On Efficient Radio Resource Calendaring in Cloud Radio Access Network

Mira Morcos[a,b], Jocelyne Elias[c], Fabio Martignon[d,*], Tijani Chahed[a], Lin Chen[b]

[a]*Telecom SudParis*
[b]*Paris-Sud University*
[c]*LIPADE Laboratory, Paris Descartes University*
[d]*University of Bergamo, Italy*

Abstract

We propose in this paper a radio resource allocation scheme in the context of Cloud-based Radio Access Networks (C-RAN) run by a single operator. We specifically leverage bandwidth calendaring, a technique that allows shifting bulk data transfers, typically of large size with less stringent real-time constraints, to future epochs when the network is less congested. In particular, we propose an *auction-based framework* for bandwidth calendaring, where the C-RAN operator, as the spectrum auctioneer, runs an auction with its users, with the aim of maximizing its revenue. The auction-based mechanism takes as input the set of the users' bids and outputs the calendaring and pricing decisions. We first formulate the calendaring problem using Integer Linear Programming (ILP) and the pricing problem using the Vickrey–Clarke–Groves (VCG) pricing scheme. We further make use of the Bayesian settings to compute the optimal revenue. Due to the exponential time induced by the NP-hardness of the ILP formulation, we propose an effective approach that satisfies desired auction properties such as individual rationality and truthfulness while achieving a sub-optimal revenue, in polynomial time. We explicitly evaluate the impact of mobile systems features such as spatial frequency re-use and interference among mobile users, and study their impact on the overall system's performance. Extensive simulations, conducted in representative network scenarios, demonstrate the effectiveness of our proposal in improving the performance of C-RAN scheduling.

Keywords: ***Index terms—Resource Allocation, Calendaring, C-RAN, Auction, Truthfulness.***

1. Introduction

Extensive research is being conducted by academic and industrial players to boost the future mobile network's performance. Indeed, the 5G architecture will face multiple challenges to support not only the growth of mobile data traffic but also the deployment of new wireless applications requiring low latency, limited energy consumption and high scalability to accommodate diverse connected devices. Multiple technologies are being proposed for both the radio access network (RAN) and the core network, including massive MIMO, ultra-densification, Millimeters Waves, etc. [1, 2, 3, 4]. Notably, Software Defined Networks (SDN) and Network Functions Virtualization (NFV) are two key technologies that will play an essential role in future mobile networks, to optimize resource usage, help reduce costs and enhance network scalability [5, 6].

The paradigm of Cloud-based RAN (C-RAN) has been proposed as a promising architecture [3, 7, 8], wherein Base Band Units (BBUs) are separated from Remote Radio Heads (RRHs) in the base stations and pooled together in a centralized fashion [9]. Accordingly, the C-RAN will naturally implement SDN and NFV concepts [10, 11]: (1) A software based RAN allows a centralized orchestration of geographically distributed resources, and by that optimizes resource usage, quality of service, interference and handover management and (2) Virtualization of physical resources will help mobile operators and service providers reduce their Operational Expenditure (OPEX) and Capital Expenditure (CAPEX) by sharing physical equipment owned by an infrastructure provider.

Bandwidth calendaring (termed as calendaring for brevity throughout the paper) is a technique deployed in the context of data centers and wide area networks and refers to the possibility of shifting some bulk data transfers, typically of large size with less stringent real-time constraints, to be scheduled on future occasions, when the network is less congested [12, 13]. One such example is an update for a popular application which could be pushed towards user devices at night. It exploits the knowledge, or estimation, of future arrivals to pack current and future demands in an optimal way in the network.

Unlike traditional Radio Access Networks (RAN) where usually small-scale radio resource distribution mechanisms are run locally and distributed, the C-RAN as central entity paves the way to new resource allocation techniques that could yield to a better management, thus resulting in a higher capacity support for its clients. This is true since centralized resources are pooled together and can be allocated to the users who benefit more from their utilization.

*Corresponding author
Email addresses: mira.morcos@telecom-sudparis.eu (Mira Morcos), jocelyne.elias@parisdescartes.fr (Jocelyne Elias), fabio.martignon@lri.fr (Fabio Martignon), tijani.chahed@telecom-sudparis.eu (Tijani Chahed), lin.chen@lri.fr (Lin Chen)

In this paper, we exploit the centralized feature of the C-RAN to enhance resource management, in particular by applying calendaring decisions to incoming traffic. We tackle the calendaring problem from an economical point of view, and propose an auction-based framework where the C-RAN operator acts as the auctioneer, selling spectrum to its users (the bidders) with the objective of maximizing its profit [14, 15].

The auction-based calendaring mechanism takes as input the set of bid vectors and outcomes calendaring and pricing decisions. The calendaring decision consists of performing admission control and determining the optimal starting time for each admitted request. The pricing decision is executed according to the Vickrey–Clarke–Groves (VCG) pricing scheme, where users submit their bids simultaneously.

We first formulate the calendaring decision problem as an integer linear program (ILP) maximizing the C-RAN expected revenue. Due to the fact that the computing time of this latter formulation is exponential with respect to the input, we further propose an efficient auction approach which respects all auction desired properties, especially truthfulness (defined as inciting the users to bid their true valuations), while achieving a sub-optimal (yet high) revenue with respect to the one obtained with the ILP formulation. We explicitly model key features of mobile systems, such as spatial frequency re-use and interference among mobile users, and study their impact on the overall system's performance.

We conduct a thorough simulation campaign to test our proposed framework and heuristics in typical case studies, varying several key system parameters. Numerical results demonstrate the effectiveness of our proposed mechanism.

The main contributions of this paper can therefore be summarized as follows:

1. We propose an auction framework for radio resource calendaring in C-RAN, generating optimal revenue, and formulate it as an ILP model that maximizes the C-RAN operator's profit.

2. We further design a truthful auction approach that solves the calendaring problem in polynomial time while achieving a sub-optimal revenue.

3. We prove the efficiency of our truthful approach in satisfying auction's desired properties, especially truthfulness wherein users do not have any incentive to lie neither about their valuations nor the duration nor the amount of resource blocks they require.

4. We perform extensive simulations in typical network scenarios to show the effectiveness of our truthful auction approach.

5. We evaluate the impact of mobile systems' key features, such as interference and frequency re-use to show the impact of these latter on the performance of our models and algorithms.

The remainder of this paper is organized as follows. Section 2 discusses related work. Section 3 presents the system model and the assumptions we make in our work. Section 4 describes the optimal calendaring model as well as our heuristic to compute sub-optimal yet good solutions for the resource calendaring problem. Section 5 discusses the auction properties guaranteed by our proposed framework. Section 6 illustrates and discusses numerical results. Finally, Section 7 concludes the paper and outlines potential research directions.

2. Related works

This section discusses related work, focusing first on the calendaring technique, which has been applied in different networking contexts, and then on auction mechanisms, in particular those specifically tailored for the C-RAN scenario.

Calendaring. Calendaring gained momentum in transferring large, inter-datacenter traffic through Wide-Area Networks (WAN) which constitute expensive and business-critical resources [16, 17]. It has been made possible thanks to SDN, which allows for logically centralized control of resources [18]. Naboo [19], for instance, is a bandwidth-on-demand and calendaring SDN application proposed by Cisco which allows customers to dynamically request and provision bandwidth requirements, and which helps in turn to decrease OPEX by scheduling large transfers at times when the network is less loaded. The work in [20] introduces the concept of service engineered path, in the context of programmable networks. Bandwidth calendaring is used to schedule a reserved session for the users through SDN-oriented API OpenFlow, notably for scheduled datacenter backups.

Bandwidth calendaring appeared also in the context of so-called transport SDN [21], an extension of SDN to the transport layer, which allows the end-to-end infrastructure, including datacenters and the WAN connecting them, to be managed by a single SDN interface. Packet Design is a tool that has been introduced in [22], providing resource management and orchestration in SDN-based networks. The work in [23] reports on Nokia Network Service Delivery Platform (NSP), an SDN-based network implementing bandwidth calendaring and on-demand services. The authors in [24] propose a calendaring mechanism based on the use of deadlines for inter-datacenter WAN traffic which needs to be completed within a certain service time while ensuring high utilization of the network.

The work in [25] considers Cloud-enabled RAN (CE-RAN), where intelligence is placed at the edge of the mobile network and in the proximity of end users to improve online experience. The authors focus on service mapping and quality of service assurance, and propose a service placement solution that takes into account both quality of user experience and limited hardware capabilities available at the network edge.

Recently, new infrastructure providers have started testing the deployment of the SDN and NFV technologies on both the RAN and Core Networks [26, 27]. In particular, the TIP project vRAN Fronthaul Group in [27] has already demonstrated the feasibility and the advantages related to the adoption of the vRAN architecture. In this paper, we specifically apply the calendaring technique to future SDN-based C-RAN [28, 29], as a tool to orchestrate large data transfers on the wireless access.

Auction frameworks. Auction mechanisms are well suited for dynamic resource orchestration. In particular, for the wireless spectrum market, multiple auction frameworks have been proposed to implement spectrum allocation between primary and secondary users in cognitive radio networks [30, 31]. In SDN networks and cloud computing environments [32, 33, 34] auctions can be used to allocate resources such as virtual machines, power or storage. The authors in [32] propose an auction for network resources allocation in the context of a multi-tenant Software-Defined Networks (SDNs) managed by a FlowVisor. The work in [35] suggests a single-item auction for bandwidth reservation in distributed Cloud environments. The auction model consists of a Cloud running a sealed bid auction to allocate bandwidth to a number of Cloud-tenants competing to rent an amount of bandwidth in order to satisfy their real-time services. In [34], the authors propose a combinatorial auction for multiple instances of virtual machines in Cloud computing networks.

Knowing that the C-RAN paradigm will require dynamic resource management, the authors in [36, 37, 38] consider auctions as a promising technique for resource sharing between virtual operators. In [36], a coupled, two-level auction is proposed to implement resource allocation between the infrastructure provider and the mobile virtual operators and their users, in the context of massive MIMO networks. In [37], the authors present a revenue maximizing and truthful online auction for dynamic spectrum access. The auction model consists of users bidding for channel reservation for a given duration. The authors assume that the timing of bid placement is also a strategy for the users to maximize their benefits, and prove their mechanism to be strategy proof in terms of valuation and timing. In [38], an auction based model is proposed in the network slicing context.

The novelty of our work consists of (1) applying calendaring to the context of a C-RAN, which, to the best of our knowledge has not been yet considered despite its technical challenges related to the radio resource distribution, (2) developing an auction framework tailored for our problem that can guarantee revenue maximization for C-RAN operators. The key technicality in our auction-based calendaring scheme is to ensure truthfulness without sacrificing drastically the revenue for the C-RAN operator, given that achieving both truthfulness and maximizing revenue simultaneously is impossible [39].

3. System model

We consider a centralized C-RAN operator and K users geographically distributed in one cell. Our motivation to consider this scenario is that it corresponds to the most competitive case where efficient bandwidth calendering algorithms are called for. Specifically, in our model, each user requires spectrum access for large data transfers, in a period of time (or a time window), denoted by W. This window is divided into M time slots, and N resource blocks are available to be allocated at each slot.

Each user is mapped to a request, k, which is characterized by a 3-tuple: (1) the time at which the resource (connection) request arrives, t_0^k, which therefore denotes also its earliest starting time, (2) the amount of resources required by the connection, denoted by R^k, and (3) the connection's duration, m^k, fitting into the time window W. We can deduce the latest possible starting time, M^k, which is equal to $M - m^k$. Let R_t, R_c and R_b denote, respectively, the set of available time slots, the set of users (connection requests), and the set of resource blocks available in each slot.

Due to the C-RAN limited capacity in terms of resource blocks, not all the requests can be served immediately; a subset of them will be shifted, starting in following time slots, while yet another subset will be rejected. We assume that some connections (the shiftable ones) can tolerate a certain delay and can be shifted at maximum $M^k - t_0^k$ time slots. Consequently, calendaring consists of performing admission control and assigning a starting time to each admitted request in the time window W.

We consider only the case of an offline scenario, where calendaring decisions are taken assuming perfect knowledge of the bids of all future bandwidth reservations. Moreover, bidders are assumed to be single-minded: they are satisfied only if they are fully served. For all these reasons, we consider the non-preemptive case and assume that an accepted request cannot be dropped or interrupted if it starts to be served. We also assume that the amount of requested resource blocks is constant over the service duration. Table 1 summarizes all the parameters and the notation we use in our model.

3.1. Auction Agents

The C-RAN operator, the owner of spectrum licenses, presides the auction by taking the role of auctioneer. The users are the bidders: they compete with each other to obtain the resource blocks they require. We consider the auction as a non-cooperative game where users do not share their true valuations with each other. The commodities are radio resource blocks, and we assume that there is a fixed number of them (N) to be allocated at each time slot $n \in R_t$.

3.2. Auction Framework

We specifically design an auction based on the Vickrey–Clarke –Groves (VCG) auction type, which is a sealed bid auction where users submit simultaneously their requests (termed as bids) by declaring their valuations for a bundle of commodities to the auctioneer, the central C-RAN operator in this case. VCG is known to guarantee an optimal social welfare [40]: the allocation decision is in fact made by maximizing the social revenue. As for the payment rule, the pricing scheme is tailored to enforce truthfulness by making bidding the true valuation a dominant strategy [41]. However, knowing that VCG can sometimes generate low revenues [42, 41], we further make use of a Bayesian formulation, where we suppose that users valuations are drawn from a known distribution, which is a natural assumption, commonly adopted in the literature. Hereafter we first describe the bidding language used in our framework, and then the whole auction process.

Parameter	Definition
R_c, K	The set and total number of connection requests
R_b, N	The set and total number of available resource blocks at each time slot
R_t, M	The set and total number of available time slots
M^k	The *latest* starting time slot in which connection k can start.
t_0^k	Time slot in which the connection (or user) k arrives
b^k	User k's bid
R^k	Number of resource blocks requested by connection k along all the duration of the connection
m^k	Duration of connection k (expressed in number of time slots)
v^k	User k's true valuation of being served of R^k resource blocks for m^k consecutive time slots
w^k	User k's revealed valuation of being served of R^k resource blocks for m^k consecutive time slots
w_n^k	User k's valuation for receiving the R^k resource blocks for m^k consecutive time slots starting at time slot n.
$\phi^k(w^k)$	User k's virtual valuation of being served of R^k resource blocks for m^k consecutive time slots
$\phi_n^k(w^k)$	User k's virtual valuation for receiving the R^k resource blocks for m^k consecutive time slots starting at time slot n.
B_{-k}	Set of users bid excluding user k's bid b^k
Variable	**Definition**
x_n^k	Binary decision variable that denotes the time slot in which the connection starts (is scheduled). This variable is equal to 1 exactly in one and only one slot, and 0 elsewhere
Y^k	Binary decision variable that denotes if user k is admitted in the system ($Y^k = 1$) or rejected ($Y^k = 0$)
$r_n^{k,j}$	Binary decision variable that tells if the j-th resource block is allocated to user k at time slot n. This variable is equal to 1 if true, and 0 otherwise

Table 1: Parameters and variables definition

3.2.1. Bidding Language

User k requiring R^k resource blocks for m^k consecutive time slots starting at time slot t_0^k makes the bid $b^k = (w^k, R^k, m^k)$, where w^k expresses the *declared valuation* (or satisfaction) of the user if its connection request k is fully served before its deadline M^k. A request k is fully served if and only if it receives R^k resource blocks for m^k consecutive time slots, starting at any time slot n verifying $n \in [t_0^k, M^k]$. Note that user k receives R^k resource blocks for m^k consecutive time slots if it is admitted in the system, and 0 otherwise.

Let v^k denote user k's private, true valuation for being fully served. v^k is monotonically non-decreasing with respect to the bid parameters R^k and m^k. User k is truthful when he bids $w^k = v^k$. We deduce w_n^k, user k's valuation for receiving R^k resource blocks for m^k consecutive time slots starting at time slot n:

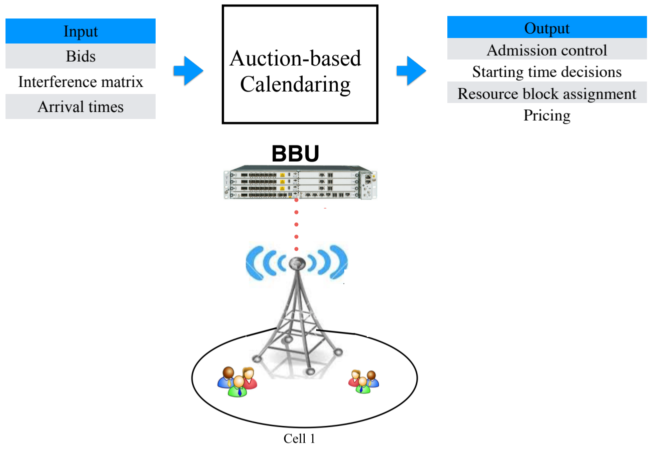


Figure 1: System model

$$w_n^k = \begin{cases} w^k & \text{for } n \in [t_0^k, M^k], \\ 0 & \text{otherwise.} \end{cases}$$

Definition 3.1. *At a given time slot n, a connection k is* ***shiftable*** *if $n < M^k$ and* ***un-shiftable*** *if $n = M^k$*

3.2.2. Auction process

We suppose that the C-RAN runs the auction periodically. The period can be the length of the considered window, W. The procedure is as follows:

1. As a first step, the auctioneer will initiate an auction over N resource blocks available in a time window W, i.e., starting at a time $t = 0$ until $t = M$.
2. Users wishing to start their services at a given time in the considered time window W, i.e., whose $t_0^k \in W$, will participate to the auction by submitting their bids.
3. Finally, the C-RAN operator will provide admission (winner determination), calendaring and pricing decisions.

Figure 1 summarizes our system model and auction process, showing a Cloud-based Base Band Unit (BBU) that manages, in a centralized fashion, distributed Remote Radio Heads (RRH), serving users located in multiple cells. It also illustrates our proposed auction-based mechanism that takes as input the set of bids, the characteristics of the wireless environment (summarized by the interference matrix) and the arrival times of users, generating as output both calendaring and pricing decisions.

4. Problem formulation

We describe and discuss in this section our proposed mathematical formulation of the calendaring problem, and the approach we use to determine the prices to be charged to admitted users. We first formulate the calendaring problem as an ILP model. Due to the high computing time induced by the ILP formulation, especially in large-scale scenarios, we propose a heuristic that can solve the calendaring and price determination problems in polynomial time while guaranteeing truthfulness and individual rationality (the user does not have to pay more than its valuation).

4.1. ILP formulation - Revenue Maximizing Auction (IRMA)

We formulate hereafter the optimal calendaring problem using an ILP approach. The objective of the C-RAN operator is to allocate resources to maximize its revenue, which is expressed as the sum of users charged prices, while respecting capacity and interference constraints.

We define the binary decision variables x_n^k and $r_n^{k,j}$, $\forall n \in R_t, k \in R_c, j \in R_b$ as follows:

$$x_n^k = \begin{cases} 1 & \text{if user } k \text{ is scheduled to start in time slot } n \\ 0 & \text{otherwise.} \end{cases}$$

$$r_n^{k,j} = \begin{cases} 1 & \text{if resource block } j \text{ is allocated to user } k \text{ at time slot } n \\ 0 & \text{otherwise.} \end{cases}$$

Finally, let p^k be the price charged to user k if he is admitted in the system. The calendaring problem can therefore be formulated as follows:

$$\max \sum_{k \in R_c} p^k Y^k; \tag{1}$$

$$Y^k = \sum_{n \in R_t : n \geq t_0^k} x_n^k$$

$$s.t. \sum_{n=t_0^k}^{M^k} x_n^k \leq 1, \quad \forall k \in R_c \tag{2}$$

$$\sum_{k \in R_c : n \geq t_0^k} r_n^{k,j} \leq 1, \quad \forall n \in R_t, j \in R_b \tag{3}$$

$$\sum_{\tau \in R_t : \tau \leq \min\{n, m^k\}} x_{[n-\tau+1]}^k \leq \sum_{j \in R_b} r_n^{k,j}, \quad \forall n \in R_t, k \in R_c \tag{4}$$

$$\sum_{j \in R_b} r_n^{k,j} = R^k \Big(\sum_{\tau \in R_t : \tau \leq \min\{n, m^k\}} x_{[n-\tau+1]}^k \Big), \tag{5}$$

$\forall n \in R_t : n \geq t_0^k, k \in R_c$

$$\sum_{k \in R_c, j \in R_b} r_n^{k,j} \leq N, \quad \forall n \in R_t. \tag{6}$$

Objective function (1) represents the total revenue, which is to be maximized by the C-RAN operator. Note that Y^k indicates if user k is admitted in the system ($Y^k = 1$) or not ($Y^k = 0$). Constraint (2) ensures that a given connection is scheduled to start at most once. Note that this constraint permits to implement *admission control*, since the C-RAN operator is allowed to refuse connections (which cannot be accommodated due to limited capacity and/or tight scheduling requirements). If, on the other hand, we want to allow the model to perform calendaring on all the connections, it suffices to replace the inequality in such constraint by a strict equality. In this latter case, however, it may happen that some given network instances are unfeasible. Constraint (3) ensures that a given resource block j, at a given time slot n, is allocated to exactly one user. Constraints (4) and (5) guarantee that connection k is served by allocating to it R^k resource blocks during m^k *consecutive* time slots. Finally, constraint (6) ensures that the capacity at each time slot (denoted by N), is not exceeded.

In section 6, we show how to modify these constraints to model mobile systems features in such way that our calendaring approach can be applied in scenarios where admission control and resource block assignment should take into account both partial interference and frequency re-use constraints.

4.1.1. Bayesian mechanism design formulation

To guarantee revenue maximization, we use the approach of Bayesian optimal mechanism design [30], where we consider that user k's valuation, w^k, is drawn from a given distribution $F(w^k)$, known to the auctioneer. We also consider that users bid truthfully, i.e., $w^k = v^k$. According to Myerson's theorem [43], for maximizing profit, we need to maximize virtual valuations. Based on this, we maximize the expected surplus as follows:

$$E\Big[\sum_{k \in R_c} p^k Y^k \Big] = E\Big[\sum_{k \in R_c} \phi^k(w^k) Y^k \Big] \tag{7}$$

where

$$\phi^k(w^k) = w^k - \frac{1 - F(w^k)}{f(w^k)}$$

is user k's virtual valuation for receiving the resources; $\phi^k(w^k)$ is monotone non-decreasing in w^k, and is expressed in terms of $F(w^k)$, the probability distribution function of w^k, and its density distribution function $f(w^k)$.

Let $\phi_n^k(w^k)$ be the virtual valuation of user k for receiving the resources starting at time slot n. We have:

$$\phi_n^k(w^k) = \begin{cases} \phi^k(w^k) & \text{for } n \in [t_0^k, M^k] \\ 0 & \text{otherwise.} \end{cases}$$

Given expression (7), we obtain:

$$E\Big[\sum_{k \in R_c} \phi^k(w^k) Y^k \Big] = \\ = E\Big[\sum_{k \in R_c} \phi^k(w^k) \sum_{n \in R_t : n \geq t_0^k} x_n^k \Big] = E\Big[\sum_{k \in R_c} \sum_{n \in R_t} \phi_n^k(w^k) x_n^k \Big]$$

Hence:

$$\max \sum_{k \in R_c} p^k Y^k = \max \sum_{k \in R_c} \phi^k(w^k) Y^k = \max \sum_{k \in R_c} \sum_{n \in R_t} \phi_n^k(w^k) x_n^k \tag{8}$$

Replacing $\max \sum_{k \in R_c} p^k Y^k$ in Expression (1), the ILP model becomes:

Algorithm 1 Truthful Resource-Aware Approach (TRAA): Calendaring algorithm

Input: K, N, M, v_k^n, t_0^k, m^k, R^k
Output: x_n^k, $r_n^{k,j}$, p^k, $\forall n \in R_t$, $k \in R_c$, $j \in R_b$
Init: $Y^n = N, \forall n \in R_t$; $C^k = 0, \forall k \in R_c$
  for $n = 1$ **to** M
    for $k = 1$ **to** K
      if $C^k \neq 1$ & $t_0^k \leq n$ & $n \leq M - m^k + 1$ & $u_n^k \neq 0$
        for $n = 1 : M$
          $W_n^k(b^k) = \frac{\Delta U_n^k(w^k)}{R^k m^k} + \frac{\phi_{n+1}^k(w^k)}{\alpha R^k m^k}(1 + \Delta U_n^k(w^k))$
        end
      end
    end
    $[B,I]=$ sort(L), in decreasing order, $L = \{\Delta W_n^k(b^k)\}$, B is the sorted list and I is the list of corresponding connection indexes.
    for $j = 1 : size(L)$
      $k' = I(j)$
        if $R^{k'} \leq N$
          $x_n^{k'} \leftarrow 1$& $C^{k'} \leftarrow 1$
          for $l = 0 : m^{k'} - 1$
            for $i = 1 : R^{k'}$
              $r_{n+l}^{k',Y^{n+l}-i+1} = 1$
            end
            $Y^{n+l} = Y^{n+l} - R^{k'}$
          end
        end
    end
  end

$$\max \sum_{k \in R_c} \sum_{n \in R_t} \phi_n^k(w^k) x_n^k \tag{9}$$

subject to constraints (2)-(6).

4.1.2. Price determination

If user k is admitted in the system ($Y^k = 1$), he will pay the following VCG price:

$$p^k = \phi^{k^{-1}}(p_{VCG}^k) \tag{10}$$

where

$$\begin{aligned} p_{VCG}^k = &\max_{R_c - \{k\}} \sum_{k' \neq k, n \in R_t} \phi_n^{k'}(w^{k'}) x_n^{k'} \\ &- \max_{R_c} \sum_{k' \neq k, n \in R_t} \phi_n^{k'}(w^{k'}) x_n^{k'}. \end{aligned} \tag{11}$$

On the other hand, when user k is rejected, $p^k = 0$.

Due to the computing time complexity, that will be further quantified in the performance evaluation section, we propose hereafter a truthful auction approach that yields a sub-optimal (yet high) revenue with respect to the one obtained with the IRMA scheme in a polynomial time.

4.2. Truthful Resource Aware Approach (TRAA)

In this section, we propose an algorithm that solves the calendaring decision problem and determines the price each user admitted in the system has to pay in a short computing time. We also prove that the proposed algorithm (in particular, its pricing scheme), guarantees auction desired properties, such as *truthfulness* and *individual rationality*.

4.2.1. Calendaring decision

Definition 4.1. *Let us define the set of users' weights at time slot n as* $\{W_n^k\}_k = \{W_n^1, \ldots, W_n^K\}$ *and the weight of a given user k at time slot n as:*

$$W_n^k(b^k) = \frac{\Delta U_n^k(w^k)}{R^k m^k} + \frac{\phi_{n+1}^k(w^k)}{\alpha R^k m^k}(1 + \Delta U_n^k(w^k)) \tag{12}$$

where $b^k = (w^k, R^k, m^k)$, $\phi_{n+1}^k(w^k)$ *is the virtual valuation of user k for receiving the resources starting at time slot* $n+1$, α *(*> 1*) is a positive parameter that can be set by the auctioneer, and* $\Delta U_n^k(w^k)$ *is defined as:*

$$\Delta U_n^k(w^k) = \phi_n^k(w^k) - \phi_{n+1}^k(w^k)$$

$\Delta U_n^k(w^k) = \phi_n^k(w^k)$*, for un-shiftable connections, since* $\phi_{n+1}^k(w^k) = 0$*, while it is 0 for shiftable connections.*

$W_n^k(b^k)$ can be expressed as follows:

$$W_n^k(b^k) = \begin{cases} \frac{\phi_n^k(w^k)}{R^k m^k} = \frac{\phi^k(w^k)}{R^k m^k} & \text{for un-shiftable connections,} \\ \\ \frac{\phi_{n+1}^k(w^k)}{\alpha R^k m^k} = \frac{\phi^k(w^k)}{\alpha R^k m^k} & \text{for shiftable connections.} \end{cases}$$

These weights $W_n^k(b^k)$ can take two different values according to the connection's type (shiftable or not), as shown above. The auctioneer gives priority to the un-shiftable one if two connections of different types have the same weight. These weights are tailored to make our algorithm satisfy desirable economic properties, as will be discussed in Section 5.

The calendaring decision is detailed in Algorithm 1: At each time slot n, the algorithm sorts the set of weights $\{W_n^k\}_k$ in decreasing order. Then, it starts assigning resource blocks to users by following their order in the sorted list of weights until no resource blocks are left. The algorithm postpones the rest of *shiftable* connections verifying $n < M^k$ and rejects all the others. This procedure is repeated $\forall n \in [1, M]$.

We observe that there are two necessary conditions for user k to be scheduled to start at time slot n: (C1) $W_n^k(b^k) > 0$, this condition is verified when n verifies $t_0^k \leq n \leq M^k$ (see definition 4.1) and when $\phi^k(w^k) > 0$ i.e., $w^k > w_0^k$, with $\phi^k(w_0^k) = 0$ since $\phi^k(w^k)$ is monotone increasing in w^k, and (C2) there are enough resource blocks at time slot n for user k.

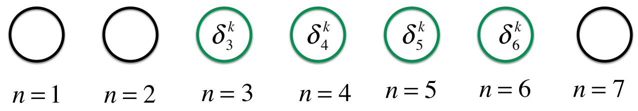


Figure 2: An example that shows how the critical price in TRAA is determined. User k has $t_0^k = 3$, $m^k = 2$ and $M^k = 6$. Accordingly, the price δ_n^k will be calculated at time slots $3 \le n \le 6$ and $p^k = \delta^k = \min\{\delta_n^k\}$.

4.2.2. Price determination

Each user k admitted in the system will be charged by the auctioneer the *critical price*, denoted by δ^k (i.e., $p^k = \delta^k$). This price is such that if $w^k \ge \delta^k$, user k is admitted in the system, while if $w^k < \delta^k$ user k is rejected. We next show how to determine this *critical price*.

Critical price determination: The critical price will be defined, for a fixed set of bids B_{-k} of all users excluding user k, as follows:

- at each time slot $n \in [t_0^k, M^k]$, we determine the *critical weight* $V_n^k = W_n^{k'}(b^{k'})$, with $k' \in \{R_c - k\}$ a user other than user k. $W_n^{k'}(b^{k'})$ represents the critical weight defined as follows: if we remove user k's weight from the list, and apply the calendaring decision described in 4.2.1, $W_n^{k'}(b^{k'})$ is the weight that would disqualify user k's connection from starting at time slot n: i.e., it is the maximum weight such that if $W_n^k(b^k) < W_n^{k'}(b^{k'})$, we will have $x_n^k = 0$.
- We then define the set of prices $\{\delta_n^k\}_{t_0^k \le n \le M^k}$ at each time slot $t_0^k \le n \le M^k$; $\delta_n^k = \max\{w_0^k, c_n^k\}$, where w_0^k is such that $\phi^k(w_0^k) = 0$, and $c_n^k = \phi^{k^{-1}}(R^k m^k V_n^k)$.
- The critical price is $\delta^k = \min_n\{\delta_n^k\}$.

We note that $V_n^k = W_n^{k'}(b^{k'})$ depends only on the set of bids B_{-k} excluding user k's bid b^k, and so it does not depend on bid b^k.

If user k is admitted in the system and scheduled to start at time slot n, we have $W_n^k(b^k) > V_n^k$. If user k is not admitted, we have $W_n^k(b^k) < V_n^k \; \forall n \in [t_0^k, M^k]$.

Figure 2 shows a simple example that explains how the critical price δ^k is obtained from calculating δ_n^k at each time slot $n \in [t_0^k, M^k]$.

5. Auction Properties

Designing auction mechanisms faces multiple challenges, since efficient auction mechanisms must satisfy specific economic properties:

1. *Individual rationality*, which guarantees that no user pays a price higher than its valuation.
2. *Incentive compatibility*, also referred to as *truthfulness*, a crucial property which forces bidders to submit their true bid, not only by declaring their true valuation but also by truly asking for the real amount of resources they require and for the real duration they need for their transmission.
3. *Computing time,* where polynomial time is most desired in auction mechanism design.

We discuss hereafter, and prove, these properties for the TRAA scheme.

5.1. Individual rationality

We have to prove that when a generic user k bids his true valuation, v^k, his payoff $u^k(v^k)$ will not be negative:

$$u^k(v^k) = v^k - p^k \ge 0$$

where $p^k = \delta^k$.

We know that when user k wins, we have $\delta^k \le w^k \le v^k$ (see proof in Appendix A), leading to $u^k(v^k) \ge 0$.

5.2. Truthfulness

We prove the truthfulness of TRAA considering multiple cases, as follows:

5.2.1. User misreporting at most one parameter

We prove that, for a given set of bids B_{-k}, user k cannot obtain a higher payoff by misreporting at most one parameter, i.e., either v^k, R^k or m^k.

Theorem 5.1. *According to [30, 44], in a single-minded auction where losers pay* 0*, truthfulness is guaranteed if:*

- *The allocation is monotone, i.e., if $b^k = (v^k, R^k, m^k)$ is a winning bid, $b^k = (w^k, R^k, m^k)$ with $w^k > v^k$ is also a winning bid and $b_1^k = (w^k, R'^k, m'^k)$ with $R'^k < R^k$ and/or $m'^k < m^k$ is also a winning bid.*
- *The winner is charged the critical price.*

Lemma 5.2. *The decision making of the TRAA scheme is monotonic.*

Proof 5.2. *Please refer to Appendix A for the complete proof.*

Lemma 5.3. *The winner k is charged the critical price such that if $w^k < \delta^k$ user k will lose, while if $w^k \ge \delta^k$ user k will win.*

Proof 5.3. *The proof is in Appendix B.*

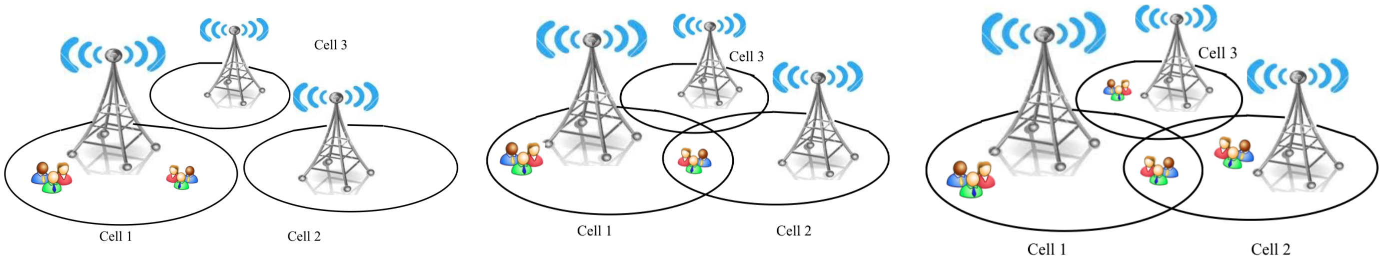
Hence, our proposed TRAA scheme is truthful.

5.2.2. User misreporting at least two parameters

Lemma 5.4. *User k will not maximize his utility by misreporting at least two parameters.*

We prove that a given user k cannot achieve a higher utility by bidding b'^k having at least 2 parameters different from the ones in its truthful bid b^k. We consider only the cases where $R'^k > R^k$ and $m'^k > m^k$, supposing that the user does not have an advantage to partially complete his service, and so will not ask for $R'^k < R^k$ and $m'^k < m^k$.

Proof 5.4. *The proof is given in Appendix C.*



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Figure 3: Scenarios' topology description: In scenario 1 (*"No interference"*) we consider K users geographically located in a cell. In scenario 2 (*"Partial interference"*) we consider K users geographically located in one cell with partial interference due to the overlap with other cells. In scenario 3 (*"Partial interference and frequency re-use"*) we consider K users geographically located in multiple cells.

6. Performance evaluation

We now evaluate numerically the performance of the proposed auction-based calendaring approaches, considering different network scenarios with partial and complete interference, as well as frequency re-use. We specifically compare the following 4 approaches:

- *ILP formulation - Revenue Maximizing Auction (IRMA)*: the optimal ILP formulation described in Section 4.1.
- *Truthful Resource Aware Approach (TRAA) scheme*: based on the sub-optimal formulation described in Section 4.2.
- *IRMA with No Calendaring (IRMA-NoCal)*: It does not perform calendaring. We consider that none of the users can be delayed, and can only be served at his arrival time t_0^k. We implement this approach using the same ILP formulation (1)-(6), where the latest starting time M^k of each user coincides with t_0^k.
- *TRAA with No Calendaring (TRAA-NoCal)*: the TRAA scheme where we set $M^k = t_0^k$.
- Earliest Deadline First *(EDF):* a benchmark algorithm commonly adopted in the literature [45, 46, 47]. EDF is similar to the RAA approach, but instead of sorting the users' weights, as defined in Section 4.2.2, this algorithm sorts users according to their deadlines, and by that gives priority to the connections with the earliest deadline.

We analyze the performance of these approaches by measuring the revenue obtained by the C-RAN operator, the rejection rate and the computing time, varying the number of connections participating in the auction (K) and the length of the time window/number of time slots (M).

We implemented our ILP models and algorithms in MATLAB, and solved network instances on a server equipped with an Intel CPU at 2.60 GHz and 64 GByte of RAM. All numerical results are obtained by averaging 50 random extractions to achieve 95% confidence intervals, illustrated in the figures. In the following, we start by describing the network settings we based our simulations on, then, we describe the scenarios we implemented and finally we present and discuss numerical results.

6.1. Network settings

We consider a C-RAN with a central BBU and distributed RRHs managed by a single operator. As for radio resources, we consider pooled resource blocks available at the BBU.

6.1.1. Wireless environment

Differently from data centers and SDN-based fixed networks, the nature of radio resources imposes additional constraints when it comes to resource allocation. We integrate *interference management* in our optimal calendaring (IRMA) model and heuristic scheme (TRAA), and therefore we add interference constraints in our formulations. Specifically, we model the radio conditions and the location of the users within their cell using an interference matrix, which is given as input to our resource allocation mechanisms. We consider 3 different scenarios with 3 representative topologies (illustrated in Figure 3); we note, however, that our proposed models and mechanisms are flexible and can be applied to any cellular topology.

- In **scenario 1**, we consider K users geographically distributed in one cell that does not overlap with neighboring cells, as shown in Figure 3a. To avoid intra-cell interference, our model allocates a given resource block to at most one user.
- In **scenario 2**, the K users are geographically distributed in one cell, which overlaps with neighboring cells causing partial interference, as shown in Figure 3b. To avoid inter-cell interference, users located in the overlapping area cannot receive resource blocks with sub-carriers already used in the other overlapping cells.
- In **scenario 3**, we consider K users geographically distributed in multiple overlapping neighboring cells, also causing partial interference (Figure 3c). Nevertheless, in this scenario resource re-use can be performed while taking into account partial interference constraints: a given resource block can be allocated to two different users if the distance between them is large enough so that they do not interfere with each other.

	Scenario					
	1				2	3
Interference type	None				Partial-s = 40%	Partial
Resource re-use	None				None	Yes
	Sub-scenario					
Parameter	**(a)**	**(b)**	**(c)**	**(d)**	-	-
	General parameters					
M	10	10	10	$\in [0, 20]$	10	10
N	10	10	10	10	10	10
K	$\in [20, 100]$		50	$\in [20, 100]$	$\in [20, 100]$	
α	5	5	5	5	5	5
	Per connection request parameters					
v^k u.d. $\in$	[0, 1]	[1, 5]	[1, 5]	[1, 5]	[1, 5]	[1, 5]
t_0^k, R^k, m^k	u.d. $\in [1, 5]$					
R^k	constant (u.d. $\in [1, 5]$)			variant	constant (u.d. $\in [1, 5]$)	

Table 2: Settings and parameters used in the numerical evaluation.

6.1.2. Auction settings

The C-RAN operator presides an auction by taking the K bids and interference constraints as input, then he generates allocation decisions by assigning starting times and resource blocks to admitted users. The considered time window W consists of M time slots, with N resource blocks available at each time slot n. We consider that user k bids truthfully ($w^k = v^k$) and that user k's true valuation v^k for the bundle of resource blocks he requires as well as the connection's duration are generated from uniform distributions in the intervals $[0, 1]$ and $[1, 5]$ in sub-scenarios (a) and (b), respectively. We deduce v_n^k which is equal to v^k if $n \in [t_0^k, M^k]$ and 0 otherwise. Table 2 summarizes the parameters' settings for all scenarios.

6.2. Scenario 1 - No interference

In this scenario, as stated before, we consider K users geographically distributed in one cell, with no inter-cell interference. To avoid intra-cell interference, frequency re-use cannot be performed; in other words, no resource block can be allocated to more than one user at a given time slot n (Constraint (3) in the ILP formulation in Section 4.1).

Figures 4 and 5 illustrate the revenue, the rejection rate and the computing time as a function of the number of users K, when varying this latter in the range $[20, 100]$. In scenario $1(a)$ (Figure 4) users' valuations are generated from a uniform distribution in $[0, 1]$, while in scenario $1(b)$ (Figure 5), users' valuations are generated from a uniform distribution in $[1, 5]$. This setting justifies the higher range of revenues obtained in scenario $1(b)$ compared to that obtained in scenario $1(a)$.

The results obtained in scenarios $1(a)$ and $1(b)$ follow a similar trend: they show that the TRAA approach can perform the calendaring mechanism in a negligible time compared to IRMA (see Figures 4c and 5c), and constitutes a good compromise between guaranteeing a high revenue for the operator (Figures 4a and 5a) and a low rejection rate (Figures 4b and 5b), which are both close to the ones obtained by the optimal IRMA approach. Knowing that the main objective of the C-RAN operator is to maximize its revenue, these results prove that our proposed TRAA scheme is efficient in guaranteeing a close to the optimum revenue (with a maximum gap of 24% with respect to IRMA) and in computing the calendaring decisions in a polynomial time, while guaranteeing truthfulness.

Figure 6 illustrates the impact of the window size on the revenue, rejection rate and computing time. The results show that the revenue increases when M increases, while the rejection rate decreases. In fact, the larger the window size, the more connections that can fit in this latter. The TRAA approach, however, performs well in guaranteeing 50 % of the optimal revenue with a very low computing time that increases linearly with M.

Figure 7 illustrates the total revenue, rejection rate and computing time as a function of the number of users. We assumed in this scenario that the number of resources blocks R^k required by a given connection k, is variant with respect to n, during m^k. The results being similar to those obtained from scenario 1(a), prove that our proposed mechanism is flexible and can be adopted in more realistic scenarios where the number of resources is variant with respect to time.

We further highlight the advantage of *calendaring* by comparing the calendaring-based approaches (IRMA and TRAA) to the baseline approaches (IRMA-NoCal, TRAA-NoCal and EDF), respectively, which do not perform calendaring. We can see from Figures 4a and 5a that IRMA and TRAA generate a higher revenue (in the range of 30%) with respect to the one obtained by IRMA-NoCal and TRAA-NoCal, respectively, and in the range of 55% w.r.t. the one obtained by EDF, while accepting a higher number of users (10% - Figures 4b and 5b), thanks to the shifts performed by IRMA, which in turn lead to a higher revenue compared to the baseline approaches.

6.3. Scenario 2 - Partial interference

In this scenario, we consider K users geographically distributed in a cell that overlaps with neighboring cells, causing partial interference.

To adapt our auction mechanism to such scenario, we consider an interference matrix, A_n, such that an element a_n^{kj} indicates if the allocation of a given resource block j will cause interference if allocated to user k at time slot n. Specifically, a_n^{kj} is defined as follows:

$$a_n^{kj} = \begin{cases} 1 & \text{if resource block } j \text{ will cause} \\ & \text{interference if allocated to user } k, \\ 0 & \text{otherwise.} \end{cases}$$

To limit complexity, we assume in our performance evaluation that $A_n = A \ \forall n \in [0, M]$. In particular, we consider a percentage s of users located in the overlapping area. The matrix A is generated in such a way that for each resource block j, a fraction s of the matrix elements verify $a_n^{kj} = 1$. Note, however, that our models and algorithms are general, and can be applied with any time-varying sequence of the interference matrix A_n. Based on these new settings, the four approaches considered in scenario 1 are modified as follows:

- *IRMA and IRMA-NoCal*: we modify Constraint (5) of the ILP formulation in Section 4.1 as follows:

$$\sum_{j \in R_b : a_n^{kj}=0} r_n^{k,j} = R^k \Big(\sum_{\tau \in R_t : \tau \le \min\{n, m^k\}} x^k_{[n-\tau+1]} \Big), \quad (13)$$

$$\forall n \in R_t : n \ge t_0^k, k \in R_c$$

- *TRAA* and *TRAA-NoCal*: we modify the two algorithms taking as additional input the interference matrix A to avoid interference.

Figure 8 illustrates the total revenue, rejection rate and computing time as a function of the number of users, when this latter varies in the range [20, 100]. The results obtained in this scenario are similar to those of scenario 1, and prove that our proposed mechanism is flexible and can be adopted in network topologies characterized by partial interference. Figure 10 illustrates the degradation in terms of revenue and rejection rate induced by the interference, since this latter feature provides additional constraints to the admission control process, leading to a higher number of rejected users, and hence to lower revenue values.

6.4. Scenario 3 - Partial interference and frequency re-use

In this scenario, we assume that the K users are *randomly* distributed in 3 cells, which are partially overlapped with each other.

To adapt our calendaring mechanism to such environment, we incorporate both interference and frequency re-use features in our C-RAN scenario. To this aim, we consider a symmetric interference matrix A_n, as defined above for the previous scenario.

Moreover, to perform resource re-use, we consider a matrix E_j where element e_j^{lk} expresses if a given resource block j can be allocated to two different users l and k as follows:

$$e_j^{lk} = \begin{cases} 1 & \text{if resource block } j \text{ can be allocated to user } l \\ & \text{and user } k \text{ in the same time slot } n, \\ 0 & \text{otherwise.} \end{cases}$$

This can be determined straightforwardly from the interference matrix A_n. As in the previous scenarios, we compare the four approaches proposed in this paper, which we modified according to scenario 3's settings:

- *IRMA and IRMA-NoCal*: we modify constraint (5) of the ILP formulation in Section 4.1 as follows:

$$\sum_{j \in R_b : a_n^{kj}=0} r_n^{k,j} = R^k \Big(\sum_{\tau \in R_t : \tau \le \min\{n, m^k\}} x^k_{[n-\tau+1]} \Big), \quad (14)$$

  and constraint (3) as follows:

$$r_n^{l,j} \le 1 - r_n^{k,j}, \quad \forall k \in R_c, j \in R_b, n \in R_t, l \in R_c : e_j^{lk} = 0. \quad (15)$$

- *TRAA* and *TRAA-NoCal*: we modified these two approaches to perform interference-aware calendaring with resource re-use.

The results obtained in this scenario (see Figure 9) are in line with the previous ones and confirm that our proposed calendaring mechanism is indeed flexible and can be adopted in a more general topology, where we perform resource re-use, taking into account interference constraints. For example, by comparing scenario 2(a) (Figure 8b) to scenario 3(a) (Figure 9b), we can observe that the operator's revenue in scenario 3 is higher (the rejection rate is up to 20% lower) than the one obtained in scenario 2, and this is due to frequency re-use, which allows the operator to allocate more efficiently its resources w.r.t. the case where no frequency re-use is allowed, thus increasing its profit.

7. Conclusion

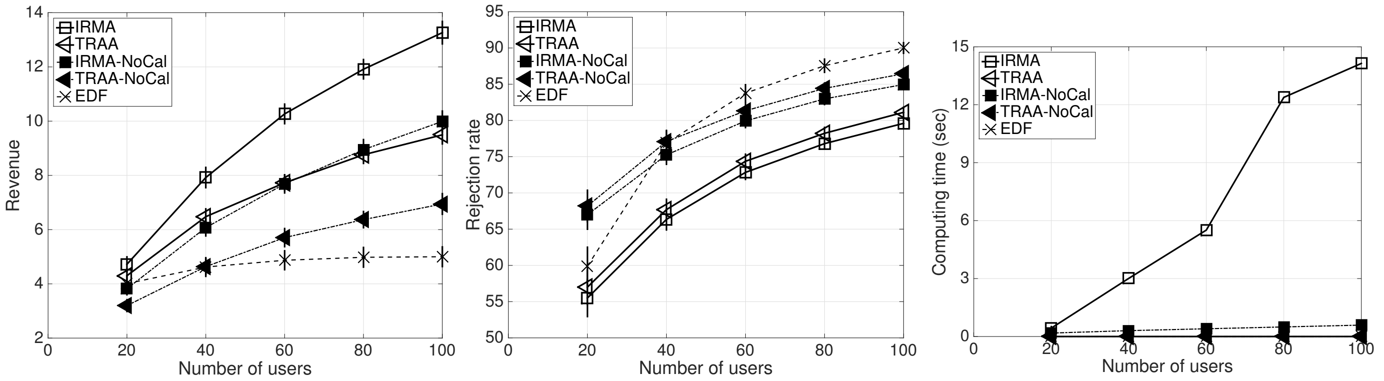
We considered in this paper an auction-based formulation for radio resource calendaring in a C-RAN scenario, a natural context in which bandwidth calendaring can be applied owing to its centralized architecture.

We first modeled the optimal calendaring decision problem as an integer linear program, and made use of the VCG pricing scheme in Bayesian settings to compute the price charged to each user admitted in the system. Then, we proposed a heuristic which we showed to perform close to the optimum in several network scenarios, with a polynomial computing time, while still respecting auction desired properties: individual rationality and truthfulness.

We explicitly modeled key features of mobile systems: spatial re-use and interference among users, and studied their impact on the overall system's performance.

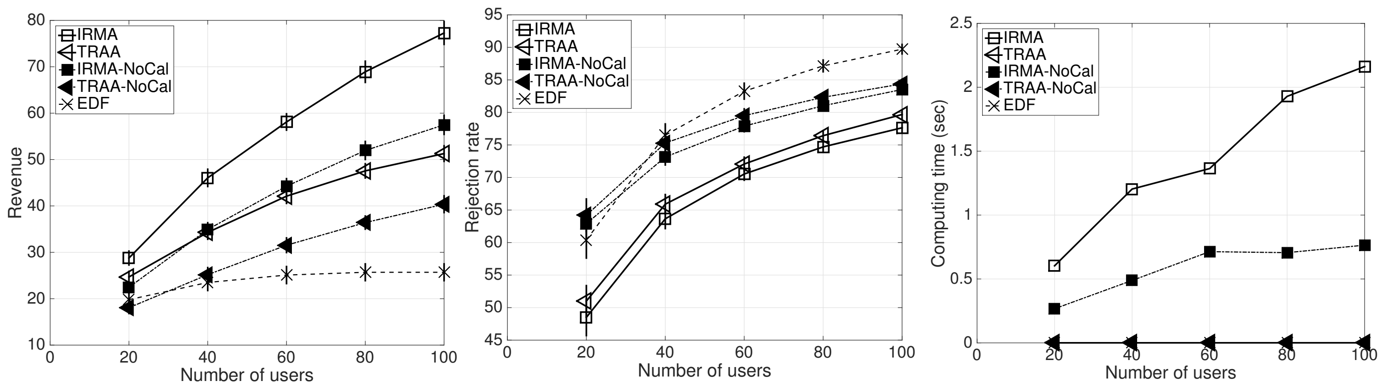
Our numerical evaluation, conducted in several, typical network scenarios, demonstrates an improvement in the performance achieved, notably in terms of the C-RAN operator's revenues, which increase up to 30% with respect to baseline approaches that do not exploit bandwidth calendaring. It also shows the efficiency of our truthful approach in guaranteeing truthfulness without sacrificing drastically the revenue of the C-RAN operator.

Future research directions include the extension of our work to online algorithms, in order to perform admission and scheduling decisions on-the-fly, based on past observations of the system.



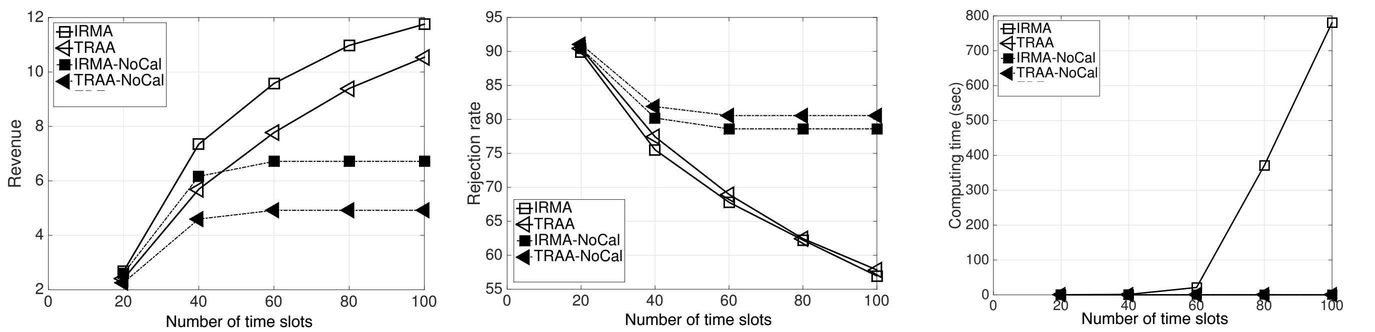
(a) Revenue (b) Rejection rate (c) Computing time

Figure 4: Scenario 1(a)



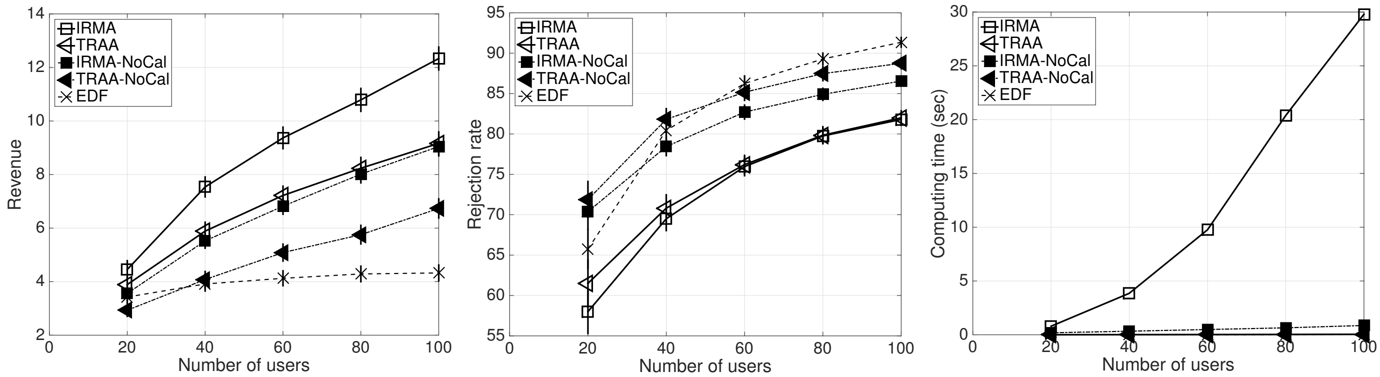
(a) Revenue (b) Rejection rate (c) Computing time

Figure 5: Scenario 1(b)



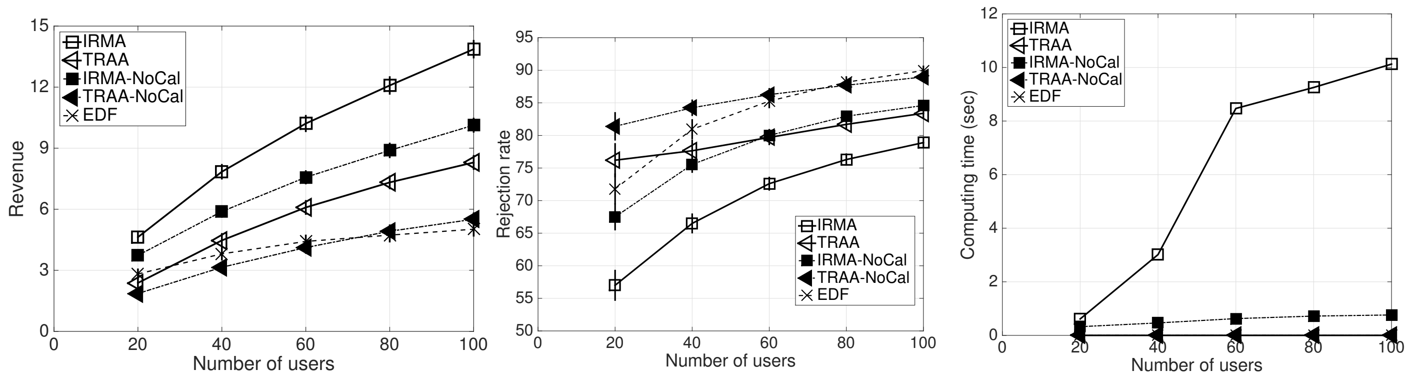
(a) Revenue (b) Rejection rate (c) Computing time

Figure 6: Scenario 1(c)



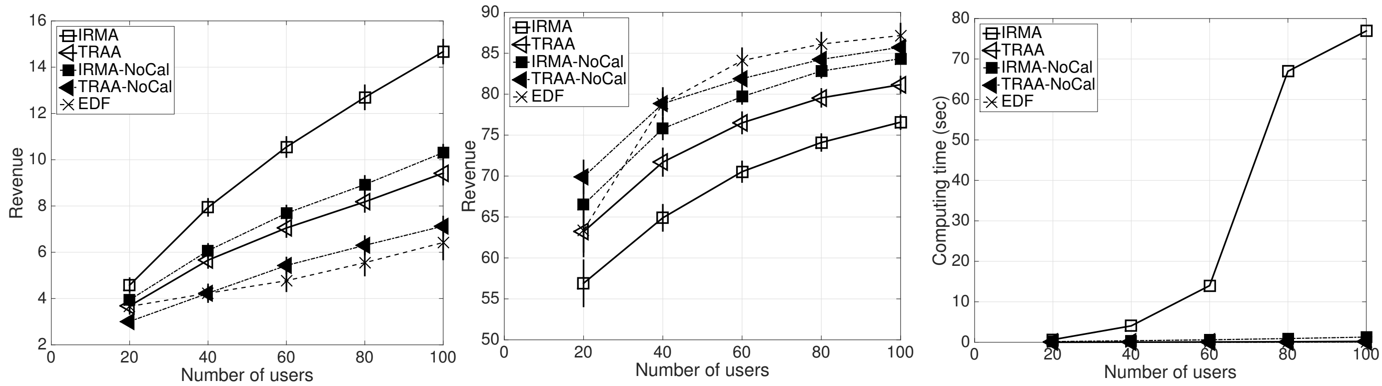
(a) Revenue (b) Rejection rate (c) Computing time

Figure 7: Scenario 1(d)



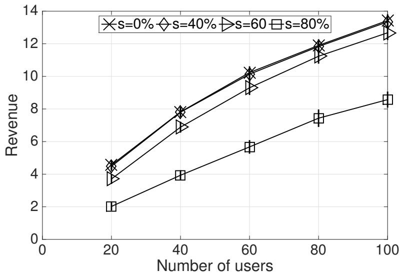
(a) Revenue (b) Rejection rate (c) Computing time

Figure 8: Scenario 2

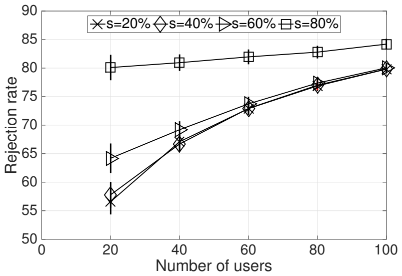


(a) Revenue (b) Rejection rate (c) Computing time

Figure 9: Scenario 3



(a) Revenue



(b) Rejection rate

Figure 10: Scenario 2 - Varying the percentage of users located in the overlapping area (s).

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Appendix A. Proof of Lemma 5.2

Lemma 5.2: The decision making of the TRAA scheme is monotonic.

Proof: We now prove that when user k wins by bidding its truthful bid $b^k = (v^k, R^k, m^k)$, he will still win when he bids (case 1): $\tilde{b}^k = (w^k, R^k, m^k)$ with $w^k > v^k$, (case 2): $\tilde{b}^k = (v^k, \tilde{R}^k, m^k)$ with $\tilde{R}^k < R^k$ and (case 3): $\tilde{b}^k = (v^k, R^k, \tilde{m}^k)$, where $\tilde{m}^k < m^k$

We assume that user k is designated as winner and will start its connection at time slot n, i.e., $x_n^k = 1$.

Let $L(n)$ be the sorted list of weights $\{W_n^k(b^k)\}_k$, in decreasing order, and l^k be the order of user k in $L(n)$ when bidding b^k ($l^k = 1$ if user k has the maximum value among the set $\{W_n^k(b^k)\}_k$).

Let $N_{av}(n)$ be the number of the remaining resource blocks at time slot n; we have $N_{av}(n) \geq R^k$, since $x_n^k = 1$ (because b^k is a winning bid).

- **Case 1:** user k bids $\tilde{b}^k = (w^k, R^k, m^k)$, where $w^k > v^k$. Given that the set of weights and $N_{av}(n)$ will remain unchanged (since they do not depend on user k's bid), the order $\tilde{l}^k$ in $\tilde{L(n)}$ will verify $\tilde{l}^k \leq l^k$ since $W_n^k(\tilde{b}^k) \geq W_n^k(b^k)$ (having $w^k > v^k$) and $N_{av}(n) \geq R^k$. And so, user k will still win by bidding $\tilde{b}^k$.
- **Case 2:** user k bids $\tilde{b}^k = (v^k, \tilde{R}^k, m^k)$ where $\tilde{R}^k < R^k$. Given that the set of weights excluding user k's weight and $N_{av}(n)$ will remain unchanged, we obtain $W_n^k(\tilde{b}^k) \geq W_n^k(b^k)$, since $\tilde{R}^k < R^k$, and so $\tilde{l}^k \leq l^k$. Regarding the number of resource blocks, we have $N_{av} \geq R^k > \tilde{R}^k$, and so $\tilde{b}^k$ is a winning bid.
- **Case 3:** $\tilde{b}^k = (v^k, R^k, \tilde{m}^k)$, where $\tilde{m}^k < m^k$. The same reasoning as the previous cases holds.

Appendix B. Proof of Lemma 5.3

Lemma 5.3: The winner k is charged the critical price such that if $w^k < \delta^k$, user k will lose and if $w^k \geq \delta^k$ user k will win.

Proof: We now prove that if we have $w^k < \delta^k$, user k will not be admitted. Having $w^k < \delta^k$ and $\delta^k = \min_n\{\delta_n^k\}$ gives the following:

$$w^k < \delta_n^k \ \forall n$$

$$w^k < \delta_n^k = \max\{w_0^k, c_n^k\} \ \forall n$$

$$w^k < \delta_n^k = \max\{w_0^k, {\phi^k}^{-1}(R^k m^k V_n^k)\} \ \forall n$$

Since $\phi^k(w^k)$ is monotone non-decreasing, we have the following:

$$\phi^k(w^k) < \max\{0, (R^k m^k V_n^k)\} \ \forall n$$

$$\implies \quad \phi^k(w^k) < R^k m^k \max\{0, V_n^k\} \ \forall n$$

$$\implies \quad \frac{\phi^k(w^k)}{R^k m^k} < \max\{0, V_n^k\} \ \forall n$$

$$\implies \quad \frac{\phi^k(w^k)}{\alpha R^k m^k} < \frac{\phi^k(w^k)}{R^k m^k} < \max\{0, V_n^k\} \ \forall n$$

$$\implies \quad W_n^k(b^k) < \max\{0, V_n^k\} \ \forall n$$

$$\implies \quad W_n^k(b^k) < \max\{0, W_n^{k'}(b^{k'})\} \ \forall n$$

$$\implies \quad W_n^k(b^k) < W_n^{k'}(b^{k'}) \ \forall n.$$

Appendix C. Proof of Lemma 5.4

Lemma 5.4: User k will not maximize his utility by misreporting at least two parameters.

Proof: We distinguish the following 2 cases:

- **Case 1**: If *user* k is **admitted** when bidding its truthful bid $b^k = (v^k, R^k, m^k)$, its utility will be $u^k(b^k) = v^k - \delta^k$. We now prove that user k will not maximize his utility by bidding $\tilde{b}^k = (w^k, \tilde{R}^k, \tilde{m}^k)$ with $\tilde{R}^k > R^k$ and/or $\tilde{m}^k > m^k$:

  Assuming that user k wins when bidding $\tilde{b}^k$, we have:

$\phi^{k^{-1}}(\tilde{R}^k \tilde{m}^k V_n^k) > \phi^{k^{-1}}(R^k m^k V_n^k)$ leading to $\tilde{c}_n^k > c_n^k$, $\forall n$, since V_n^k depends only on the set B_{-k}. Hence, $\tilde{\delta}_n^k > \delta_n^k$ $\forall n$ and $\tilde{\delta}^k \geq \delta^k$, leading to $u^k(\tilde{b}^k) = v^k - \tilde{\delta}^k \leq v^k - \delta^k \leq u^k(b^k)$, $\forall w^k < v^k$ and $w^k \geq v^k$.

If user k loses, its utility $u^k(\tilde{b}^k)$ is equal to 0, leading to $u^k(\tilde{b}^k) < u^k(b^k)$.

- **Case 2**: If user k is **not admitted** when bidding his truthful bid $b^k = (v^k, R^k, m^k)$, his utility will be $u^k = 0$. We now prove that user k will not maximize his utility by bidding $\tilde{b}^k = (w^k, \tilde{R}^k, \tilde{m}^k)$ with $\tilde{R}^k > R^k$ and/or $\tilde{m}^k > m^k$:
  - if $w^k < v^k$: we have $W_n^k(\tilde{b}^k) \leq W_n^k(b^k) < V_n^k$ $\forall n$, since $w^k < v^k$ and $\tilde{R}^k > R^k$ and/or $\tilde{m}^k > m^k$. And so user k will not be admitted and its utility will be equal to 0
  - if $w^k > v^k$: assuming user k wins by bidding $\tilde{b}^k$, there exists $n \in R_t$ such that $W_n^k(\tilde{b}^k) > V_n^k > W_n^k(b^k)$ (knowing that user k loses when bidding b^k, we have $V_n^k > W_n^k(b^k)\,\forall n$). This leads to $\phi(w^k) > \tilde{R}^k \tilde{m}^k V_n^k > \frac{\tilde{R}^k \tilde{m}^k}{R^k m^k}\phi(v^k) > \phi(v^k)$ and also to $w^k > \phi^{k^{-1}}(\tilde{R}^k \tilde{m}^k V_n^k) > \frac{\tilde{R}^k \tilde{m}^k}{R^k m^k} v^k > v^k$, where $\phi^{k^{-1}}(\tilde{R}^k \tilde{m}^k V_n^k) = \tilde{\delta}^k$, and so $\tilde{u}^k = v^k - \tilde{\delta}^k < 0 < u^k$.
  - if $w^k = v^k$ since user k is not admitted when bidding v^k, we have $W_n^k(v^k, R^k, m^k) < V_n^k$ $\forall n$. With $\tilde{R}^k > R^k$ or $\tilde{m}^k > m^k$ we will have $W_n^k(v^k, \tilde{R}^k, \tilde{m}^k) < W_n^k(v^k, R^k, m^k) < V_n^k$ $\forall n$ and so user k will not be admitted to the system.