Data-driven optimization technologies facilitating efficient use of spectrum in the 6G era

White paper

Foad Sohrabi, Harish Viswanathan, Jinfeng Du, Aliye Özge Kaya, Navin Hathiramani
and Pavan Koteshwar

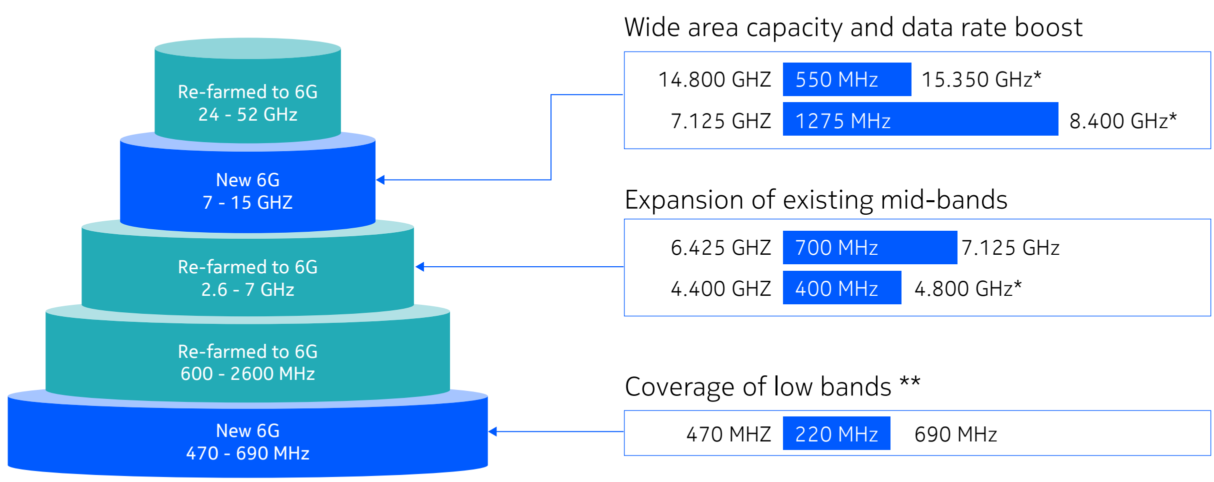
Rapid growth in overall mobile data consumption and the evolving needs of consumers for quality of experience have been the main drivers of spectrum growth in mobile systems. With ambition to deploy 6G on the same site grid as that of 5G to avoid expensive densification, it is essential to find the required spectrum in the mid-band frequencies. However, exclusive licensed spectrum is limited. With swaths of spectrum below 15 GHz where other services will continue operating, co-existence between cellular and incumbent services such as satellite, fixed services or radar systems is critical to make such spectrum available for 6G systems. To enable efficient use of spectrum, new technologies will need to be explored, such as extreme multiple-input multiple-output (MIMO) and AI, the adoption of which will open up new opportunities. We propose in this paper, new data-driven optimization techniques facilitating efficient use of spectrum in the 6G era. First, we describe a co-existence technique for efficient protection of fixed incumbent receivers within an established protection area through massive MIMO beamforming using a data-driven optimization technique. Second, we describe a closely related data-driven approach for protecting satellite receivers from cellular interference through the control of radiated power above the horizon, while maximizing terrestrial cellular network spectral efficiency. Third, we introduce spectrum sensing-based, fast-time scale, physical resource block blanking of cellular signals to protect mobile satellite receivers using a combination of satellite trajectory data and sensing at the base station (BS) sites. Fourth, we describe how the concept of a dynamic spectrum mask that allows different levels of out-of-band emissions based on occupancy of the adjacent band can be a new paradigm to improve the energy efficiency performance of cellular devices. Taken together, these techniques can enable efficient use of spectrum in portions of the 7.125–8.4 GHz and 3.1–3.45 GHz bands in the US between mobile systems and incumbent services such as terrestrial fixed services, fixed and mobile satellite services, and others.

Contents

Introduction

Rapid growth in overall mobile data consumption volumes and the evolving requirements of new generations of technologies, devices, applications and services have been the main drivers for more spectrum in mobile systems. Our forecast [1] predicts a continued surge in global consumer mobile traffic, fueled by accelerated 5G adoption, improved streaming video quality, expanding augmented/virtual reality (AR/VR) ecosystems, the rise of cloud gaming, and the increasing integration of artificial intelligence (AI). At the World Radiocommunication Conference (WRC) in 2023, the International Telecommunication Union (ITU) agreed to study the 7.125–8.4 GHz band for potential International Mobile Telecommunications (IMT) identification as one of the prime 6G bands, with decision-making planned for WRC 2027. Additionally, the upper 6 GHz band (6.425–7.125 GHz) has been identified for 5G Advanced and 6G with above the horizon power limits for co-existence with satellite services [2]. An overview of the considered spectrum for 6G is summarized in Figure 1. These new spectrum bands are attractive for 6G deployments as they offer much wider bandwidth needed for 6G [4] and the possibility to deploy 6G macro cells on the existing site grid of mid-band 5G deployments using antenna arrays of the same size as 5G mid-band deployments. The antenna arrays in these upper mid-bands are expected to have a larger number of antenna elements and transceiver chains resulting in substantially higher capacity and nearly the same coverage [5, 6].

Figure 1. Overview of potential spectrum for 6G deployments [3]



Note: Only part of these spectrum blocks will be possible in each geographic region
*For study towards WRC-27
**Initial proposal to be considered for WRC-31

In many countries, however, parts of the spectrum bands newly agreed for study for 6G will continue be occupied by some incumbents providing different types of terrestrial- and satellite-based fixed and mobile services. Co-existence and compatibility with the incumbents need to be studied, and in some cases efficient technologies need to be developed to get access to those portions of spectrum, while sharing spectrum across generations by one provider in the to-be re-farmed 5G bands will be addressed by Multi-RAT Spectrum Sharing (MRSS) [21]. Spectrum sharing with incumbents has been a topic of intense research and development for decades with numerous sharing technologies and policies proposed over the years [7–10].

Citizens Broadband Radio Service (CBRS) spectrum allocation to mobile systems in the US is arguably the most successful example of spectrum sharing. In CBRS, a three-tier sharing framework is established where the incumbents have the highest priority for spectrum usage followed by priority access licensees (PAL) while obeying transmission power limits. PAL users obtained spectrum in the lower end of the band during an auction process and have priority to employ their assigned channels in their licensed areas, in addition to being entitled to interference protection from general authorized access (GAA) users. GAA constitutes the third tier of the framework and allows GAA users access to spectrum not used by other tiers. With the established framework the shared spectrum, for example, with the US Department of Defense or DoD, is enabled for wireless service deployments, which have access to the spectrum when, for example, navy radars are not in use. Thus, access to this spectrum is protected for certain users, such as navy radar operations, and other users of the spectrum may be required to suspend their activities to ensure no interference with these incumbent users.

Spectrum access servers are utilized as a means for protecting the incumbent and allocating unused spectrum for CBRS users. The CBRS framework for incumbent protection has been evolving and enhancements were recently adopted [11] to account for traffic load and time-division duplex patterns as well as more realistic path loss models in aggregated interference calculation. Such advanced spectrum sharing techniques are of intense interest and form the main focus of this paper.

Artificial intelligence/machine learning (AI/ML), particularly deep learning techniques, are emerging tools being applied to communication systems and can also be leveraged for efficient use of spectrum. Viewed as optimization techniques, these differ substantially from traditional techniques because of their heavy reliance on data for training and structure abstraction as well as artificial neural networks. These methods are thus often called data-driven techniques.

While effective spectrum sharing and co-existence has always relied on accurate spectrum usage data gathered from data bases and sensors, it has not relied on data-driven optimization of the cellular transmitted signal in time, frequency and spatial dimensions. AI/ML techniques in the air interface are widely considered in the industry to be an essential ingredient in 6G [12-15], with extensive discussions ongoing in 3GPP on the use of AI/ML techniques already for the 5G Advanced standard.

AI/ML offers new possibilities for spectrum access when combined with advances in communication technology. The evolution from 5G massive MIMO to extreme MIMO (eMIMO) in 6G is one example offering new possibilities for more efficient use of spectrum. Extreme MIMO, with its very large number of transceiver (TRX) chains and potentially thousands of antenna elements, makes it possible to accurately beamform the transmitted signal in certain directions with narrow beamwidth (5˚or narrower) while creating nulls in other directions allowing for more efficient spatial sharing of spectrum with incumbent receivers. We propose application of data-driven optimization to determine beamforming weights that protect incumbent receivers, with the ability to adapt to the changing requirements on interference suppression/mitigation specifications.

Spectrum sharing between satellite and terrestrial mobile services has some unique challenges. For example, the high demand for spectrum for different services is often in the same densely populated area at the same time. The satellite beam-frequency association could also be reconfigured based on satellite traffic distributions [16-18]. Fortunately, not all spectrum is used in all neighboring satellite beam spots due to the need for frequency reuse among neighboring beams to mitigate inter-beam interference, which provides opportunities for spectrum sharing even when satellite traffic is heavily loaded in a beam spot [19]. Aided by new spectrum sensing capabilities at base stations (BSs) and predictable trajectories for incumbent satellite services, we consider adaptive physical resource block (PRB) blanking to mitigate interference in the same bands and proactively expand/reduce spectrum sharing by exploiting the dynamic nature of spectrum use by incumbent networks. Additionally, new AI/ML-based short-term traffic prediction techniques enable us to optimize and allocate BSs for spectrum sensing based on the predicted traffic load.

One of the advantages of deep learning-based transmitter and receiver processing is its ability to deal with signal distortion introduced by non-linearities in the transmit-receive chain. As a concrete example, it is possible to drive the power amplifier into the non-linear regime to increase energy efficiency, with the resultant distortion corrected by the receiver using deep learning models [20]. However, the non-linearity results in higher out-of-band emissions. Dynamic spectrum masks that are adjusted according to adjacent channel occupancy can be a new opportunity that extends spectrum sharing to include adjacent channels. This concept is further elaborated in this paper.

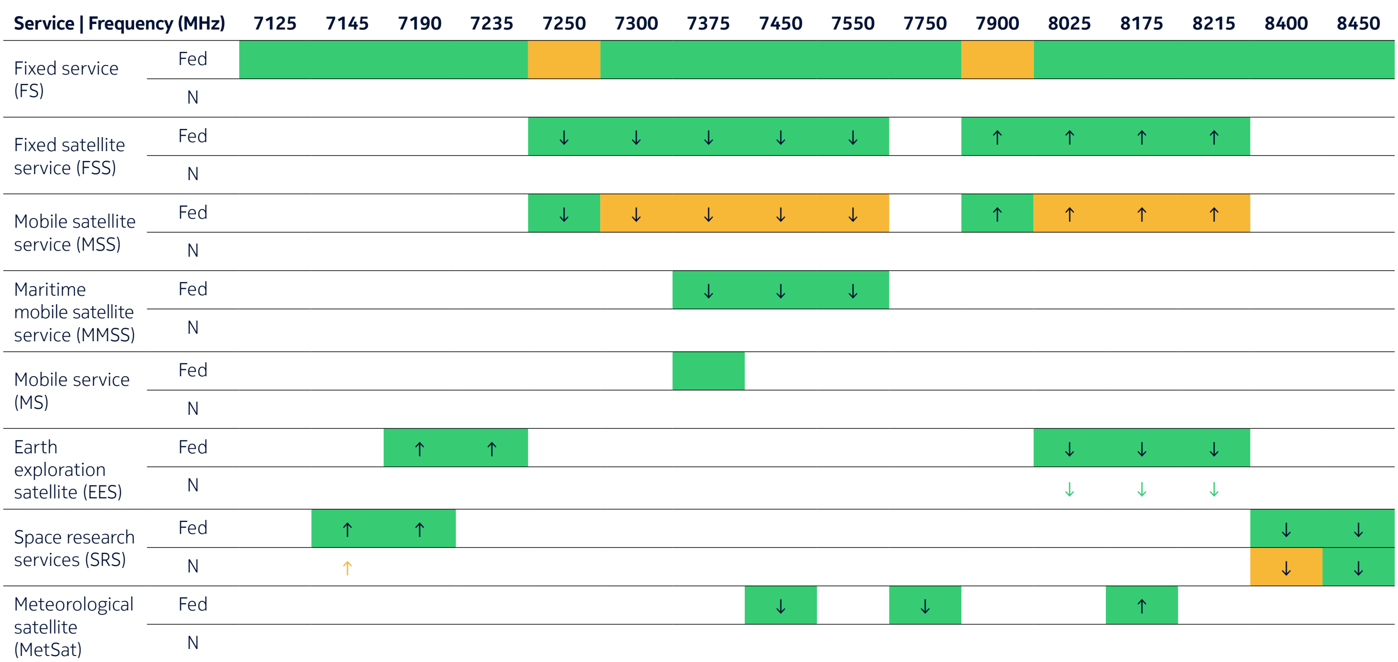
We focus on four novel spectrum access techniques that may be suitable for the 6G era as enablers for the use of portions of spectrum where incumbent services will continue operating. First is efficient protection of fixed incumbent receivers with known protection areas through massive MIMO beamforming using a data-driven optimization technique. Second, we describe a closely related data-driven approach for protecting signal reception at satellites from cellular interference through limitation of above-the-horizon (ATH) radiated power while maximizing terrestrial cellular network spectral efficiency. Third, we describe how to improve PRB blanking of cellular signals to protect mobile satellite receivers using a combination of satellite trajectory data and spectrum sensing at BS sites. Fourth, we describe how the concept of a dynamic spectrum mask that allows different levels of out-of-band emissions based on occupancy of the adjacent band can be a new paradigm to improve the energy efficiency performance of cellular devices. The first three focus on co-existence/sharing with incumbents, and the last one focuses on effective spectrum utilization between terrestrial networks that occupy adjacent bands.

In the next section, we provide a summary of incumbents in the key band under consideration for 6G in the US, what kind of protection is required, and how it corresponds to the four concepts described in this paper. The next four sections describe each concept in turn, and we conclude with a summary in the last section.

Spectrum landscape of 7.125–8.4 GHz in the US

The spectrum landscape in the US for the 7.125-8.4 GHz band is shown in Figure 2, generated based on data from [9]. Different parts of the band are occupied by different types of fixed and mobile satellite services as well as terrestrial fixed services, assigned with either primary (green) or secondary (orange) user status. To maximize spectrum for future 6G systems, efficient use of spectrum with incumbents will be needed, with transmissions of BSs and user devices not causing harmful interference. Additionally, the cellular system receivers should be resilient to interference generated by the incumbent systems. We focus on protection of the incumbent in this paper.

Figure 2. Spectrum landscape in the US for 7.125–8.5 GHz where allocations for Earth-to-space (↑) and space-to-Earth (↓) links of satellite services are shown under either primary (green) or secondary (orange) allocations for federal (Fed) and non-federal (N) use. Green and orange arrows (without background color) indicate primary and secondary allocations, respectively, that have limitations in either frequency range or geographical areas. This figure is generated based on data from [9], and the length of each grid/sub-band is roughly proportional to the bandwidth available.



There exist three types of scenarios for coexistence or sharing spectrum with incumbents in the 7.125–8.4 GHz, corresponding to three different types of receivers to be protected from cellular use of their spectrum, as shown in Table 1:

a) Stationary terrestrial receivers whose locations are well known—typically Earth stations of fixed satellite services or receiver parts of fixed terrestrial services

b) Satellite receivers that receive signals from Earth stations or other mobile transmitters, typically moving relative to the ground along certain trajectories, such as low-earth orbit (LEO) satellites, or stationary relative to Earth, such as geostationary satellites like the Wideband Global Satcom (WGS) system [17], and may or may not be available to provide service to terminals that are in the vicinity of a particular location on the ground

c) Mobile terrestrial receivers whose exact locations are unknown but the transmitting satellite's trajectory or location is known, and the presence of satellite transmission signals can be detected.

Table 1 shows the coexistence or sharing spectrum strategy that can be implemented in the cellular system to protect the incumbent.

Table 1. Incumbent receiver categories and associated protection strategies

	Stationary		Mobile	
Terrestrial receiver	Fixed service Fixed satellite service (↓) Earth exploration satellite (↓) Space research service (↓) Meteorological satellite (↓)	**Beamforming optimization (Sec. III)**	Mobile satellite service (↓) Maritime mobile satellite service (↓)	**Adaptive PRB blanking (Sec. V)**
			Other co-priority terrestrial networks in adjacent bands	**Adaptive spectrum mask (Sec. VI)**
Satellite receiver	**ATH power control (Sec. IV)** and/or **Adaptive PRB blanking (Sec. V)**			

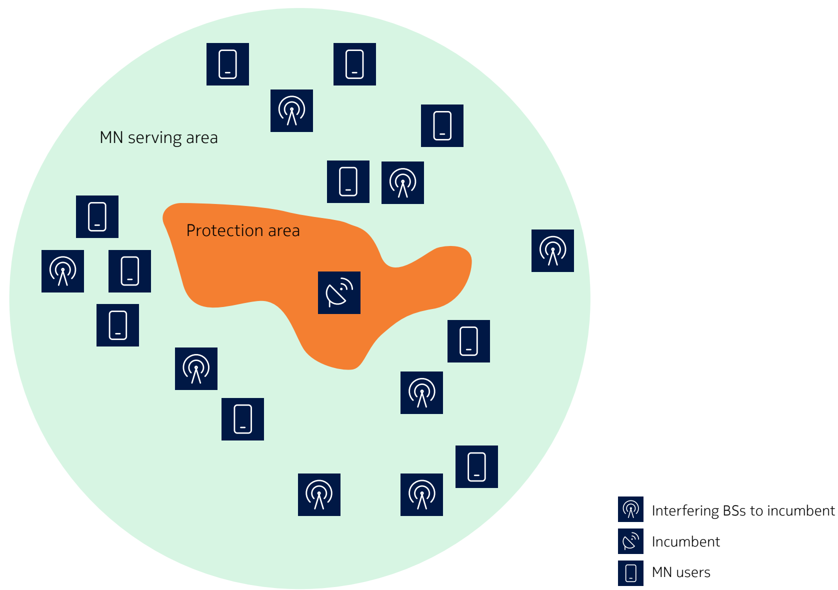
Beamforming optimization for efficient use of spectrum with incumbents of known location or protection areas

This section focuses on scenarios where the mobile network (MN) has access to information about a protection area for incumbents such as satellite ground stations or radars and aims to protect them from harmful interference caused by the MN transmissions. There is a straightforward approach to managing the total interference generated by the MN within the incumbent operational area. By allowing the BS to obtain samples or models of the channel state information (CSI) within the protection area, it is able to reduce transmit power to ensure that the received power at the incumbent(s) in the protection area remains within acceptable levels. This approach, however, while effective in controlling the interference level at the incumbents, can lead to significant MN coverage and data rates degradation, particularly in areas with high incumbent protection requirements.

One viable solution to address this issue is to leverage the spatial domain. The emergence of 5G and beyond technologies has introduced massive MIMO systems, where BSs employ large antenna arrays. In these systems, beamforming techniques, alongside power control, can play a crucial role in shaping the signal transmission and mitigating interference. However, conventional beamforming methods do not specifically address the challenge of protecting incumbents from interference in shared spectrum scenarios. This motivates the development of novel beamforming techniques that can effectively control the level of interference experienced by incumbents in a designated protection area, thus enabling the coexistence of MNs and incumbent services without significantly compromising the performance of either.

To illustrate the concept, we consider a cellular mobile network where BSs provide service to mobile users while co-existing with another service that requires low interference. To accommodate this requirement, a protection area is established where the MN must carefully control its interference levels. Figure 3 illustrates an example of this setup. For simplicity, we consider no collaboration between BSs and focus on a single-cell scenario, with the overall interference constraint in the protection area being distributed among neighboring cells. It’s important to note that for MN users located within the protection area, it may not be feasible to provide service using this frequency band. To address this challenge, one potential solution is to cover mobile users within the protection area using an alternate frequency band.

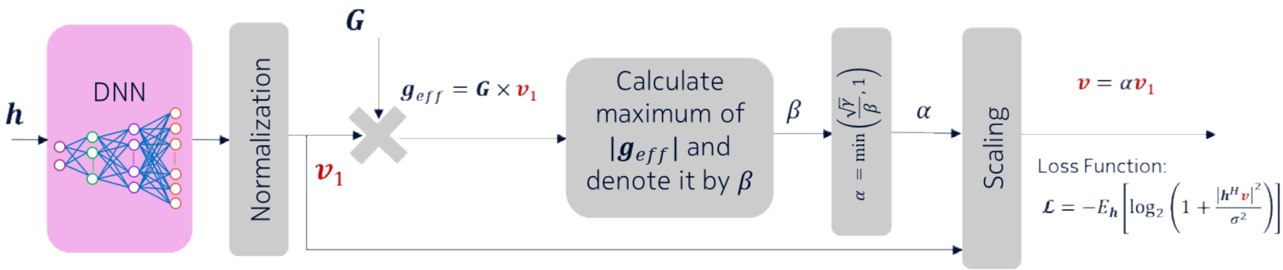
Figure 3. Cellular network with BSs serving MN users while sharing spectrum with an incumbent service requiring low interference in a protection area.



Following the aforementioned assumptions, consider a single-cell scenario in which a BS with $\mathbf{N}$ antennas (and fully digital beamforming architecture) serves a single-antenna user while controlling its interference to a protection area for other incumbents. Suppose that the BS has access to MN user CSI (e.g., $\boldsymbol{h}\in\mathbb{C}^{N\times 1}$) and a data set of CSI samples from the protection area (e.g., $\mathbf{G}\in\mathbb{C}^{s_1\times N}$). These samples may be obtained based on some channel models, some historical data sets, or from some real-time measurements, with some levels of inaccuracy handled using an appropriate power margin. The problem of interest is designing a precoder $\mathbf{v}$ to maximize an MN key performance indicator (KPI) (e.g., the user rate $\mathbf{R}(\mathbf{h},\mathbf{v})=\log(1+\|\mathbf{h}^H \mathbf{v}\|^2/\sigma^2)$ where σ^2 is the noise power), while being compliant with the interference limit in the protection area (i.e., $\|\mathbf{G}\mathbf{v}\|^2 \leq \tau\mathbf{1}$ where τ is the interference threshold). The interference limit can be set forth by a spectrum sharing coordinator or controller to allow distributed per-BS interference control while maintaining a reasonable overall aggregated interference level, accounting for power margins needed to mitigate inaccuracy in CSI samples from the protection area. The spectrum sharing coordinator/controller could be the same entity that provides the MN the needed information about the protection area.

To achieve data-driven precoding for efficient use of spectrum: We consider the codebook-free precoding in which the precoder satisfies the power constraint, i.e., $\|\mathbf{v}\|^2 \leq \mathbf{P}$. For this case, we can use the neural network architecture depicted in Figure 4, which takes both the MN user's CSI $\mathbf{h}$ and the protection area channel samples $\mathbf{G}$ as inputs and then generates a precoder that optimizes an MN utility function while adhering to the interference constraint for samples within $\mathbf{G}$.

Figure 4. The data-driven approach for designing codebook-free beamforming for co-existence with incumbents in protection zone

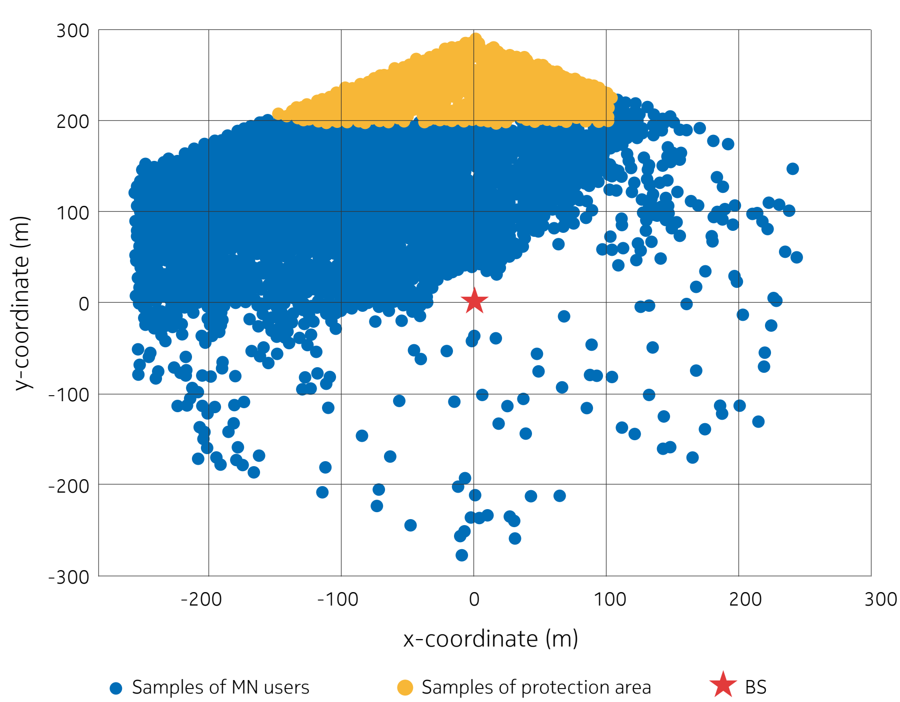


In the first stage of this architecture, there is a deep neural network (DNN) followed by a power normalization layer used to generate an initial precoder based on $\mathbf{h}$. In the second stage, the power of the initial precoder is scaled down to ensure the final precoder satisfies the interference constraint for any channel samples in $\mathbf{G}$. For training such a network, the training loss can be set as a negative sign of the desired KPI for the mobile network (e.g., MN user data rate).

It should be mentioned that, while the idea of data-driven precoding for efficient spectrum access is presented only for codebook-free precoding, this idea can simply be applied for designing a codebook in codebook-based precoding as well.

Numerical results: To evaluate the performance of the presented methods, we consider the set up illustrated in Figure 5. Here, the orange points indicate the locations of the channel samples for the protection area, and the blue points indicate the location of the MN channel samples.

Figure 5. Simulation setup: 128-antenna BS in Urban Macro (UMa) non-line-of-sight channel at 7 GHz

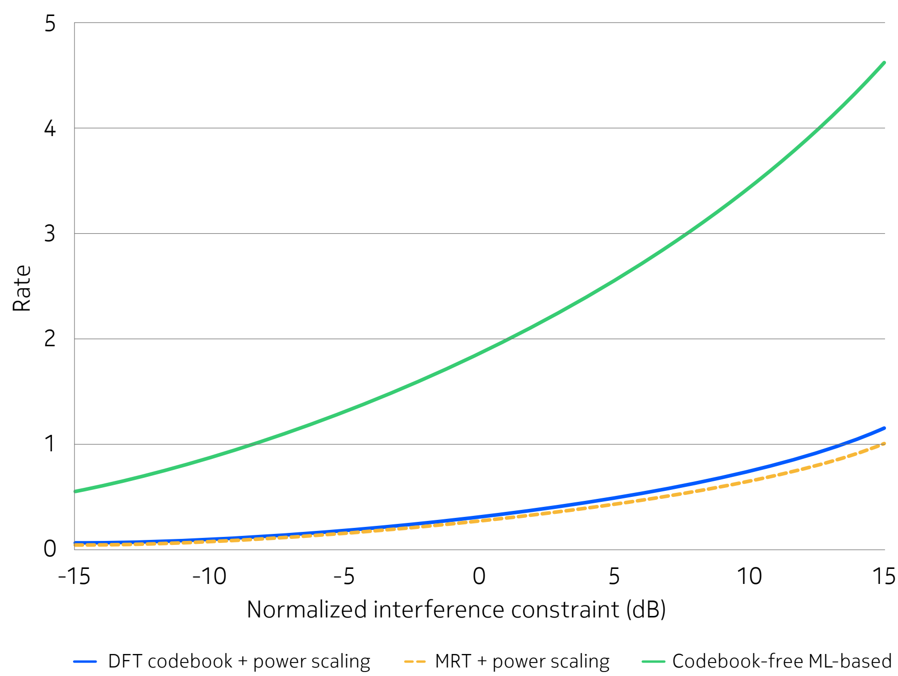


To compare the performance of the proposed methods, we consider the following two baselines:

- Maximum ratio transmission (MRT) + power scaling: MRT is known to be optimal codebook-free beamforming for single layer transmission under the sum power constraint. To further make this design compliant with the interference constraint, the power is scaled down.
- Discrete Fourier transform (DFT) codebook + power scaling: The DFT codebook is a widely used codebook for MIMO beamforming. To further make this codebook compliant with the interference constraint, the power of each codeword is properly scaled down.

Figure 6 illustrates the performance of different methods. The data-driven methods, both codebook-free and codebook-based, achieve significantly better performance compared to their conventional counterparts. This demonstrates that data-driven methods effectively enable co-existence through beamforming designs specifically tailored for this purpose. Unlike prior art, these methods go beyond simple power reduction.

Figure 6. Average rate versus the normalized interference constraints for different methods



Above the horizon radiated power control for protecting satellite receivers

To control the radiated powers above the horizon to protect satellite incumbents, we assume there is no information about the incumbent location or channel model. Accordingly, the radiated power constraint should be defined as an average. In the existing systems, where the spectrum is mainly allocated to MNs, the BS transmitter configuration and beamforming designs usually need to comply only with the maximum effective isotropic radiated power (EIRP) limits. However, for new bands where MNs need to coexist with satellite networks, other EIRP limits may be established. For example, WRC-23 introduced a set of new ATH-EIRP limits [2] for the n104 band, as shown in Table 2. Such new constraints require the development of novel techniques to design BS configurations and beamforming strategies that meet ATH EIRP limits with minimum performance degradation.

Table 2: ATH EIRP constraints based on WRC-2023 [2]

Evaluation angle θ above horizon ($\theta_L \leq \theta < \theta_H$)	Expected EIRP (dBm/MHz)
0° ≤ θ < 5°	27
5° ≤ θ < 10°	23
10° ≤ θ < 15°	19
15° ≤ θ < 20°	18
20° ≤ θ < 30°	16
30° ≤ θ < 60°	15
60° ≤ θ ≤ 90°	15

A generic extreme MIMO architecture, as illustrated in Figure 7, implements a massive number of radiators with a three-stage beamforming process to balance performance with hardware cost, computational complexity, and power consumption. The first two stages—digital precoding and adaptive analog precoding—are based on user CSI. The third stage, called fixed analog precoding, involves fixed phase shifts and attenuations at each radiator, designed during the production phase.

Figure 7: A generic extreme MIMO architecture

To optimize the system performance while respecting ATH-EIRP constraints, we can design both BS configuration parameters in the production phase as well as the adaptive beamforming strategies.

Design of BS configurations, including fixed analog precoding, radiator spacings, and radiator gain patterns: To address this problem, we can use a data-driven approach to tailor our design for a given channel distribution. To showcase this approach, let's focus solely on the fixed analog beamforming design problem assuming radiator spacing and gain pattern are given. For such a setting, we can collect a channel dataset H for users in the topology of interest. Our goal is to maximize a measure of utility, $\max E_H [KPI(V_{FA})]$, while satisfying the expected EIRP limit for each constraint bin, $EIRP_{bin_j}(V_{FA}) \leq EIRP_{lim,j}, \forall j$. To use the data-driven approach, inspired by the Lagrangian method, we define a loss function as an aggregation of the original objective function and the sum of the EIRP-constraint violations, as follows:

$$L(V_{FA}) = -E_H [KPI(V_{FA})] + \lambda \sum (EIRP_{bin_j}(V_{FA}) - EIRP_{lim,j})^+,$$

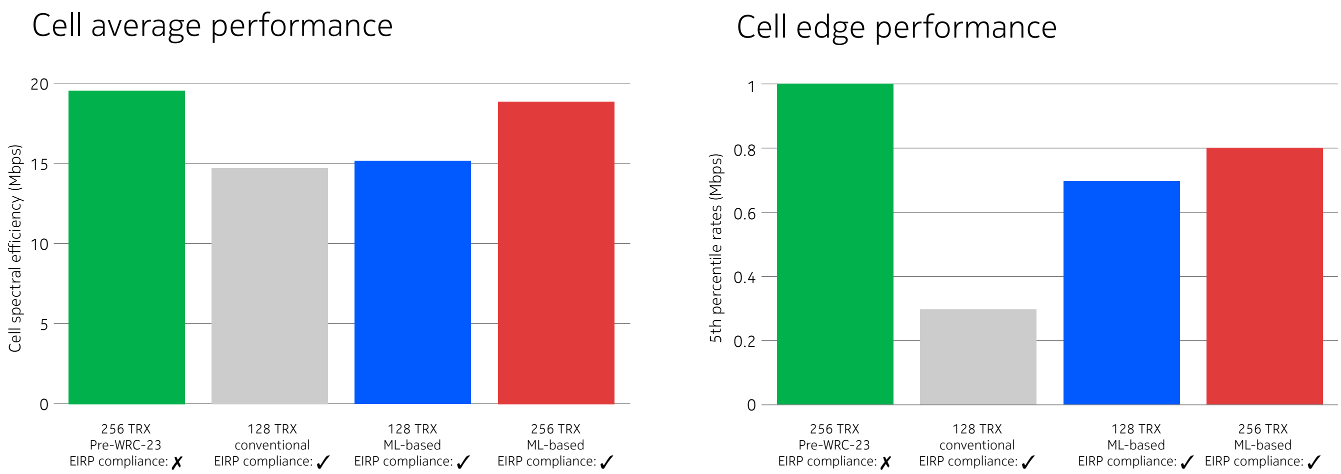
where $(x)^+ = \max(x,0)$. By selecting a sufficiently large λ, we ensure the second part of the loss function becomes zero, achieving ATH-EIRP compliance. Using the collected channel dataset and defining the fixed analog beamformer as a trainable parameter, we can employ SGD approaches to optimize the fixed analog beamformer, minimizing the defined loss function.

It should be emphasized that once the BS configuration, including radiator spacing and array element beamformed radiation pattern, is designed, it becomes integrated into the product and cannot be changed. A mismatch between the channel data used for optimizing the BS configuration and actual real-time channel conditions can still lead to violations of ATH-EIRP limits. To address this, we need to optimize operational parameters, including the design of the adaptive analog beamformer and power allocation. However, it can be shown that similar principles can be used to adaptively design operational network parameters.

Numerical results: In this section, we evaluate the performance of the data-driven approach, which we refer to as the ML-based solution, for simplicity. For illustrative purpose, we consider the ATH EIRP constraints in Table 2. While we focus on presenting the results for the one-time BS configuration parameter design, it's worth noting that the effectiveness of the data-driven approach can also be demonstrated for adaptive analog codebook design. We compare the ML-based solution with solely fixed analog beamforming design to two other methods. The first is the conventional commercial BS design method, which essentially employs electrical downtilting towards the most densely populated areas. The second is the conventional filter-based design, which enforces ATH-EIRP limits for almost all possible precoders in a codebook (such as the DFT codebook). It's important to note that while the filter-based design approach can produce some ATH-EIRP-compliant solutions in certain scenarios, it often involves a tedious process of manually adjusting phases and amplitudes to meet the constraints. Moreover, this approach doesn't consider the channel distribution, which can result in suboptimal solutions.

We evaluate the system performance of the various designs in Figure 8. The green bars represent a conventional design, which is non-compliant with ATH EIRP limits in Table 2 but serves as an upper-bound performance benchmark. Gray bars indicate the filter-based design with 128 TRXs, while blue and red bars correspond to ML-based designs with 128 and 256 TRX, respectively. Although both ML-based and filter-based designs with 128 TRXs comply with ATH EIRP limits in Table 2, ML-based solutions show superior cell-edge performance. Additionally, the ML approach enables a higher number of TRXs, allowing improved cell average performance by serving more layers with 256 TRXs. This simulation confirms that our proposed framework effectively produces high-quality solutions for limiting ATH EIRP. The ML-based approach not only meets ATH EIRP requirements but also offers enhanced performance, particularly in challenging network conditions.

Figure 8: The system performance comparison of different methods



Spectrum sensing-based adaptive physical-resource block blanking

One of the most challenging incumbents to protect are the mobile satellite service devices. Because the incumbent receivers are mobile, it is not possible to protect them by creating static interference-free zones in any particular area as in the case of fixed receivers. Furthermore, for incumbents belonging to the military service, it is very difficult to get information about the location of the devices, thus it may not be possible to create dynamic interference-free zones around the mobile devices. Hence a possible solution could be to avoid cellular interference in the entire area of the satellite footprint in the appropriate frequencies where there could potentially be satellite receivers. Typical satellite services operate a constellation of satellites, which uses multiple beams to cover different portions of the Earth's surface. Different frequency carriers are assigned to different beams of a satellite to avoid interference across overlapping beams. Satellite services may partition their allocated spectrum in a band per beam spot on the Earth's surface. Frequency allocation for satellite coverage in a given geographical area is different from its neighboring satellite cells (as defined by its beam spot on the surface), and the spectrum occupancy could be dynamically reconfigured [17, 18] depending on traffic demands. Furthermore, only one or two beams typically illuminate each ground location across multiple satellites of the constellation. Hence only a portion of the spectrum allocated to the satellite service is occupied in any given ground location. In addition, if there are no devices being served in the footprint of a beam, the transmission is suppressed in that beam in order to save power. For these reasons, there is opportunity for dynamic spectrum sharing through blanking of PRBs corresponding to frequencies occupied by the satellite service.

A potential approach for dynamic spectrum sharing is for cellular BSs to sense the presence of satellite transmissions and, when signal is present, suppress the PRBs corresponding to satellite transmissions. Because the satellite signal footprint is large, with the beam spot on the Earth's surface ranging from a radius of tens of kilometers (e.g., LEO satellites [16]) to hundreds of kilometers (e.g., the WGS system [17]), there will be a large number of BSs within the footprint area, and the burden of sensing can be shared across the BSs, with some focused on sensing on specific bands and a select few targeting wideband sensing as needed. In other words, not all BSs need to suppress uplink transmissions in this band for sensing at the same time. Only a subset of BSs, selected/configured by a sensing management function, need to skip scheduling uplink transmissions in certain PRBs to facilitate sensing while other BSs may continue to schedule UEs, under certain constraints, to better facilitate spectrum sensing in adjacent spectrum. However, as soon as the presence of the satellite signal is confirmed, all BSs in the footprint of the satellite beam should suppress scheduling downlink and uplink transmissions in the band occupied by the satellite downlink until the sensing confirms that satellite transmissions have terminated.

An alternative to sensing can be based on a spectrum access server that informs the MN of the satellite's services impending use of frequencies in different geographical areas. Further, regulatory authorities could encourage sharing of at least some limited, non-strategic information between satellite and terrestrial service providers to improve spectrum sensing accuracy and to enable better spectrum sharing.

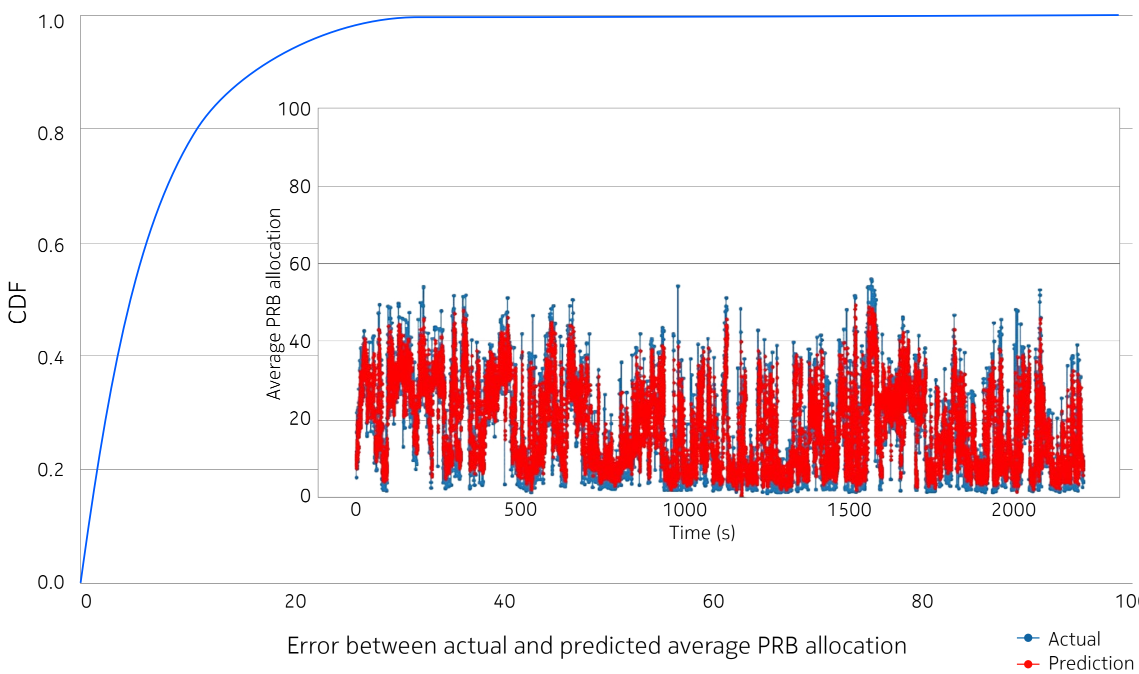
Base station traffic prediction for resource optimization in spectrum sensing

The dynamic PRB blanking assumes that each network could sense the frequency occupancy within certain areas (as defined by the satellite beam spot). This requires accurate prediction of traffic load at BSs and reserving the required resources ahead of time. From an MN point of view, the spectral efficiency of this sharing mechanism is dependent on efficiently enabling resources for incumbent detection in a fast and reliable manner. One method to achieve this could be predicting future PRB usage and employing lower PRB usage periods for sensing.

The selection of the candidate BSs for spectrum occupancy sensing can be achieved by accurate prediction of traffic demand at each BS. In order to have sufficient time to identify candidate BSs and optimize/distribute the spectrum sensing task to selected BSs, the traffic prediction process should begin about 100ms ahead of the actual time when the sensing operation will be required. Traffic prediction on such short time scales can be done using ML models that learn the underlying behavior of traffic. We used the neural network to predict future PRB usage for the next 500 ms based on the previous PRB usage within the last 10 s, each sampled at 100 ms intervals. Therefore, the input to the neural network has the length 100 and the output, 5.

To assess the performance of the neural network we have compared the absolute error in PRB prediction (i.e., the gap between the actual utilization and the predicted utilization) sampled at 100 ms intervals. We tested the neural network using a measured network dataset for downlink traffic traces for a period of 2,250 seconds, where 100 PRBs are available. The actual and predicted PRB allocations are plotted in Figure 9, where the insert shows that the predicted and actual values follow similar trends throughout the data. The cumulative distribution function (CDF) of error as the absolute difference between actual and predicted PRB allocations demonstrates good prediction accuracy; for 80% of the test data instances, the predicted PRB usage differed at most by 10 PRBs from the actual one.

Figure 9. CDF of error as absolute difference actual and predicted PRB allocations over 2,250 s, with point-wise comparison between actual and predicted PRB utilization shown in the insert



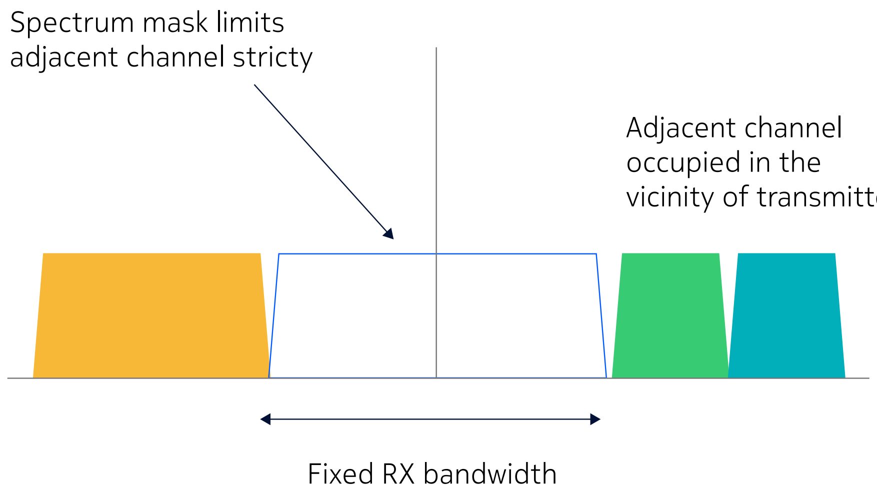
There are some challenges that need to be addressed to enable sensing-based sharing with mobile terminals:

- The waveform of incumbent signal transmission might include spectrum spreading, which requires innovative solutions for reliable spectrum occupancy sensing. Such methods may require distributed and cooperative wideband spectrum sensing from multiple BSs to minimize probabilities of misdetection and false alarms.
- Since the location of a serving beam is also moving (unless active beamforming such as phased array is used), the cluster of cooperative BSs for sensing would also need to be updated accordingly, which may call for a centralized spectrum sensing server to orchestrate the sensing over a large geographical area.
- Due to the presence of adjacent carrier leakage from orthogonal frequency-division multiplexing (OFDM) waveforms, PRB blanking may need to be extended to neighboring subcarriers to suppress the leakage level below the tolerance level of incumbent receivers.
- In a time-division duplex (TDD) system, spectrum sensing at BS sites should be done during scheduled uplink periods or guard symbols period. In synchronized TDD settings, long downlink transmission may lead to long waiting times before a new incumbent transmission is detected. One possible solution is to ensure that, at any period of time, there are always some un-occupied PRBs that are not being used by any of the MN BSs, and some of the BSs are assigned for spectrum monitoring tasks. A new PRB allocation method is needed to minimize the interference to newly arising incumbent transmissions.

Adaptive spectrum masks for adjacent channel sharing

MN transmitters and receivers are typically designed for a given bandwidth in each band with strict out of band emission limits meeting required spectrum masks. The bandwidth is based on spectrum allocations for MNs and is specified in standards such as 3GPP. Typically, the spectrum adjacent to MN bandwidth in any given band is allocated to some other services, and those devices are protected from interference from MN signals through the spectrum masks imposed. This situation is illustrated in Figure 10, where the MN carrier is at the center and adjacent channels are fully occupied by other services.

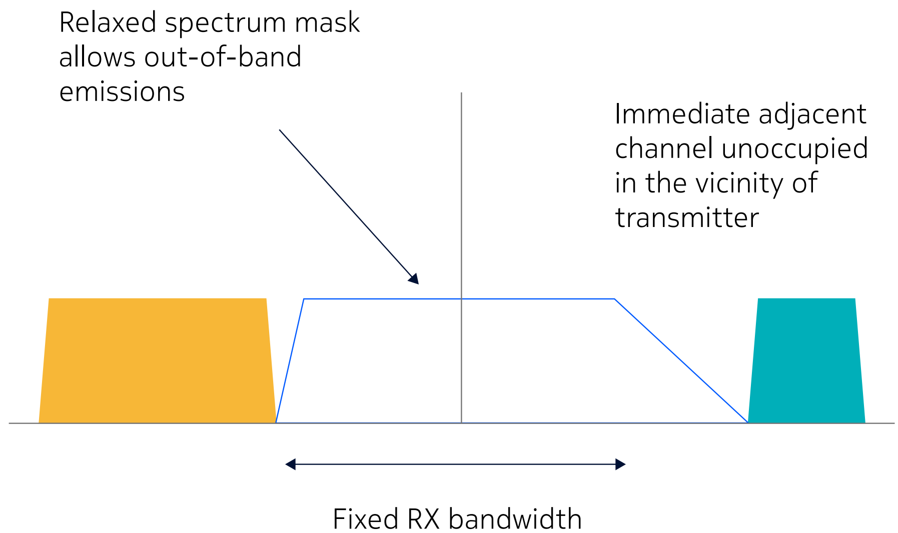
Figure 10. Illustration of a spectrum mask for an MN carrier located at the center and adjacent channels are fully occupied by other services



In many circumstances, however, the spectrum channels adjacent to the MN spectrum are only lightly used or unoccupied in a particular geographical area. One example is when the spectrum adjacent to the MN carrier is allocated for some fixed services. In this case, the fixed service is not deployed everywhere, and in the neighborhood of many MN BSs, the adjacent spectrum band will be unoccupied. In the state-of-the-art approach, the spectrum mask will remain the same and the cellular transmitters will continue to transmit signals limited to the fixed bandwidth for which they were designed. This is because there is no simple way to exploit this adjacent bandwidth for a linear transceiver that has not been originally designed to occupy this adjacent bandwidth. Since this spectrum is not available everywhere to the MN, it will not be economical to design a transmitter and receiver to have wider bandwidth than that allocated for MN use that includes this additional bandwidth.

One approach to exploiting this adjacent unoccupied bandwidth without modifying the radio bandwidth of the TRX is through an adaptive spectrum mask that accounts for the occupancy of adjacent spectrum. Figure 11 shows how the spectrum mask can even be modified on one edge, for example, on the side adjacent to the fixed service spectrum, when the adjacent spectrum is unoccupied.

Figure 11. Illustration of relaxed spectrum mask for the center carrier on its right where the adjacent spectrum is unoccupied.

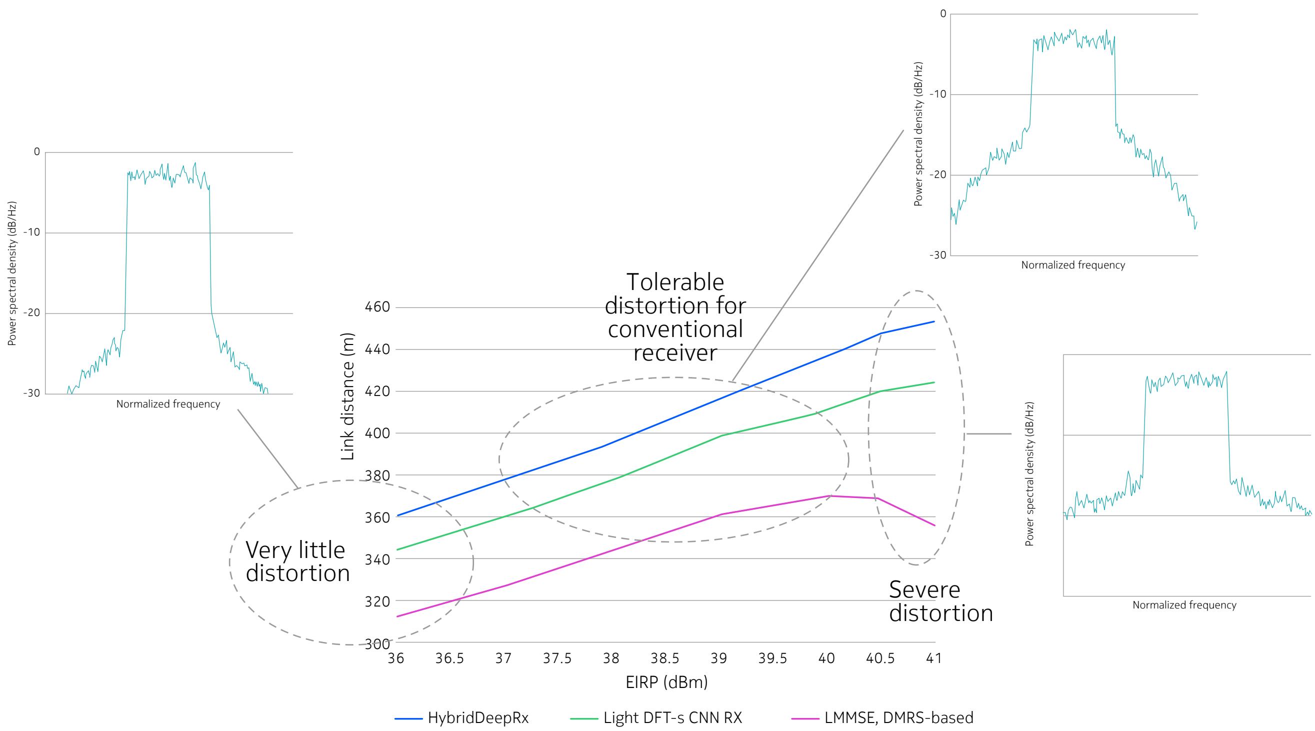


When the mask is relaxed, it will be possible to achieve a lower error vector magnitude using an appropriate pre-distortion algorithm that exploits this new relaxed spectrum mask. Another approach to exploit the relaxed spectrum mask is to increase the transmitter output power by operating the power amplifier (PA) closer to the saturation power in its non-linear regime. Normally, such an approach causes in-band signal distortion and the received signal-to-interference-plus-noise ratio (SINR) does not improve even though the output power is higher. However, with an AI receiver, one can suppress distortion introduced at the transmitter through non-linear post distortion compensation at the receiver and improve the SINR of the signal because of the higher transmit power.

Figure 12 shows the benefit of relaxing the spectrum mask in terms of the higher link distance that can be achieved for the same throughput because of the higher transmitter output power. The improvements in EIRP and corresponding link distance is plotted for three different receivers, namely, a classical linear minimum mean square error (MMSE) receiver, a convolutional neural network receiver, and a more sophisticated time and frequency domain hybrid AI receiver. The HybridDeepRx receiver is better able to exploit the additional transmit power as it is best at post-distortion compensation.

The practical implementation of the proposed adjacent channel spectrum sharing concept, which targets higher leakage levels to adjacent bands when neither are occupied by an incumbent nor by another MN, requires a spectrum access server that can provide information to the MN for each geographic area about the occupancy of adjacent channel spectrum in that area. The MN BS can then choose one from a small set of pre-determined spectrum masks depending on the adjacent channel occupancy, and the BS should signal to the mobile devices about the choice of the spectrum mask to use through, for example, the system information block signaling. The BS and mobile devices served by that BS can then configure the transceiver according to the choice of the spectrum mask, resulting in better performance.

Figure 12. The benefit of relaxing the spectrum mask is the higher link distance that can be achieved for the same throughput because of the higher transmitter output power under a relaxed spectrum mask. Also, the power spectral density plots for three different power levels show how adjacent channel leakage power increases with increasing transmit power level.



Summary

Effective and efficient spectrum access mechanisms that allow 6G to co-exist or share different parts of the upper mid bands with incumbents that will continue operating in that spectrum are essential to meet 6G spectrum demands. Sufficiently high transmit power needs to be supported to ensure similar coverage from the same site grid deployment as 5G. 6G technologies such as extreme MIMO facilitate much finer granularity of spectrum access in the spatial domain thanks to the much narrower beamwidth from large antenna arrays. Scalable beamforming algorithms with adaptive power control can protect incumbents without substantially reducing cellular capacity under the spectrum co-existence scenario. Additionally, AI-native support in 6G enables data-driven solutions for interference suppression and traffic prediction. Combined with effective spectrum sensing techniques, dynamic PRB blanking could be realized to share spectrum with satellite services. Relaxing spectrum masks for unoccupied adjacent channels could extend the notion of spectrum beyond co-channel to adjacent channels and improve spectrum use.

One of the major challenges of data-driven optimization techniques is obtaining robust field data sets to train the relevant models. For sharing and co-existence in particular, the data sets not only involve the MN but also the relevant incumbent systems. Standardizing frameworks for obtaining relevant data sets in parallel to appropriate sharing policy frameworks is important for the industry. Further research is also required on spectrum sharing based on spectrum sensing by cellular BSs. Research questions include how well the incumbent's potential use of spectrum in any given location can be predicted, how best to organize the spectrum sensing across the network, what kind of sensing accuracy can be achieved, and how fast the network can react to an incumbent starting to use their spectrum. For military satellites that may include frequency hopping or frequency spreading. It will be a challenge for effective spectrum sensing, and some minimum information sharing would be needed to make sensing-based sharing a reality.

Abbreviations

ATH	Above the horizon
AI/ML	Artificial intelligence/machine learning
BS	Base station
CBRS	Citizens Broadband Radio Service
CDF	Cumulative distribution function
CSI	Channel state information
DFT	Discrete Fourier transform
DNN	Deep neural network
DoD	Department of Defense (US)
EIRP	Effective isotropic radiated power
Fed	Federal
GAA	General authorized access
IMT	International Mobile Telecommunications
ITU	International Telecommunication Union
KPI	Key performance indicator
LEO	Low-earth orbit (satellite)
MIMO	Multiple-input multiple-output
MMSE	Minimum mean square error
MN	Mobile network
MRT	Maximum ratio transmission
OFDM	Orthogonal frequency-division multiplexing
PA	Power amplifier
PAL	Priority access licensees
PRB	Physical resource block
RX	Receiver
SINR	Signal-to-interference-plus-noise ratio
TRX	Transceiver
TDD	Time-division duplex
WGS	Wideband Global Satcom
WRC	World Radiocommunication Conference

References

[1] Nokia, Global Network Traffic Report, Oct 2023. Online: https://onestore.nokia.com/asset/213660

[2] World Radiocommunication Conference 2023 (WRC-23) Provisional Final Acts, International Telecommunication Union, Dec. 2023. Online: https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.15-2023-PDF-E.pdf

[3] B. Bertenyi, G. Kunzmann, S. Nielsen and K. Pedersen, "Transforming the 6G vision to action," Nokia White Paper, Jun 2024. Online: https://www.nokia.com/asset/214027

[4] [4] M. Baker, "6G to be optimized for upper mid-band spectrum," Nokia blog post, Dec 2024. Online: https://www.nokia.com/blog/6g-to-be-optimized-for-upper-mid-band-spectrum/

[5] H. Holma, H. Viswanathan, and P. Mogensen, "Extreme massive MIMO for macro cell capacity boost in 5G-Advanced and 6G," Nokia White Paper, Oct 2021. Online: https://www.nokia.com/asset/210786

[6] F. Chaves, D. Chizhik, J. Du, A. Ghosh, B. Love, and E. Visotsky, "Coverage evaluation of 7-15 GHz bands from existing sites," Nokia White Paper, Apr 2024. Online: https://www.nokia.com/asset/213702

[7] L. Zhang et al., "A survey of advanced techniques for spectrum sharing in 5G networks," in IEEE Wireless Communications, vol. 24, no. 5, pp. 44-51, Oct 2017.

[8] L. Zhang et al., "Spectrum sharing in the sky and space: A survey," Sensors, Special Issue Cognitive Radio Applications and Spectrum Management II, vol. 23, no. 1, Jan 2023.

[9] A preliminary view of spectrum bands in the 7.125 - 24 GHz range; and a summary of spectrum sharing frameworks, Report of FCC Technological Advisory Council, Aug 2023.

[10] Recommendations to the federal communications commission based on lessons learned from CBRS, Report of FCC Technological Advisory Council, Dec. 2022.

[11] FCC public notice DA 24-553, "Wireless telecommunications bureau and office of engineering and technology announce modified aggregate interference model used by spectrum access system administrators," 2024.

[12] J. Hoydis, F. A. Aoudia, A. Valcarce, and H. Viswanathan, "Toward a 6G AI-native air interface," IEEE Communications Magazine, vol. 59, no. 5, pp. 76-81, May 2021.

[13] M. Honkala, D. Korpi, and J. M. J. Huttunen, "DeepRx: Fully convolutional deep learning receiver," in IEEE Transactions on Wireless Communications, vol. 20, no. 6, pp. 3925-3940, Jun 2021.

[14] W. Yu, F. Sohrabi, and T. Jiang, "Role of deep learning in wireless communications," in IEEE BITS the Information Theory Magazine, vol. 2, no. 2, pp. 56-72, Nov 2022.

[15] J. Pihlajasalo et al., "Deep learning OFDM receivers for improved power efficiency and coverage," in IEEE Transactions on Wireless Communications, vol. 22, no. 8, pp. 5518-5535, Aug 2023.

[16] I. Portillo, B. G. Cameron, and E. F. Crawley, "A technical comparison of three low Earth orbit satellite constellation systems to provide global broadband," 69th International Astronautical Congress (IAC), Bremen, Germany, Oct 2018.

[17] D. H. Roper, W. E. Babiec, and D. D. Hannan, "WGS phased arrays support next generation DoD SATCOM capability," IEEE International Symposium on Phased Array Systems and Technology (PAST), Boston, MA, USA, 2003.

[18] H. B. Tanveer et al., "Making sense of constellations: Methodologies for understanding Starlink's scheduling algorithms," ACM SIGCOMM'18, Budapest, Hungary, Aug 2018 (updated arXiv:2307.00402).

[19] F. B. Mismar and A. Ö. Kaya, “Uncoordinated interference avoidance between terrestrial and non-terrestrial communications,” ICC 2024 - IEEE International Conference on Communications, Denver, CO, USA, 2024.

[20] D. Korpi, M. Honkala, and J. M. J. Huttunen, “Deep learning-based pilotless spatial multiplexing,” 57th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2023.

[21] L. U. Garcia, Kamakshi L K, I. Hmedoush, A. N. Batteto, N. Hathiramani and K. Ranta-aho, “Simplifying spectrum migration from 5G to 6G,” Nokia White Paper, Jul 2023. Online: https://www.bell-labs.com/institute/white-papers/simplifying-spectrum-migration-from-5g-to-6g

Nokia OYJ
Karakaari 7
02610 Espoo
Finland
Tel. +358 (0) 10 44 88 000

Document code: CID214478 (July)