Computer Communications 114 (2017) 22–35

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Virtualized resource sharing in cloud radio access networks: An auction approach

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ARTICLE INFO

Keywords:
Cloud radio access networks (C-RAN)
Network function virtualization (NFV)
Mechanism design

ABSTRACT

As mobile terminals proliferate and mobile Internet traffic explodes, demand for efficient and high capacity cellular access escalates. Two fundamental techniques are being implemented to help meet such a demand. The first is virtualization based, centralized cloud processing. Baseband signals are sampled and transmitted through front-haul links to a mobile cloud, for processing by mobile base station instances deployed in an on-demand fashion. User and channel information are aggregated to the cloud, facilitating optimized decision making. The second is the separation of infrastructure ownership from service provisioning in cellular networks. The "Tower" company now specializes in deployment and maintenance of the cloud-radio access network (C-RAN) infrastructure. Mobile operators focus instead on their sole business of wireless service provisioning. Mobile operators lease C-RAN resources that include spectrum resources at remote radio heads, front-haul bandwidth and mobile base station instances. This work proposes a natural auction approach for inter-operator resource sharing, where each operator bids a capacitated sub-network of the C-RAN. Drawing from the theories of Maximal-in-Range auctions and efficient graph algorithms, we design and test a C-RAN resource auction that is truthful, polynomial-time computable, and achieves close-to-optimal social welfare.

1. Introduction

As mobile devices and applications proliferate and mobile access to the Internet grows, demand on capacity and efficiency of cellular networks escalates. The transition from 4G (LTE and LTE-Advanced) to 5G cellular technologies in the upcoming years aims to provide substantially enhanced system capacity and data transmission efficiency through a number of new technologies that include cloud computing based radio access networks (C-RAN) and network function virtualization (NFV) [30]. The fundamentally new technologies in future cellular networks demand new resource management algorithms and protocols that work in concert with infrastructure and hardware changes. This work draws the community's attention to the problem of virtualized resource sharing among mobile operators in a C-RAN, and designs and tests auction based solutions.

An important infrastructure revolution in cellular networks is the deployment of C-RAN, for cloud computing based, centralized information processing and system optimization. A traditional base station (BS) includes a complex signal processing unit, for A/D D/A conversion [31]. The processing capacity of the BS needs to be large enough even in peak hours. However, traffic volume at a BS fluctuates dramatically across the temporal domain, and peak traffic volume may be substantially higher than average. As a result, the utilization of an individual BS is rather low. As inter-BS sharing of processing resources is infeasible in the traditional cellular infrastructure, considerable processing capacity and energy are wasted. The cloud radio access network (C-RAN) is a new cellular network infrastructure based on cloud computing and NFV [32]. Remote Radio Heads (RRHs) at BSs are to be greatly simplified, with functions pushed toward mobile clouds (data centres) that each manages a group of BSs. Analog signals from RRHs are sampled, quantized, and transmitted through a front-haul network to the cloud. The cloud hosts a pool of virtual BS instances for processing baseband signals with functions such as channel coding and modulation. Virtual BS instances are provisioned in an elastic fashion, following realtime demand from RRHs. Centralized information and processing in the C-RAN further facilitates system-wide optimization and cost-saving, such as centralized management, cooperative communication and joint decoding [21].

Another important trend in cellular networks is service-infrastructure separation, *i.e.*, the separation of infrastructure ownership

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http://dx.doi.org/10.1016/j.comcom.2017.09.012
Received 30 September 2016; Received in revised form 11 May 2017; Accepted 25 September 2017
Available online 05 October 2017

from cellular service provisioning. Constructing and operating BSs represents a major expense of traditional mobile operators. For example, carriers in China spent more than $200 billion US to maintain and build BSs from 2008 to 2012, but the utilization rate of the processing resources and fibre-optic links is only 1/3 [2]. The creation of the "Tower" company was recently witnessed in a few markets around the world since 2013 [3]. In China, a national Tower company was created in July 2014, taking over BSs from three major mobile operators [3]. The Tower company is responsible for designing, building and maintaining BSs. It further operates regional data centres that manage BSs and process baseband signals. In the US, AT&T sold their BS subsystem in October 2013 to Crown Castle, currently the largest provider of shared cellular infrastructure in the US with approximately 40,000 BS towers [1]. The vision of 5G and beyond is that the Tower company is dedicated to the deployment and ownership of the C-RAN infrastructure. Mobile operators are freed from infrastructure maintenance, and focus explicitly on their core business of providing the best mobile Internet service. Using virtualization technologies, mobile operators lease resources (spectrum resources at BSs, virtual BS instances and front-haul bandwidth) from the Tower company to serve their customers.

Similar to the cloud computing market where long term contracts and short term auctions complement each other for meeting customers' need of virtual machine instances, mobile operators are expected to sign long term contracts for baseline service coverage, and acquire additional resources in short term through auctions to cover temporal and spatial demand spikes. This work proposes an auction based market mechanism for such short-term C-RAN resource leasing. Such a C-RAN auction has a salient feature that separates itself from wireless spectrum auctions [12] and virtual machine auctions [26] that have been extensively studied — the bid of each mobile operator is naturally expressed as a sub-network of the C-RAN, and the C-RAN faces a sub-network packing problem in social welfare maximization. We study the C-RAN resources auction under two front-haul models: point-to-point, *i.e.,* every BS has its own fibre to the cloud, and daisy chain, *i.e.*, BSs share fibre links to the cloud in groups.

The underlying sub-network packing structure renders the C-RAN auction NP-hard, even if truthful bids are given for free. The key techniques we employ for designing an efficient and truthful auction include (a) exploiting the planarity of the C-RAN topology, and (b) Maximum-in-Range (MIR) auction theory. **First**, we design an exact algorithm to maximize social welfare over a given solution space of feasible C-RAN resource allocation. The time complexity of the exact algorithm is highly dependent on the structure of the feasible solution space to which it is applied, and is exponential over the entire feasible solution set. **Second**, our auction pre-commits to a set of carefully chosen solutions of social welfare maximization problem, such that (a) the chosen set is well-structured and allows polynomial-time maximization of the social welfare using the exact algorithm, and (b) the set is sufficiently large and effective, so the optimal solution inside this set approaches global maximum sufficiently closely. An alternative view to the second step is that the exact algorithm together with the pre-commit-ment step constitutes an approximation scheme to the C-RAN welfare maximization problem. **Third**, we adapt VCG-style payments to work in concert with the exact algorithm and the pre-commitment step, and show that the auction is truthful. The end result is a C-RAN resource auction that is truthful, polynomial-time computable, and guarantees $(1 - \epsilon)$ economic efficiency. We next provide a more detailed overview of the key steps.

We formulate the C-RAN social welfare maximization problem as an integer linear programming problem, which is proven to be NP-hard even for a constant number of BSs or a constant number of mobile operators. We first design an exact algorithm for computing an optimal allocation among a given feasible solution set. The exact algorithm exploits the unique planar topology of a C-RAN, and combines dynamic programming and planar graph bisection techniques in an algorithm that is as computationally efficient as possible, while guaranteeing output optimality. The running time of the exact algorithm is exponential on the original solution space, and is proven to be polynomial on the well-structured subspace of solutions that we pre-commit to.

Given the exact algorithm, an obvious solution is to apply it together with the VCG auction framework to obtain a truthful C-RAN auction. However, such a VCG auction can handle only very small C-RAN topologies. Empirical results show that the computation time of the VCG auction for a C-RAN system with a few layers of BSs already exceeds one minute. A key step in our C-RAN auction design is to utilize the exact algorithm on a well-structured subspace of solutions, obtaining a much more efficient approximation scheme. Our empirical studies suggest that our C-RAN auction algorithm can handle a C-RAN topology consisting of thousands of base stations in seconds. The idea in our approximation scheme design (solution subspace selection) is based on the observation that the running time of the exact algorithm is exponential to the parameter k, for a C-RAN topology that is k-outerplanar (k layers of BS cells). Instead of working directly on a k-outerplanar C-RAN, the auction examines instead a sequences of dissected outerplanar graphs, each with a series of k'-outerplanar components, where k' is a constant smaller than k. Our approximation scheme is parameterized by a tunable constant ϵ, based on which we can tradeoff between solution optimality and computational complexity.

Given the approximation scheme, our final step towards the C-RAN auction design is to apply the MIR auction design technique that has recently witnessed a number of successful applications [4,22]. We take a retrospect on the approximation scheme, verify that it effectively pre-commits to a well-structured subset of feasible solutions. The approximation ratio analysis provides a guarantee that the optimal solution in the subset is indeed close to the optimal solution in the entire feasible solution set. The approximation scheme can therefore be combined with a VCG-style payment mechanism to become an MIR auction, which is efficient, elicits truthful bids for C-RAN resources from mobile operators, and guarantees close-to-optimal social welfare.

To verify the efficacy of the proposed C-RAN auctions for inter-operator resource sharing, we have conducted extensive real-world trace-driven simulation studies, verifying the time efficiency, the social welfare performance, and details in the resulting resource allocation in both point-to-point and daisy chain front-haul models. Simulation results for large scale C-RAN systems show that the proposed auctions can handle C-RAN graphs with up to thousands of BSs; the resource allocation from the auction achieves about 99% of maximum social welfare. That suggests in real world systems, the performance of the auction algorithm can be much better than the guaranteed approximation ratio, which corresponds to the theoretical worst case.

In the rest of the paper, we review background and related work in Section 2, and describe the C-RAN system model in Section 3. Sections 4 and 5 present the auction schemes for C-RANs with point-to-point front-hauls and daisy chain front-hauls, respectively. Section 6 presents performance evaluation. Section 7 concludes the paper.

2. Background and related work

Resources for lease through the C-RAN auction include spectrum resources, virtual BS instances and front-haul bandwidth. Although existing studies abound on spectrum auctions [10,12] and cloud resource auctions [34,37], this work is the first that tailors a truthful auction for the C-RAN system to allocate all three types of resources, which has a unique sub-network packing structure.

We briefly overview the background on C-RAN spectrum resources. Current mobile networks support both frequency-division duplex (FDD) and time-division duplex (TDD) modes [16]. FDD splits the channel frequency into many small *subcarriers* spaced at 15kHz, and then modulates each individual subcarriers using a digital modulation scheme (*e.g.,* 64-QAM). TDD splits a subcarrier into alternating time periods for downlink and uplink transmission. In future mobile