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Trade-Off Between Power and Bandwidth Consumption in a Reconfigurable Xhaul Network Architecture

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ABSTRACT The increasing number of wireless devices, the high required traffic bandwidth, and power consumption will lead to a revolution of mobile access networks, which is not a simple evolution of traditional ones. Cloud radio access network technologies are seen as promising solution in order to deal with the heavy requirements defined for 5G mobile networks. The introduction of the common public radio interface (CPRI) technology allows for a centralization in BaseBand unit (BBU) of some access functions with advantages in terms of power consumption saving when switching off algorithms are implemented. Unfortunately, the advantages of the CPRI technology are to be paid with an increase in required bandwidth to carry the traffic between the BBU and the radio remote unit (RRU), in which only the radio functions are implemented. For this reason, a tradeoff solution between power and bandwidth consumption is proposed and evaluated. The proposed solution consists of: 1) handling the traffic generated by the users through both RRU and traditional radio base stations (RBS) and 2) carrying the traffic generated by the RRU and RBS (CPRI and Ethernet flows) with a reconfigurable network. The proposed solution is investigated under the lognormal spatial traffic distribution assumption. After proposing resource dimensioning analytical models validated by simulation, we show how the sum of the bandwidth and power consumption may be minimized with the deployment of a given percentage of RRU. For instance we show how in 5G traffic scenarios this percentage can vary from 30% to 50% according to total traffic amount handled by a switching node of the reconfigurable network.

INDEX TERMS Radio access network, common public radio interface, 5G environment, statistical multiplexing gain.

I. INTRODUCTION

The widespread availability of mobile devices, such as tablets and smartphones, and a lots of dedicated applications has led to quickly increase mobile data traffic in the last few years. Furthermore, based on different studies and predictions [1], it is possible to conclude that beyond 2020, mobile networks will be asked to support more than 1,000 times today's traffic volume. Demands for higher mobile networks capacity, for increased data rates and for larger number of simultaneously connected devices are just few of the requirements posed in the evolution of radio access networks. Other fundamental factors are energy saving and cost of systems, latency, spectrum availability and spectral efficiency. Naturally, one of the solutions to deal with the very high capacity and coverage demand is the strong radio site densification (e.g. through small, pico, femto cells), that could be also obtained by different deployment architectures.

Cloud Radio Access Network (C-RAN) or centralized RAN could be seen as a promising solution to deal the 5G requirements [2], [3]. Traditional C-RANs are organized as a three element network, that contains BBU pool, RRUs and the network interconnecting BBUs and RRUs. The BBU provides baseband signal processing functions and the RRU provides Radio Frequency signal transmission and reception functions. The network between the BBU and the RRUs is called fronthaul network [4], [5]. There are two well-known standard interfaces to encapsulate In-Phase and Quadrature (IQ) samples between RRU and BBU: Common Public

Radio Interface (CPRI) and Open Base Station Architecture Initiative (OBSAI) [6], [7]. Furthermore both standards introduce the possibility to switch off or switch on the BBU when the traffic changes during the day [7].

The separation of base radio station in BBU/RRU leads to important advantages, as energy saving, improving security and deployment of infrastructure ready to support advanced interference management features, like Coordinated MultiPoint (CoMP) [6].

Unfortunately the main disadvantage of a traditional C-RAN solution is the high traffic to be carried in the fronthaul network. In fact the amount of IQ sampled data becomes at least ten times than that of the RF signal maximum bandwidth and it must be transmitted via an optical link [6], [7].

For this reason new solutions have been proposed in literature in order to save the used bandwidth and at the same time by maintaining the advantages of power consumption saving and interference management of the centralized solution. IQ data compression techniques can reduce the bandwidth [8], [9], the compression ratio is 1/2 which is insufficient for future radio access.

The most interesting solutions have been proposed for the Long Term Evolution (LTE) network case and their basic idea is to reduce the used bandwidth by making the optical transmission rate proportional to the wireless link data rate [10]. The reduction can be obtained with a different functional split different from that of the tradition solution. The functional split options, which can achieve a significant bandwidth reduction are the Split MAC Physical (SMP) and Split Physical Processing (SPP) solutions reported in Fig. 1.a and 1.b respectively.

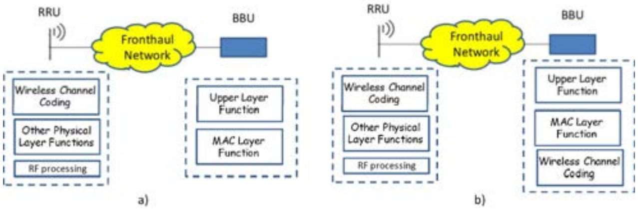

FIGURE 1. Split MAC physical (a) and split physical processing (b) solutions.

In the SMP solution all of the physical layer functions are implemented in the RRU. Conversely the MAC layer functions are implemented in the BBU. With this solution, LTE MAC frames called transport blocks, and control signals in the physical layer are forwarded through the fronthaul network, rather than IQ samples as occurring in the traditional solution. The optical transmission rate is greatly reduced to approximately the wireless transmission data rate. The drawback of the the SMP solution is the difficulty of implementing centralized processing for joint transmission and reception.

In the SPP solution, the wireless channel coding is migrated towards the BBU while the others physical layer functions as modulation and Multiple Input Multiple Output (MIMO) are implemented in the RRU. This solution allows the inter-cell interference management and the required optical link capacity can be reduced to nearly that of the SMP solution and it depends on the wireless transmission coding rate.

In this paper we analyze a network solution in which the radio component is composed by RRU and traditional Radio Base Station (RBS). The fronthaul network is able to carry both CPRI and Ethernet flows and for this reason it is also referred to as Xhaul network [11], [12]. The investigated solution is bandwidth and power efficient. The bandwidth efficiency is due to: i)the use of RBSs requiring the transport of flows with bit rate proportional to the user traffic; ii)the use of a switching off algorithm of the RRUs in low traffic periods; iii) the use of a reconfigurable network allowing for the sharing of circuits between RRU and BBU. Conversely the power efficient is guaranteed by the sharing of processing resources of the servers from the BBU instantiated on them with the consequence of saving in fixed power consumption.

The main contributions of the paper are: i) the definition of analytical models for the bandwidth dimensioning, based on a lognormal traffic assumption and validated by simulation; ii) the evaluation of power/bandwidth trade-off solutions based on the optimal determination of the percentage of RRUs to be used in order to minimize the sum of the bandwidth and power costs. The proposed solution will be investigated in real traffic scenario by using measured traffic intensity of the City of London [24].

The reference scenario considered in our analysis is reported in Section II. Meanwhile, the cost evaluation model is reported in Section III and the dimensioning analytical models are reported in Section IV.

The main results for 4G and forecast 5G network areas are illustrated in Section V. Finally conclusions and future research items are illustrated in Section VI.

II. XHAUL ARCHITECTURE

The Xhaul architecture is reported in Fig. 2. It handles a reference area divided in macro areas, each one covered by a macro base station (macro BS). Each macro area is divided into sub-areas, each one covered by a certain number of RRUs and traditional micro base stations (micro RBSs). A reference area is handled by a Central Office (CO) that contains a certain number of BBU servers managed by a Control and Management (‘‘C&M’’) module. The ‘‘C&M’’ has the role of activating/deactivating/migrating BBU instances in the BBU servers with each BBU instance related to an active RRU, and moreover of implementing algorithms for the consolidation of BBU instances that lead to save energy. The main steps of this algorithm will be reported in the beginning of Section IV. In the CO, Ethernet switch is also located to handle the Ethernet traffic generated by the micro RBSs.

BBUs in the Central office and radio stations (RRU and micro RBS) are connected between them by a reconfigurable transport network though some Access Switches (ASs) and one HUB switch a shown in Fig. 2. The agility of the network is concentrated into the ASs and HUB switch that allow for

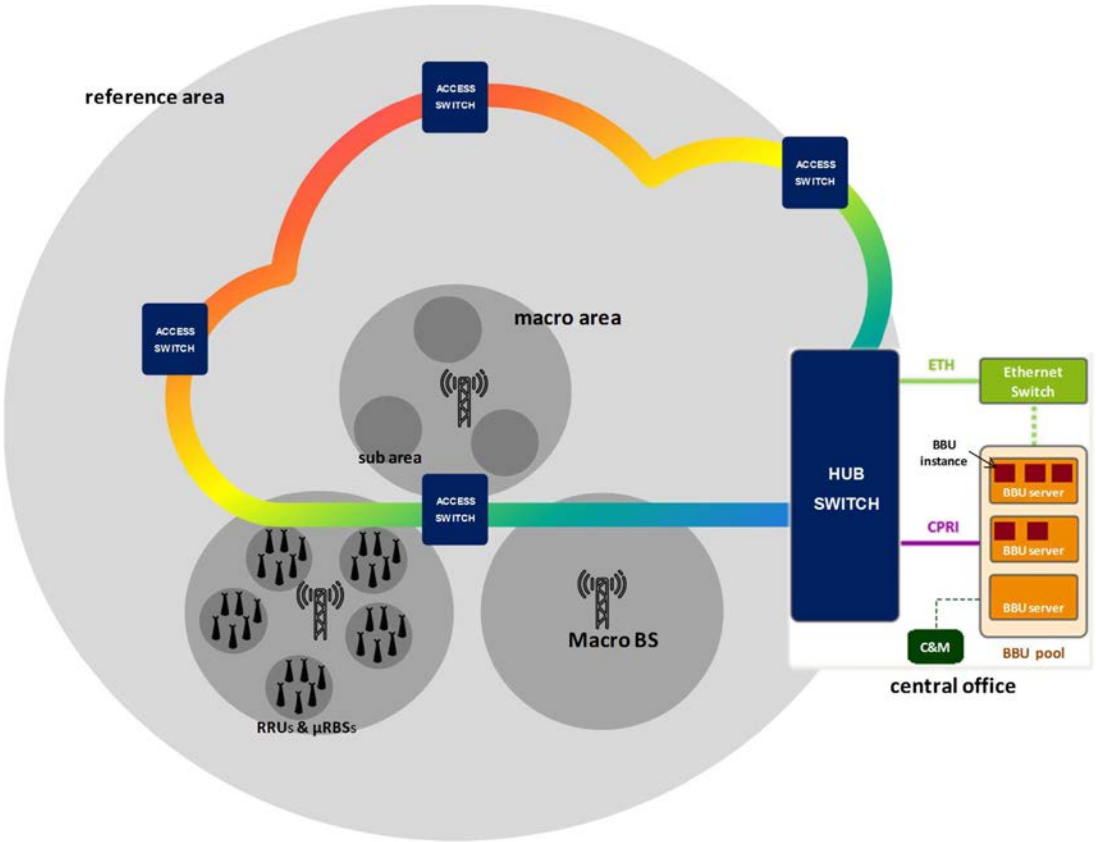

FIGURE 2. Xhaul network architecture.

the flexible allocation of circuits between RRUs and CO. Though we assume that any RRU has always switched on its radio interface, a circuit is allocated to it only if they handle traffic and a corresponding BBU is instantiated and connected to it.

The network reconfiguration allows for a bandwidth saving and this may occur on a hourly basis according to the traffic variations. The reconfiguration capability of ASs and the HUB switch provides a flexible allocation of the bandwidth and server resources to the RRUs and micro RBSs. Efficient implementations of reconfigurable networks consider solutions that combines DWDM and OTN, whose benefits are largely studied in several works [13]–[22], enabling hybrid transport of CPRI and Ethernet flows.

The advantages of the proposed Xhaul architecture are threefold: i) the use of an aggregation segment allows for the transport bandwidth sharing among RRUs and micro RBSs connected to the same AS that leads to a bandwidth saving if suited dimensioning procedures are applied; ii) the Xhaul network is reconfigurable with the possibility of bandwidth saving in low traffic periods; iii) the Xhaul network supports hybrid solution in which both CPRI and Ethernet technologies are employed in the access network with the possibility to optimize the total cost of bandwidth and power consumption.

The analytical evaluation of the total cost is carried out in the next Section III. Obviously such a cost depends on the bandwidth needed between any AS and the CO. For this reason bandwidth dimensioning models are introduced in Section IV.

TABLE 1. Network parameters in Xhaul reference architecture.

Parameter	Description
B_{CPRI}	bandwidth required by one CPRI flow
K^{BBU}	maximum number of BBU instances supported in any BBU server
C^{RRU}	capacity of an RRU
C^{RBS}	capacity of a micro RBS
n_{RRU}	number of RRUs installed in a sub-area
n_{RBS}	number of micro RBSs installed in a sub-area
T	number of sub-areas handled by an AS
$n^{AS}_{RRU} =$	$T \cdot n_{RRU}$ number of RRUs installed in the region handled by the AS
$n^{AS}_{RBS} =$	$T \cdot n_{RBS}$ number of micro RBSs installed in the region handled by the AS

In table 1, we summarize the network parameters of the Xhaul network architecture. In particular, B_{CPRI} is the bandwidth required by one CPRI flow, K^{BBU} is the maximum number of BBU instances supported in any server, C_{RRU} and C_{RBS} are the capacity of any RRU and any micro RBS, n_{RRU} and n_{RBS} are the number of RRUs and micro RBSs installed in a sub-area, n_{RRU}^{AS} and n_{RBS}^{AS} are the number of RRUs and micro RBSs in the region handled by the AS, that are related to the number T of sub-areas connected to a AS.

TABLE 2. Parameters related to the cost model.

Parameter	Description
C_{tot}^{avg}	average total cost during the cycle-stationary period
C_k^{BW}	bandwidth cost in the k-th stationary interval
C_k^{PWR}	power cost in the k-th stationary interval
μ_{BW}	cost per consumed bandwidth unit
$nc_{AS,CPRI}^k$	number of CPRI circuits needed between any AS and the CO in the k-th interval
$nc_{AS,GE}^k$	number of GEth circuits needed between any AS and the CO in the k-th interval
μ_{PWR}	cost per consumed power unit
P_{tot}^k	total power consumption in the k-th interval
P_{radio}	radio component of power consumption
P_k^{BBU}	baseband processing component of power consumption in the k-th interval
P_{RBS}	power consumption of a micro RBS
P_{RRU}	power consumption of an RRU
P_{server}	fixed power consumption associated to each server
P_{ins}^{BBU}	power consumption associated with one BBU instance

III. COST EVALUATION OF XHAUL ARCHITECTURE

We introduce an analytical model in order to evaluate the total cost of the Xhaul solution as a function of the network and traffic parameters. We consider two main cost components: i) the bandwidth consumption expressed in terms of CPRI and GEthernet circuits needed between any AS and the CO; ii) the power consumption of both radio stations and servers. In Table 2, we report the main parameters characterizing the cost model. We assume a cycle-stationary traffic scenario with N denoting the number of stationary intervals. Our objective is to evaluate the average total cost defined by the following expression:

$$C_{tot}^{avg} = \frac{1}{TN}\sum_{k=0}^{N-1}(\mu_{BW}B_k^{BW} + \mu_{PWR}P_k^{tot}) \quad (1)$$

wherein μ_{BW} and μ_{PWR} denote the cost per consumed bandwidth unit (1 Gbps) and power unit (1 W) respectively; B_k^{BW} and P_k^{PWR} denote the bandwidth and power consumption in the $k-th$ ($k = 0, \ldots, N-1$) stationary interval.

For the evaluation of B_k^{BW} we do not take into account the bandwidth contribution due to MBS. This is due to the fact that this contribution has no significance impact on the cost optimization procedure that we carry out later. For the contribution B_k^{BW} we can simply write:

$$B_k^{BW} = nc_{AS,GE}^k + nc_{AS,CPRI}^k \cdot B_{CPRI} \quad (2)$$

wherein $nc_{AS,GE}^k$ and $nc_{AS,CPRI}^k$ are the number of GEth flows (that hold 1 Gbps traffic) and CPRI flows between any AS and the CO needed in the k-th interval respectively, B_{CPRI} is the bandwidth required (in Gbps) by one CPRI flow.

The total power consumption P_k^{tot} is evaluated considering the sum of several contributions, related to the radio and baseband processing components P_{radio} and P_k^{BBU} respectively. We can write:

$$P_k^{tot} = P_{radio} + P_k^{BBU} \quad (3)$$

For the radio component P_{radio} we assume a power consumption independent of the handled traffic according to the today's technology. Let us denote with P_{RBS} and P_{RRU} the power consumption of micro RBS and RRUs respectively. Thus we can simply write:

$$P_{radio} = P_{RBS} \cdot n_{RBS}^{AS} + P_{RRU} \cdot n_{RRU}^{AS} \quad (4)$$

wherein n_{RBS}^{AS} and n_{RRU}^{AS} are the parameters introduced in Section II and denoting the number of micro RBSs and RRUs handled by any AS respectively.

The second contribution P_k^{BBU} can be defined as the sum of a fixed contribution for the server rack (power supply, conditioned air, etc.) and a variable contribution related to the BBU instance processing. The fixed contribution is related to both the used number of servers and the fixed power consumption associated to each server (P_{server}), whereas the variable one is related to the number of BBU instances (equal to the number of needed CPRI flows) and the power consumption associated with one BBU instance (P_{ins}^{BBU}). In our analysis, we assume that the variable component of the power consumption is a linear function of the processing capacity. Hence, the power consumption P_k^{BBU} related to the baseband processing can be expressed as follows:

$$P_k^{BBU} = P_{server} \cdot \lceil \frac{nc_{AS,CPRI}^k}{K_{BBU}} \rceil + P_{ins}^{BBU} \cdot nc_{AS,CPRI}^k \quad (5)$$

wherein K_{BBU} is the maximum number of BBU instances supported in any server. Finally by inserting (4) and (5) in (3), (3) and (2) in (1), we can achieve the average total cost C_{tot}^{avg}.

You can notice how we need the knowledge of $nc_{AS,GE}^k$ and $nc_{AS,CPRI}^k$ for the evaluation of C_{tot}^{avg}. These parameters characterize the number of GEthernet and CPRI circuits needed between any AS and the CO and are determined according to a dimensioning procedure illustrated in the next Section IV.

IV. ANALYTICAL MODELS FOR RESOURCE DIMENSIONING

We introduce resource dimensioning models for the case in which the operation mode of the Xhaul architecture is the following:

- the installed micro RBSs are always turned on and provides a basic capacity for the covergae of the sub-area;
- the installed RRUs have their radio interface always turned on for technological reasons but they handle traffic and are in an active state only when are connected by

the network to a corresponding BBU instantiated; they provides additional capacity needed in the intervals in which the traffic increases; the RRUs are only used when the basic capacity provides by the micro RBSs is not sufficient to support the user traffic; for this reason BBU instances are only instanced for the corresponding RRUs used; a server consolidation/de-consolidation algorithm is applied in order to instantiate/remove BBU and to minimize, in each stationary interval, the number of switched on servers.

The introduced analytical models allow us to evaluate the number $nc^k_{AS,GE}$ and $nc^k_{AS,CPRI}$ of GEthernet and CPRI circuits respectively needed between any AS and the CO. The number $nc^k_{AS,GE}$ and $nc^k_{AS,CPRI}$ are important to make the network planning of the access network in each hour interval that gives informations for dimensioning the transport network. The evaluation of the number of needed circuits is based on the following traffic assumptions:

- the traffic is cycle-stationary with N stationary periods; for instance N equals 24 when the classical daily traffic variation has to be reproduced;
- the user peak traffic generated in the sub-areas, expressed in Gbps, are independent and identically distributed (i.i.d.) variables; therefore the user peak traffic generated in any sub-area in the k-th stationary interval is characterized by a variable A^k that according to [23] we assume log-normal distributed of parameters (μ^k, σ^k);

Next we evaluate the number $nc^k_{AS,GE}$ and $nc^k_{AS,CPRI}$ of GEthernet and CPRI circuits in Subsection IV-A and IV-B respectively.

A. EVALUATION OF THE NUMBER $nc^k_{AS,CPRI}$ OF CPRI CIRCUITS

The decrease in offered traffic and the application of the switching off technique of BBU instances leads to the need of carrying a number of CPRI flows lower the number of installed RRUs. To evaluate the values $nc^k_{AS,CPRI}$ $(k = 0, 1, ..., N-1)$, we start by the knowledge of the statistical on the number N^k_{AS} $(k = 0, 1, ..., N-1)$, denoting the sum of used RRUs in the region handled by the AS in the k-th interval. Next we show how it is possible to evaluate the probabilities $p_{N^k_{AS}}(j)$ $(j = 0, 1, ..., Tn_{RRU})$ of the random variable N^k_{AS}. Hence the dimensioning of the number $nc^k_{AS,CPRI}$ of CPRI circuits between the AS and and CO in the k-th interval is performed by guaranteeing high the probability of the event that a number of used RRUs is lower than or equal to $nc^k_{AS,CPRI}$. In other words we choose $nc^k_{AS,CPRI}$ as the α-th percentile of N^k_{AS} $(k = 0, 1, ..., N-1)$ that is the smallest value for which the following expression holds:

$$Pr(N^k_{AS} \leq nc^k_{AS,CPRI}) \geq 0.01 \cdot \alpha \quad (k = 0, 1, ..., N-1) \tag{7}$$

We can equivalently write (7) in terms of survivor function of N^k_{AS} as follows:

$$Pr(N^k_{AS} > nc^k_{AS,CPRI}) < 1-0.01 \cdot \alpha \quad (k=0, 1, \ldots, N-1) \tag{8}$$

For the evaluation of the probabilities $p_{N^k_{AS}}(j)$ of the random variable N^k_{AS}, if as reference we consider an Access Switch that handles the traffic of T sub-areas, and we denote with N^k_t the number of CPRI circuits needed for the sub-area SA_t $(t = 1, \ldots, T)$, we can write the following expression for N^k_{AS}:

$$N^k_{AS} = \sum_{t=1}^{T} N^k_t \quad (k = 0, 1, \ldots N-1) \tag{9}$$

The lack of traffic correlation assumed, leads to i.i.d random variables N^k_t $(t = 1, \ldots, T)$. Then we can write the following expression (10) for the probabilities N^k_t:

$$p_{N^k_{AS}}(j) = \otimes^T p_{N^k_{SA}}(j)\, j = 1, \ldots, Tn_{RRU} \;\; k = 0, 1, \ldots N-1 \tag{10}$$

wherein $p_{N^k_{SA}}(h)$ denotes the probabilities of N^k_t and the symbol $\otimes^T$ denotes the convolution operator applied T times.

For the evaluation of the probability $p_{N^k_{SA}}(h)$ $(h = 0, 1, \ldots, n_{RRU})$, that is the probability that h RRUs are used in the target sub-area, we remember our assumption of minimizing the number of CPRI circuits that leads to employing as much as possible the capacity of micro RBSs and only when this capacity is occupied, RRU capacity is used.

Next we consider three cases: i) $h = 0$; ii) $1 \leq h \leq n_{RRU} - 1$; iii) $h = n_{RRU}$.

In the case $h = 0$, we observe that N^k_{SA} is equal to 0 up to when the traffic A^k offered to the sub-area is smaller than or equal to $n_{RBS}\, C_{RBS}$ that is the total sum of the capacities of the n_{RBS} micro RBSs assigned to the target sub-area.

In the case $1 \leq h \leq n_{RRU} - 1$, we observe that N^k_{SA} is equal to h when the traffic A^k offered to the sub area is in the interval $[n_{RBS}C_{RBS} + (h-1)C_{RRU}, n_{RBS}\, C_{RBS} + h\, C_{RRU}]$.

In the case $h = n_{RRU}$, we observe that N^k_{SA} is equal to n_{RRU} when the offered traffic is higher than or equal to $n_{RBS}C_{RBS} + n_{RRU}C_{RRU}$.

According to the observations above, we obtain the expression reported at the top of pag. 5 for the probabilities $p_{N^k_{SA}}(h)$ $(h = 0, 1, \ldots, n_{RRU})$. Finally by inserting (6), as shown at the top of the next page, in (10), we can evaluate the probabilities $p_{N^k_{AS}}(j)$ $(j = 0, 1, \ldots, Tn_{RRU})$ of the random variable N^k_{AS}.

B. EVALUATION OF THE NUMBER $nc^k_{AS,GE}$ OF GEthernet CIRCUITS

To evaluate the values $nc^k_{AS,GE}$ $(k = 0, 1, \ldots, N-1)$, we start by the knowledge of the statistical on the number $N^k_{AS,E}$, denoting the number of GEthernet flows to be carried between the AS and and CO in the k-th interval. Next we show how it is possible to evaluate the probabilities $p_{N^k_{AS,E}}(j)$ $(j = 0, 1, \ldots, \lceil Tn_{RBS}C_{RBS} \rceil)$ of the random variable $N^k_{AS,E}$.

$$p_{N^k_{SA}}(h) = \begin{cases} \frac{1}{2}erfc(-\frac{\log_e(n_{RBS}C_{RBS}) - \mu^k}{\sigma^k\sqrt{2}}) & h=0 \\ \frac{1}{2}erfc(-\frac{\log_e(n_{RBS}C_{RBS}+hC_{RRU}) - \mu^k}{\sigma^k\sqrt{2}}) - \frac{1}{2}erfc(-\frac{\log_e(n_{RBS}C_{RBS}+(h-1)C_{RRU}) - \mu^k}{\sigma^k\sqrt{2}}) & h=1,\ldots,n_{RRU}-1 \\ 1-\frac{1}{2}erfc(-\frac{\log_e(n_{RBS}C_{RBS}+n_{RRU}C_{RRU}) - \mu^k}{\sigma^k\sqrt{2}}) & h=n_{RRU} \end{cases} \tag{6}$$

$$p_{N^k_{AS,E}}(j) = \begin{cases} \frac{1}{2}erfc(\frac{\mu^k_{AS}}{\sigma^k_{AS}\sqrt{2}}) & if\ j=1 \\ \frac{1}{2}erfc(-\frac{\log_e j - \mu^k_{AS}}{\sigma^k_{AS}\sqrt{2}}) - \frac{1}{2}erfc(-\frac{\log_e(j-1) - \mu^k_{AS}}{\sigma^k_{AS}\sqrt{2}}) & if\ 2 \le j \le \lceil Tn_{RBS}C_{RBS}\rceil - 1 \\ 1-\frac{1}{2}erfc(-\frac{\log_e(\lceil Tn_{RBS}C_{RBS}\rceil - 1) - \mu^k_{AS}}{\sigma^k_{AS}\sqrt{2}}) & if\ j = \lceil Tn_{RBS}C_{RBS}\rceil \end{cases} \tag{11}$$

As in the case of dimensioning of CPRI circuits, we choose $nc^k_{AS,GE}$ as the α-th of $N^k_{AS,E}$ $(k=0,1,\ldots,N-1)$ that is the smallest value for which the following expression holds:

$$Pr(N^k_{AS,E} > nc^k_{AS,GE}) < 1-0.01\cdot\alpha \quad (k=0,1,\ldots N-1) \tag{12}$$

For the evaluation of the probabilities $p_{N^k_{AS,E}}(j)$ of the random variable $N^k_{AS,E}$, if as reference we consider an Access Switch that handles the traffic of T sub-areas, $N^k_{AS,E}$ denotes the number of GEthernet flows that depends on the traffic generated by the micro RBSs located in the sub-areas. To evaluate the probabilities $p_{N^k_{AS,E}}(j)$ we need to knowledge the total traffic amount (Gbps) $A^k_{AS,E}$ expressed in Gbps and emitted by the micro RBSs handled by the AS. If we denote with $A^k_{SA_t}$ the traffic amount generated by the micro RBSs located in the sub area SA_t $(t = 1,\ldots,T)$, the following expression holds:

$$A^k_{AS,E} = \sum_{t=1}^{T} A^k_{SA_t} \quad (k=0,1,\ldots,N-1) \tag{13}$$

We have assumed the random variables $A^k_{SA_t}$ $(t = 1,\ldots,T)$ independent and identically distributed (i.i.d.) with log-normal distributions of parameters (μ^k, σ^k). In this case it has been proved that the probability density $p_{A^k_{AS,E}}(x)$ of $A^k_{AS,E}$ can be approximated as log-normal probability density of parameters $(\mu^k_{AS}, \sigma^k_{AS})$ given by the following expressions [28]:

$$\sigma^k_{AS} = \sqrt{\log_e(\frac{1}{T}(e^{(\sigma^k)^2}-1)+1)} \tag{14}$$

$$\mu^k_{AS} = \log_e(Te^{\mu^k}) + 0.5((\sigma^k)^2 - (\sigma^k_{AS})^2) \tag{15}$$

At this point we can evaluate the probabilities $p_{N^k_{AS,E}}(j)$ $(j = 1,\ldots,\lceil Tn_{RBS}C_{RBS}\rceil)$ from the probability densities $p_{A^k_{AS,E}}(x)$ of the random variable $A^k_{AS,E}$. We can follow the same approach applied in Section IV-A and obtain the expression (11) reported, as shown at the top of this page.

V. NUMERICAL RESULTS

The objective of our study is not only to evaluate the advantages in terms of CPRI flow bandwidth consumption saving that a reconfigurable optical network allows us to achieve when strategies for the BBU instance switching off are applied, but also to evaluate a trade-off between employment of RRUs and micro RBSs with regard to the energy and bandwidth consumption.

As depicted in Fig. 3, the reference scenario is an area of 1 km^2 handled by a central office that contains a certain number of BBU servers. We assume that the area is divided into squared sub-areas, where in each of them there is a building surrounded by streets and squares. Each sub-area is covered with a given number of RRUs and micro RBSs, that generate CPRI and GEthernet flows respectively.

This scenario assumption is suited to model a broadband access in dense urban areas [1]. In fact in our study, we consider a dense outdoor area (streets, square) and an indoor ultra-high broadband access area, related to a certain number of buildings positioned in that area. According to this model, 225 buildings are present in the reference area, each building having a floor surface of $1600m^2$. The indoor area is 360, 800 m^2, it means ≅ 36% of the reference area. The remaining 64% is assumed as outdoor area.

We assume that the traffic offered to each sub-area is cycle-stationary with $N = 24$ stationary intervals modeling the daily traffic trend. The peak traffic offered to any sub-area is distributed according to a log-normal distribution [23] of parameters (μ^k, σ^k) for the k-th stationary interval. The trend of the average peak traffic versus the daily hours is assumed to be equal to the one measured for the City of London [24]. The trend normalized to the average peak traffic during the Peak Hour Interval (PHI) is reported in Fig. 4. The average peak traffic during the PHI is chosen to be equal to 0.52 Gbps and 26.16 Gbps that are typical values expected in 4G and 5G traffic scenarios [1] for each sub-area respectively. Finally the parameters μ^k and σ^k of the log-normal distribution are chosen so as to guarantee for the distribution matching of

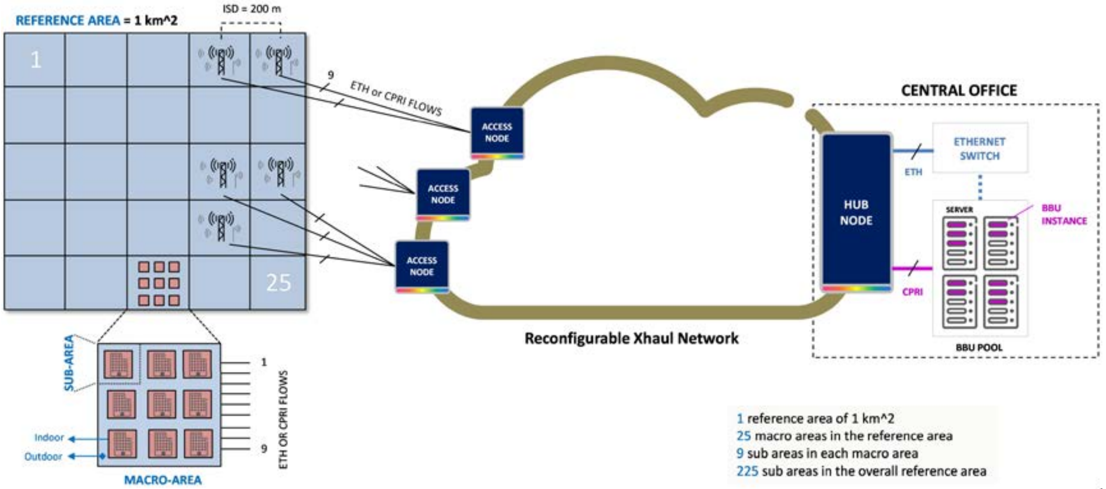

FIGURE 3. Reference scenario.

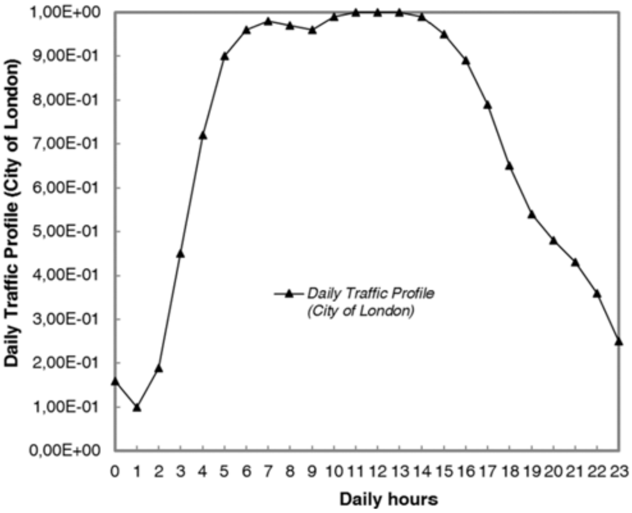

FIGURE 4. Daily traffic profile.

both the forecast average peak traffic and a typical standard deviation equal to 0.25 [23].

To support the user traffic, the number n_{RRU} and n_{RBS} of RRUs and micro RBSs installed in each sub-area are dimensioned according to the procedure illustrated in Appendix VI. We denote with γ the ratio of the number n_{RRU} of RRUs to the total number $n_{RRU} + n_{RBS}$ of radio stations, that is:

$$\gamma = \frac{n_{RRU}}{n_{RBS} + n_{RRU}} \tag{16}$$

Next we report some network resource dimensioning results in Section V-A while bandwidth/power trade-off solutions will be investigated in Section V-B.

A. NETWORK DIMENSIONING

Next we report some dimensioning results in the case of a AS handling the traffic of $T = 45$ sub-areas. Both 4G and 5G traffic scenario will be considered in order to show the very high differences between these two scenarios and the goodness of our approach in both of them.

In the 4G scenario case we assume an LTE bandwidth equal to 20 MHz and MIMO 2 × 2 is assigned to each station. RRUs are characterized by a capacity of $C_{RRU} = 150\ Mbps$. Each RRU generates one CPRI flow @2.5$Gbps$ [7]. Micro RBSs are also employed with capacity of $C_{RBS} = 150\ Mbps$. The ratio γ of the number of RRUs to the total number of radio stations is chosen equal to 0.7. If the dimensioning of RRUs and micro RBSs is performed so as to guarantee the $\alpha = 99.99$th percentile of the user peak traffic offered to the sub-area, we achieve the values n_{RRU} and n_{RBS} reported in the first column of Table 3.

TABLE 3. Dimensioning values n_{RRU} and n_{RBS} of installed RRUs and micro RBSs per sub area in 4G and 5G traffic scenarios.

	4G	5G
n_{RRU}	7	75
n_{RBS}	2	32

If RRU switching off strategies were not applied, it would be needed to guarantee a number of CPRI circuits equal to the number n_{AS}^{CPRI} of hardware elements generating CPRI traffic and tied to the AS. The values of n_{AS}^{CPRI} is equal to n_{RRU}^{AS} that is given by T times the value of n_{RRU}. In this case of 4G traffic scenario, we achieve a value of 351 for n_{AS}^{CPRI}.

Conversely a remarkable reduction in CPRI circuits is possible to achieve if switching off algorithms are adopted. Based on a traffic profile and an expected traffic demand, the switching off algorithm leads to do a network planning of the active elements in each hour interval in order to satisfy that expected traffic demand with a certain blocking probability.

We have evaluated the survivor function of the variable N_{AS}^{k} for each stationary interval and by applying the procedure

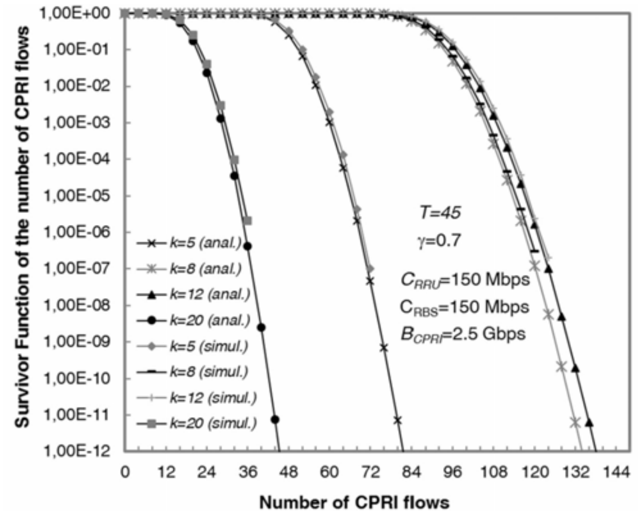

FIGURE 5. **Survivor function of the random variables N_{AS}^{k} for k equal to 5, 8, 12 and 20 in a 4G traffic scenario. Both analytical and simulation results are reported.**

mentioned in Subsection IV-A, the number of CPRI circuits to be supported between the Access Switch and the CO. The survivor functions of N_{AS}^{k} are diagrammed in Fig. 5 for the values of k equal to 5, 8, 12 and 20. In particular notice from Fig. 4 how $k = 12$ corresponds to the case of the PHI. We report both the analytical and simulation results.

First of all we can notice how the analytical results are in good agreement with the simulation ones. The analytical model has been also validated for other case studies not shown in this paper.

The application of the methodology illustrated in Subsection IV-A and applied with $\alpha = 1 - 10^{-7}$ leads to dimensioning values of the number $nc_{AS,CPRI}^{k}$ of CPRI flows @2.5 *Gbps* equal to 72, 121, 125 and 38 for k equal 5, 8, 12 20 respectively. All of the dimensioning values of $nc_{AS,CPRI}^{k}$ $(k = 0, 1, \ldots, N-1)$ are reported in Fig. 6. These values explain very well the advantages in the application of a switching off technique with respect to the case in which the dimensioning is performed on the number RRUs installed. For instance when $k = 12$, that is in the PHI, the percentage advantage in terms of CPRI circuits is in the order of 64%.

We also report the results for the dimensioning of the number $nc_{AS,GE}^{k}$ of GEthernet circuits in Figs 7. In this figure we show the number of GEthernet circuits needed between the AS and the CO in each daily time interval. We can see a remarkable reduction in number of GEthernet circuits in the daily intervals when the traffic is very low. For instance in the time interval $k = 2$ only 3 GEthernet circuits are needed instead of 14 if the dimensioning were dimensioned according to the capacity of micro RBSs installed.

Next we show some results for a 5G traffic scenario. In this case the traffic density is much higher. To handle this remarkable traffic amount, we have chosen of employing network elements able to provide larger capacity, thus an LTE bandwidth equal to 20 *MHz* and MIMO 8 × 8 are employed for each station, that leads to a capacity C_{RBS} and C_{RRU} equal to 600 *Mbps*. In this case, RRU generates one CPRI flow @10 *Gbps* [7]. The number n_{RRU} and n_{RBS} of RRUs and micro RBSs respectively needed per sub-area and dimensioned according to the procedure of Appendix VI are reported in the second column of Table 3. The dimensioning values $nc_{AS,CPRI}^{k}$ and $nc_{AS,GE}^{k}$ $(k = 0, 1, \ldots, N-1)$ are reported in Figs 8 and 9. Even in this case we can see how a much more severe dimensioning is needed. Though the switching off technique allows for a remarkable reduction in number of 10 *Gbps* CPRI circuits, we notice that the traffic amount required is very high and challenging solutions are required for the network design.

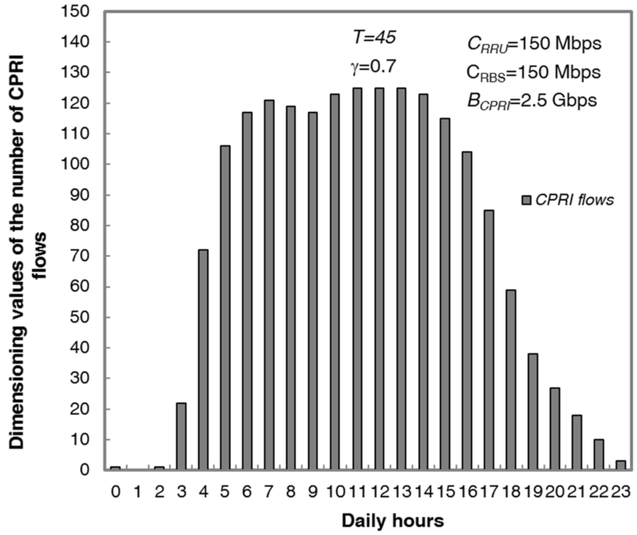

FIGURE 6. **Dimensioning values $nc_{AS,CPRI}^{k}$ as a function of the daily intervals in a 4G traffic scenario.**

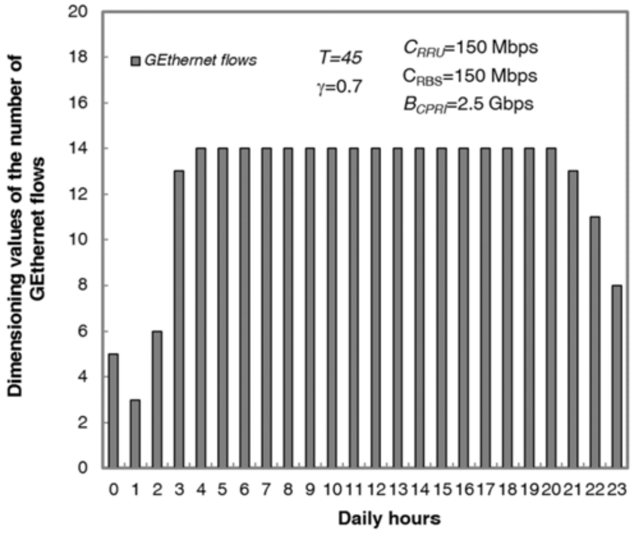

FIGURE 7. **Dimensioning values $nc_{AS,GE}^{k}$ as a function of the daily intervals in a 4G traffic scenario.**

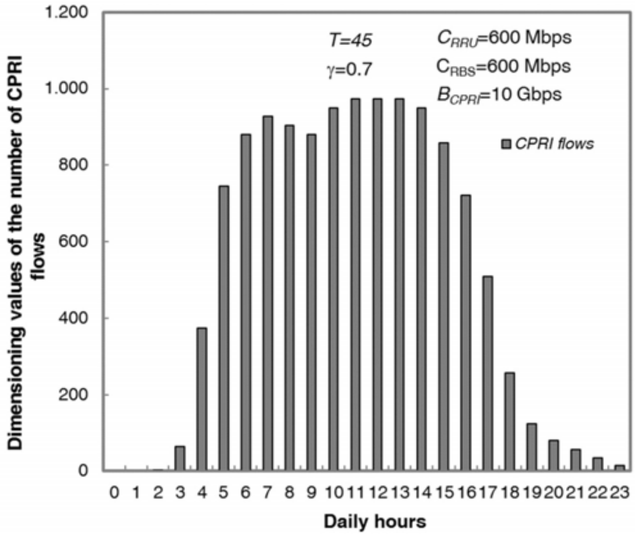

FIGURE 8. **Dimensioning values $nc^k_{AS,CPRI}$ as a function of the daily intervals in a 5G traffic scenario.**

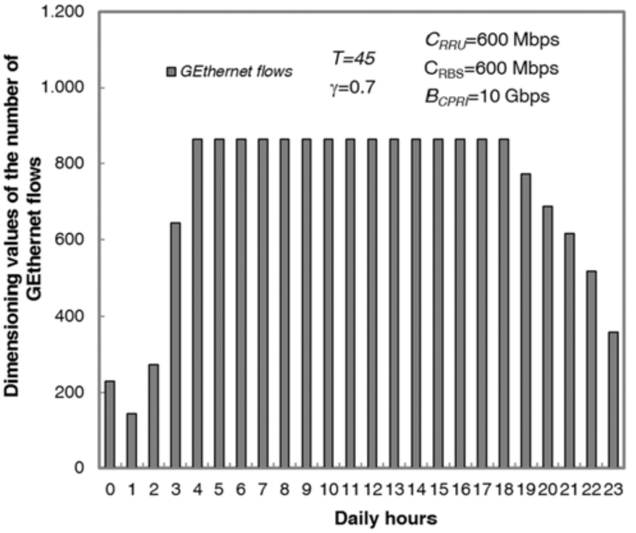

FIGURE 9. **Dimensioning values $nc^k_{AS,GE}$ as a function of the daily intervals in a 5G traffic scenario.**

B. OPTIMAL BANDWIDTH/POWER CONSUMPTION TRADE-OFF

We report some results evaluated by the model reported in Section III. In our study, we consider the RBS power consumption P_{RBS} equal to 300 Watt ([25], [26]). The same value for the total power consumption $P_{RRU,BBU}$ of a CPRI network element is assumed. $P_{RRU,BBU}$ is expressed by:

$$P_{RRU,BBU} = P_{RRU} + P_{server}/K_{BBU} + P^{BBU}_{ins} \tag{17}$$

The value of K_{BBU} is chosen equal to 4 while the constant server power P_{server} is fixed equal to 30% of the maximum server power. Furthermore we will denote with δ the ratio of the radio power consumption P_{RRU} to the total power consumption $P^{tot}_{RRU,BBU}$. It is important to note that the RRU is always on, thus only the baseband processing component gives a variable contribution to the total power consumption. Our objective is to evaluate the optimum value of γ allowing for a right trade-off between bandwidth and power consumption. Obviously the study depends on the values of the parameters μ_{BW} and μ_{PWR} introduced in Section III and characterizing the costs per bandwidth unit (1 Gbps) and per power unit (1 W) respectively. In particular we have noticed that when $\mu_{BW} = 1$, the region in which the trade-off exists is when μ_{PWR} ranges from 0.001 to 0.86. In fact when μ_{PWR} is smaller (larger) than 0.001 (0.86), the bandwidth cost (power cost) is dominant and we have the trivial solution $\gamma = 0$ ($\gamma = 1$), in which only micro RBSs (RRUs) are used.

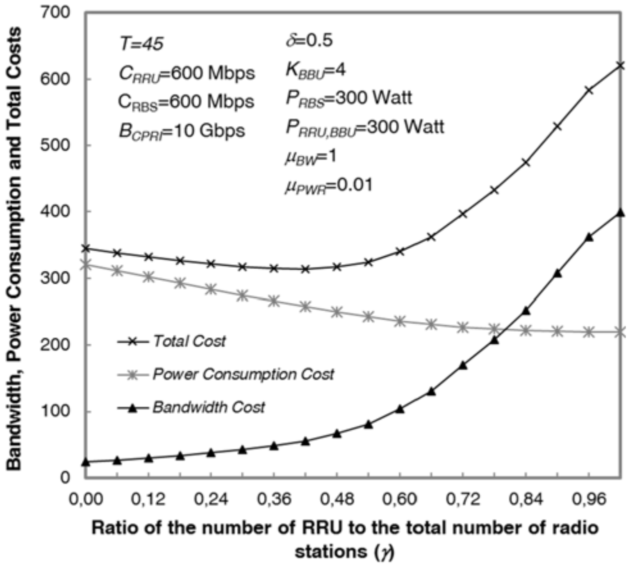

FIGURE 10. **Bandwidth, power consumption and total costs as a function of the ratio γ of the number of RRUs to the total number of radio stations. The AS handles $T = 45$ sub-areas and the ratio δ of the radio power consumption P_{RRU} to the total power consumption $P_{RRU,BBU}$ of an RRU is chosen equal to 0.5.**

We report in Fig. 10 the bandwidth and power consumption costs given by the two contributions of the second hand of expression (2) for $\mu_{BW} = 1$, $\mu_{PWR} = 0.01$, $\delta = 0.5$ and when $T = 45$ sub-areas are handled by an AS. We also report in Fig. 10 the total cost expressed by (2). As it is possible to note, the power consumption decreases when the γ ratio of the number n_{RRU} of RRUs to the total number of radio stations increases. In fact when this increase occurs a larger number of RRUs is used in place of RBSs and it is possible to save the energy consumption related to the deactivation of BBU instances that are not used when the traffic is low. At the same time we notice that the increase of γ leads to bandwidth cost increases very quickly due to the high bandwidth required by the CPRI flows. As reported in Fig. 10, the total cost initially decreases, then starts to grow. As a consequence, we can notice a minimum point that represents the trade-off between bandwidth and power cost. For the case study considered, the minimum point is achieved for a value of γ equal to 0.4.

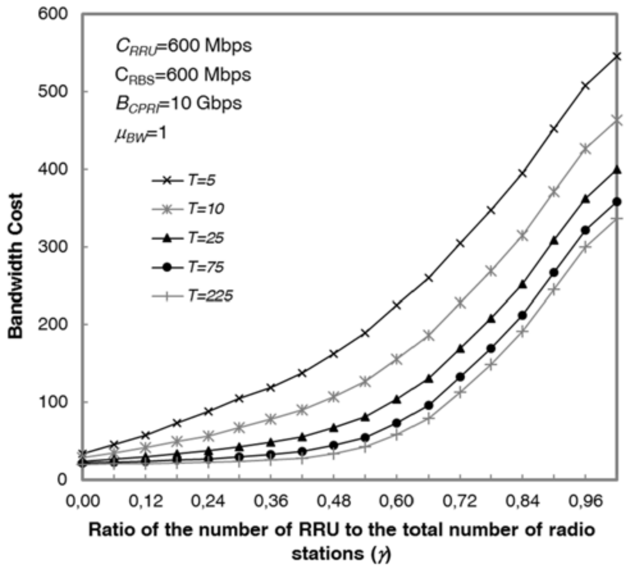

FIGURE 11. Bandwidth cost as a function of the ratio γ of the number of RRUs to the total number of radio stations. The ratio δ of the radio power consumption P_{RRU} to the total power consumption $P_{RRU,BBU}$ of an RRU is chosen equal to 0.5 and the AS handles a number T of sub-areas varying from 5 to 225.

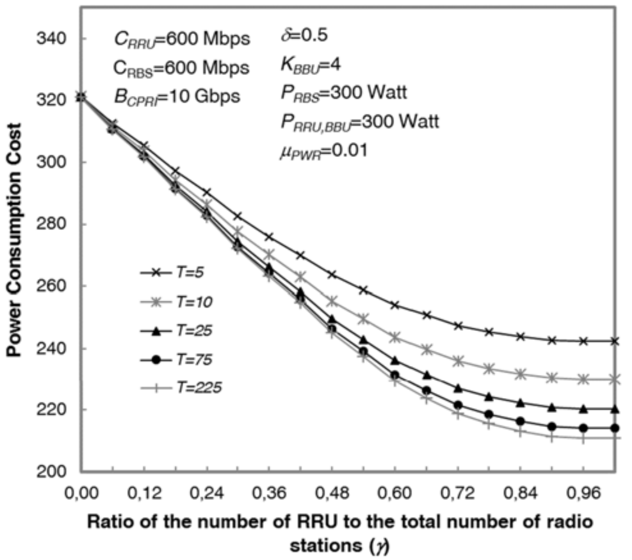

FIGURE 12. Power consumption cost as a function of the ratio γ of the number of RRUs to the total number of radio stations. The ratio δ of the radio power consumption P_{RRU} to the total power consumption $P_{RRU,BBU}$ of an RRU is chosen equal to 0.5 and the AS handles a number T of sub-areas varying from 5 to 225.

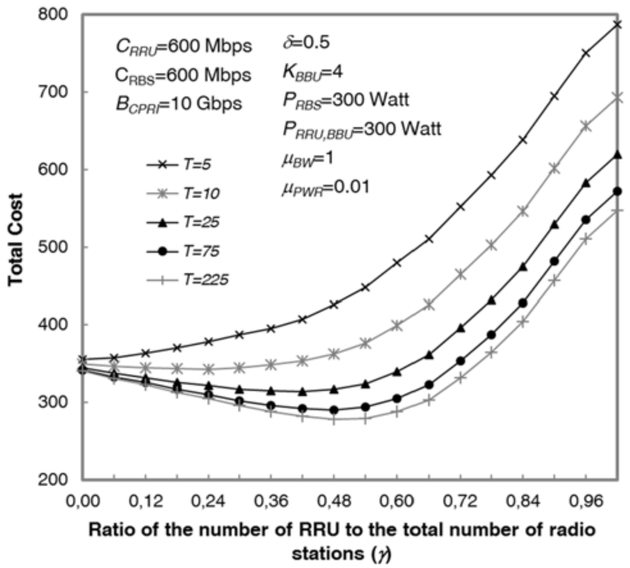

FIGURE 13. Total cost as a function of the ratio γ of the number of RRUs to the total number of radio stations. The ratio δ of the radio power consumption P_{RRU} to the total power consumption $P_{RRU,BBU}$ of an RRU is chosen equal to 0.5 and the AS handles a number T of sub-areas varying from 5 to 225.

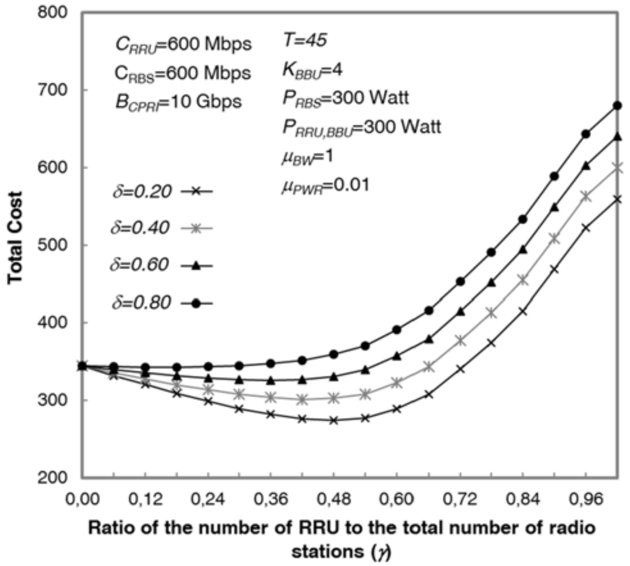

FIGURE 14. Total cost as a function of the ratio γ of the number of RRUs to the total number of radio stations. The AS handles a number T of sub-areas equal to 45 and the ratio δ of the radio power consumption P_{RRU} to the total power consumption $P_{RRU,BBU}$ of an RRU equals 0.20, 0.40, 0.60 and 0.80.

We report the bandwidth, power and total costs as a function of γ and for T varying from 5 to 225 in Figs 11, 12 and 13 respectively. The value of δ is chosen equal to 0.5. We can notice from Figs 11-13 how the bandwidth, the power consumption and total costs decrease how the number T of sub-areas handled by any AS is increased. This is due to the high statistical multiplexing gain especially for the bandwidth used. Owing to the central limit theorem, the bandwidth and the power consumption tend to deterministic values for T tending to infinity and for this reason the decrease of the bandwidth, power consumption and the total costs reduces for values of T greater than 75 and tend to an asymptotic value. We also notice from Figs 11-13 that the minimal point tends to move towards higher values of γ for T increasing. For instance the optimal values of γ are 0.26 and 0.48 for T equal to 10 and 75 respectively. This shifting is due to the higher decrease in bandwidth with respect to power consumption when the number T of sub-areas handled by an AS is increased.

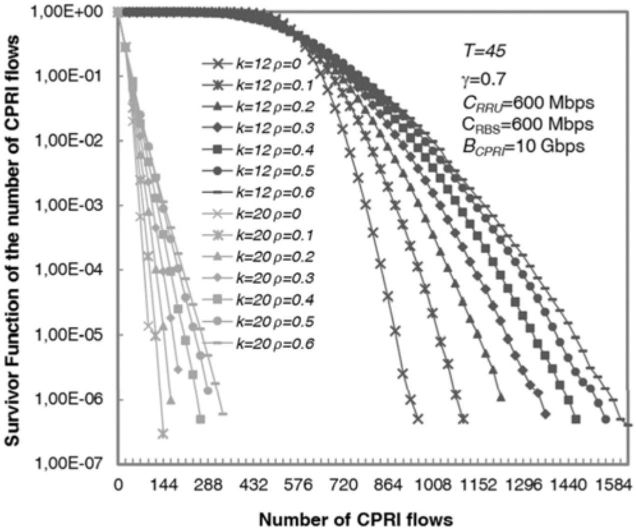

FIGURE 15. **Survivor Function of the random variables N_{AS}^k for k equal to 12 and 20 in a 5G traffic scenario where the spatial correlation parameter ρ varies from 0 to 0.6.**

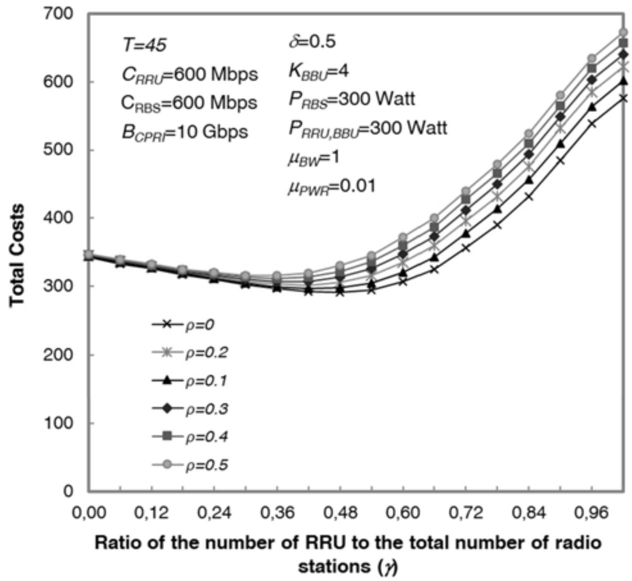

FIGURE 16. **Total cost as a function of the ratio γ of the number of RRUs to the total number of radio stations. The AS handles a number T of sub-areas equal to 45, the ratio δ of the radio power consumption P_{RRU} to the total power consumption $P_{RRU,BBU}$ of an RRU equals to 0.50 and the spatial correlation parameter ρ varies from 0 to 0.5.**

As further contribution to the investigation done in this work, we report in Fig. 14 the total cost as a function of γ when $T = 45$ and for values of δ equal to 0.20, 0.40, 0.60 and 0.80. We can notice from Fig. 14 how the minimal points moves towards lower values of γ for δ increasing. As a matter of example, the minimum values of γ equal 0.55 and 0.42 for T equal to 0.20 and 0.80 respectively. The reason is due to higher radio power consumption P_{RRU} of an RRU that makes less power efficient the use of RRUs.

Finally, in our analysis we also consider the impact on the cost of a spatial correlation of the traffic distribution. In particular, we consider the case in which the spatial correlation coefficient has a negative exponential trend [27] as a function of the distance between sub-areas. Next we denote with ρ the correlation coefficient of the traffic of two adjacent sub-areas. We report in Fig. 15 the survivor function of the number of needed CPRI flows when an AS handles $T = 45$ sub-areas and for values of ρ varying from 0 to 0.6. The 5G traffic scenario is considered and the values of k equal to 12 and 20 are considered. We can notice that higher dimensioning values of the number of CPRI circuits are needed for ρ increasing. As a matter of example if we fix $\alpha = 1-10^{-6}$, the number of needed CPRI circuits is equal to 936, 1224, 1440 and 1584 for ρ equal 0, 0.2, 0.4 and 0.6 respectively.

We report in Fig. 16 the total cost as a function of γ for the same values of Fig. 14 and when δ is chosen equal to 0.5. The values of ρ from 0 to 0.5 are considered. In the case of higher traffic correlation, we can notice that the value of γ in which the cost is minimum tends to move towards lower values. For instance, the minimum values of γ equal 0.48 and 0.30 for ρ equal to 0 (no correlation) and 0.5 (maximum correlation) respectively. This is due to the increase in requested bandwidth that leads to the use of RRUs less convenient with respect to the one of RBSs.

VI. CONCLUSIONS

A dimensioning procedure has been proposed to evaluate the number of CPRI and GEthernet circuits that a network has to guarantee between an Access Switch and the CO. The AS handles the traffic generated by a set of sub-areas. The user traffic is managed by both micro RBSs and RRUs that generate GEthernet and CPRI flows respectively. The dimensioning procedure allows for a saving of needed CPRI circuits with respect to the case in which the number of CPRI circuits is statically fixed to the number of RRUs installed in all of the sub-areas handled by the AS and dimensioned in each area according to the traffic amount during the Peak Hour Interval. This CPRI circuits saving is due to two reasons: i) the application of an algorithm of BBU instance deactivation applied when the offered traffic decreases; ii) the statistical multiplexing advantages that leads to a less severe dimensioning, even during the Peak Hour Interval, due to the fact that the AS has to provide CPRI circuits for an aggregate of sub-areas while the number of RRUs installed is dimensioned according to the traffic amount offered to every single sub area. The obtained results show how the introduced dimensioning procedure allows, even during the Peak Hour Interval, for remarkable gains that can reach about 60% and 70% in 4G and 5G traffic scenarios respectively.

By means of an analytical model we have also been able to evaluate a bandwidth/power trade-off solution of the proposed architecture. We have shown how the choice of the right mix of RRU/RBS in a sub-area allows for the minimization of the total cost expressed in terms of bandwidth and power consumption costs. Furthermore we have shown how the optimal mix depends on some parameters as the number of sub-areas handled by any AS, the radio power consumption of an RRU,..... For instance we have achieved that the optimal mix is composed by the 35% of RRUs in the case in which the AS handles 45 sub-areas and the radio power consumption of an RRU is the 20% of the total power consumption of a CPRI network element.

We have also evaluated the impact on the cost in the case of traffic correlation. We have observed how a higher correlation leads to more severe bandwidth dimensioning with the consequence of making less convenient the use of RRUs.

APPENDIX

NETWORK RESOURCE DIMENSIONING PROCEDURE OF THE NUMBER OF MICRO RBSs AND RRUs USED

The procedure consists in dimensioning the number of network elements (micro RBSs and RRUs) so as to guarantee that the provided capacity satisfies the α-th of the peak traffic generated in the Peak Hour Interval (PHI). Next we define:

- k_p: index of the Peak Hour Interval for the sub area traffic profile;
- A_{k_p}: random variable characterizing the peak traffic generated during the PHI in a sub-area; its distribution is log-normal with parameters μ^{k_p} and σ^{k_p};

Having fixed the ratio γ of the number n_{RRU} of RRU to the total number $n_{RBS} + n_{RRU}$ of radio stations installed, for the dimensioning of the number n_{RRU}, n_{RBS} of RRUs and micro RBSs respectively we observe that the entire capacity of a sub-area is given by the following expression:

$$C = n_{RRU}(\frac{(1-\gamma)}{\gamma}C_{RBS} + C_{RRU}) \tag{18}$$

In order to guarantee the α-th percentile of the peak traffic in a sub-area during the PHI, we have to choose the smallest n_{RRU} such that the following expression holds:

$$\begin{aligned} &Pr(A_{k_p} \leq n_{RRU}(\frac{(1-\gamma)}{\gamma}C_{RBS} + C_{RRU}))\\ &= \frac{1}{2}erfc(-\frac{\log_e n_{RRU}(\frac{(1-\gamma)}{\gamma}C_{RBS} + C_{RRU}) - \mu^{k_p}}{\sigma^{k_p}\sqrt{2}})\\ &\geq 0.01 \cdot \alpha \end{aligned} \tag{19}$$

The number n_{RBS} of micro RBSs is given by:

$$n_{RBS} = \lceil \frac{(1-\gamma)}{\gamma} n_{RRU} \rceil \tag{20}$$

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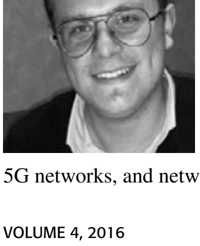

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