HEURISTICS FOR COMBINATORIAL AUCTION-BASED CHANNEL ALLOCATION APPROACHES IN MULTI-CONNECTIVE WIRELESS ENVIRONMENTS

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Abstract: In this paper we discuss the applicability of combinatorial auction-based channel allocation approaches in multi-connective environments, where tenants place bids for the subsets of channels. Two heuristical approaches are defined in order to reduce the computational requirements of the channel allocation algorithms. Each heuristics is based on the limitation of the bid set of tenants to avoid the combinatorial explosion, which arises if all subsets of the channels is considered in the process. The first proposed method narrows down the bid set based on the distance of the relevant base stations, while the second proposed method uses a many-to-many matching algorithm to pre-allocated the channels to tenants. In the combinatorial auction, tenants place bids only for the subsets of the pre-allocated channels. We compare the performance of the two proposed approach via simulation.

Keywords: combinatorial auction, resource allocation, multi-connectivity, wireless networks

1 INTRODUCTION

Ultra-reliable low latency communications (URLLC) is identified as one of the essential use cases of emerging fifth generation (5G) mobile wireless communications systems [2]. URLLC requirements are highly relevant in emerging applications as industrial automation and vehicular communications. One possible concept for enabling URLLC is multi-connectivity [6], i.e. using multiple communication paths at once. In this case, the redundancy of communication channels increases the reliability of the communication architecture. In the current paper we are focussing on channel allocation problems, where the channels (representing the communication paths) are considered as indivisible goods, which have to be allocated to objects (e.g. mobile industrial robots or similar entities) called *tenants* in our context. As one channel may be allocated to one tenant, while one tenant may receive multiple channels, the task boils down to a combinatorial optimization problem, where we look for the optimal allocation, according to a certain measure (e.g. the total capacity of the system) [5].

As each bundle (subset) of the available channels implies a different outcome for each tenant, the combinatorial auction (CA) method [7] seems a reasonable candidate to serve as the principle of the allocation algorithm. In real-life applications however, the number of objects (channels) to be allocated often exceeds the limit, which can be handled computationally by this approach. In this paper we introduce problem-specific heuristics to define two channel allocation algorithms in an assumed industrial environment, and compare their efficiency in the terms of the total allocated capacity and required computational time, based on simulations. In both of the proposed algorithms, we will suppose that tenants, who will be acting like bidders of the CA, will consider only a subset of the available channels. This assumption allows to significantly reduce the number of bids considered in the CA process.

2 MODEL

In this section we describe the computational framework used for the description of multi-connective communications.

2.1 General framework

In the current paper, we will assume that the available channels are served by base stations (BSs) to the tenants. Let us denote the the number of tenants by n_T, and the number of base stations by n_{BS}. In addition, the vector $n_{ch} \in \mathbb{R}^{n_{BS}}$ describes the number of channels at the individual base stations. The set of all channels is denoted by CH. We assume furthermore, that different channels of any BS exhibit the same properties.

The connectivity function of tenant k, denoted by $\rho_k : 2^{CH} \rightarrow \mathcal{R}$, describes the maximal achievable rate of communication for tenant k, if any subset of CH is allocated to tenant k. We assume that $\rho_k(S_1) \leq \rho_k(S_2)$ if $S_1 \subseteq S_2$.

For the exact determination of the connectivity function, in this paper we use the URLLC multi-connectivity model described in [3], with the path loss model

$$PL(d) = PL(d_0) + 10\delta log_{10}\left(\frac{d}{d_0}\right) \tag{1}$$

and parameters summarized in Table 1.

parameter	notation	value	unit
Rician factor	K	14.1	dBm
channel bandwidth	B	20	MHz
reference distance	d_0	15	m
reference PL	$PL(d_0)$	70.28	dB
PL exponent	δ	2	-
outage probability threshold	ϵ	10^{-9}	-
transmit power	P^T	15-25	dBm
interference power	P^I	-50	dBm

Table 1: Model parameters. The value of P^T was considered as a random variable for each BS in the simulations, with uniform distribution between 15 and 25.

We consider a 100m x 50m factory area, with 8 BSs, located on the factory walls (with random positions). We assume that each BS offers 1-3 channels, but the total channel number is no more than 20. In addition, we assumed 6 tenants with random positions.

To give an impression about the connectivity function in the case of this modelling framework and parameters, let us consider a tenant at the position (8.47,11.52) and two BSs, at the positions (0,0) and (100,13) respectively, both with 2 channels available. We assume the transmit power values $P_1^T = 23$ for BS 1 and $P_2^T = 16$ for BS 2 respectively.

If a single channel of BS 1 is assigned to the tenant, its resulting capacity will be 0.054 Mbps. If we assign one channel of BS 2 to the tenant (BS 2 is more far from the tenant) this value is 0.0037. In the case of two channels from BS 1, the result is 16.042, while in the case of two channels from BS 2 this value is 1.4595. Considering one channel from BS 1 and one from BS 2, the resulting capacity is 4.4016. In general, any number of channels may be assigned to a single tenant. If e.g. both channels of BS 1 and both channels of BS 2 is assigned to the tenant, the resulting capacity will be 20.5995. Based on the formulas described in [3], and on the parameters summarized in Table 1, the resulting capacity for all possible channel combinations may be calculated for the tenant (and for any other tenants in different positions). The principle behind the calculations is the reliability-based approach. In the URLLC framework, the communication fails if all of the assigned channels are down, and these events are considered independent. This explains, why an additional channel beyond the first significantly enhances the performance (redundancy arises), while additional channels after e.g. 3 or 4 already assigned channels do not bring too much additional benefit.

2.2 Assignment algorithms

The following assignment algorithms have been considered in the study.

2.2.1 Random assignment (RA)

This algorithm was used as a reference case. In this case, the available channels are randomly assigned to tenants, considering only $\bar{n}_{ch} = 4$ as a limiting factor, which describes that no tenant may receive more than 4 channels.

2.2.2 Distance-based semi-random assignment (DbsRA)

This algorithm is similar to the RA method, but in this case, to increase efficiency, each channel is allocated with higher probability to closer tenants. The probability weighting used is inversely proportional to the distance of tenants.

2.2.3 Distance-based Combinatorial auction (DbCA)

The input of the CA algorithm [7] is the set of bids. Each participant or player (here the tenants) submits a finite number of bids, where each bid corresponds to the value of a certain bundle of the available goods (in this case the channels). In this model, the value of a certain bundle of channels is determined by ρ_k for tenant k. The next step of the CA algorithm is to solve an integer optimization problem, which maximizes the value of the accepted bids, under the constraints that (I) for each player maximum one of its bids may be accepted, and (II) one item may be assigned maximum to one player.

If we consider all subsets of the available channels for all tenants, the principle of the CA boils down to brute-force optimization, and leads to a computationally infeasible problem (for 20 channels, every tenant would submit $2^{20} - 1$ bids). In the case of the DbCA, we use a very simple principle to reduce the cardinality of the bid sets: Every tenant considers only the channels of the two closest BS (thus maximum 6 channels in the case of the current parametrization). This way, the number of bids submitted for each tenant is $< 2^6$.

It may however happen, that according to this 'pre-assignment' of channels, channels of one or more BSs will not appear in the bids (if there are BSs present, which are relatively far from every tenant compared to other BSs). Not assigning a channel would significantly decrease the overall performance of the system (unused resource), thus in this case, we randomly assign these channels to tenants to complete the pre-assignment process. In the next step, all tenants evaluate all possible subsets of the pre-assigned channels, and thus determine the bids of the CA process.

2.2.4 Gale-Shapley based Combinatorial auction (GSbCA)

In the case of this method, the pre-assignment of channels is performed differently compared to the DbCA method. In this case, for the first step of the pre-assignment, we use the many-to-many matching version of the Gale-Shapley algorithm [1]. To do this, first we have to set up preferences for the tenants over the channels and vice versa. In this case this is done by simply considering the tenant-BS distances (for each channel we consider the relevant BS), in the sense that closer entities prefer each other to more far alternatives. In addition we have to define quotas for both the tenants and the channels (denoted by q_T and q_{ch} respectively).

In this case we assumed $q_T = q_{ch} = 6$, implying that to each tenant maximum 6 channels are allocated in the pre-assignment process, and any channel is allocated to maximum 6 tenants.

This method does not guarantees either that all channels will be pre-assigned to, thus again, we assign the potentially remaining channels at random to tenants. After the pre-assignment is done, the further steps of the algorithm are the same as in the case of the DbCA method.

3 RESULTS AND DISCUSSION

We evaluated the proposed assignment algorithms via simulation. The algorithms have been performed in the case of 1000 scenarios. In each scenario, the following variables have been randomized:

- The positions of the BSs at the boundary of the simulation area.
- The positions of the tenants in the simulation area.
- The number of channels per BS (1-3) with a total maximum of 20.
- The transmit power of BSs (15-25 units).

The results of the simulations in the context of the total assigned capacity are depicted in Fig. 1.

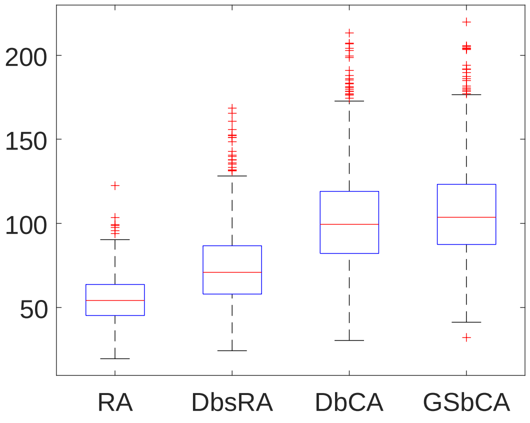

Figure 1: Total capacity in MBps in the case of the various assignment algorithms. In the box plot, the central mark is the median, while the edges of the box are the 25th and 75th percentiles respectively. The whiskers extend to the most extreme data points which are considered not to be outliers, and the outliers are plotted individually with red crosses. The median vales are respectively 54.18, 70.87, 99.38 and 103.63 for the four algorithms.

In the case of the RA and DbsRA, due to the highly indeterministic nature of the algorithms, 10 runs were performed for each scenario, and the average values were considered as the result for the actual scenario. As it can be seen in Fig. 1, the DbCA algorithm implies a 83.42 % improvement in the total system capacity, compared to the RA. One may argue that the RA includes extremely contra-intuitive assignments as well (as it is possible that every channel is assigned to more distant tenants). If we compare the improvement to the DbsRA, this improvement of the DbCA is 40.23 %. These values are 91.27 % and 46.22 % in the case of the GSbCA.

The results of the simulations in the context of computational time are depicted in Fig. 2.

The results depicted in Fig. 2 show that the CA-based algorithms require significantly more time compared to the very simple reference scenarios (RA and DbsRA), but typically they may

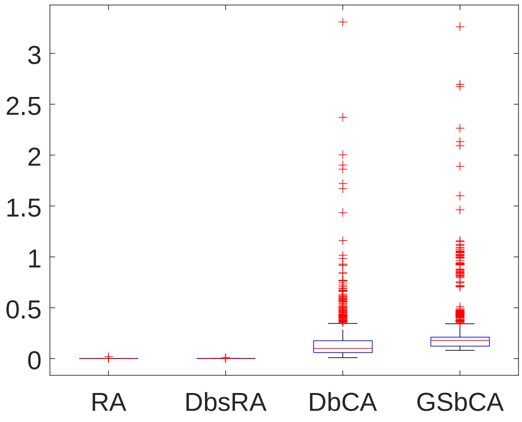

Figure 2: Computational time in s in the case of the various assignment algorithms. The median vales are respectively 0.0008, 0.0011, 0.1007 and 0.1782 for the four algorithms. The simulations were run on a standard desktop PC (Intel core i5 @ 2.9 GHz, 16 GB RAM, 64 bit OS, MATLAB environment).

be performed in 1 sec, or in a few seconds worst case. Considering movement-induced reconfiguration in the case of industry-automation applications (as e.g. mobile industrial robots), this seems to be an acceptable value.

3.1 Discussion

One additional aspect, which may be considered as a measure of channel assignment algorithms is fairness. In this context, fairness usually translates to the capacity value of the tenant with minimal capacity in a particular scenario. In this paper, it was not among our aims to include any fairness guarantees in the assignment algorithms, but for the sake of completeness, results in this context may be depicted as well. The minimal assigned capacity values are depicted in Fig. 3.

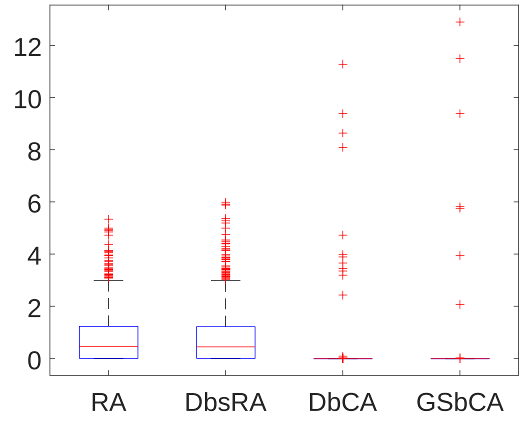

Figure 3: Fairness: Minimal capacity in MBps in the case of the various assignment algorithms. The median vales are respectively 0.46, 0.44, 0 and 0 for the four algorithms.

As it may be seen in Figs. 3 and 1 as well, there is usually a tradeoff between fairness and efficiency. More efficient algorithms in general tend to allocate every channel to tenants, for which the greatest resulting capacity may be provided, thus potentially leaving some tenants without any resources. There are algorithms, as e.g. the 'weakest selects' algorithm [4], which aim to optimize not the total efficiency, but the fairness of the resulting allocation. The framework of the CA algorithm however allows the inclusion of constraints corresponding to the minimal resulting value (capacity) of participants, thus this issue may be explicitly addressed in the future.

In addition, let us note that although the number of channels per BS was randomized in the simulations, the range of this parameter was assumed to be low (1-3), while the number of BSs was relatively high compared to the number of tenants (8 vs 6). To determine if the results are valid for qualitatively different configurations as well (few BSs, each with high number of channels), further studies are necessary.

4 CONCLUSIONS AND FUTURE WORK

In this paper we proposed two CA-based allocation algorithms for channel allocation in multi-connective wireless environments. Based on simulations we have shown that the considered algorithms are efficiently allocating the resources in the analyzed setups, while their computational requirements also remain on an acceptable level. The next step will be to compare the performance of the algorithms and their potential future adjusted versions (let us consider e.g. the inclusion of constraints allowing minimum allocated capacity for each tenant) with other allocation schemes used in the multi-connective context, like the Gale-Shapley algorithm used [3], according to various measures, including fairness as well.

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