Cooperative Dynamic Spectrum Access for Large-Scale Networks using Directional Antennas

Irfan Tamim*, Carlos E. Caicedo Bastidas†, Igor Kadota‡, Gil Zussman*
*Columbia University, USA †Syracuse University, USA ‡Northwestern University, USA
*{it2304, gil.zussman}@columbia.edu †ccaicedo@syr.edu
‡kadota@northwestern.edu

***Abstract*—The management of RF spectrum resources between heterogeneous RF devices has become more challenging with the advent of 5G, 6G and the desire to enable more spectrum sharing interactions in different bands. Most of the research on Dynamic Spectrum Access (DSA) algorithms considers non-cooperative scenarios with RF devices using omnidirectional antennas. In this paper, we study the effects of antenna directionality on cooperative DSA. Specifically, we develop a custom simulator for large-scale DSA networks that leverages IEEE 1900.5.2 Spectrum Consumption Models (SCMs) to enable coordination and computation of aggregate interference to deconflict spectrum use in large scale scenarios. SCMs offer a mechanism for RF devices to describe the characteristics of their use of spectrum and their needs in terms of interference protection. We create SCMs for RF systems with directional antennas based on measurements from a directional mmWave antenna and from the operational characteristics defined by the European Telecommunications Standards Institute (ETSI). We leverage these SCMs to perform a comparative analysis of spectrum use efficiency in cooperative DSA networks with up-to 300 links of transmitter-receiver RF devices using omnidirectional antennas vs similar networks using directional antennas with different half-power beam widths. The simulation results show the benefits to spectrum use efficiency that can be achieved with directional antennas and how large-scale DSA methods can be studied and designed with the use of SCMs that incorporate detailed characteristics of directional antennas.**

***Index Terms*—Dynamic Spectrum Access, spectrum sharing, Spectrum Consumption Models, wireless networks, 5G, mmWave**

I. Introduction

Dynamic Spectrum Access (DSA) is key to enabling the efficient use of the Radio Frequency (RF) spectrum required by emerging and future applications [1]. The goal of DSA is to mitigate harmful interference and foster harmonious coexistence among heterogeneous devices. Most of the research on DSA mechanisms considers non-cooperative DSA networks with RF devices using omnidirectional antennas (see survey [2]). Motivated by the requirements for spectrum sharing and agility of next generation networks, including 5G/6G, and by recent IEEE standardization efforts on DSA [3], we focus on cooperative DSA networks with RF devices using directional antennas. In cooperative DSA, RF devices share information that allows them to find a configuration (e.g., frequency and power) for spectrum use that achieves no (or a low incidence of) harmful interference to any of the devices.

In previous work we developed, simulated, and prototyped a collaborative DSA mechanism based on IEEE 1900.5.2 Spectrum Consumption Models (SCM) [4], [5]. SCMs provide: (i) a standardized mechanism for RF devices to declare how they intend to use the spectrum (in the case of transmitters) or their needs in terms of spectrum protection (in the case of receivers and passive devices); and (ii) a computational method to arbitrate compatibility (i.e., non-interfering co-existence) [3]. In particular, we developed a DSA algorithm that leverages the SCMs of RF devices cooperating to share spectrum in order to determine the frequency and power characteristics of spectrum assignments to deconflict the use of spectrum among them. *A key limitation of our prior work and that of many other DSA mechanisms in the literature, is that they assume that all RF devices use idealized omnidirectional antennas.*

Different methods and applications for performing DSA with directional antennas have been investigated in the literature. The work in [6] proposed using directional antennas in Unmanned Aerial Vehicles (UAVs) operating in the 5.7GHz band. New spectrum sharing methods were discussed to reduce resource collisions and the benefits of using directional antennas were analyzed. The work in [7] proposes DSA techniques focused primarily on maximizing the sum-rate performance for primary and secondary spectrum users which is achieved by optimizing several constraints and achieving reductions on interference by using directional antennas instead of omnidirectional ones. The network performance goals for 5G and beyond are considered in [2] including how DSA along with directional and smart antennas will contribute to the management of interference.

In this paper, we study a cooperative DSA mechanism for networks with RF devices that have *directional antennas*. Our main contributions include: (i) creation and use of SCMs based on a real-world directional antenna pattern; (ii) modification and optimization of our large-scale DSA simulation platform [5] to incorporate directional antennas and account for their effects on the computation of aggregate interference; and (iii) an analysis of the effects of antenna directionality on spectrum sharing in large-scale scenarios. We compare different wireless network topologies in which devices have omnidirectional antennas, directional antennas, or a mix. We also consider directional antennas with different half-power beam widths. The simulation results show that in networks with up to 300 pairs of RF devices, the use of directional antennas can reduce the number of frequency channels required to achieve spectrum compatibility by $> 70\%$

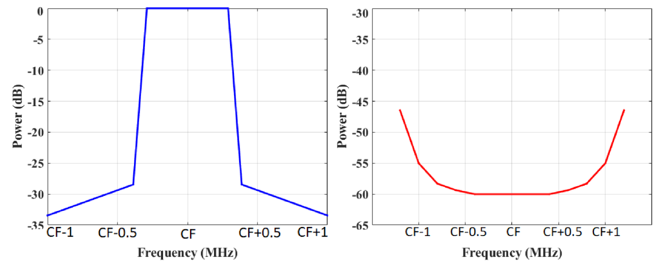
when compared to an equivalent scenario that uses omni-directional antennas. More importantly, the results suggest that this reduction in spectrum use increases as the network size increases. To the best of our knowledge, this is the first work to create SCMs based on directional antennas and leverage such SCMs to deconflict spectrum use.

The remainder of this paper is organized as follows. Section II introduces SCMs. Section III describes how directional SCMs were created and presents the SCM-based DSA algorithm and simulation platform used the analyze large-scale spectrum use deconfliction scenarios. Section IV discusses the simulation results for several omnidirectional and directional antenna operation scenarios. Section V concludes the paper and discusses future work.

II. Primer on Spectrum Consumption Models (SCMs)

To describe the spectral, spatial, and temporal characteristics of spectrum use by any RF device and/or system, SCMs use a set of up to 11 data elements also referred to as constructs which are defined in the IEEE 1900.5.2 standard [3], [8]. The constructs can be used to build different types of SCMs, including: (i) *Transmitter models*: SCMs that convey the extent (including direction) and strength of RF emissions from a transmitter; (ii) *Receiver models*: SCMs that can be used to determine when an RF receiver is experiencing a harmful amount of total aggregate interference; and (iii) *System and Set models*: SCMs that group several transmitter and receiver SCMs. Out of the eleven SCM constructs, the ones that we used to model RF transmitter and receiver devices in the scenarios presented in this work are described below. Unless otherwise stated, each construct must be used in both transmitter and receiver models.

- *Reference Power:* Value that provides a reference power level for the emission of a transmitter or for the allowed interference in a receiver. It serves as the reference power value for the spectrum mask, underlay mask, and power map constructs.
- *Spectrum mask:* Data structure that conveys the relative spectral power density of emissions by frequency. This construct is mandatory for Transmitter models only (see an example in Fig. 1(a)).
- *Underlay mask:* Data structure that conveys the relative spectral power density of allowed interference by frequency. This construct is mandatory for Receiver models only (see an example in Fig. 1(b)).
- *Power map:* Data structure that defines a relative power flux density per solid angle. It conveys the direction of the dispersion of electromagnetic energy from a transmitter's antenna or of the concentration of energy at a receiver.
- *Propagation map:* Data structure that defines a path loss model per solid angle (i.e. per direction in 3D-space).
- *Schedule:* This construct specifies the time in which the model applies (start time, end time). It can also be used to describe periodic/cyclic activity of the RF device.
- *Location:* Specifies the location of an RF device. Several types of locations are supported: a point, a volume, a trajectory or an orbit.



(a) Measured Tx spectrum mask (b) Measured Rx underlay mask

Fig. 1: Illustration of SCM constructs.

Additional SCM constructs can be used to describe inter-modulation effects, policy or protocol based spectrum coexistence, and broadcasting behavior. Using the information captured in an SCM's constructs, an RF management system can use the procedures defined in the IEEE 1900.5.2 standard to evaluate whether the spectrum use of two or more transmitters and receivers and combinations of them are compatible. The compatibility test indicates whether the different RF devices can coexist without causing harmful interference to each other or if any of them will interfere with each other (i.e., they are non-compatible). This computation can be extended to large-scale scenarios with multiple RF devices where aggregate interference effects need to be taken into account as part of any dynamic spectrum assignment decision.

III. Cooperative DSA with Directional SCMs

In this section, we describe the creation of SCMs that incorporate measurements of a directional horn antenna's radiation pattern used in 28 GHz transmission experiments and the radiation pattern envelopes (RPEs) defined by the European Telecommunications Standards Institute (ETSI) for fixed radio systems operating between 24 GHz and 30 GHz. We refer to these SCMs as *directional SCMs*. We then describe the DSA simulator that leverages directional SCMs to deconflict spectrum use in large-scale networks.

A. Creating Directional SCMs

For our purposes, the main SCM constructs that we will focus on include the transmitter's spectrum mask, the receiver's underlay mask, and the power map. The spectrum mask and underlay mask we used were derived from measurements of Software-Defined Radios transmitting BPSK modulated signals with a 1 MHz bandwidth. Details of the measurements are provided in [4]. In essence, the spectrum mask captures how the power of the transmitted signals is distributed over frequency and the underlay mask captures the aggregate interference tolerable by a receiver as a function of frequency. The spectrum and underlay masks we used are illustrated in Figs. 1(a) and (b), respectively.

The power map construct contains the information about an RF devices's antenna radiation pattern. This paper considers SCMs with omni-directional and directional antenna

Type of Antenna	Horn (Real)	Horn (RPE)	ETSI Class 1 (RPE)	ETSI Class 2 (RPE)	ETSI Class 3 (RPE)	ETSI Class 4 (RPE)
ID	Hr	He	C1	C2	C3	C4
HPBW	10°	12°	15°	12.5°	7.6°	5°

TABLE I: Half Power Beam Width (HPBW), in degrees, of the antennas used in the simulations.

patterns. Omni-directional patterns were obtained from measurements using Software-Defined Radios described in our prior work [4], [5]. Directional patterns were generated from two sources: (i) Anechoic chamber measurements of the radiation patterns of a horn antenna with a 10° Half Power Beam Width (HPBW) and 24 dBi gain used in a mmWave measurement campaign on the NSF PAWR COSMOS testbed as reported in [9] and [10]. The 2-D azimuth and elevation radiation patterns of the antenna were used to produce a total of $30,000$ azimuth angle, elevation angle, and gain triplets that provide a 3D description of the antenna pattern which was incorporated into the power map construct of the SCMs of the devices that use that antenna. (ii) Antenna radiation patterns based on the Radiation Pattern Envelope (RPE) definitions of the ETSI EN 302 217-4 standard for fixed radio systems operating between 24 GHz to 30 GHz [11]. Four ETSI RPE classes are defined in the standard and each one has a different HPBW. We also generated an RPE for the real Horn antenna and added it to the set of antenna patterns. Table I summarizes the characteristics of the antennas that we incorporated into different directional SCMs.

To facilitate comparisons among the antennas and to study the effects of directionality, all transmitter and receiver devices will be assumed to be at the same height making the azimuth plane at a zero degree elevation the most active/influential in the dispersal and/or reception of energy for transmitter and receiver antennas respectively. Figure 2 shows the measured azimuth and elevation radiation patterns for our real Horn antenna (for more details see [10, Fig. 1]) and the Horn RPE that we generated. Figure 3 shows the azimuth plane radiation patterns for the ETSI Class 1 to Class 4 antennas (C1 to C4) and compares them with the pattern of the real Horn antenna.

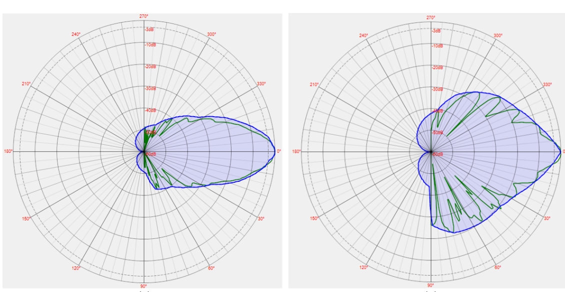


Fig. 2: Real Horn antenna (green) and its RPE (Blue). (a) Azimuth pattern. (b) Elevation pattern.

B. DSA Simulator for Large-Scale Networks

In this section, we describe the DSA simulator and the Spectrum Deconfliction (SD) algorithm that processes the SCMs from transmitter-receiver pairs in the network aiming to find frequency and transmission power settings that achieve spectrum use compatibility.

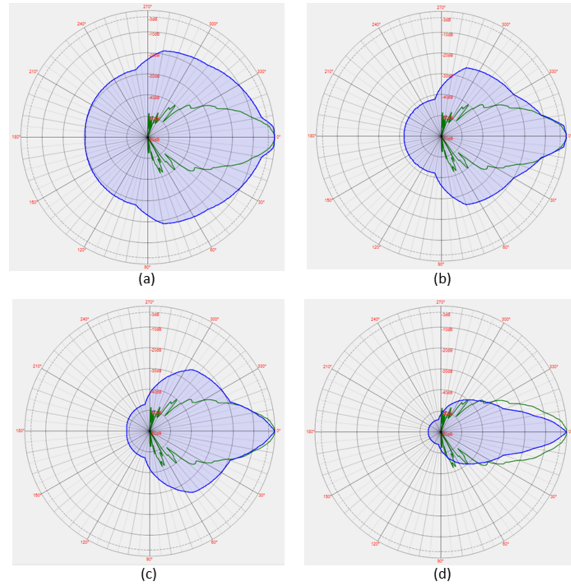


Fig. 3: ETSI RPE in blue and Horn antenna in green. (a) Class 1. (b) Class 2. (c) Class 3. (d) Class 4.

The DSA simulator assumes that transmitter (Tx) and receiver (Rx) pairs join the simulated network scenario sequentially, i.e., one at a time. When a new Tx-Rx pair joins, the SD algorithm (proposed in [5]) processes the SCMs of the new and existing RF devices to perform a Compatibility Test (CT). The CT verifies whether an initial proposed central frequency f_c and transmit power level P for the new Tx-Rx pair are compatible with the devices already in operation in the network. To that end, the CT verifies: (i) if the new Tx can reach the new Rx; (ii) if the aggregate interference experienced by the new Rx from the operations of the Tx devices already present in the scenario is below its interference tolerance (given by its underlay mask); and (iii) if the contribution of the new Tx to the aggregate interference value seen in every other receiver does not exceed their tolerance. In case the CT is negative because the new Tx causes too much interference to existing receivers, the SD algorithm evaluates if a reduction of the new Tx's power level by an amount that does not exceed a predefined power adjustment threshold (e.g., 3 dB) could result in a positive CT. If the CT is positive, the proposed operational parameters (f_c and P) are recorded in the SCMs of the new Tx and Rx and they are allowed to start operation. Otherwise, if the CT is negative even after a tentative power adjustment, a new frequency channel for the Tx-Rx pair to use is proposed, (e.g., move the center frequency to $f_c + 1$MHz), and the CT computation starts over again.

A key limitation of the SD algorithm and the corresponding DSA simulator developed in [5] is that their CT computations assumed that all devices used omnidirectional antennas, leveraging the pattern's radial symmetry to eliminate concerns about antenna orientation from the computations of aggregate interference. In contrast, the directional SCMs which are the focus of this work do not have radial symmetry (see Fig. 3), making the CTs significantly more complex. Specifically, to compute aggregate interference at a new Rx, the CT accounts for the interference caused by each existing Tx, which is a function (among other parameters) of the distance between Tx and Rx, and the relative orientation between their antennas which in turn determines the effective antenna gain values that need to be considered. Notice that in the case of omni-directional antennas, the orientation is irrelevant as the antenna gain is the same in all directions. We modified and optimized the DSA simulator to incorporate directional SCMs and account for their effects when performing CTs.

IV. Simulation Results

In this section, we use the DSA simulator described in Sec. III-B to evaluate the effects of directional antennas on spectrum usage and computation time for spectrum deconfliction in small and large-scale networks. We consider three network configurations denoted as: (i) *omni-omni*, where all transmitters and receivers use omnidirectional antennas; (ii) *dir-omni*, where transmitters use directional antennas and receivers use omnidirectional antennas; and (iii) *dir-dir*, where all transmitters and receivers use directional antennas.

In every scenario, the transmitter's main lobe is oriented towards its paired receiver and vice versa. We use omni-directional antennas with a gain of 10 dBi, and, unless otherwise stated, the directional antennas operate based on the characteristics of our real 28 GHz Horn antenna with a 24 dBi gain. In all scenarios, the transmit power of the antenna is set so that it can achieve a 100 meter coverage range with its intended receiver. Note that this does not mean that the receiver is always located at a 100 meter distance from its paired transmitter.

In Sec. IV-A, we simulate a small network with 9 links (i.e. transmitter-receiver pairs). In Sec. IV-B, we simulate several large-scale networks with up to 300 links placed at random locations. In Sec. IV-C, we simulate large-scale networks with the different antennas described in Table I. In Sec. IV-D, we evaluate the computation time of our DSA simulator.

A. Small Network with Fixed Topology

Figure 4 displays the topology used for the omni-omni, dir-omni, and dir-dir configurations using a small network with 9 links placed in a circular pattern. RF devices that compose link j, denoted by Txj and Rxj, join the network one at a time following the sequence $j \in \{1, 2, \ldots, 9\}$.

Figure 4 also presents the results in terms of number of links that end up using a frequency channel once the SD algorithm achieves spectrum use compatibility for this small network topology. Recall that the SCM-based spectrum deconfliction algorithm attempts to minimize frequency use, i.e., to use as few frequency channels as possible. The results suggest a significant reduction in frequency usage when using directional antennas over their omnidirectional counterparts in a small topology. In particular, achieving compatibility in omni-omni, dir-omni, and dir-dir configurations requires a

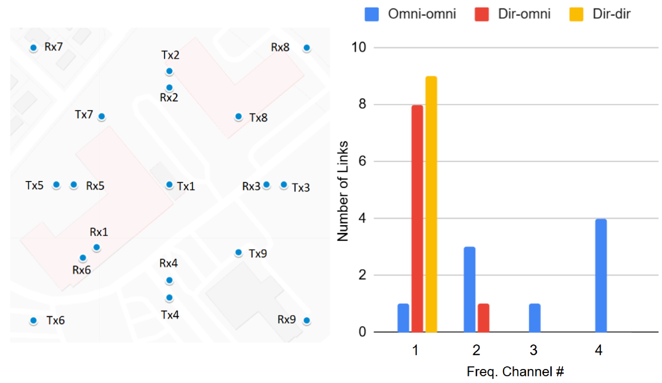


Fig. 4: Small network topology and de-confliction with 9 links.

total of 4, 2, and 1 frequency channels, respectively, and the maximum number of links allocated to a single channel was 4, 8, and 9, respectively. Next, we evaluate spectrum use in large-scale networks.

B. Large-scale Networks with Random Topology

We simulate omni-omni, dir-omni, and dir-dir configurations in large-scale networks with random topologies that have 50, 100, 150, 200, 250 and 300 links, where each link is a Transmitter and Receiver device pair (Tx-Rx). For each combination of antenna configuration and network size, (e.g., dir-dir with 200 links) we simulate 100 different random topologies.

Tx-Rx pairs join the simulated area of operation sequentially. We place each new pair at a random location within an operational area of 0.5 square miles following these guidelines: (i) the new transmitter must be separated by at least 10 meters from any other transmitter; (ii) transmitter power is such that its maximum coverage range is 100 meters and (iii) receivers are placed (uniformly at random) between 10 and 100 meters away from their corresponding transmitter. For better comparisons, the coordinates of the Tx and Rx devices of each random topology case are kept consistent among omni-omni, dir-omni, and dir-dir configurations.

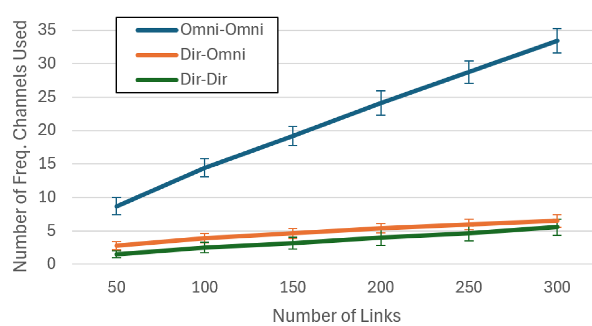


Fig. 5: Average number of frequency channels used to de-conflict 100 random topologies, each with N links, where N ranges from 50 to 300.

Figure 5 displays the average number of frequency channels required to achieve spectrum use compatibility for networks with up to 300 links. The graph shows that, as expected, frequency channel usage increases linearly as the number of links being deconflicted grows. The results also show that dir-omni and dir-dir configurations, when compared to omni-omni, significantly reduce frequency usage. For instance, compared to omni-omni, on average, dir-omni scenarios with 100, 200 and 300 links use 73.0%, 77.6%, and 80.6% fewer frequency channels, respectively. Dir-dir scenarios with up to 300 links further improve performance by using between 82.8% to 83.4% fewer frequency channels than those using omni-omni.

The results from Figure 5 further suggest that, in terms of spectrum use efficiency, the benefits of using directional antennas increase as the network size increases. Additionally, we observed that the assignment of spectrum resources is sped up due to a reduction in Tx power adjustments since a directional antenna emits power in a reduced number of directions. Recall that power adjustment occurs when an interfering transmitter can maintain compatibility with all other receivers by reducing its output power by no more than 3dB. If due to this power reduction, the transmitter loses coverage to its paired receiver, then a Non-reachability event occurs and the center frequency channel must be shifted to retry compatibility. Table II shows the average number of Power Adjustment and Non-reachability cases for networks with 100, 200 and 300 links using omni-omni, dir-omni and dir-dir configurations. When compared to omni-omni cases for networks with up to 300 links, in terms of the combined average occurrences of these two events, dir-omni cases demonstrate a moderate reduction between 13.6% to 24.3% and dir-dir cases demonstrate a high reduction between 84.0% to 94.2%.

Focusing on a specific set of scenarios, figure 6 displays a histogram of the total number of channels required to deconflict 100 random topologies, each with 300 links. Omni-omni scenarios used between 30 and 40 frequency channels to deconflict all Tx-Rx pairs, with most topologies requiring 33 channels. In contrast, dir-omni cases used between 5 and 9 frequency channels, with most topologies requiring 6 channels, and dir-dir cases used between 3 and 8 frequency channels, with most topologies requiring 5 or 6 channels.

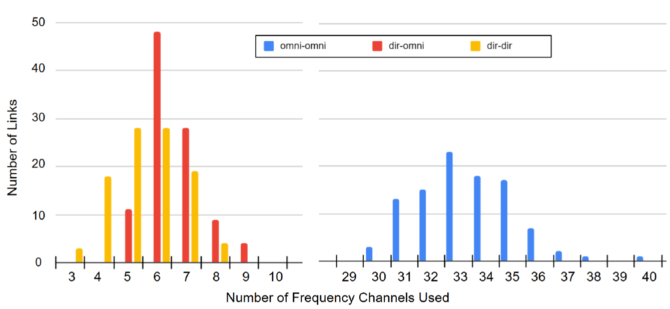


Fig. 6: Histogram showing the number of channels required to deconflict 100 random topologies, each with 300 links.

Overall, the results in Figs. 5 and 6 suggest that *dir-dir performs more efficiently than dir-omni and omni-omni, and that the difference becomes more pronounced as more links are added*. The collaborative DSA algorithm discussed in Sec. III-B is able to deconflict spectrum use by leveraging the characteristics of the boundaries of the use of spectrum provided by the SCMs of the Tx and Rx devices in each topology, which allow us to analyze different scenarios and the impact of antenna configuration parameters. Next, we evaluate the effects of HPBW on frequency usage efficiency.

C. Impact of Antenna Directionality

Figures 7 and 8 show the results of the simulations of dir-omni and dir-dir configurations for large-scale network scenarios with random topologies, where we compare the spectrum use performance of each scenario when antennas with different HPBW values (described in Table I) are used. The HPBW value is a proxy for the width of the antenna pattern's main lobe and its directivity. Increasing the HPBW widens the main lobe and reduces directivity. The dashed lines in Figures 7 and 8 show results using SCMs modeling the ETSI C1, C2, C3 and C4 class antennas and the solid lines show results using the SCMs modeling our Horn antennas. For both dir-omni and dir-dir configurations, the results suggest that decreasing the HPBW has a positive effect on the spectrum utilization efficiency of the network by reducing the number of channels required to deconflict spectrum use for a given number of Tx-Rx pairs.

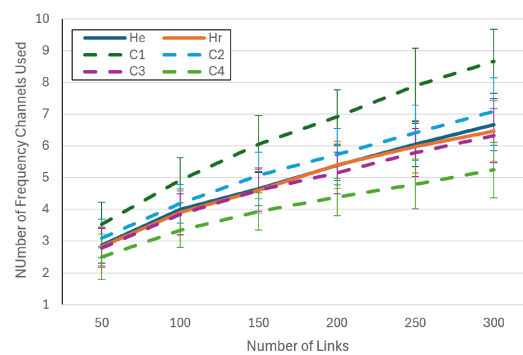


Fig. 7: Average frequency usage to deconflict 100 random topologies with up to 300 dir-omni links using different directional SCMs.

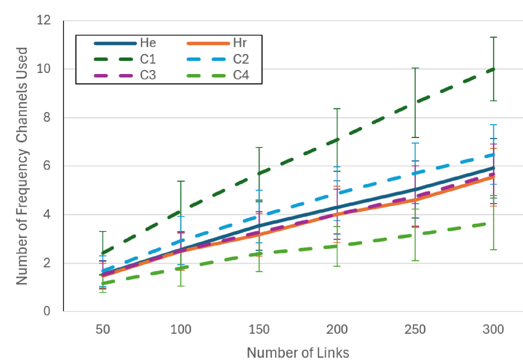


Fig. 8: Average frequency usage to deconflict 100 random topologies with up to 300 dir-dir links using different directional SCMs.

The results serve as input for future analysis on the cost/benefit tradeoff on the performance of dir-omni vs. dir-dir configurations. In scenarios with C1 antennas which have the largest HPBW value, dir-omni cases have very comparable

TABLE II: Counting the average number of power adjustments (pow adj) events and non-reachable (non-reach) events for networks with 100, 200 and 300 links configured as omni-omni, dir-omni, or dir-dir. Averaging is performed over the 100 random topolgies.

	100 Links			**200 Links**			**300 Links**		
Averages	**Omni-Omni**	**Dir-Omni**	**Dir-Dir**	**Omni-Omni**	**Dir-Omni**	**Dir-Dir**	**Omni-Omni**	**Dir-Omni**	**Dir-Dir**
# pow adj	80.14	79.15	4.8	168.85	175.13	23.68	295.75	271.12	50.76
# non-reach	12.47	0	0.59	33.88	0	3.24	62.5	0	7.14

performance and even show a tendency to outperform their respective dir-dir cases as the number of links increases. In constrast, dir-dir cases using C4 antennas which have the smallest HPBW value of the antennas we analyzed, show a trend to outperform the dir-omni cases as the number of links increases.

Overall, the results in figures 7 and 8 further showcase the benefits of using directional antennas on spectrum usage and how those benefits can be studied and modeled via SCMs.

D. Computation Time

To round up our evaluation of the performance of directional SCMs, we assess the computation time required to deconflict spectrum use in our simulated scenarios. All simulations for this paper are run on a Dell R810 server with 128 GB RAM and Intel Xeon E7-4830@2.13GHz processors with a total of 64 cores. Figure 9 shows the average time required per link to achieve compatibility across 100 topologies, each with up to 300 links placed randomly, for omni-omni, dir-omni and dir-dir configurations. This computation time excludes (i) pauses between the generation of new Tx-Rx pair (link) instances (recall that the Tx-Rx pairs join the system sequentially); (ii) time to turn on the RF devices; (iii) SCM transmission times, which usually take a few milliseconds.

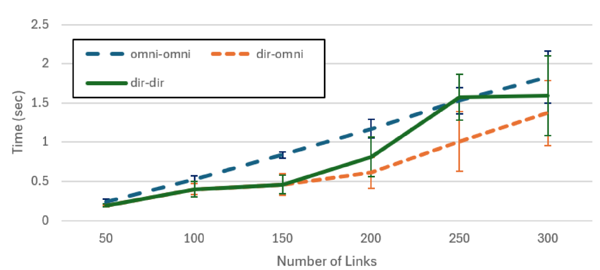


Fig. 9: Average computation time required per link to reach compatibility using different configurations for networks with up to 300 links.

The data shows no strong correlation between the per-link computation time and antenna configuration, with some unpredictability introduced due to server resource managements and scheduling. Nonetheless, we do observe that computational time increases linearly with the network size, and that even very dense networks with 300 links require, on average, less than 2 seconds per link to reach compatibility.

V. Conclusion and Future Work

In this paper, we introduced a large-scale DSA simulator that used directional SCMs from mmWave RF devices to compute aggregate interference within the network and efficiently allocate spectrum resources. Moreover, we conducted extensive simulations of large-scale networks (with up to 300 links) to investigate the effects of antenna directionality on spectrum usage. To the best of our knowledge, this is the first work to create SCMs based on measurements of directional antennas and leverage such SCMs to deconflict spectrum use. Our results showcase the benefits of SCM-based collaborative DSA algorithms for large-scale networks that can leverage dynamic selection of central frequency of operation, power adaptation and antenna characteristics and how SCMs could be used to study cost/benefit trade offs in networks with different antenna configurations.

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