Radio resource allocation in low- to medium-load regimes for energy minimization with C-RAN

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***Abstract*—Radio resource allocation is critical in order to manage available bandwidth and optimize network behavior. In Centralized-Radio Access Networks (C-RAN), simple Radio Units (RUs) are deployed and can be controlled remotely to allow cooperation. In this paper, we consider micro-cell systems with low-to-medium load regimes. We study the resource allocation problem with minimization of the energy consumption due to radio transmission and signal processing. We propose to mix two transmission modes over a reference period allowing resource reuse: one with all RUs transmitting the same signal, the other with each RU transmitting a specific signal. We impose the same target rate for each user equipment (UE), the same transmit power for the RUs, and a maximum resource block (RB) number, which defines the constraints. The resulting optimization problem is formulated so as to be mixed integer linear programming (MILP). Simulations are run using CPLEX Python API and show the efficiency of the proposed scheme to increase the capacity while consuming the least energy. We also observe that the mode with all RUs simultaneously serving the same UE is more efficient (fewer RB and lower consumed energy) than the mode with a single RU activated at a time.**

***Index Terms*—C-RAN, radio resource allocation, 5G, energy consumption**

I. Introduction

Fifth Generation (5G) wireless networks are intended to deliver high data rates, serve large numbers of users, and achieve high reliability and low latency. Energy consumption is increasing due to this evolution in demands, indirectly increasing carbon footprints. Due to environmental concerns, improving the energy efficiency of systems has recently become a major issue [1]. Some use cases have strong variations of the load (e.g., air terminal), and the network is often built to address the high regime (to simultaneously serve a high number of active users). However, periodically (e.g., at night or on weekends in business centers), only a few devices are active. One way to improve the energy efficiency of wireless systems is to make the network reactive to load variations.

Centralized-RAN (C-RAN) is an evolution of the traditional Radio Access Network (RAN) supported by 5G networks. In this centralized architecture, Base Station (BS) functions are split between two units: Radio Units (RUs) located at tower sites to achieve the desired coverage, and Centralized Units (CUs) where all processing functions can be centralized [2].

The reduction in power consumption with C-RAN has attracted the interest of researchers. The authors of [3] have proposed the scheduling and coordination of beamforming in C-RAN. Depending on their position, the User Equipments (UEs) are merged into groups, and each group is served by a set of RUs. Radio resources can be reused by RUs from the same or different groups. Cooperative beamforming between RUs of the same group is envisaged to combat interference. Their proposal proved to be highly energy-efficient. Nevertheless, in their study, they consider that the number of RUs in a cluster must be at least equal to the number of UEs. Needing as many RUs as UEs can increase the cost of deployment.

The optimization of the UE-RU association is another way to manage the interference produced in a multi-cell scenario. In [4], the energy consumption on the DownLink (DL) and UpLink (UL) in a C-RAN is minimized, and joint UE-RU association and beamforming solution are used to manage interference. In this study, one UE can be connected to one RU in each direction and can be served through beamforming. More recently, a distributed UE-RU association and an RU clustering in C-RAN was proposed in [5]. They divide their problem into two subproblems: UE association and RU clustering. Each UE can only be connected to one RU. The RUs connected to the same CU share the radio resources available on this CU without interference. RUs connected to different CUs interfere if they use the same resources. They showed lower energy use, increased throughput, and quick adaptation to traffic variations. Energy minimization through bandwidth allocation and UE-RU association have been considered separately. However, it is essential to treat these tasks together, as the association problem has a direct impact on resource allocation and both have an impact on energy consumption.

All mentioned studies have focused on fully loaded systems to optimize resource allocation. Few studies have proposed allocation solutions in low-load systems where some network resources are available and can be exploited to improve network performance, for example by reducing energy consumption. The trade-off of bandwidth during a low-load regime with the traditional BSs system has been proposed in [6]. The method involves allocating more bandwidth to UEs since some bandwidth is unused and therefore available. The allocation of a higher number of resources enables the use of lower-order modulation and thus decreases the total energy consumption while maintaining the UE throughput request.

The BSs consume a significant part of the total energy. The predominant source of consumption depends on the cell size. Radio power generation is critical in macro-cells, unlike in micro-cells where distances and ranges are shorter [7]. Energy consumed by processing units and electronic components can therefore be predominant. So, in small-cell scenarios, C-RAN deployment can be advantageous as it centralizes the power-consuming processing part while distributing the low-energy radio part to achieve the desired coverage.

This paper considers the reduction of energy use through optimized radio resource allocation for the DL of a micro-cell C-RAN system. We define a set of network configurations designed for the low-to-medium load regime. Given a fixed RU transmit power, a maximum Resource Block (RB) number, a target user rate, and an active users number, we search for the best UE-RU association and radio resource allocation that minimize energy consumption.

This paper is structured as follows. The system model is provided in Section II. Then, in Section III we detail the energy consumption model that we use. The considered resource allocation and the energy consumption computation are given in Sections IV and V, respectively. The optimization problem is formulated and explained in Section VI. In Section VII, we discuss the results before concluding in Section VIII.

II. System model

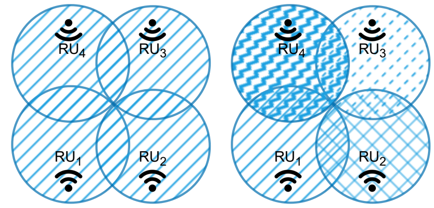
A. Network deployment

We consider an indoor service area where micro-cells are deployed with C-RAN. Multiple RUs are implemented to achieve indoor coverage and are connected to a CU hosted in a central site. The number of deployed RUs is given by I. Each RU_i position is fixed and located by its coordinates (x_i, y_i). To keep simple mathematical expressions, we consider as our reference system a service zone that is a rectangular area of dimensions $A{\times}B$ m^2. The position of UE_j, given by (x_j, y_j), is assumed to be uniformly distributed in the service area such that $0 \leq x_j \leq A$ and $0 \leq y_j \leq B$. Note that any kind of deployment could be considered with the same model.

B. Modes of operation

In 5G New Radio (NR), Synchronization Signal Blocks (SSBs) are periodically transmitted by the BS to achieve coverage, allowing the UE to know the identity of the available cell, to synchronize, and to connect to it [8].

In our work, we consider three operating modes. In low-load systems, serving one UE at a time is sufficient. Thus, in mode 1, all RUs serve simultaneously one UE at a time. In this mode, the system is one big cell and the UE is unaware of the presence of multiple RUs (see Fig. 1a). A virtual RU, denoted by RU_{I+1}, operates in this mode as if all RUs were active to serve one UE simultaneously. In mode 2, one RU can be active at a time and can serve one UE on specific RBs. Each RU is in an independent cell (see Fig. 1b). In mode 2, the UE is assigned to the best-serving RU, i.e., the one that provides



(a) Mode 1 (b) Mode 2

Fig. 1: Modes of operation (patterns illustrate cells' identities).

the highest Signal to Interference and Noise Ratio (SINR). In modes 1 and 2 there is no resource reuse. In a medium-load system, serving multiple UEs in parallel is important to flow the needed load (up to the number of RUs users served on the same RBs) but there are no specific techniques needed like beamforming (up to the number of beams users served on the same RBs). If needed, multiple RUs can transmit on the same RB in the absence of interference constraints. To this end, mode 3 is a mixture of modes 1 and 2 with possible resource reuse. Mode 3 has different possible configurations and is detailed later in Section IV.

C. Traffic model

Many previous studies have considered a full-buffer traffic model. This model considers that there is an infinite amount of data to transmit. All users are active at all times. In our study, we consider a user-requested service that needs a certain target DL data rate R_T to be guaranteed [9].

D. Propagation model

We consider an Indoor Factory where the heights of the receiving and transmitting antennas are lower than the average clutter height. The clutter density is less than 40% [10]. We take the path-loss model given in Table 7.4.1-1 of [11] defined by the 3rd Generation Partnership Project (3GPP) in dB for an Indoor Factory Sparse clutter, Low BS height (InF-SL) with:

$$\text{PL}_{\text{InF-SL,dB}} = 25.5\log(d_{i,j}) + 33 + 20\log(f_\text{c}), \tag{1}$$

where $\log(u)$ is the logarithm with base 10 of u, f_c the central frequency in GHz, $d_{i,j}$ the 2D distance between $\text{RU}_i(x_i, y_i)$ and $\text{UE}_j(x_j, y_j)$ having the same height, measured in m: $d_{i,j} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}$. The path-loss parameters α and r_0 can be derived from $\text{PL}_\text{dB} = 10\alpha\log(d_{i,j}) - 10 \times \alpha\log(r_0)$ being defined by (1) for a given value of f_c.

A log-normal shadowing is considered by 3GPP. It is modeled by $e^{\sigma\xi}$ with ξ being a normal random variable (r.v.): $\xi{\sim}N(0,1), \sigma{=}\frac{\ln(10)}{10}\sigma_\text{dB}$, and $\ln(u)$ the natural logarithm of u.

We also assume the RUs to be equipped with directive antennas with the following gain in dB [12]:

$$G_\text{dB}(\theta_{i,j}) = G_\text{A} - \min\left[12\left(\frac{\theta_{i,j}}{\theta_\text{3dB}}\right)^2, A_\text{m}\right], \tag{2}$$

where G_A is the antenna gain in the boresight direction, θ_3dB the 3 dB-beamwidth, A_m the maximum attenuation, and $\theta_{i,j}$

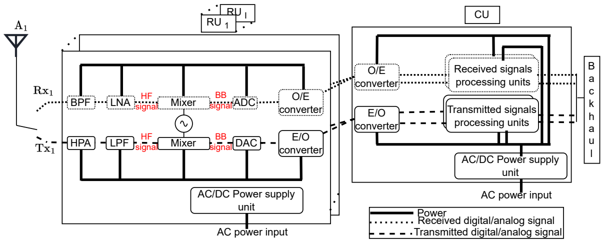


Fig. 2: Power-consuming units in a C-RAN architecture (DL).

the angle between RU_i and UE_j, measured from the antenna boresight: $\theta_{i,j} = \arctan\left(\frac{x_j - x_i}{y_j - y_i}\right)$. The UE is considered equipped with an omnidirectional antenna.

Thus, the power received by UE_j (function of (x_j, y_j)) from RU_i with transmission power P_t per RB is:

$$P_{\text{r},i,j} = P_\text{t}\left(\frac{r_0}{d_{i,j}}\right)^\alpha G(\theta_{i,j}) e^{\sigma \xi_{i,j}}. \quad (3)$$

The power received by RU_{I+1} is: $P_{\text{r},I+1,j} = \sum_{i=1}^{I} P_{\text{r},i,j}$.

III. Energy consumption model

Reference [13] gives a detailed power consumption model for C-RAN with a correlation between BS component consumption and consideration of load variations. Fig. 2 shows the BS diagram with C-RAN in the DL.

- The RU consumes energy through the radio power generation (high power amplifier consumption model taken from [14] with η_PA as Power Amplifier (PA) gain) and fixed power consumption ($P_\text{RU,f}$) of electronic components such as the low-pass filter, mixer, digital-to-analog converter, and optical-to-electrical (O/E) converter.
- In the CU, the main consumption is due to the energy consumption of Signal Processing (SP) E_SP (detailed in Section III-B). A fixed power $P_\text{CU,f}$ is consumed by the E/O converter, and the SP fixed power is denoted by $P_\text{SP,f}$.
- In the RU and CU, the AC/DC power supply is characterized by its efficiency $\eta_\text{AC/DC}$ that describes how much actual power is delivered relative to the input power [15].

We consider instantaneous RU and CU switch-on and switch-off without any energy cost.

A. Reference period of study

We evaluate the energy consumption of the BS including the consumption of SP, electronic components, and radio power generation. The SP consumes energy, whose amount depends on the number of allocated RBs to serve the UE. The fixed power consumed by electronic components and the power consumed for radio power generation are evaluated over the transmission duration to compute their energy consumption. Thus, we choose a reference period T equal to the SSB transmission period, i.e., there is one SSB transmission in T. We determine the transmission duration by the number of RBs needed to guarantee the target throughput R_T, divided by M_RB the number of available RBs per slot, and multiplied by T.

B. Packet processing energy consumption

The energy consumption model of the SP unit is taken from [13] and consists of two main parts. A fixed amount of this energy consumption comes from the SP unit components, mainly from the motherboard, peripherals, and fans. The resulting fixed power is denoted by $P_\text{SP,f}$ and evaluated over the activity period. The second contribution to the SP energy consumption is variable and used to encode packets. This energy is divided into two terms. The first one in Joules per bit, denoted by $E_\text{SP,v}$, accounts for layer 1 functions (coding, modulation...). The second one in Joules per packet, denoted by $E_\text{SP,f}$, corresponds to signal processing run in upper layers. The SP energy consumed for J UEs on the DL is:

$$E_\text{SP} = \underbrace{T_\text{DL} \underbrace{P_\text{SP,f}}_{\text{Power}}}_{\text{Energy proportional to } T_\text{DL}} + \underbrace{E_\text{SP,v} L_\text{P,T} + E_\text{SP,f} N_\text{Pkt}}_{\substack{\text{Processing energy} \\ \text{proportional to } L_\text{P,T} \text{ and } N_\text{Pkt}}}, \quad (4)$$

where $L_\text{P,T} = J R_\text{T} T$ is the length of transmitted packets (N_Pkt packets), and T_DL the RU/CU DL activity period during T.

IV. Downlink resource allocation

The I RUs are independent and share the same resources available in the system. Thus, resource reuse is possible. It consists in allocating the same resources to two different users, each served by an RU if the interference conditions allow it.

Let us refer to the jth UE by UE_j where $1 \le j \le J$ and to the ith RU by RU_i where $1 \le i \le I+1$. We introduce an activity state for each RU denoted by s_i for RU_i:

$$s_i = \begin{cases} 1 & \text{if } \text{RU}_i \text{ is active} \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

The activation configuration ν determines which RUs are idle and which are active. An active RU can serve a maximum of one UE per RB. Each ν is determined by $I+1$ (I real and one virtual RU) states s_i: $\nu = (s_1, s_2, ..., s_{I+1})$. For I real RUs we have 2^I configurations that include the configurations where one or more RUs are active and exclude the configuration where all the RUs are idle. The configurations are numbered from 1 to 2^I. The first I configurations are those that have only one RU in use. Then we have the configurations where more than one RU are active and each serves one dedicated UE on the same RB. Configuration $\nu = 2^I - 1$ is the configuration where all RUs are active and each one is serving different UEs on the same RBs. Then, we have the configuration $\nu = 2^I$ where RU_{I+1} is active and the I real RUs are idle. Indicator $d(\nu, i)$ determines if RU_i is active in configuration ν or not:

$$d(\nu, i) = \begin{cases} 1 & \text{if } \text{RU}_i \text{ is active in configuration } \nu \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

A. RU-UE-configuration assignment

The objective is to minimize the energy consumption while serving UEs on the available RBs. The optimization problem determines the UE's serving RU and the number of needed

RBs for this service (depending on the chosen configuration by the optimization problem). To allocate the RBs, we need to determine which RU serves the UE and in which configuration. This is determined by $\boldsymbol{x} = (x_{i,j,\nu})$, where:

$$x_{i,j,\nu} = \begin{cases} 1 & \text{if RU}_i \text{ is serving UE}_j \text{ with configuration } \nu \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

This decision variable is the output of the optimization problem that schedules the service of UEs. The constraint on this variable ensures that each UE is served and only served once:

$$\sum_{i,\nu} x_{i,j,\nu} d(\nu, i) = 1 \;\forall\, j. \tag{8}$$

B. DL transmission model

1) SINR computation: On the DL, if multiple RUs transmit on the same RBs, they interfere with each other. Thus, the perceived SINR by the UE depends on the powers of the signal of interest, the interfering signal, and the receiver's noise:

$$\gamma_{i,j,\nu} = \begin{cases} \frac{P_{\mathrm{r},i,j}}{\sum_{i' \neq i} P_{\mathrm{r},i',j} d(\nu,i') + N_\mathrm{p}} & \text{if } \nu \neq 2^I, d(\nu,i) = 1\; \forall i \neq I+1 \\ \frac{\sum_{i=1}^{I} P_{\mathrm{r},i,j}}{N_\mathrm{p}} & \text{if } \nu = 2^I,\, d(\nu, I+1) = 1 \\ \text{n.a.} & \text{otherwise} \end{cases} \tag{9}$$

where $N_\mathrm{p} = 10^{\frac{N_\mathrm{NF}}{10}} K_b T_\mathrm{K} w_\mathrm{RB}$ is the UE's noise power, with N_NF being the noise figure, K_b the Boltzmann constant, T_K the UE's temperature, and w_RB the elementary RB bandwidth.

2) Computation of the number of needed RBs: We aim to provide each UE with the target data rate R_T. The perceived data rate per RB with configuration ν and a UE-RU pair (j, i), is computed using the modified Shannon formula [16]:

$$R_{(i,j,\nu)} = w_\mathrm{RB} \delta_\mathrm{BW} \log_2 \left(1 + \frac{\gamma_{i,j,\nu}}{\delta_\mathrm{SINR}}\right), \tag{10}$$

where δ_BW and δ_SINR are correction factors of the bandwidth and the SINR, respectively. The number of RBs per slot to serve UE$_j$ by RU$_i$ in configuration ν with R_T is:

$$m(i, j, \nu) = \frac{R_\mathrm{T}}{R_{(i,j,\nu)}}. \tag{11}$$

Each UE requests the same service with R_T, but the number of needed RBs varies for each UE. This number relies on the perceived rate (see (11)) determined by the SINR $\gamma_{i,j,\nu}$ in (10).

C. Occupied resources on the system level

Each UE$_j$ is served by an RU$_i$ in a configuration ν using $m(i, j, \nu)$ RBs. Each active RU in a configuration occupies a number of RBs. The number of occupied RBs at the system level y_ν during configuration ν is determined by the maximum number of RBs occupied by all active RU in that configuration:

$$y_\nu = \max_i \left(\sum_j m(i, j, \nu) x_{i,j,\nu} \right). \tag{12}$$

V. DL data transmission energy consumption

The optimization problem objective is to minimize the CU and RUs energy consumption. The CU's energy consumption has three parts. The first part is the fixed power $P_\mathrm{CU,f}$ consumed by electronic components during the CU's activity period as soon as the system is active. It is independent of the number of active RUs or served UEs. The second part is the fixed SP energy $E_\mathrm{SP,f}$ consumed per processed packet per UE. We consider one packet per slot. Thus, to evaluate the energy consumption, we count the number of occupied slots to serve all UEs. Here, each RB is counted as many times as used to serve different UEs, i.e. an RB used to serve two UEs by two RUs is counted twice. The third part is the energy consumption that depends on the packet length $E_\mathrm{SP,v}$. It is multiplied by the number of served UEs. Constants $P_\mathrm{CU,f}$, $E_\mathrm{SP,f}$, and $E_\mathrm{SP,v}$ include $\eta_\mathrm{AC/DC}$. We refer the reader to Section III-B for their definition. The CU's energy consumption is thus:

$$E^\mathrm{DL}_\mathrm{CU}(\boldsymbol{x}) = \frac{\sum_\nu y_\nu}{M_\mathrm{RB}} P^\mathrm{DL}_\mathrm{CU,f} T + \frac{M_\mathrm{r} + M_\mathrm{v}}{M_\mathrm{RB}} E_\mathrm{SP,f} \frac{T}{T_\mathrm{s}} + J E_\mathrm{SP,v} L_\mathrm{P,T} \tag{13}$$

where $\sum_\nu y_\nu$ is the total number of RBs occupied by the selected configurations on the system level, T_s the slot duration, $M_\mathrm{r} = \sum_{i=1}^{I} \sum_j \sum_\nu m(i, j, \nu) x_{i,j,\nu}$, and $M_\mathrm{v} = \sum_j m(I{+}1, j, 2^I) x_{I+1,j,2^I}$ the number of RBs occupied by the I real RUs and RU$_{I+1}$, respectively.

RUs consume energy through electronic components and radio power generation. Each RU is active for the duration of the required RBs to meet the UE's target data rate. The energy consumed by the I RUs counts the transmission and fixed power consumption during all the RBs needed to serve the J UEs. The virtual RU assumes simultaneous activation of the I real RUs to serve a UE. The energy consumed by I real RUs and a virtual RU to serve J UEs is:

$$E^\mathrm{DL}_\mathrm{RU}(\boldsymbol{x}) = \frac{M_\mathrm{r} + I M_\mathrm{v}}{M_\mathrm{RB}} \left(P_\mathrm{RU,f} + \frac{M_\mathrm{RB} P_\mathrm{t}}{\eta_\mathrm{T}} \right) T, \tag{14}$$

where $P_\mathrm{RU,f}$ includes $\eta_\mathrm{AC/DC}$, and $\eta_\mathrm{T} = \eta_\mathrm{PA} \eta_\mathrm{AC/DC}$.

VI. Optimization problem formulation

This Section is dedicated to the formulation of the optimization problem. The cost function is the BS energy consumption involved to transmit data on the DL. The first decision variable $\boldsymbol{x} = (x_{i,j,\nu})$ is given in Section IV-A. It determines the serving RU and configuration for each UE. We rewrite (12) as $y_\nu \geq \sum_j m(i, j, \nu) x_{i,j,\nu}$. The second decision variable is y_ν of length 2^I. It represents the system-level number of RBs. The problem is formulated with constraints on these variables:

$$\underset{\boldsymbol{x}, y_\nu}{\text{minimize}} \; E^\mathrm{DL}_\mathrm{CU}(\boldsymbol{x}, y_\nu) + E^\mathrm{DL}_\mathrm{RU}(\boldsymbol{x}, y_\nu) \tag{15a}$$

$$\text{s.t. } \textbf{C1: } \sum_{i,\nu} x_{i,j,\nu} d(\nu, i) = 1 \;\; \forall\, j \tag{15b}$$

$$\textbf{C2: } \sum_\nu y_\nu \leq M_\mathrm{RB} \tag{15c}$$

$$\textbf{C3: } x_{i,j,\nu} \in \{0, 1\} \;\; \forall\, i, j, \nu \tag{15d}$$

$$\textbf{C4: } y_\nu \geq \sum_j m(i, j, \nu) x_{i,j,\nu} \;\; \forall\, i, \nu \tag{15e}$$

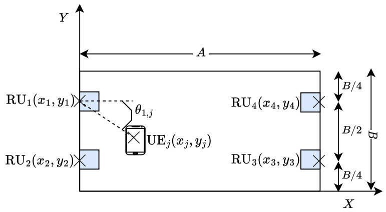


Fig. 3: RU placement for $I = 4$.

The objective function in (15a) is the minimization of the DL data transmission energy consumption ((13) and (14)) and is linear. Constraints explained hereinafter are set to ensure proper system operation and service scheduling among users. Constraint **C1** in (15b) is defined in Section IV-A. It ensures that all UEs are served once by one RU in one configuration. Constraint **C2** in (15c) is the blocking constraint that forces the algorithm to find a solution without exceeding the number of RBs available in the system (M_{RB}). The number of occupied RBs on the system level in configuration ν is determined by y_ν and is used to evaluate the system blocking. Constraint **C3** in (15d) defines $x_{i,j,\nu}$ as binary variables.

In our resolution, the preliminary task is the computation of $m(i, j, \nu)$ for all triplets (i, j, ν). Then, these values are used in the optimization resolution. This step linearizes constraint **C4** that imposes restrictions on the number of occupied system-level RBs in configuration ν. In each configuration, each active RU serves a certain number of UEs. The RBs occupied by RU_i are the sum of the RBs necessary to serve all UEs served by this RU_i ($\sum_j m(i, j, \nu) x_{i,j,\nu}$). The RBs occupied by each RU are evaluated for all active RUs in the considered configuration ($\forall\ i$). The number of occupied RBs at the system level in configuration ν (y_ν) must be greater than the RBs occupied by each active RU in ν. This must be true for all the considered configurations ($\forall\ \nu$). The formulated problem is thus Mixed Integer Linear Programming (MILP).

VII. Results and Discussions

A. Simulations

We consider four RUs in a rectangular area fixed as in Fig. 3. The load in the network is represented by J, the number of available UEs. For each load, J UEs' positions inside the rectangular area are randomly chosen with random shadowing. We calculate $m(i, j, \nu)$ for the available UEs in all the possible configurations. The optimization problem is run using CPLEX Python API. These steps are done 10000 times for each value of J. The simulations were performed on a remote server with 792 GB of RAM and 96 cores with simultaneous multi-threading. Table I lists the simulation parameters.

The running time increases with J because the number of variables and constraints in (15) increases. One simulation takes less than 0.2 s for $J < 35$. When the required total RB number gets close to the maximum available RB number (M_{RB}), the running time increases but remains acceptable: 0.5 s per simulation for $J = 45$ and 7.2 s for $J = 50$.

TABLE I: Simulation parameters.

Symbol	Parameter	Value
A (m)	Indoor area length	100
A_{m} (dB)	Antenna maximum attenuation	18
B (m)	Indoor area width	50
$E_{\text{SP,f}}$ (J)	Fixed SP energy consumption per packet	0.0312 [13]
$E_{\text{SP,v}}$ (J/bit)	Variable SP energy consumption per bit	3.75×10^{-8} [13]
f_c (GHz)	Central frequency	26
G_{A} (dBi)	Antenna gain	7 [17]
M_{RB}	Available RBs within one time slot	135
N_{NF} (dB)	UE noise figure	7 [18]
$P_{\text{CU,f}}$ (W)	CU fixed power consumption	6.25 [13]
$P_{\text{RU,f}}$ (W)	RU fixed power consumption	1.22 [13] [19]
r_0 (m)	Path-loss reference distance	0.0039
R_{T} (Mbps)	Target DL data rate	2
T (ms)	Reference period	20
T_{s} (ms)	Time slot duration	0.25
T_{K} (K)	Receiver temperature	290 [18]
w_{RB} (kHz)	RB bandwidth	720 [20]
W (MHz)	System bandwidth	100
α	Path-loss exponent	2.55
δ_{BW}	Bandwidth correction factor	0.56 [16]
δ_{SNR}	SINR correction factor	2 [16]
$\eta_{\text{AC/DC}}$	AC/DC power supply gain	0.8
η_{PA}	PA gain	0.7
θ_{3dB}	Half power beamwidth	90° [17]
μ	NR numerology	2
σ_{dB} (dB)	Shadowing standard deviation	5.7 [11]

In (15), only **C2** can stop the solver from finding a solution. Thus, when the solver fails, the system is considered blocked. The blocking probability estimate is the system blocking occurrences over the number of iterations. The objective function of successful trials is averaged to get the energy consumption.

B. Blocking probability

Now, let us evaluate the blocking probability of the problem in (15). The blocking occurs when the system requires more than M_{RB} RBs to serve the UEs. Fig. 4 shows the blocking probability as a function of the number of UEs present in the network for modes 1, 2, and 3, with a transmission power per RB of -13 dBm. We see that considering different configurations with four RUs and a virtual RU increases the system capacity. For a blocking probability of 10^{-2}, in mode 2, 17 UEs can be served compared to 32 in mode 1, and 50 in mode 3. The better SINR in mode 1 increases the perceived data rates and reduces the number of RBs needed to achieve R_{T}, enabling more UEs to be served before reaching M_{RB}. The proposed solution (mode 3) increases the system capacity by 56% compared to mode 1. This increase can be further explained by examining the configurations' usage.

In Fig. 5, we evaluate the configurations' usage in mode 3. The X-axis corresponds to the set of available configurations. Each configuration is identified by the active RUs it contains. For example, configuration 8 is denoted by RU(1,4), which means that RU_1 and RU_4 are active and serve different UEs on the same RBs. On the Y-axis, we count the number of RBs where each configuration is used. For example, for $J = 50$, when RU_1 and RU_4 are active, they reuse 2.7 RBs to serve

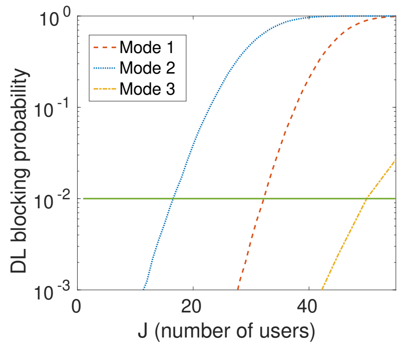


Fig. 4: DL blocking probability with $P_{\mathrm{t}} = -13$ dBm per RB.

different UEs on these RBs. Fig. 5 has a zoom-in in the box to better see configurations used on less than 6 RBs.

For low loads like $J = 10$, we see in Fig. 5, that the solver of the optimization problem tends to serve UEs with configurations having one active RU: first four configurations (transmission by one RU, mode 2) and mostly in $\nu = 16$ where only RU_{I+1} is active (simultaneous transmissions, mode 1). Simultaneous transmissions increase the perceived SINR and reduce the number of RBs where the BS is active to reach R_{T}. This reduction achieves the energy minimization objective.

When the load increases and the maximum system capacity (M_{RB}) tends to be reached, configurations with resource reuse are used as shown in Fig. 5. This shows the importance of reusing resources to serve a larger number of UEs. For $J < 40$, resource reuse by two RUs is applied on less than one RB per configuration. For $J \geq 40$, more configurations with resource reuse are used (on more than one RB per configuration). The configurations with three and four RUs reusing resources are increasingly used in these cases. For 45, 50, and 55 UEs, the use of the first four configurations is reduced and with 50 and 55 UEs, the use of the last configuration is also reduced.

Thus, the usage of configurations without resource reuse initially increases with J until reaching a maximum value, after which it decreases. Conversely, the usage of configurations with resource reuse consistently increases with J.

C. Energy consumption

Fig. 6 shows the energy consumed by the BS for DL data transmission. The curves end at $J = 32$, 17, and 50 for modes 1, 2, and 3, respectively (see Fig. 4 at 10^{-2} blocking probability). Although all RUs transmit in mode 1, the energy consumed is lower than mode 2 where one RU serves a UE. Simultaneous transmissions improve the received SINR and reduce the number of RBs where the BS is active. This shows the dominance of CU's energy use at $P_{\mathrm{t}} = -13$ dBm (Fig. 7).

Energy consumption in mode 1 is comparable to mode 3 when $J \leq 32$. In mode 3, energy consumption increases linearly with the number of UEs up to $J = 45$. However, beyond this point energy consumption escalates more rapidly due to the increased interference caused by resource reuse (see Fig. 5). This requires more RBs to serve UEs and results in

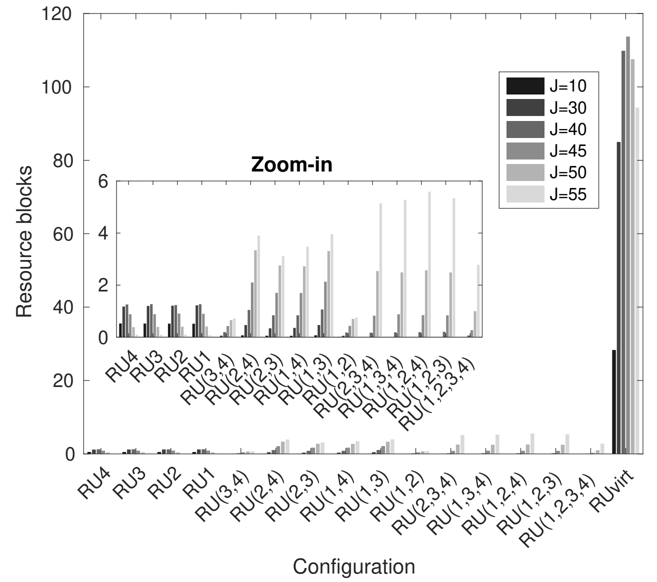


Fig. 5: Configurations usage for $I = 4$ (in each configuration, J increases from the left to the right).

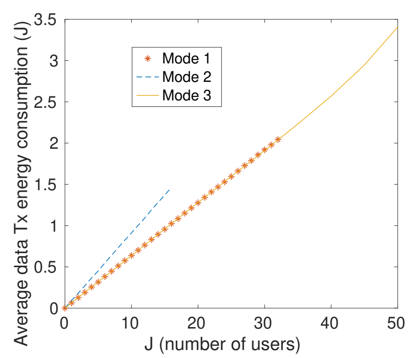


Fig. 6: Data transmission energy consumption.

higher energy consumption. Consequently, Fig. 5 shows that resource reuse is not widely used unless it becomes necessary, i.e. when M_{RB} is reached without using resource reuse.

Figures 5 and 6 show how load (J) affects configuration choices. Mode 1 is more energy-efficient than mode 2. In mode 3, when there are enough RBs to serve UEs without reuse, the preferred configuration is with RU_{I+1}. But with higher load, RB reuse is necessary, despite increased energy consumption.

With the proposed optimization problem, P_{t} has a direct impact on resource allocation and energy consumption since the allocation is computed in order to minimize the energy consumption. Increasing P_{t} has an impact on the number of needed RBs. For example, it improves the perceived SINR and reduces the number of RBs needed in the case of a single transmission without interference (first four configurations). In Fig. 7, we examine the energy consumption distribution with a variation of P_{t} for $J = 40$ in mode 3. The energy consumed is divided into five parts including the fixed consumption of the CU ($f(P_{\mathrm{CU,f}})$), signal processing in the CU ($f(E_{\mathrm{SP,v}})$ and

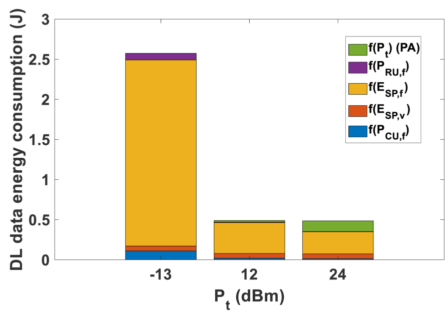


Fig. 7: Energy consumption at different P_{t} in mode 3 ($J = 40$).

$f(E_{\mathrm{SP,f}})$), the fixed consumption of the RU ($f(P_{\mathrm{RU,f}})$), and the consumption of the PA for radio power generation ($f(P_{\mathrm{t}})$).

We can see that increasing the transmission power from -13 dBm to 12 dBm reduces the total energy consumption of the BS. Further increasing the transmission power to 24 dBm has almost no impact on the total energy consumption. When transmitting with low power, the generation of the radio power is not considerable and the CU energy consumption is predominant. Nevertheless, for $P_{\mathrm{t}} = 24$ dBm, the part consumed for radio power generation is not to be neglected. Further increase of the transmission power, beyond 24 dBm for instance, increases the total energy consumption. When the transmission power increases, the number of RBs where the BS is active for transmission is always reduced and the BS is active for a shorter period. However, the energy consumption for data transmission increases when the transmission power is considerable, even if the BS is active for a shorter period because its generation is energy hungry.

VIII. Conclusion

In this paper, we have investigated DL radio resource allocation for a centralized RAN architecture under a minimum energy consumption criterion. We considered I RUs that can be active all together to serve UEs simultaneously (mode 1), or active one at a time (mode 2), or a combination of these two modes with possible resource reuse (mode 3).

We showed that using mode 1, where all RUs serve the UE simultaneously, can save energy and serve more UEs compared to mode 2, where a UE is served by one RU in low-load regimes without resource reuse. This is due to the higher SINR provided by simultaneous transmissions in mode 1. Also, the network coverage is not affected, since no RUs are switched off. Combining these modes in mode 3 with potential resource reuse can serve up to 56% more UEs while minimizing energy usage. Increasing transmission power can reduce energy consumption, but beyond a certain threshold, the power generation consumes significant energy, leading to higher total energy consumption. There is a minimum energy consumption that can be achieved by varying the transmission power.

In summary, mode 1 is effective in reducing energy consumption in low-load regimes, while combining modes 1 and 2 in mode 3 gives both low energy consumption and reasonable capacity for up to 50 users. To extend this work, multiple antenna RUs can be deployed with beamforming to carry a high load in a congested system while using minimal energy.

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