




RESEARCH ARTICLE

Integrating dynamic spectrum access and device-to-device via cloud radio access networks and cognitive radio

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Summary

Dynamic Spectrum Access (DSA) can be integrated with Device-to-Device (D2D) communications to enable the exploitation of unused spectrum portions and to address the spectrum scarcity problem. Spectrum management mechanisms integrated into DSA and D2D allow low-power communications between User Equipments without interfering with licensed primary users. However, these mechanisms tend to be energy and processing intensive, being unfeasible to implement in User Equipments with strict battery and processing limitations. On the other hand, Cloud Radio Access Networks already leverage the virtually unlimited computing capacity of clouds for baseband processing functions. Thus, in this article, we propose the Cognitive Radio Device-to-Device (CRD2D) approach aiming to offload spectrum management functionality to the cloud taking advantage of Cloud Radio Access Networks architecture to support the integration of DSA and D2D.

KEYWORDS

cloud radio access networks, cognitive radio, C-RAN, device-to-device, DSA, dynamic spectrum access, D2D

1 | INTRODUCTION

Dynamic Spectrum Access (DSA) is a key technology to support the worldwide growth of spectrum demand through opportunistic access to unused licensed frequencies, ie, spectrum holes.¹ For the past 10 years, the most successful implementation of DSA is oriented to fixed and long range communication for rural area deployments using spectrum holes over analog TV bands, *a.k.a.* white spaces.² At the same time, in urban areas, where spectrum scarcity is more evident, there is no well-established deployment of DSA due to the high density of licensed Primary Users (PUs). Recent advancements point to the usage of DSA for low-power and low-range communications, creating small cells with fewer chances to interfere with PUs.³ Therefore, as an effort to introduce DSA in urban areas, we investigate the usage of Device-to-Device (D2D) networks. On D2D, User Equipments (UEs) may exploit spectrum holes to offload content or act as a relay node to others, using low-power and short-range communications within the next generation of mobile networks (5G).⁴

The integration of D2D and DSA requires complex processing as it relies on spectrum management mechanisms to detect and exploit spectrum holes.⁵ These mechanisms require continuous processing of workload based on spectrum samples, which increases in complexity according to the bandwidth, number of channels analyzed, and environmental

variables considered (eg, noise, waveform, and power).⁶ User Equipments do not support the continuous processing of heavyweight workloads given their limitations, such as restrained processing capacity and energy source based on batteries. In this case, it is possible to overcome these limitations by relying on Cloud Radio Access Network (C-RAN) architecture to perform DSA spectrum management operations.

Cloud Radio Access Network introduces digital functional units called Baseband Processing Units (BBUs) that are connected through optical links to radio units called Remote Radio Heads (RRHs). These RRHs are responsible for sampling the spectrum as well as transmitting and receiving signals. The role of BBUs, in turn, is to centralize the computing of heavy workloads, such as radio resource management and signal processing.⁷ We argue that the centralized processing inherent of C-RANs can be used to process the workload of DSA on establishing D2D networks. Since C-RAN was conceived to support licensed access regime technologies,⁸ such as Long Term Evolution, its architecture and units are not prepared to support DSA and D2D, thus requiring redesign.

Therefore, in this article, we propose a Cognitive Radio Device-to-Device (CRD2D) approach to integrate DSA and D2D within a C-RAN architecture. This approach enables UEs to receive decision messages from BBUs based on spectrum sampling from RRHs, exploiting underused spectrum bands with low power connectivity to relay or offload data among other devices. We evaluate the proposed approach in selecting channels for D2D communication, comparing spectrum management algorithms. As our main contributions, we highlight (1) the proposal of CRD2D approach, (2) an analysis and discussion of requirements raised when Cognitive Radio (CR) and C-RAN are merged within CRD2D, and (3) an experimental comparison between different spectrum management algorithms to improve the performance of CRD2D. Our results present a comparison of spectrum management algorithms considering the following criteria: (a) interference with licensed user, (b) transmission throughput achieved, (c) execution time, and (d) complexity. To the best of our knowledge, we are the first to propose an approach that considers the integration of DSA and D2D into a C-RAN architecture to supply the growth of spectrum demand.

The remainder of this article is organized as follows. In the next section, we describe the concepts, requirements, and challenges of employing DSA and D2D communication in a C-RAN architecture. In Section 3, the proposed CRD2D approach is presented and described. Moreover, in Section 4, we detail our experimental scenario designed to evaluate spectrum management algorithms and discuss the results obtained. Finally, our conclusions and directions for future work are presented in Section 5.

2 | CONCEPTS, REQUIREMENTS, AND CHALLENGES

Dynamic Spectrum Access is a key technology to address the ever growing spectrum demand that when integrated with low power D2D communications enables urban deployments. However, UEs cannot cope with the spectrum management inherent from this integration due to their processing and energy supply limitations. Thus, C-RAN elements (ie, BBU and RRH) can be used to perform spectrum management sparing UEs processing and energy resources. Because these elements were not conceived to detect spectrum holes and orchestrate the establishment of D2D communication, adaptations are required to support such feature. To determine which are the adaptations required in C-RAN, we rely on CR functions, namely, (a) spectrum sensing, (b) spectrum decision, (c) spectrum sharing, and (d) spectrum mobility.⁹ In the remainder of this section, we review each of these functions, discussing their conceptual definition from literature, the necessary adaptations to perform them over C-RANs, and the requirements and challenges involved in implementing these adaptations.

2.1 | Spectrum sensing

Concept: Spectrum sensing is responsible for detecting PUs and determining the vacancy status of a spectrum hole by using techniques such as energy detection, cyclostationary, and matched filtering.¹⁰ The ability to accurately detect spectrum holes in a coverage area determines a sensed area, as presented in Figure 1. Outside the sensed area (blind area), no reliable information can be retrieved about spectrum holes, invalidating the creation of opportunistic communications.

Adaptation: In C-RAN, spectrum sensing must be split in 2 parts: sampling and processing. The sampling part of spectrum sensing needs to be performed by RRHs. In comparison with the UE antennas, RRHs can cover much larger regions, expanding significantly the sensed area. On the other hand, the processing of spectrum samples must be performed by BBUs, which are far more capable performing computing intensive operations.

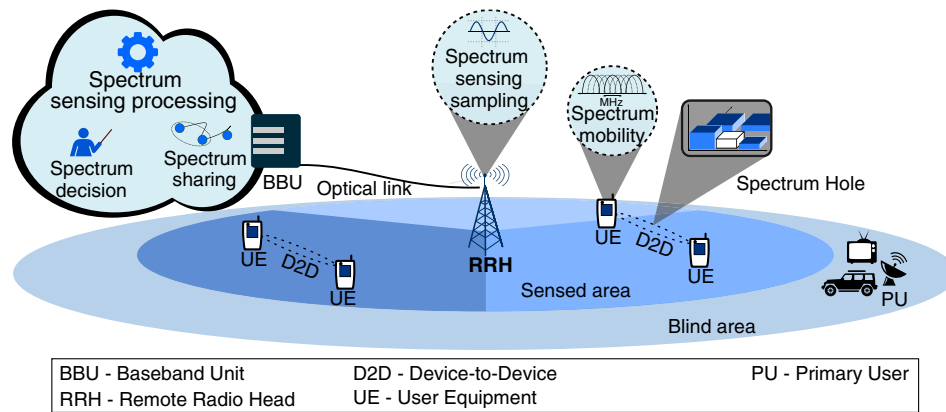


FIGURE 1 Cognitive radio functions adapted to Cloud Radio Access Networks

Requirements: Baseband Processing Units need to be redesigned to perform spectrum sensing techniques, which require plenty of processing capacity. Because RRH's sensing samples must be processed in a different module within the BBU, the fronthaul network must be able to forward the sensing samples multiplexing the traffic to the correct module within the BBU before baseband processing. Moreover, the RRH must present an antenna dedicated to performing spectrum sampling.

Challenges: A major challenge in this context is to reduce the delay incurred due to remote sample processing (eg, queuing, propagation, and transmission delay). This delay is added to the time required by the sensing technique to process the spectrum samples that must be a fraction of the spectrum hole duration; otherwise, the D2D communication loses throughput by missing transmission opportunities. Furthermore, spectrum sensing must be processed within a stringent time budget (few milliseconds) to keep the spectrum hole status validity. As the UE is not performing spectrum sensing, the radius of the sensed area and accuracy in the detection of PUs become a direct function of the RRH coverage area, the spectrum sensing mechanism, and the type of PU considered (eg, radar, television, or another operator).⁶

2.2 | Spectrum decision

Concept: This function is responsible for deciding which spectrum holes will be assigned for each opportunistic transmission.¹¹

Adaptation: In C-RAN, the spectrum decision must be centralized within the BBU to control all D2D communication occurring, coordinating remotely which are the spectrum holes in use, between which UEs, and during what period.

Requirements: Baseband Processing Units are specifically designed for baseband processing. Thus, they require redesign to support spectrum decision and other CR functions. Moreover, spectrum decision requires storage to support the execution of algorithms based on statistical spectrum analysis that estimate the status of spectrum holes.¹²

Challenges: As the spectrum decision is also a time-constrained function that scales with the network size and the number of spectrum holes, the primary challenge to perform it over C-RANs is again the delay inserted because of remote processing requiring minimization of its execution time. Additionally, as opposed to baseband processing—which tends to have a relatively fixed workload—the variability of opportunistic D2D communications introduces unpredictability, pushing the scalability aspect of C-RAN to allocate CPU and memory resources more flexibly to speed up the decision process.

2.3 | Spectrum sharing

Concept: Spectrum sharing is responsible for orchestrating devices that are interested in sharing the same spectrum holes.¹³

Adaptation: In C-RAN, information from UEs interested in performing D2D needs to be transmitted to BBUs to be processed. This enables BBUs to exchange such information and identify overlapping D2D communications competing for a spectrum hole even under the coverage area of different RRHs.

Requirements: Spectrum sharing requires a backhaul interconnecting BBUs to synchronize and retrieve the list of UEs that are interested in performing D2D. Also, this function is time-constrained and scales in complexity according to the number of spectrum holes sensed and UEs.

Challenges: The main challenge of spectrum sharing is to provide an efficient mechanism to trigger the communication between BBUs wisely (eg, synchronizing spectrum sharing lists only among RRHs with overlapping areas), avoiding extra delay to be added. Furthermore, as spectrum sharing requires BBUs to communicate, it is restricted to the topology employed hindering expansions.

2.4 | Spectrum mobility

Concept: The spectrum mobility function enables a UE to hop among spectrum holes according to the spectrum decision coordination.¹⁴

Adaptation: In C-RAN, the spectrum mobility must reside inside the UE to control and manage the UE D2D radio interface parameters (such as bandwidth and central frequency) to exploit spectrum holes.

Requirements: Spectrum mobility requires programmability to control the UE radio interface parameters. Moreover, this function must be coordinated by the spectrum decision function within the BBU. Thus, the UE must be able to receive signaling messages from the BBU to establish D2D communications with other UEs.

Challenges: The primary challenge in performing spectrum mobility in the UE is controlling the delay between detecting a PU and notifying the UE to leave the spectrum hole. Also, the coordination of D2D pairs regarding their radio parameters must be carefully performed avoiding misconfiguration and desynchronization, causing throughput degradation and potentially missing spectrum holes.

Cognitive Radio functions add several requirements and challenges to C-RAN, forcing adaptations in BBUs, RRHs, and UEs. The faster the CR functions are executed, the larger is the transmission window over a spectrum hole. Moreover, it is natural to expect that the centralization provided by the BBU simplifies the synchronization and control of active D2D communications. However, splitting functions between BBUs, RRHs, and UEs insert delay due to remote processing, being the greatest challenge of deploying D2D communication using DSA in C-RAN. Thus, in the next section, we propose the CRD2D approach that merges CR functions within a C-RAN architecture to support the integration of DSA and D2D, addressing the requirements presented and discussing the challenges raised.

3 | CRD2D APPROACH

In this section, we describe the CRD2D modules necessary to integrate DSA and D2D with a C-RAN architecture. In Figure 2, the 3 main elements of CRD2D can be seen in light gray boxes. Darker boxes with solid borders are modules that are either new or redesigned to employ CRD2D. Lighter boxes with dashed borders are already existing modules required but not modified. In the next subsections, we describe each element of the CRD2D approach, discussing their functionality, benefits, and drawbacks.

3.1 | User equipment

In CRD2D, inside the UE (eg, a smartphone) resides the CRD2D framework, a software library for applications that need to rely on D2D communications. This framework is fundamental to identify potential candidate applications to create a D2D network on demand according to the content they want to share or use, for example, proximity-aware social networking, gaming, or media sharing. The CRD2D framework makes use of the CRD2D API to cooperate with other 3 modules in the UE: (1) D2D radio interface; (2) Cognitive radio module; and (3) Common radio interface. This API aims to create a single set of abstractions and operations to access all CR and D2D functionalities from all the independent modules involved. The D2D radio interface is used for D2D communications leveraging Spectrum holes. The Cognitive radio module enables the UE to perform spectrum mobility by providing the parameters to control the D2D radio interface,

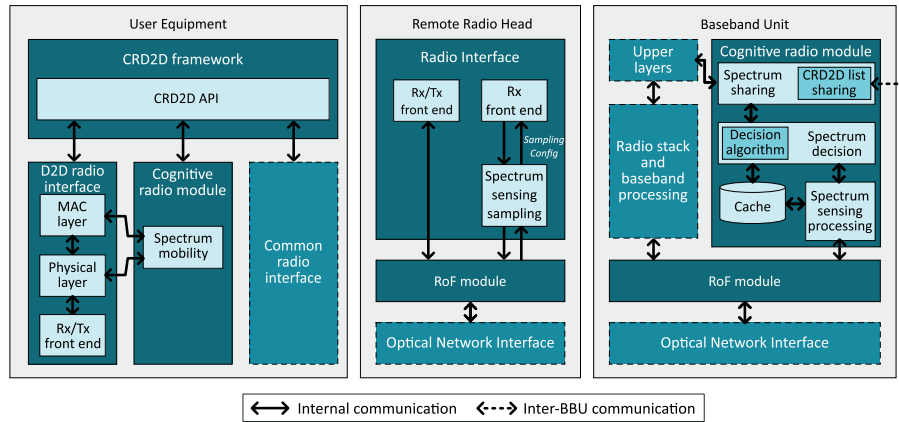


FIGURE 2 A Cloud Radio Access Networks architecture augmented with Cognitive Radio Device-to-Device (CRD2D) modules. Abbreviations: D2D, Device-to-Device; BBU, Baseband Processing Units

which include higher-level MAC layer operations such as establishing D2D connections and Physical layer parameters such as the channel central frequency. Finally, the Common radio interface is required to exchange signaling messages (eg, to send the list of potential D2D candidates) with the RRH, employing a general purpose cellular communication technology (eg, LTE or WiMAX).

3.2 | Remote radio head

Remote Radio Heads are the points-of-attachment for UEs, being responsible for transmitting and receiving signals in a C-RAN. In CRD2D, the RRH must be redesigned to present at least 2 antennas per sector with (1) one *Rx/Tx front end* and (2) another *Rx front end*. In the former, the RRH receives and transmits data using a general purpose cellular technology to exchange signaling messages with the UE. The latter is dedicated exclusively to perform channel sampling to detect PUs.

The samples captured by the *Spectrum sensing sampling* function can be sent raw (without processing) directly to the BBU where they will be processed within the *Spectrum sensing processing* function. It is possible that within the *Spectrum sensing sampling* function at the RRH, some lightweight processing of spectrum sensing based on thresholds (eg, employing energy detection techniques) is performed to reduce the overload caused on the optical network during transmissions of sensing samples. Either way, all the RRH antennas have their workload sent to the *Radio over Fiber (RoF) module*, which de-/multiplex the workloads to be sent through the *Optical Network Interface* to the BBU.

3.3 | Baseband unit

In CRD2D, within the BBU, the *RoF module* converts the RRHs optical signal back to the radio spectrum domain to be processed by (1) the *Radio stack* and (2) the *Cognitive radio module*. The former performs baseband and radio stack processing of the RRHs according to the technology in use. In the latter, the CR functions (1) spectrum sensing (processing), (2) spectrum decision, and (3) spectrum sharing are executed within the *Cognitive radio module*.

The arrived sensing samples serve as input to the *Spectrum sensing processing* function, which may use techniques such as energy detection, cyclostationary, or matched filter. The results of this processing populate the cache and serve as input to the *Spectrum decision* function. A *Decision algorithm*—usually a solution for a combinatorial problem¹¹—will use cached information and current spectrum sensing results to estimate the vacancy status of spectrum holes for the next transmission window. Afterward, spectrum holes will be assigned to pairs of CRD2D candidates. The *Spectrum sharing* function is used to detect the presence of UEs that are interested in performing D2D adding new CRD2D candidates as input to the *Spectrum decision* function and sharing this information with other BBUs via the *CRD2D list sharing* module.

3.4 | Modus operandi

It all starts when an application contacts the CRD2D framework publishing some content to be exchanged using a D2D communication. This framework will assemble a local list of CRD2D candidate applications, add other relevant information such as localization, and then forward it to the RRH through the UE's Common radio interface. In the RRH, the

Rx/Tx front end samples the signal received, which is forwarded to the BBU through the *RoF module* and *Optical interface*. After the samples are processed within the Radio Stack and baseband processing, the Spectrum sharing function captures the list from the *Upper layers* and processes it to form pairs of CRD2D candidates, considering the region under the RRH coverage and application or content type, for example. This list is also shared with the *Cognitive radio modules* of other BBUs via the *CRD2D list sharing* to increase the chances of performing CRD2D communications under different RRH coverage areas.

Given the existence of at least 1 pair of active candidates as input to the *Spectrum decision* function, spectrum sensing needs to be triggered to identify the vacant spectrum holes to perform D2D. To improve the energy efficiency in CRD2D, we argue that the *Spectrum sensing sampling* function at RRHs is only activated when a pair of D2D candidates is active/identified changing the status of the RRH's *Rx front end* from standby to active. This activation is controlled by the *Spectrum sensing processing* function at the BBU by sending activation messages to the RRH's *Spectrum sensing sampling* through the *RoF module*. This also makes it possible to configure the *Rx front end* to receive signals from specific spectrum bands where spectrum holes can occur to limit the number of samples that need to be transferred. The *Rx front end* will retrieve spectrum samples from a configured band continuously, generating constant bit rate traffic over the optical link between the BBU and the RRH to send this samples towards the *Spectrum sensing processing* function.

The *Spectrum decision* function receives the spectrum sensing results triggering a *Decision algorithm* to determine which are the spectrum holes and the most suitable D2D candidates to use them. The *Decision algorithm* associates pairs of D2D candidates to spectrum holes and sends this information back to the *Spectrum sharing* function. The *Spectrum sharing* function, then, notifies the selected candidates sending messages through the BBU radio stack, traversing the optical links, back to the RRH, and finally reaching the *Common radio interface* of UEs. The arrived message contains information such as the *Spectrum hole* central frequency, bandwidth, maximum transmission time (ie, transmission deadline), and power allowed. This information is forwarded from the UE's *Common radio interface* via the *CRD2D API* to the *D2D framework* to coordinate the application content delivery. Afterward, the *CRD2D framework* forwards the information to the *Spectrum mobility* function to perform adjustments in the *D2D radio interface* to establish a D2D communication with the other UE. After D2D connections are established, the *CRD2D framework* can finally send actual application data over the *D2D radio interface*.

3.5 | Discussion

The CRD2D approach enables moving the most computing intensive CR functions to the BBU. Such approach is fundamental to enable UEs to spare energy and exploit underused frequencies when performing content distribution within C-RAN. However, the employment of this approach into a C-RAN architecture raises several challenges that require further investigation. The remote processing performed by CRD2D in C-RAN requires several signaling messages to be exchanged that can overload the control channels between RRH and UE. In this case, the usage of Multiple-Input Multiple-Output and Coordinated Multi-Point techniques are a promising solution to add extra capacity and to avoid the control channel to get overloaded. Currently, the optical environment is the only medium able to cope with the bandwidth and latency required to perform remote processing. Nevertheless, the literature typically considers optical links of length ranging from 20 to 40 km,^{8,15} which adds propagation delay to the overall signal sample processing process and may compromise the communication performance required to perform CR functions and baseband processing.

The overall delay, including all the messages exchanged and remote processing, dictates the time to use a spectrum hole, which indirectly impacts in the throughput achieved by CRD2D candidates. In this case, decreasing one of its components execution time (ie, processing delay) is essential, leading to the use of low complexity decision algorithms and spectrum sensing techniques. As a trade-off, employing low complexity algorithms may lead to poor accuracy when detecting PU.

Considering the proposed architecture and its inherent challenges, we deployed a prototype as a proof-of-concept of CRD2D using Software-Defined Radio platform based on the GNU Radio framework and ETTUS Universal Software Radio Peripheral (USRP) hardware devices. The prototype evaluation is focused on the minimization of the overall delay of a CRD2D by employing and comparing different *Decision algorithms*, detailed in the next section.

4 | CRD2D PROOF OF CONCEPT

The experimental evaluation scenario was designed to represent a CRD2D with an underlying C-RAN infrastructure using USRP hardware devices implementing the following methodology.

TABLE 1 Scenario parameters

Parameter	Value
Frequency, GHz	{1.1, 1.5, 1.7, 1.9}
Bandwidth, kHz	{200, 400, 500, 400}
Licensed user frequency occupation, %	{35, 30, 20, 15}
Licensed user modulation and coding scheme	OFDM with BPSK
Licensed user transmission power, dBm	-10
CRD2D device modulation	GMSK
CRD2D device transmission power, dBm	-10
Symbol rate, symbol/s	10^4
Transmission period, s	5
Packet size, bytes	512
Delay between packets, s	10^{-3}
Bit error rate	$[10^{-6}..10^{-8}]$
Sensing technique	Energy Detection
Sensing threshold, dBm	-33
Sensing duration, s	0.1
Sensing accuracy, %	≥ 99

Abbreviations: CRD2D, Cognitive Radio Device-to-Device; OFDM, Orthogonal Frequency-Division Multiplexing; BPSK, Binary Phase Shift Keying; GMSK, Gaussian Minimum Shift Keying.

4.1 | Methodology

Six USRP devices have been used to represent (1) an operator's RRH performing spectrum sensing considering 4 channels $C = \{c_1, c_2, c_3, c_4\}$, (2) 4 UEs that compose the D2D network and can create at maximum 2 pairs of D2D communicating at same time, and (3) a PU that randomly alternates its transmission channel from $\{c_{1-4}\}$ after 2 ms and will force the interruption of D2D communications. In addition to the USRP devices, a personal computer represents the operator's BBU, being responsible for computing the decision algorithms using data provided by the RRH (that in this experiment also performs a simple spectrum sensing mechanism based on energy detection) and orchestrating the D2D communication. In this scenario, UEs will be used as caching repositories to redistribute content to their neighbors. The BBU follows a finite state machine to coordinate (1) the spectrum sensing, (2) the selection of UEs that will communicate using D2D, (3) the execution of the decision algorithm, and (4) the UEs transmission. All control messages were sent within the minimum transmission time interval of 1 ms, respecting the current cellular radio technology*. The transmission window between CRD2D candidates was fixed to 5 s, time during which the RRH spectrum sensing ceases its operation.

Since our goal is to evaluate the decision algorithms in a real C-RAN deployment scenario, we chose algorithms from the literature that have presented promising results. The algorithms, as classified by Tragos et al.¹⁶ are Simulated Annealing (Heuristics), Hungarian (Graph based), Fuzzy Logic, Genetic (Evolutionary), and Binary Linear Programming (BLP). It is important to note that the original solutions were developed in simulated environments and often employed parameters that are not easily achievable in an experimental scenario. To overcome such obstacles, we adapted some solutions when deploying them in our experiment. Due to lack of space, we encourage the reader to access the link[†], where each solution with its source code are available with detailed descriptions and modifications performed.

Each algorithm requires a different set of parameters as input. The experimental scenario was designed with a set of available frequencies $C = \{1.1, 1.5, 1.7, 1.9\text{GHz}\}$, as can be observed in Table 1. Since in the designed scenario, a licensed user is always occupying 1 frequency, and there is a maximum of 2 simultaneous transmission, we considered 4 frequencies as the minimum set F to perform the spectrum decision without a trivial solution. In other words, if we have a total of 3 available frequencies and the licensed user is occupying one of them, the trivial solution is to allocate the remaining 2 frequencies to the 2 transmission links. The bandwidth associated with each frequency was defined as $B = \{200, 400, 500, 400\text{kHz}\}$. Different bandwidths were defined to evaluate the performance of algorithms under different transmission capacities.

*LTE: <http://www.3gpp.org/dynareport/36133.htm>

[†]Sources: <https://github.com/ComputerNetworks-UFRGS/OpERA/tree/master/python/decision>

The radio device that represented the licensed user alternated its transmitting frequency among the same frequencies defined in C with different occupancy probabilities, $O_p = \{35\%, 30\%, 20\%, 15\%\}$. Each $c_i \in C$ is associated to an occupancy probability $p_i \in O_p$. Considering different values for the occupancy probability, it was possible to evaluate the ability to handle interference of each decision algorithm. We defined that all links of the CRD2D network interfere with each other. Moreover, we fixed the interference matrix $I_{n,n}$ according to Equation 1:

$$\forall i, j; I_{i,j} = \begin{cases} 1, & i \neq j \\ 0, & i = j \end{cases}. \quad (1)$$

The modulation and coding scheme of the licensed user was defined as the Orthogonal Frequency-Division Multiplexing in combination with Binary Phase Shift Keying. The CRD2D devices used Gaussian Minimum Shift Keying modulation scheme, with a symbol rate of 10^4 symbols/second. Furthermore, all radios were configured with a -10 dBm transmission power. The size of the packet transmitted by each cognitive radio device was 512 bytes, with a 1 ms delay between each packet. The bit error rate for each cognitive radio device randomly varied between 10^{-6} and 10^{-8} . The initial value for the utility matrix was defined as 1 for all links in all frequencies, as determined in Equation 2. Also, whenever the link l transmits over the frequency c with a bit rate k , the utility of the element $u_{l,f} \in U$ is modified according to Equation 3, with similar behavior of a reinforcement learning approach¹⁷:

$$\forall i, j; U_{i,j} = 1, \quad (2)$$

$$u_{l,f} = 0.75 \times u_{l,f} + 0.25 \times k. \quad (3)$$

The technique applied to the spectrum sensing was the energy detection, which considers the frequency as occupied if the sensed energy is above a defined threshold. We assured an accuracy ratio above 99% for the spectrum sensing to disassociate its performance from the spectrum decision. This assurance was possible because there was only 1 licensed user transmitting over the sensed frequencies with a well-known signal. The energy detection threshold was adjusted to -33 dBm, almost 3 times lower than the energy of the licensed user, acting as a nearly perfect spectrum sensing for this specific scenario. Moreover, the spectrum sensing was performed during 0.1 seconds, while the transmission period was 5 seconds.

4.2 | Results

All decision algorithms were evaluated according to execution time, overall D2D throughput, interference level, and complexity. Each experiment was limited to 10 minutes providing a variable number of samples for each metric evaluated (eg, time spent by a decision algorithm, throughput obtained in a D2D transmission window). We have taken samples of size 28 for each metric and relied on t-student distribution to present the results with a 95% confidence interval ($tvalue = 2.0484$). Moreover, for comparison purposes, we included a baseline algorithm entitled *Select First Available* (SFA), which just selects the first spectrum hole detected.

The first evaluation was regarding to the execution time of each algorithm, which is one of the most important criteria to decrease the overall delay of CRD2D. Figure 3 presents the execution time of a single channel selection. The fastest decision is made by the baseline algorithm, because it only chooses the first spectrum hole detected. By far, the longest decision times were taken by the Simulated Annealing algorithm which took more than 1 s in average. The Genetic and BLP algorithms took more than 50 ms in our scenario. Simulated Annealing and Genetic algorithms are similar because they were designed using the same number of iterations ($t = 1000$) to converge, although the first performs worse. Binary Linear Programming considers the number of D2D links and available channels, so as the number of links and channels increases, the time taken by the BLP should surpass all the others. Excluding the SFA, the Hungarian Algorithm presented the fastest execution time, approximately $23\mu s$, because it only considers 2 transmitting links in its analysis due to the creation of an availability matrix. Finally, the Fuzzy Logic algorithm presented an average time of 3 ms, but its execution is not affected by the number of D2D links.

The second evaluation was regarding to the overall throughput obtained by using D2D communication. For this analysis, we measured the received data in each UE during the experiments. This measurement discarded all data affected by interference and, therefore, incorrectly received. Given the comparison nature of our experiment and that the throughput using spectrum holes can change according to the bandwidth considered, we decided to present the throughput obtained by each algorithm relative to the baseline, SFA algorithm, which is represented by the value 1 in the y-axis in the Figure 4.

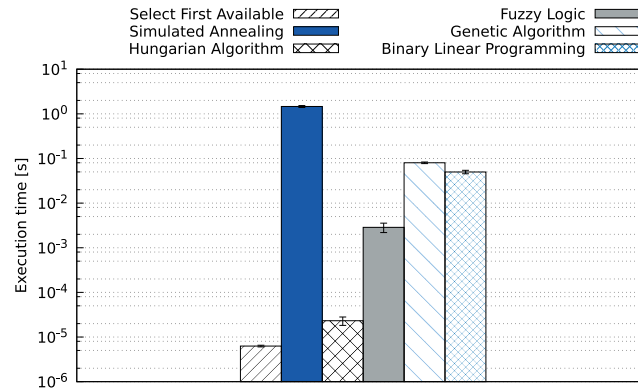


FIGURE 3 Execution time for a single channel selection

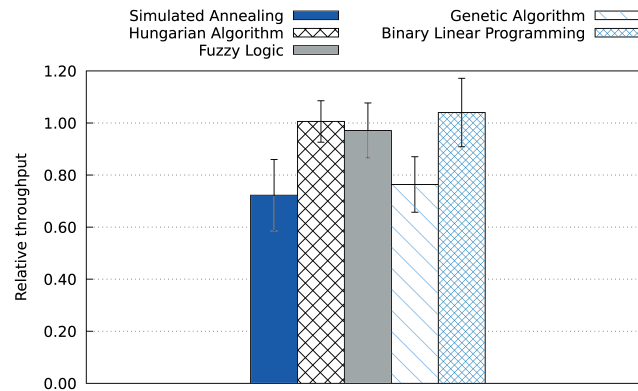


FIGURE 4 Relative throughput for each algorithm

The worst performance was presented by Simulated Annealing and Genetic algorithms, with approximately 75% of the baseline throughput. As discussed before, these algorithms were among the highest decision times, according to Figure 3. The BLP presented a slightly greater overall throughput by achieving nearly 5% more than the baseline. This behavior occurred because BLP was designed to find the solution with the highest possible throughput. However, BLP had an execution time similar to the Genetic Algorithm, and due to its complexity, this time shall increase for larger networks. The remaining algorithms presented similar throughput, close to the baseline algorithm. The results obtained show that the decision algorithm has little impact on the overall network throughput, because this criterion strongly depends on other parameters, such as modulation, coding scheme, and available bandwidth. Furthermore, interference with PUs must be avoided at all cost, being interference a stronger criterion than throughput for CRD2D.

The third analysis is about the interference level with PU in each available channel. We analyzed the occupation of the PU, as well as the CRD2D candidates for the same spectrum hole, as depicted in Figure 5. By combining these two, it was possible to detect the periods in which both PU and the CRD2D candidates transmitted in the same channels and at the same time, causing harmful interference. Select First Available and the Hungarian Algorithm presented the worst interference level, ie, about 52% of the PU transmission. The least interfering algorithms were the Simulated Annealing and the BLP, with an interference level around 28% of the PU transmission. In turn, the Genetic Algorithm presented an interference level of 37%, and Fuzzy Logic, 46%. An important observation here is that our PU has a very challenging behavior performing random migrations after each 2 ms. Different types of PU, such as radar or TV, present a much larger occupation time in a given channel, triggering migrations less often, which would probably enhance significantly the accuracy of the algorithms.

We summarized all obtained results in Table 2 along with a complexity analysis. All solutions present a polynomial time, and as expected, it is directly related to the number of available channels m and, except for the Fuzzy Logic, on the number of CRD2D links n established in the C-RAN. It is important to notice that the complexity of the Hungarian Algorithm was reduced to $O(nm)$ due to the simplification proposed by Zhao et al.¹³ The Fuzzy Logic algorithm has a complexity of $O(m)$, because it does not depend on n . In addition to n and m , the Simulated Annealing and the Genetic

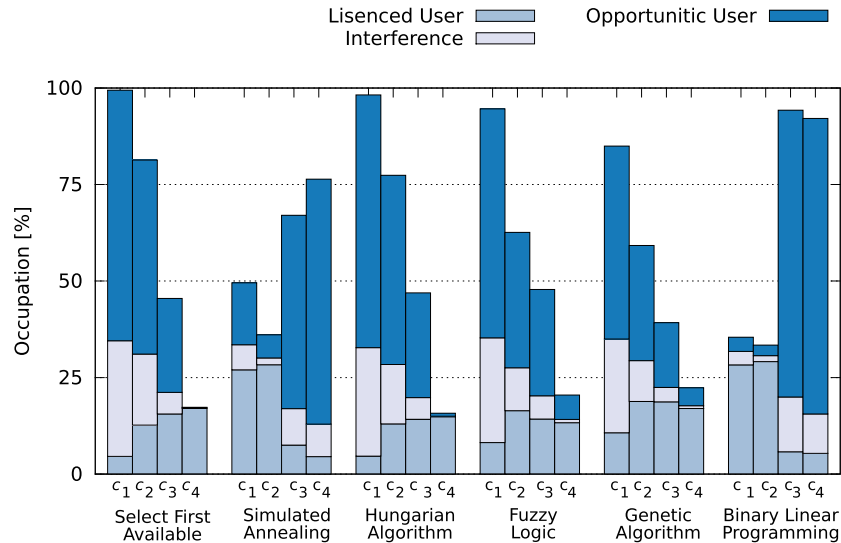


FIGURE 5 Channels usage

TABLE 2 Evaluation results summary

Algorithm	Complexity	Execution Time	Throughput	Interference
Select First Available	$O(1)$	Low	Medium	High
Simulated Annealing	$O(tnm)$	High	Low	Low
Hungarian Algorithm	$O(nm)$	Low	Medium	High
Fuzzy Logic	$O(m)$	Medium	Medium	High
Genetic Algorithm	$O(ptnm)$	Medium	Low	Medium
Binary Linear Programming	$O(n^3m^2)$	Medium	Medium	Low

algorithm take into account the number of iterations t in each execution. Besides t , the Genetic algorithm also considers the population size p . The complexity of the former is $O(tnm)$, and the later is $O(ptnm)$. The algorithm that has the greater complexity is the BLP, which is $O(n^3m^2)$.

Also in Table 2, we classified the execution time, the throughput, and the interference in 3 levels: High, Medium, and Low. Regarding to the execution time, an algorithm is classified as Low, for an execution time below 10^{-4} s, as medium for execution times between 10^{-4} and 10^{-1} s, and as High for execution times above 10^{-1} s. Considering the overall D2D throughput, the algorithms were classified based on the comparison with SFA. Those that presented performance similar to the baseline were classified as Medium, the ones with a worst performance were classified as Low. Because no algorithm presented a performance significantly better than the baseline, we did not classify any of them as high. Regarding the interference level with the PU, the algorithms were classified as Low, for an interference below 30%, as Medium for an interference between 30% and 40%, and as High for interferences above 40%.

In CRD2D for D2D communication, a low interference level is mandatory. In this sense, the interference must be the main criterion when choosing a decision algorithm. We considered the execution time as the secondary major criterion, because it is a desirable goal for decreasing the overall delay involved during remote processing of CRD2D. According to these criteria, we considered the BLP the best solution for our scenario, having the same interference level as the Simulated Annealing, but with smaller execution time and higher throughput. However, the use of the BLP is limited to small networks, due to its high complexity. In situations such as large-scale events, that deal with a high number of CRD2D users, Simulated Annealing algorithms should be considered.

5 | CONCLUSION

In this paper, we proposed the CRD2D approach to enable the remote processing of CR functions, enabling the realization of DSA with D2D over C-RAN architectures. In this approach, decision techniques play an important role, aiming to maximize the overall network throughput as well as avoiding interference with PUs. Based on the implementation of a

prototype, we evaluated different decision algorithms. Our analysis shows that for a few available frequencies and D2D communication links, complex algorithms are suitable for real deployment. However, complex solutions do not scale with the network, and heuristics solutions become interesting alternatives, such as Simulated Annealing. As future research, we envision the evaluation of decision algorithms on networks with different sizes of CRD2D in C-RAN, the design of new decision techniques by combining the best aspects of each investigated algorithm, and the evaluation of the impact caused by resource sharing in the opportunistic CRD2D communication.

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