SC2 CIL: Evaluating the Spectrum Voxel Announcement Benefits

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***Abstract*—The Spectrum Collaboration Challenge (SC2) was started by DARPA in 2016 to further expand the research on spectrum usage efficiency, and mitigate the ever-growing problem of spectrum scarcity. Teams that participated in SC2 designed and developed wireless networks, called Collaborative Intelligent Radio networks (CIRNs), to compete with other teams' CIRNs. The scoring system was created to motivate maximizing both their own and other networks' data throughput. To improve the spectrum usage efficiency, teams were encouraged to use Artificial Intelligence, as well as to collaborate with other teams and agree on spectrum usage schedules that work best for all parties. To facilitate this collaboration, DARPA has established the CIRN Interaction Language (CIL) – a language CIRNs can use to communicate with other networks and establish common spectrum goals and ways to achieve them. One of CIL's main functionalities was to enable teams to announce their intended spectrum usage and provide information other teams can use to adapt their own channel selection. While potentially a beneficial concept, CIL's effect on ensemble throughput of all networks was never evaluated, as a proper evaluation framework was never provided by DARPA, since it was not possible to disable it. This paper describes a simplified simulation of the spectrum usage announcement functionality of the CIL, explains the experiments run to evaluate CILs gains, and showcases the obtained results.**

I. Introduction

The ever-increasing shortage of spectrum motivated DARPA to establish the second Spectrum Collaboration Challenge (SC2), with the aim to boost research on innovative technologies that enable and facilitate coexistence amongst various heterogeneous wireless networks sharing the same wireless spectrum.

SC2 is structured around multiple teams that each build their own wireless communication system, a Collaborative Intelligent Radio Network (CIRN). The name CIRN was coined to outline some of the main goals of the entire challenge – to encourage teams to include Artificial Intelligence elements in their networks to help with increasing spectral efficiency and coexistence with other teams and their radios, as well as to promote collaboration between teams, mainly in terms of spectrum usage and occupancy, to achieve the common goal of increasing the combined throughput of all teams.

To enable and facilitate this collaboration, DARPA established a common language for all teams, to help them announce their intentions in spectrum usage, request channel availability, etc. The language was named CIRN Interaction Language (CIL). CIL is based on a publish-subscribe system, each team can receive the message sent by any other team, and was designed to operate using a different protocol (Ethernet) in order to bypass the challenges present in the main wireless communication channels being used competition-related throughput, and to guarantee successful delivery of the messages to all teams.

Over the course of the challenge, CIL evolved with the needs and requirements of the teams and has included various functions. This paper will focus on evaluating the spectrum usage announcement functionality of the CIL. In particular, it will attempt to measure the impact that correct spectrum voxel announcements have on the combined throughput of the participating teams. In other words, the paper will compare the achieved throughput when teams have information related to the intended spectrum usage of other teams in the near future to the scenario where teams have no information related to the spectral behavior and intentions of other teams.

The rest of the paper is organized as follows: section III introduces and briefly describes the CIRN Interaction Language. Section IV outlines the framework implemented to evaluate the CIL benefits. The evaluation results are presented in section V. Section VI explains the plans for the continuation of the work, and finally section VII concludes the paper.

II. Related Work

Spectrum sharing and coordination has been an attractive research topic for a long time. A copious amount of work has been done in this field, with various ideas and technologies emerging to tackle the issue of spectrum scarcity from the point of view of coexistence with other wireless networks and protocols.

In [1], several different categories of heterogeneous spectrum sharing are mentioned – database mediated, TV white space, actively managed by a Spectrum Access System, LTE for heterogeneous networks, Bell Labs white cell architecture, Ericsson architecture. Most of these categories assume spatial reuse and centralized coordination and licensing.

A distributed coordination scheme was proposed in [2]. Authors first describe a rendez-vous protocol to form localized groups of users which would exchange information mutually, and then this information can be propagated to other groups.

A system optimization of LTE and WiFi to enable spectrum usage coordination has been studied in [3].

Authors have proposed a distributed spectrum coordination architecture via the Internet in [4].

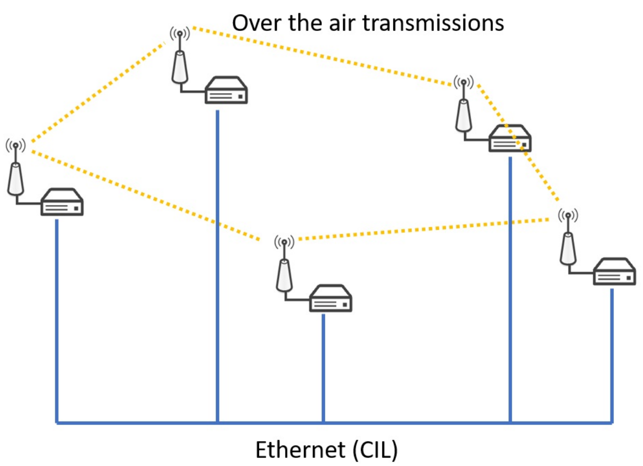


Fig. 1: CIL design schematic. Yellow dashed lines present over-the-air transmitted signals between the nodes; blue solid lines present Ethernet wires.

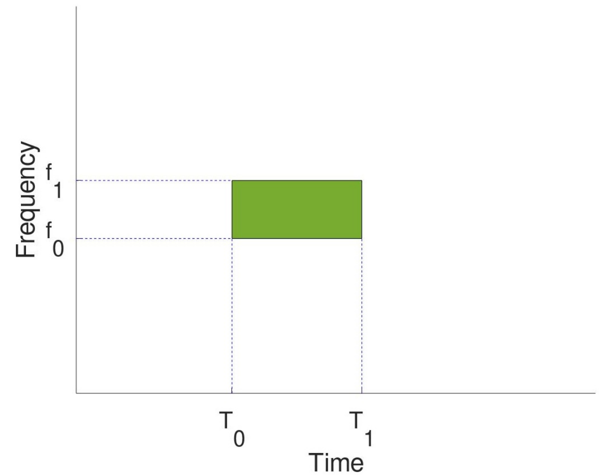


Fig. 2: A spectrum voxel. In simple terms, it is defined by the exact time when a signal will be transmitted, and the precise frequency band it will use.

Finally, [5] proposes a spectrum etiquette protocol called "common spectrum coordination channel" (CSCC), which includes announcing radio and service parameters to other networks.

Multiple other papers have been published, which affirms the attractiveness of the subject. Many of the proposed ideas are similar to the CIL. However, no practical, physical implementation and usage of such system was ever noted by the authors. This paper bases its evaluation on a protocol that has been used throughout the course of the SC2.

III. CIRN Interaction Language (CIL) Design

Collaboration between independent heterogeneous wireless networks is one of the many innovative ideas and contributions of the DARPA Spectrum Collaboration Challenge. The main goal of the collaboration is to improve the spectrum usage efficiency and coexistence by communicating intentions for future spectrum usage, informing other networks of the spectral needs and requirements and exchanging other types of information and requests. CIL's design, itself being a collaboration protocol, is also the result of the collaboration between all teams participating in the DARPA SC2.

CIL has evolved throughout the challenge, directed by input and feedback from all teams and DARPA itself, and has grown into a complex protocol that involves exchanges of various types of information and requests, and uses well-defined message structures. CIL was implemented as a publish-subscribe messaging system, where any CIRN can publish a message and all other networks are able to immediately receive it. There were multiple types of CIL messages, some used more than others. However, analyzing all types of messages and all layers of CIL functionality is beyond the scope of this paper. The paper will focus on evaluating the impact of one of the most widely used functions of the CIL – announcing the spectrum usage intentions by each CIRN. The paper will attempt to measure the impact of this function on the achieved ensemble throughput of all CIRNs.

As shown on Figure 1, CIL is designed to handle the communication between CIRNs independent of their over-the-air transmissions. Internal communication and data transfer between nodes within each CIRN was wireless, but all CIL related message exchange, as a protocol for direct communication with other CIRNs, was done over the wire. This ensures no interference in the spectrum caused by the CIL itself, as well as guaranteed delivery of CIL messages to all other CIRNs.

CIRNs are required to announce their spectrum usage by periodically sending the spectrum voxel specification to the CIL. A spectrum voxel, shown on Figure 2, can include varying degrees of information about the CIRNs intended spectrum occupancy. The required specifications are the exact time and frequency bands that the CIRN is planning to use for its transmission. Periodicity can be defined either by giving the exact start and end times of each transmission, or by specifying the duty cycle. The exact geographical location (latitude and longitude) of each transmitter can be given, along with the intended transmission power using any absolute units. This provides the opportunity for spatial reuse of the spectrum when nodes are geographically separated.

IV. CIL Evaluation Framework

The SC2 was run on Colosseum, a radio signal emulation testbed designed and built by DARPA. Colosseum contains a large number of nodes with USRP devices, with the entire wireless framework being emulated. The environment enables competition organizers to emulate any desired topological or spectral configuration, thus enabling them to run different scenarios and test teams' performance in various circumstances. Testbed users (the teams in case of SC2) can build their own LXC containers, which then run on Colosseum nodes and have direct access to the connected USRP devices. System clocks of all nodes are synchronized using NTP. CIL related communication is implemented and runs via Ethernet, and is thus independent of the wireless communication.

CIL was successfully used throughout the DARPA SC2. However, its performance and impacts upon the decisions made were never evaluated, as an environment to run similar competition scenarios without the usage of CIL was not available. The described environment in the Colosseum testbed did not include the possibility to disable CIL and run experiments with other teams' containers without it. Hence, it is unclear how significant the impact of CIL usage on the entire performance may be. Indeed, a proper evaluation would require comparison of two equal competition scenarios, which implies equal geographical distribution of nodes, exact same sets of participating teams, and equivalent traffic loads and requirements for each CIRN and their nodes. Without the proper environment provided by DARPA, it is not trivial or straightforward to design a framework that would support the entire CIL functionality and provide all resources and conditions that SC2 CIRNs were developed for and would expect to encounter in an official SC2 scenario.

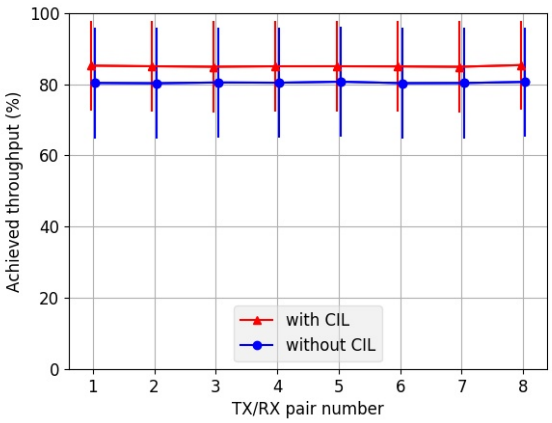
Thus, this paper focused on evaluating only the spectrum usage announcement functionality of the CIL. First, a basic evaluation system was built to emulate the simplified functionality of the CIL. The system consists of multiple USRP X310 devices, communicating over the air. Transmit/receive pairs of nodes were implemented with GNU Radio and used instead of complex wireless communication networks. The CIL was emulated by feeding the information about selected frequency bands by each TX/RX pair for future time slots to all transmitters. The evaluation was performed by running multiple throughput tests with varying number of nodes, with the simulation of CIL presence turned on and off. Each transmitter would repeatedly send a packet with a pre-determined payload, and the receiver would attempt to decode the received message and check whether the value is correct. The throughput was measured by the number of successfully decoded messages for each TX/RX pair. A throughput of 100% would indicate that all transmitted packets were successfully decoded; similarly, a throughput of 10% would indicate that only one tenth of all packets were successfully decoded. It can be seen (shown in section V) that with two transmitters using the same channel, the interference is such that their respective receivers can occasionally successfully decode a packet, but are unsuccessful for more than 99% of the transmitted packets. The results also show and analyze the variance in the achieved throughput over multiple runs of the experiment depending on the number of TX/RX pairs present in the experiment, and how this variance is affected by CIL.

The evaluation system was implemented under the assumption that spectrum usage announcement messages are simplified. The spectrum voxels in the evaluation do not include any geographical location data, so there is no spatial spectrum reuse, as the node distance can be easily calculated and all nodes with negligible interference can simply be ignored, so for the purpose of evaluating the impact of CIL on data throughput, including location information would be of little value. To simplify the experiments, time and frequency bands were observed in discrete non-overlapping slots, as any loosening of these constraints could significantly increase the complexity of spectrum usage decision making and the entire evaluation of spectrum voxel announcement impacts could be severely affected by the potentially non-deterministic nature of the AI subsystems of the CIRNs.

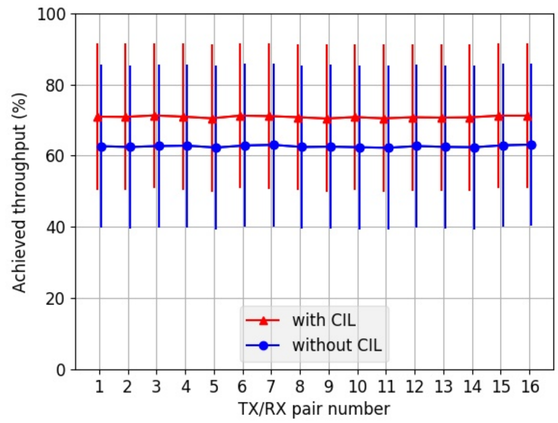
V. Evaluation Results

The evaluation system was designed as a set of transmitter/receiver pairs, where all pairs select a channel in each time slot and transmit data. Each run of the experiment was performed with and without the simulated CIL. During a run without the simulated CIL, each pair would select a channel and attempt to transfer data. If any other pair happened to randomly select the same channel, the two transmitters would interfere with each other and receivers would be unable to properly decode the received packets, causing significant drops in throughput for each transmitter/receiver pair. A larger number of pairs (relative to the number of available channels) results in the increased probability of occurrence of such interference. The testing environment had no external interference caused by any transmissions other than the transmitters used in the experiment itself. A CIL simulated run would include announcements of the selected channels for future time slots to each transmitter/receiver pair. With the available information on channel occupancy in the future, each pair can now make an informed decision on whether to transmit data in the following time slot, or back off. The evaluation system assumes that for each transmitter/receiver pair, when usage of their selected channel for an upcoming time slot has also been announced by N other pairs, they will transmit with the probability of $\frac{1}{N+1}$. There are many possible, less naive techniques with varying degrees of complexity to further increase the combined throughput by making an informed decision on using a different channel, one which wasn't found in the announced spectrum voxels. However, the discussion and evaluation of a multitude of such techniques is beyond the scope of this paper.

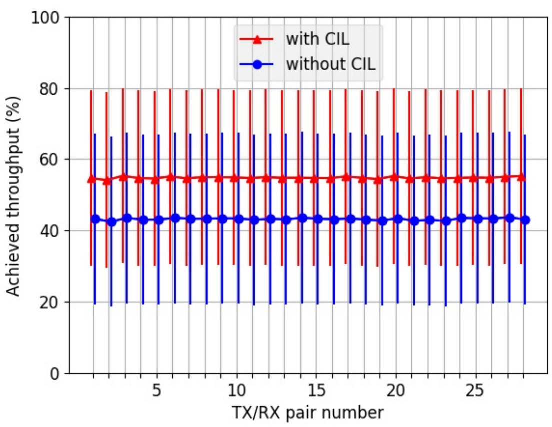
Figure 3 shows the average throughput for all time slots per TX/RX pair in a scenario with 8, 16, 28 and 40 different TX/RX pairs and 32 available frequency channels, for 500 experiment runs with 60 time slots, with each time slot being of 1 second duration. The achieved throughput is expressed as percentage of maximal theoretical throughput, which is achieved when data transmission in each time slot is performed with no interference and every single transmitted packet gets successfully received and decoded. The throughput for each experiment is shown on the y axis, and each plot has the y axis range of the entire 100% to emphasize the dependence of the benefits of CIL on the numbebler of existing transmitters (i.e. on the spectrum shortage). With 8 pairs in 32 channels, spectrum voxel announcements and the naive back-off algorithm used by transmitter result in an increase of overall achieved



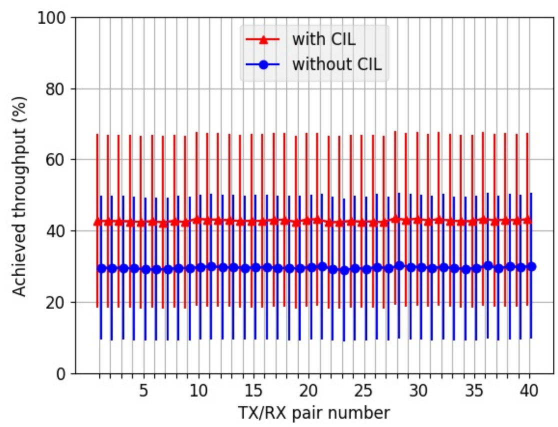
(a) Total throughput for 8 TX/RX pairs in 32 channels



(b) Total throughput for 16 TX/RX pairs in 32 channels



(c) Total throughput for 28 TX/RX pairs in 32 channels



(d) Total throughput for 40 TX/RX pairs in 32 channels

Fig. 3: Achieved combined throughput for 8, 16, 28 and 40 TX/RX pairs with 32 available channels. Throughput expressed as percentage of maximal theoretically achievable throughput by each TX/RX pair assuming no interference and 100% successful packet receiving and decoding.

throughput of about 5%, while with 40 existing transmitters this increase is above 12%.

Additionally, it is interesting to note the effect that all parameters have on the variance in throughput through multiple runs of the experiment. With a higher number of TX/RX pairs it is notable that the variance also increases, which can easily be explained by the fact that a lower number of nodes that need spectrum access result in a more orderly and predictable environment. The more detailed values of throughput variance per the number of pairs in the environment is shown on Figure 4. These values can be explained by the observation that a lower demand for spectrum results in a less variable environment. Presence of CIL further decreases the volatility of the environment in this case. However, with a higher number of TX/RX pairs, and thus proportionally higher demand for spectrum, even though CIL helps in increasing the ensemble throughput of all pairs, it also increases the volatility of the environment, indicated by the variance being higher when CIL is present. The explanation for this phenomenon can be found in the fact that the highest variance in an environment without CIL is seen for 24 pairs seeking spectrum access in 32 available spectrum channels, while with CIL the number of pairs with peak variance is exactly 32 – the same as the number of channels. Once the spectrum utilization reaches a saturation point, any further attempts at spectrum access will more often than not result in failure, which again increases the predictability of the system.

Figure 5 shows the schedule (selected channels) and achieved throughput of 4 TX/RX pairs over 5 consecutive time slots in a single run. It can be seen from the schedule plot (the first of five plots) that pairs 2 and 3 end up selecting the same channel in the last two time slots, namely slots 4 and 5. The throughput bar plots show that the pair 2 (blue) has no throughput in time slot 4, with some minor throughput in time slot 5, while pair 3 (green) has high throughput in time slot 4 with similarly minor throughput in time slot 5. This

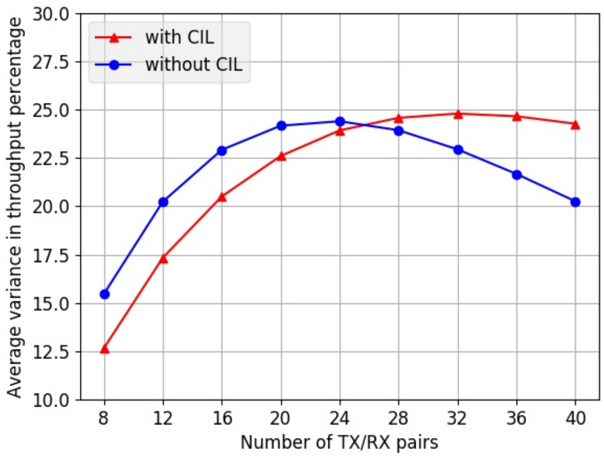


Fig. 4: Average variance in throughput for all experiments, shown by the number of pairs. A higher number of pairs increases the variance

could indicate the possibility that in slot 4, the blue pair has randomly chosen to back off, while the green pair has decided to transmit data. In the last time slot, both nodes have made the decision to transmit data, but due to the interference they posed to each other they have both been able to decode only a negligible number of packets, which resulted in non-zero but negligible throughput for both pairs.

Overall, the performed experiments show that announcing the intended spectrum voxels used for transmission can lead to an increase in combined throughput of all nodes and systems of between 4 and 12%, depending on the spectrum demand and availability. These gains were achieved with the naive random back-off algorithm described in section IV.

VI. Future Work

The planned continuation of the presented work will include a larger and more robust evaluation framework, able to provide transmission and communication evaluation of networks with more than 2 nodes. Additionally, it is important to explore the potential benefits and gains in achieved throughput with more complex and efficient spectrum voxel scheduling algorithms. These algorithms may include the solutions aided by CIRN AI subsystems dedicated to spectrum voxel scheduling and channel selection based on the information received through the CIL.

VII. Conclusion

DARPA has established the Spectrum Collaboration Challenge (SC2) as a competition between multiple teams that build intelligent and collaborative wireless communication networks - CIRNs (Collaborative Intelligent Radio Networks), with the goal to further motivate researchers to work on improved and novel ways to increase spectrum usage efficiency. To enable the collaboration between teams' networks, DARPA has introduced the CIRN Interaction Language – a language used for communication between different, heterogeneous networks to announce their spectrum usage intentions.

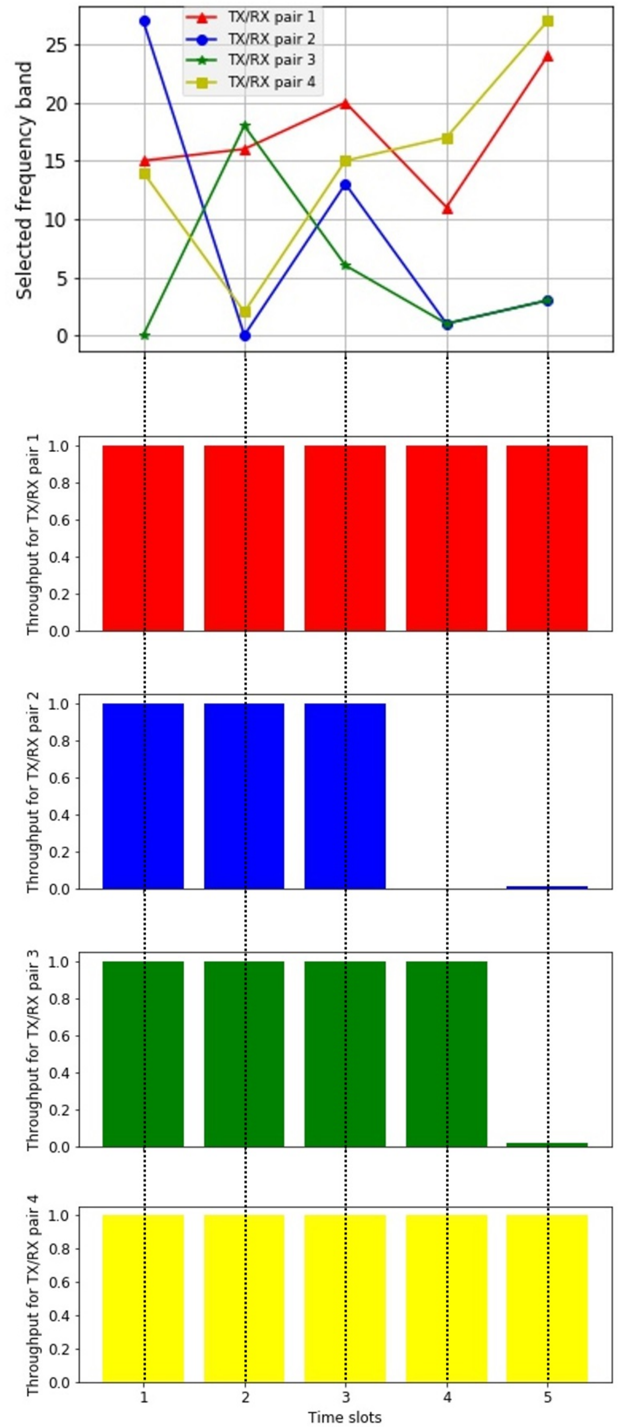


Fig. 5: A schedule and throughput per pair of 4 TX/RX pairs, showing an example of channel selection collision and the resulting throughput.

This paper describes the design of CIL and ideas behind it, affirms the fact that CIL's benefits, while clearly improving the achieved throughput of all networks, were never measured and quantified. Further, the paper proposes a simulation framework that would help evaluate the CIL's gains, describes its implementation and showcases the results of the performed evaluation experiments. The naive back-off algorithm used in the experiments results in the increase of the achieved combined throughput of all networks between 4 and 12%, depending on the number of transmitters and available channels, i.e. the spectrum demand and availability. The variance in achieved throughput for each transmitter was also shown to depend on both the number of transmitters in the spectrum and the existence of CIL. In particular, a higher number of transmitters, as well as the presence of CIL spectrum usage announcement messages, both result in increase in throughput variance, meaning that CIL not only potentially increases the ensemble throughput, but also reduces the uncertainty of expected number of successful transmissions.

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