $27.3, $26, and $23.8 million, respectively.

The capital cost of C-RAN is higher than that of D-RAN due to the high cost of fiber optic cabling and data center construction. In Open RAN, the low cost of interface boards and the centralized module is offset by the cost of acquiring software and more expensive RU modules, resulting in the highest capital costs relative to the D-RAN and C-RAN architectures.

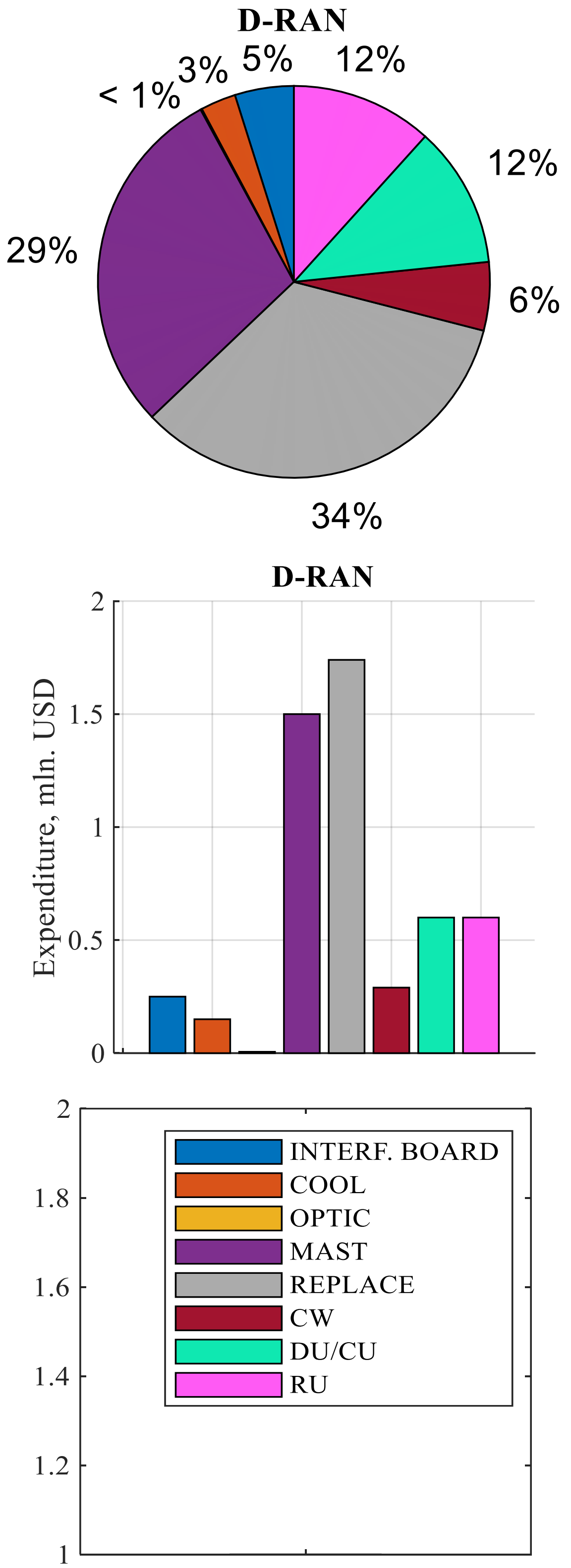

Figure 8. CAPEX Composition for D-RAN

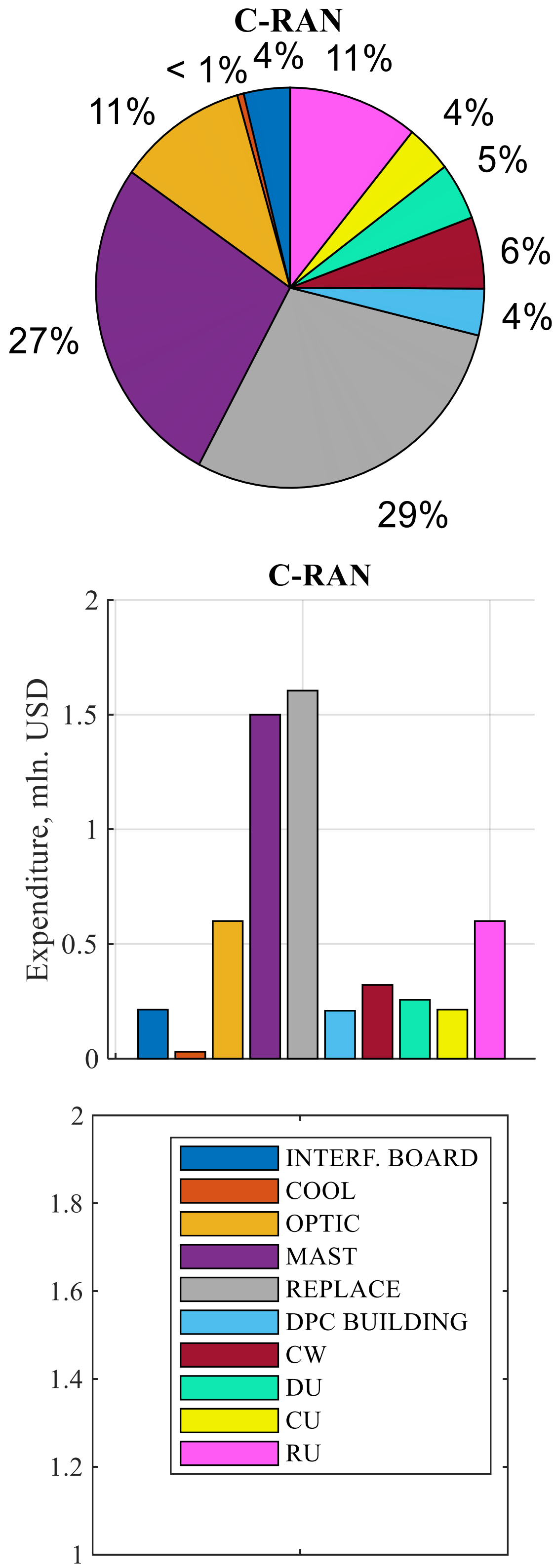

Figure 9. CAPEX Composition for C-RAN

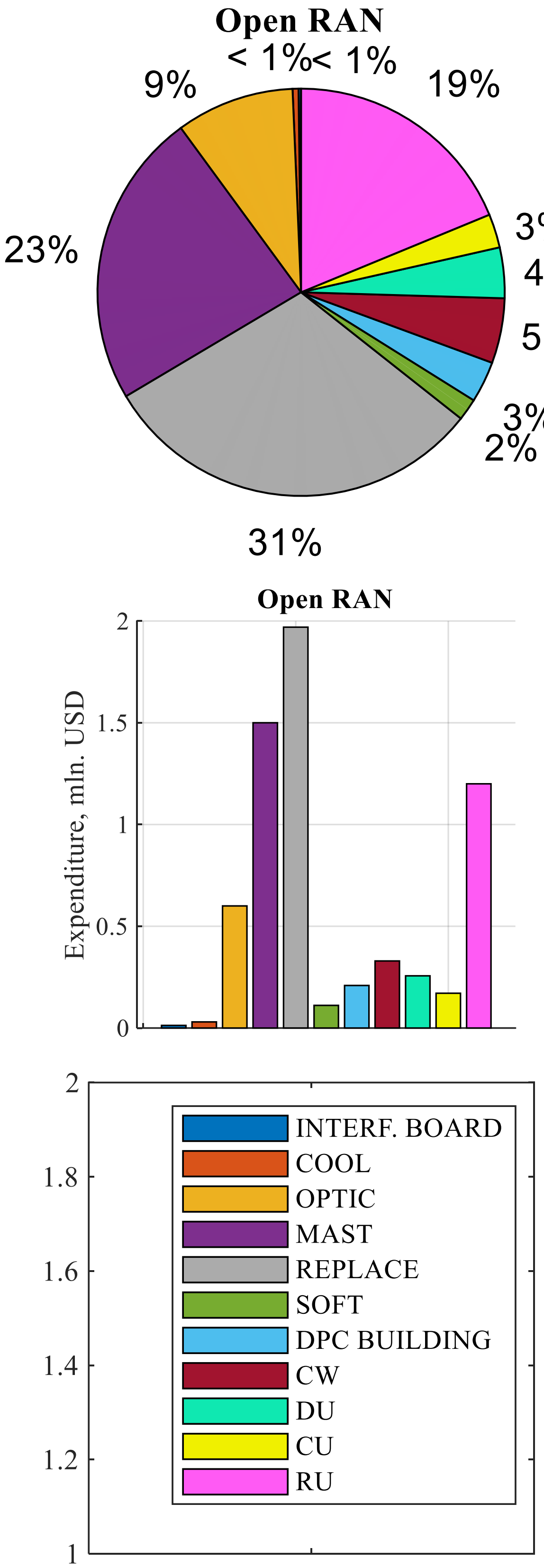

Figure 10. CAPEX Composition for Open RAN

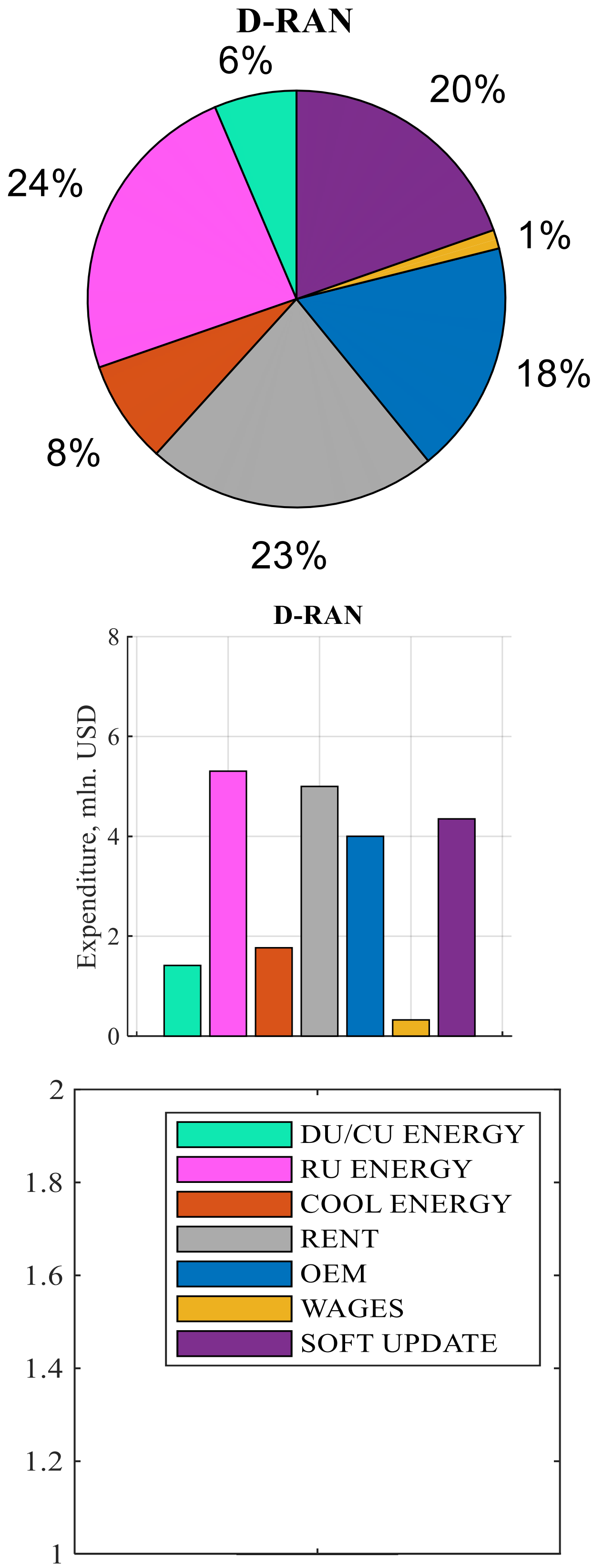

Figure 11. OPEX Composition for D-RAN

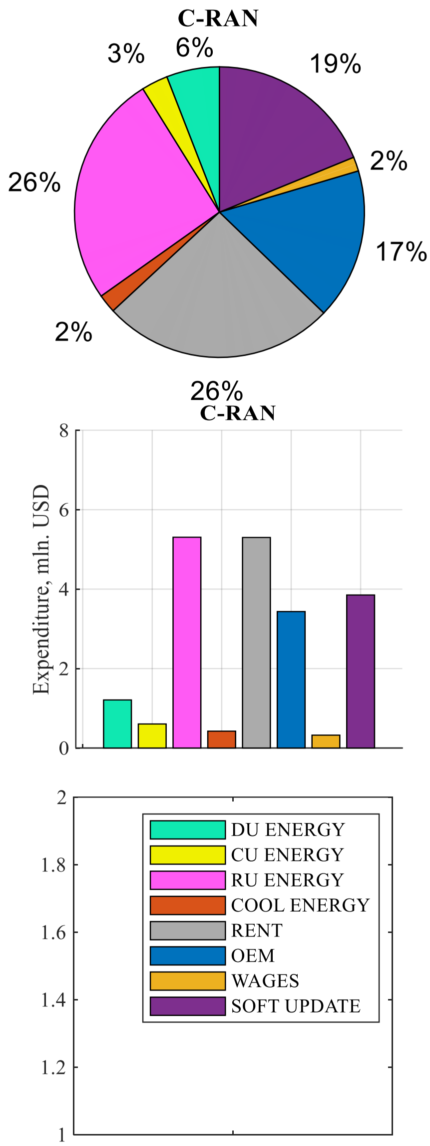

Figure 12. OPEX Composition for C-RAN

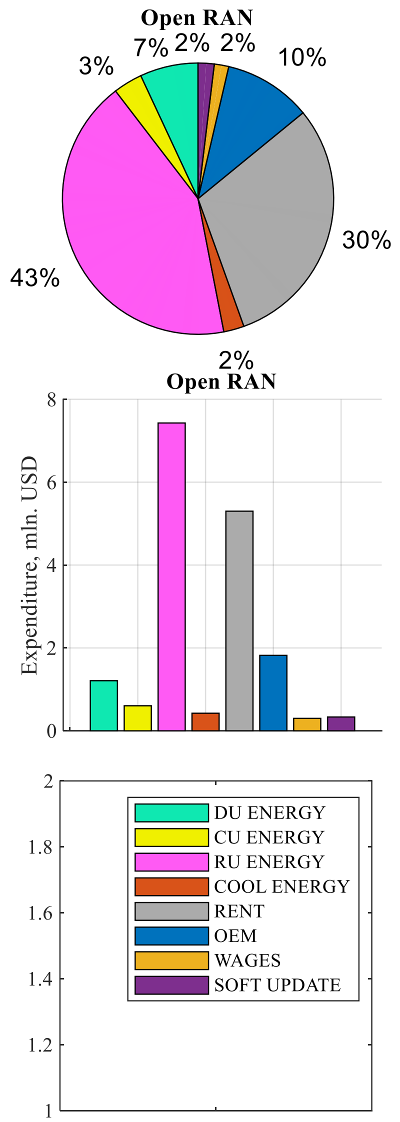

Figure 13. OPEX Composition for Open RAN

For the first three years, the total cost of the network differs slightly, but the post-warranty maintenance of the D-RAN and C-RAN networks increases their cost in subsequent years. At the end of the seven year perod, the capital expenditures of D-RAN and C-RAN rise sharply as equipment is replaced. In our case, the replacement implies the purchase of all equipment DU, CU, RU and interface boards, as well as the cost of commissioning. As a result, over ten years, the total cost of D-RAN, C-

In terms of operating costs, the D-RAN network has the highest, as here we see higher costs for cooling equipment and software updates relative to C-RAN and Open RAN. In the C-RAN network, these costs are noticeably lower. In the Open RAN network, software updates cost almost 12 times less and maintenance costs almost three times less than in C-RAN, so this architecture is the most profitable among those presented.

5. CONCLUSION

Mobile network virtualization provides operators with an excellent opportunity to use their computing resources efficiently and benefit from potential operational cost savings. Numerical results are presented to evaluate the proposed model. The results show that Open RAN has the potential to result in less computing hardware and cost savings over the life of the system. However, this is only possible in networks with a large number of base stations and operation for more than three years. The savings in energy, software upgrades and operating costs then outweigh the incremental capital costs. However, for some enterprises, the use of the Open RAN architecture can provide tremendous benefits over D-RAN and C-RAN. First of all, they include mobile operators. This paper presents calculations of specific network models with given parameters. However, they can be adapted to certain scenarios for private enterprises of various types of activity.

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