SWIFT-SAT: Software Defined Radio based Emulation of SAT-Terrestrial Network Coexistence in "FR3" Bands

1 Introduction

5G systems aim to provide an enhanced mobile user experience with $\sim$ Gbps wireless bit-rates along with low latency and improved reliability [1–3]. 5G New Radio (NR) technologies including massive MIMO [4], multiple radios [5], millimeter wave beam steering [6] and cloud radio access networks (CRAN) [7] have been proposed to achieve large gains in link level radio performance. In addition, 5G and Beyond 5G (B5G) developments have necessitated the opening up and utilizing of newer spectrum that had not been previously allocated for commercial wireless applications. This newer spectrum has included (originally sub-6 GHz) bands below 7.125 GHz referred to as Frequency Range 1 (FR1) and mmWave bands between 24-52.6 GHz referred to as FR2. In spite of these developments, emerging use cases such as self-driving connected cars, smart healthcare, AR/VR and mixed reality that require extremely high data rates and low latency, have rendered the available spectrum as insufficient. Further, there have also been practical challenges encountered in the deployment of mmWave technology that have resulted in a less than anticipated emergence of FR2 based 5G networks [8, 9].

The resulting spectrum crunch has resulted in a push for exploring higher frequencies such as in the sub-THz range [10–15]. It has also generated a lot of recent interest in using the FR3 bands between 7.125-24 GHz [9], the focus of this proposal. The FR3 bands are more attractive due to radio propagation characteristics that are more conducive to enabling terrestrial networks with infrastructure (small cell) needs that scale at manageable levels, e.g. the coverage radius of a base station (BS) in the 12 GHz band is approximately 2.33 times of the coverage radius of a BS in the 28 GHz band. The FR3 bands are also home to several SAT-based services for both active commercial use (e.g. direct broadcast satellite service (DBS) and non-geostationary orbit fixed satellite service (NGSO-FSS) deployments,in the 10.7-13.25 GHz band) and passive sensing (e.g. Advanced Microwave Sounding Unit, AMSU-A [16] or Advanced Technology Microwave Sounder, ATMS [17] sensors) on weather satellites. Therefore, understanding and enabling spectrum coexistence of such active and passive services with emerging 5G networks in the FR3 band is of utmost importance. There have been efforts recently in this direction in the 12 GHz band [18–28]. There have also been efforts in understanding mmWave (FR2) and 23.8 GHz band passive weather sensor coexistence [29–38]. However, these studies and reports have primarily been based on modeling and simulations. What has been sorely missing is the ability to drive such coexistence studies with either direct measurements (that are hard to come by or simply not available) or testbed based emulation, which can lead to data-driven machine learning (ML) solutions.

This proposal aims to develop software defined radios (SDRs) for studying SAT-terrestrial network coexistence in the FR3 bands by enabling emulation at scale and in dense 5G network scenarios. The specific coexistence scenarios to be studied include: (i) 5G Terrestrial Networks and 12.2-12.7 GHz DBS/NGSO-FSS; and (ii) 5G Terrestrial Networks in 10-10.5 GHz and Passive Sensors on Earth Observation Satellites in 10.6-10.7 GHz. The project will leverage the NSF funded PAWR platform, COSMOS [39] at WINLAB, to develop a network of SDRs that will emulate 5G radio network scenarios, SAT transceivers as well as passive radiometers (sensors), in the bands specified above. The team with expertise in SDR testbed design and emulation, RF propagation and antenna design, and PHY/MAC layer ML algorithms for spectrum coexistence, will use the COSMOS Sandox [40] to work on the following specific thrusts that are representative of 5G terrestrial network coexistence with active SAT systems and passive SAT sensors:

T1 – *SDR-based Heterodyne Design for FR3 spectrum using COSMOS Sandbox* – SDR-based Heterodyne Transceiver design for emulating 5G NR waveforms (in 12.2-12.7 GHz and 10-10.5 GHz) and DBS/NGSO-FSS downlink waveforms (in 12.2-12.7 GHz); Programmable metamaterial (MTM) based software-defined beamforming for emulating 5G NR and DBS/NGSO-FSS directional transmissions; Heterodyne Receiver design for emulation of passive sensor (radiometer) on Earth Observation Satellites in 10.6-10.7 GHz

T2 – *Emulation of Spectrum Coexistence between 5G Terrestrial Networks and 12.2-12.7 GHz DBS/NGSO-FSS* – Emulation of 5G terrestrial network with various topologies and densities; Emulation of downlink of DBS/NGSO FSS in the presence of 5G interference; Centralized spectrum server based ML algorithms for 5G and DBS/NGSO-FSS coexistence- integrated 5G radio resource management, dynamic exclusion zones and dynamic scheduling; Distributed control plane implementation of ML algorithms for 5G and DBS/NGSO-FSS coexistence; Evaluation of sensitivity to elevation and directionality of transmissions; Evaluation of reduction in "available" spectrum incurred by 5G due to coexistence with active SAT
T3 – *Emulation of Spectrum Coexistence between 5G Terrestrial Networks and Passive Sensors on Earth Observation Satellites in 10.6-10.7 GHz* – Emulation of radio frequency interference (RFI) from 5G terrestrial network in 10-10.5 GHz with various topologies and densities; Data-driven modeling of passive radiometer sensitivity to RFI and identification; Centralized spectrum server based ML algorithms for 5G and Earth Observation Satellite coexistence- radio resource management for RFI mitigation; Distributed control plane implementation of ML algorithms for 5G and Earth Observation Satellite coexistence; Evaluation of reduction in "available" spectrum incurred by 5G due to coexistence with passive SAT sensors

The project will lead to novel SDR designs, spectrum server enabled ML algorithms and testbed emulation that provide pointers for designing 5G/B5G networks that can peacefully coexist with SAT systems with active transceivers and passive sensors in the FR3 bands. Additionally, undergraduate, graduate and high school students will be engaged and trained in an area of emerging national and international interest.

2 Spectrum Sharing Challenges in the FR3 Bands

The FR3 spectrum extends from 7.125-24 GHz and includes both federal and non-federal systems with wide ranging applications such as space research, earth observation, radio astronomy, radio location, and commercial satellite services. Figures 1-2 (reproduced from [41]) show a "magnified" view of the various services in a subset of this range (from 7.125-13.75 GHz). There are SAT systems with active transceivers (space, space-earth, earth-space) and SAT systems (Earth Observing Satellites) with passive sensors. For example, the DBS and NGSO-FSS systems use the 10.7-13.25 GHz band. The passive Earth Observing Satellite sensors use the 10.6–10.7 GHz, 15.35–15.4 GHz, 18.6–18.8 GHz, and 23.6–24 GHz bands, which are recognized as needing protection by the International Telecommunications Union (ITU).

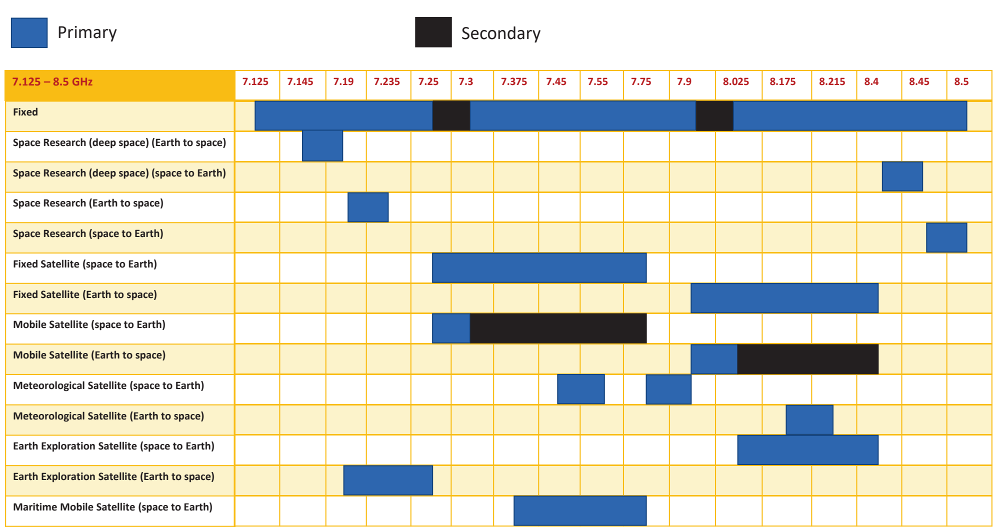


Figure 1: A "magnified" view of spectrum sharing in 7.25-8.5 GHz

As summarized in [41], the biggest challenges in spectrum sharing will be the coexistence of high powered terrestrial systems with SAT systems (both active and passive). Further, the 7.25-8.4 GHz ("NATO band") commonly used in Europe is unlikely to get support for global harmonization. There is tremendous interest in 2,500 MHz of bandwidth allocated for non-Federal use in 10.7 –13.25 GHz, including 1,050 MHz mobile allocation in 12.2 –13.25 GHz. There is also 200 MHz of bandwidth in 14.2 –14.4 GHz for non-Federal use. As such, we will focus in this proposal on two representative examples of FR3 spectrum sharing (12.2-12.7 GHz sharing for active SAT coexistence and 10.6-10.7 GHz for passive weather sensor coexistence) because of their relative importance. The 12.2-12.7 GHz coexistence scenario has been plagued by claims and counterclaims of 5G and NGSO-FSS coexistence [18, 42] based on primarily modeling and simulation efforts. Similarly, the passive weather sensor coexistence in the 10.6-10.7 GHz spectrum is of interest in light of the upcoming considerations of non-Federal 5G terrestrial networks in the 10 GHz bands [43]. In fact, the upcoming quadrennial ITU World Radiocommunications Conference (WRC)-2023 [44] has on its agenda, the consideration of the 10-10.5 GHz spectrum for international mobile telecommunications, including on a primary basis [45]. Therefore, emulation and data-driven approaches for coexistence in the two representative examples would also be very timely.

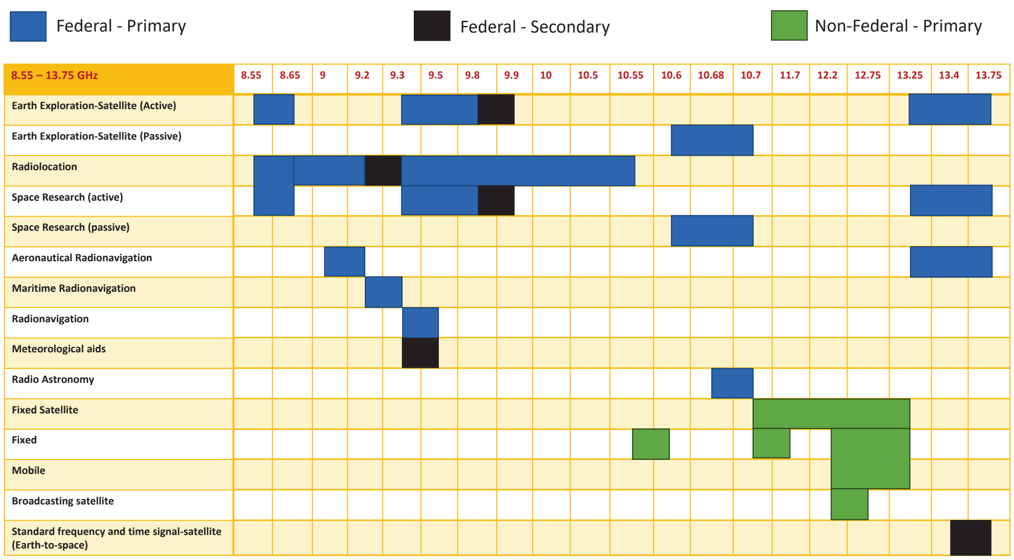


Figure 2: A "magnified" view of spectrum sharing in 8.55-13.75 GHz

3 Background: The COSMOS Sandbox@WINLAB

We first provide an overview of the COSMOS testbed [39] and COSMOS sandbox [40] as they are an important PAWR platform for this project. COSMOS is an open programmable platform deployed in a dense urban environment in New York City that enables researchers to evaluate wireless architectures and technologies for current and future wireless systems, including 5G and Beyond-5G. The testbed provides a mix of programmable SDR nodes for flexible wireless measurements and experimentation organized in a "cloud-native" architecture. The COSMOS sandbox at WINLAB in New Jersey is a controlled indoor environment. The area around the COSMOS testbed and sandbox has been designated as one of the nation's first FCC Innovation Zones [46,47], thereby allowing extensive experimentation in various frequency bands. These include transmissions in the 2.5–2.69, 3.7–4.2, 5.85–7.125, 27.5–28.35, 38.6–40.0 GHz as well as the ISM bands (other bands may be approved in part of the area based on discussions with the FCC). These bands are also adjacent to many bands of interest and can be used to emulate them. A key building block of the COSMOS sandbox is a large number of SDRs at both sub-6 GHz and mmWave frequencies, which can support spectrum use and propagation studies. The 100 sub-6 GHz USRP 2974 [48] SDRs already support spectrum measurements and we plan to integrate these radios in this proposal, with additional front ends (as will be described in 5.1) in order to support targeted measurements and experiments in the FR3 bands. *The COSMOS sandbox is also a fully RF shielded facility in an enclosure with copper "fabric" that is grounded, significantly reducing RF emanating out of the enclosure with an attenuation greater than 60 dB.* Further, the emulation will be designed using low power signals, there by reducing the outside interference even more so that interference with any of the existing services in the FR3 bands is not an issue. *As we further develop this project, we will seek experimental licenses in FR3 for outdoor emulation* (e.g. a few experimental licenses have been awarded in 13 GHz [41]).

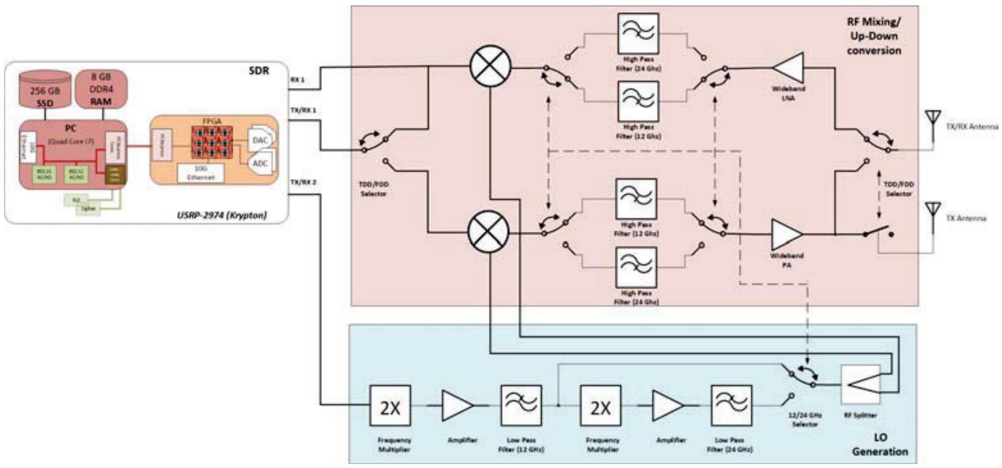
4 Addressing SWIFT Solicitation-Specific Review Criteria

This proposal addresses two *primary challenges* from the SWIFT-SAT program solicitation: (1) **Radio spectrum coexistence between terrestrial and satellite communications systems**, and (2) **Radio spectrum coexistence between terrestrial communications systems and earth-observing satellite systems**. Specifically, as outlined in sections 1 and 2, this proposal addresses spectrum coexistence between emerging 5G terrestrial networks and SAT systems in the FR3 spectrum bands. In section 5.2, the focus is on coexistence between 5G terrestrial networks and active SAT systems such as DBS/NGSO-FSS in the 12.2-12.7 GHz bands. In section 5.3, the focus is on coexistence between passive AMSR sensors (radiometers) on weather observation satellites in the 10.6-10.7 GHz band and 5G terrestrial networks in the 10-10.5 GHz band. In terms of *utilization of public wireless-related sources*, the proposal uses the PAWR platform COSMOS at WINLAB. The COSMOS sandbox forms an integral part of the SDR development in section 5.1 as well as the emulation studies of coexistence in sections 5.2 and 5.3. The *innovations in radio spectrum coexistence* developed in the proposal include: (i) development of SDRs for emulation of spectrum coexistence between terrestrial and SAT systems in the FR3 bands; (ii) improved methods to identify RFI at passive sensors and its mitigation; (iii) improved dynamic radio resource management schemes for coexistence between terrestrial and active SAT communications systems. The data-driven radio resource management (RRM) algorithms studied in the emulation assume that the 5G terrestrial network has coordinated information about the SAT system (active and passive) via a *central server mechanism*, which can also be implemented via a *distributed control plane* on COSMOS. Finally, we will also quantify the *loss in "available" spectrum* incurred by the 5G network due to mitigation strategies that are needed to enable peaceful coexistence with the SAT systems. Such technological assessments can also serve up useful pointers for economic valuations of 5G spectrum in spectrum auctions.

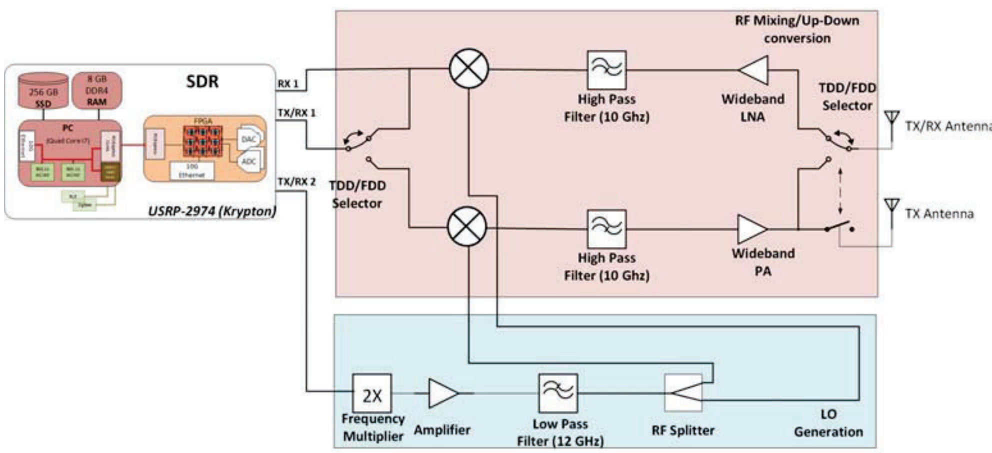
5 Proposed Research

5.1 Thrust 1: Software-Defined Radio-Based Heterodyne Transeiver Design for FR3 Spectrum using COSMOS Sandbox

Heterodyne Transceiver Design. In an effort to realize an emulation testbed for the FR3 band, the proposed research project will utilize a software-defined radio (SDR) to generate an intermediate frequency (IF) signal from 10 MHz up to 6 GHz as illustrated in Fig. 3. This IF signal can then be up-converted to the desired frequency range within the entire FR3 band (7.125-24 GHz) when utilizing the heterodyne transeiver indicated in Fig. 3(a). By employing the SDR system, a baseband digital signal is generated and subsequently converted to an analog IF signal with an upper limit of 6 GHz. This IF signal serves as the



(a)



(b)

Figure 3: Proposed SDR-Based Heterodyne Transceiver for FR3 Testbed for (a) full-band operation up to 24 GHz, and (b) lower-band operation up to 18 GHz.

foundation for the subsequent frequency conversion processes. The use of SDR offers significant flexibility as the software can be reconfigured to adapt the basic signal processing components according to the specific requirements. In particular, the flexibility in choosing a wide range of IF frequency can allow for adapting to various communication protocols in SAT and 5G networks.

To illustrate, the conversion from the IF signal to the RF signal in the FR3 band can be accomplished using RF mixers. During up-conversion, the IF signal is combined with a local oscillator (LO) signal, resulting in an RF frequency signal in the FR3 band.

$$f_{IF} + f_{LO} = f_{RF} \tag{1}$$

Conversely, in down-conversion, the RF signal is mixed with a lower-frequency LO signal, producing a difference frequency signal within the IF range of up to 6 GHz.

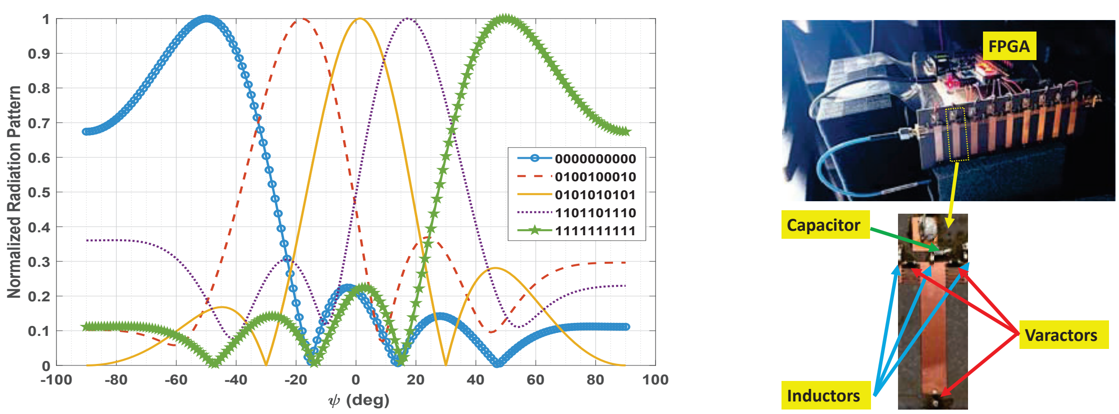
$$f_{RF} - f_{LO} = f_{IF} \tag{2}$$

The integration of SDR with external RF mixing offers a versatile and adaptable solution for various high-frequency applications that can allow us to emulate the interaction between 5G communications and satellite communications. This approach combines the flexibility and reconfigurability of SDR with the broad frequency coverage provided by RF mixers. As mentioned earlier in Fig. 3, the block diagram of the proposed implementation consists of two main subsystems: a) up/down conversion and b) local oscillator generation.

In the up-conversion process, an input IF signal ranging from 10 MHz to 6 GHz is combined with a LO signal using a mixer through nonlinear mixing. This produces an output signal containing both the sum and difference frequencies of the input and LO signals. By selecting an appropriate LO frequency, we can generate an output signal within the desired FR3 frequency range. An example of a suitable mixer component is Mini-Circuits' MMIC mixer MDB-44H+ [49]. This mixer has a wide IF frequency range of DC to 15 GHz and an LO/RF frequency range of 10 to 40 GHz. It can be used for both up-conversion and down-conversion, offering low conversion loss and excellent harmonic suppression. Additionally, the receive branch can be enhanced with an optional low-noise amplifier, while the transmit branch can be boosted with a power amplifier to enhance the system's capabilities.

To generate the desired LO signal, we can leverage the concept of using SDR for LO generation by employing a programmable 6 GHz signal source. This can be achieved by utilizing a frequency multiplier, a device that takes an input signal and produces an output signal with a frequency that is a multiple of the input frequency. In this case, for instance, we can multiply the 6 GHz signal by a factor of 2 using two stages of frequency doublers to generate a 12 GHz LO signal as shown in Fig. 3(b), satisfying the requirement for the desired RF signal in the lower FR3 band.

To ensure coherent operation between the up-converter and down-converter, a splitter is employed to distribute the LO signal to both devices. This allows both components to receive the same LO signal, simplifying the system design by minimizing the number of required LO sources. Amplifiers are utilized to correct the signal levels, while filters are implemented to suppress unwanted harmonics and absorb signal reflections. Furthermore, a final splitter component is employed to distribute the LO signal to both the transmitter and receiver mixer branches, enabling coherent operation between the transmitter and receiver.



(a) (b)

Figure 4: Programmable beamforming using MTM LWA with reconfigurable unit cells: (a) simulated software-defined beamforming with different coding sequence; (b) fabricated prototype of programmable MTM LWA at 2 GHz.

Software-Defined Beamforming Using Programmable Metamaterial Antenna. To enable flexible beamforming that can be integrated with the proposed SDR heterodyne transceiver, a software-defined programmable metamaterial (MTM) leaky wave antenna (LWA) operating in the FR3 band will be developed. As the unit cells of MTM LWA can have both positive and negative phase constants [50], the phase response of the n^{th} element for the MTM LWA containing N unit cells can be expressed as follows:

$$\zeta_n = -\sum_{m=1}^{n} \phi(m), \tag{3}$$

where

$$\phi(m) \stackrel{def}{=} \begin{cases} \beta_0 p, & \text{if } m\text{th unit cell is in mode } 0, \\ \beta_1 p, & \text{if } m\text{th unit cell is in mode } 1, \end{cases} \tag{4}$$

in which β and p denote the phase constant and unit-cell period, respectively. Consequently, the resulting radiation pattern for the programmable MTM LWA can be obtained:

$$S(\psi) = \sum_{n=1}^{N} I_0 e^{-\alpha(n-1)p} e^{j(n-1)k_0 p \sin\psi - j\sum_{m=1}^{n}\phi(m)}, \tag{5}$$

where α denotes the leakage factor, I_0 represents the input signal, and $k_0 = \frac{2\pi}{\lambda}$ is the wave number, where λ denotes the wavelength. Fig. 4(a) illustrates three different radiation patterns obtained using equation (5) for a specific frequency. In these examples, we assume $\beta_1 p = 55°$ and $\beta_0 p = -55°$ for each unit cell. The number of unit cells is set to $N = 10$, and the associated working modes are represented by a binary sequence of length 10, which labels the corresponding curves in Fig. 4(a). The results demonstrate the possibility of achieving continuous beam scanning within the range of $-50°$ and $50°$ at a fixed frequency by employing LWAs with tunable unit cells. While Fig. 4(b) shows a fabricated prototype of programmable MTM LWA with reconfigurable composite right/left-handed (CRLH) unit cells operating at 2 GHz, the proposed research task will design and develop the programmable software-defined MTM LWAs that can cover the targeted 10- and 12-GHz bands.

5.1.1 Emulation of 5G NR Protocol Stack

The 3GPP New Radio (NR) protocol stack is the basis for all 5G/B5G systems, and is the most important wireless standard for both sub-7 GHz (FR1) and mmWave (FR2) frequencies. The COSMOS Sandbox supports such experimentation since it has been integrated with full-stack LTE software frameworks with open-source UE and gNodeB codebases for experimentation, such as srsLTE/srsRAN [51] and OpenAirInterface (OAI) [52]. COSMOS already supports experimentation with both srsLTE/srsRAN and OAI using USRP SDRs (see tutorials at [53]), and in this task, we plan to develop an interface for seamless integration of these open-source full-stack frameworks so that 5G NR like waveforms can be emulated in FR3.

In particular, the telecommunications industry and spectrum regulatory authorities are increasingly interested in utilizing the 12.2-12.7 GHz band for two-way terrestrial 5G mobile services. This interest stems from the constrained propagation characteristics of mmWave bands, particularly in dense urban environments with increased blockages. Unlocking this band offers several advantages, including a contiguous bandwidth of 500 MHz for both uplink and downlink 5G communications, as well as improved propagation and building penetration capabilities compared to commercially deployed mmWave bands. Further, in accordance with the communication protocol, the 500-MHz bandwidth available in the 12.2-12.7 GHz band will be divided into five separate 100 MHz channels. The proposed programmable MTM antennas will be integrated to emulate the beamforming properties of base stations in a software-defined manner.

As an illustrative example, to generate frequencies using the proposed SDR heterodyne transceiver testbed within the desired 12.2-12.7 GHz band, a continuous wave (CW) at 5.5 GHz can be generated on the TX2 channel in Fig. 3(b). This will result in an 11 GHz LO signal ($f_{LO} = 11$ GHz) at the output of the first LO stage. The setup will be configured to pass the output of the first stage and utilize the 12 GHz filter branches. On the transmit branch, the primary signal will be generated using the primary SDR channel (TX/RX1 in Fig. 3) with the IF signal (f_{IF}) in the 1.2-1.7 GHz range. These IF signals will be added to the 11 GHz LO signal in the mixer, resulting in the desired frequency bands ($f_{RF} = 12.2 - 12.7$ GHz). Since the same LO output is used for the receiver branch, the received signal will be downconverted to an IF signal with the same f_{IF} and then processed by the RX section of the SDR. On the other hand, the potential 10-10.5 GHz band 5G NR signals will also be created using the proposed SDR heterodyne transceiver in a similar fashion. In this case, a 5-GHz CW signal will be utilized to generate a LO signal with $f_{LO} = 10$ GHz, resulting an IF signal (f_{IF}) ranging from DC to 500 MHz.

5.1.2 Emulation of DBS/NGSO-FSS SAT downlink signals in 12 GHz

Non-geostationary orbit (NGSO) fixed satellite service (FSS) deployments primarily use $10.7 - 12.7$ GHz for the downlink (Space-to-Earth). To this end, the proposed SDR heterodyne transceiver testbed can be reconfigured to emulate the satellite communications using a similar fashion described in the above section. For downlink, a 5-GHz CW signal will be utilized to generate a LO signal with $f_{LO} = 10$ GHz, resulting an IF signal (f_{IF}) in the 0.7-2.7 GHz range. In addition, the downlink band is partitioned into eight channels, each with a bandwidth of 240 MHz, and separated by a 10 MHz guard band [22]. It is assumed that the FSS receiver can simultaneously receive data from its satellite transmitter over one or more of these eight channels. Since the SDR we use (USRP-2974) can only support 160-MHz bandwidth per RF chain, both RF chains located on the SDR unit will be utilized to enhance the instantaneous bandwidth. Moreover, OFDM signals will also be incorporated into the transmitting waveforms [54], along with the proposed programmable MTM antenna-based software-defined beamforming, to emulate SAT communication links.

5.1.3 Emulation of 10.6-10.7 GHz SAT Passive Sensor (Radiometer)

The passive weather sensor in the 10.6-10.7 GHz band is the Advanced Microwave Scanning Radiometer (AMSR) [55] and has an operating bandwidth of 100 MHz. To emulate such a radiometer [56], a 5-GHz CW signal will be used to generate a LO signal of 10 GHz ($f_{LO} = 10$ GHz) by activating the frequency-doubler as shown in Fig. 3. This will result in an IF signal (f_{IF}) in the 0.6-0.7 GHz range, which will then be downconverted to baseband to process the 100-MHz bandwidth signal.

5.2 Thrust 2: Spectrum Coexistence of 5G Terrestrial Networks in 12.2-12.7 GHz

Background and Related Work: The report in [22] advocates for 5G coexistence with NGSO-FSS in 12.2-12.7 GHz based on a Monte Carlo simulation study of 5G deployment in the continental U.S. that concludes that NGSO-FSS can operate without interference from 5G in 99.85% cases. On the other hand, [23], using a receiver location and propagation channel model based approach argues that 5G operations can disrupt NGSO FSS receivers, leading to 77% service degradation. A similar negative argument for coexistence is made in [25] between 5G and DBS. The challenges and opportunities in 12 GHz spectrum coexistence have been identified in [18], where a more nuanced context aware and dynamic framework for coexistence is proposed between 5G and DBS/NGSO-FSS. Further, a simulation-based framework is developed in [28] that incorporates real world features and models to realize exclusion zones (EZs) around FSS receivers that would enable coexistence. *In spite of the above efforts, there still remains substantial disagreement on the feasibility of such coexistence*.

Proposed Research- Emulation on COSMOS Sandbox: In contrast to earlier studies, we will take an emulation based approach here. The 12 GHz SDR development in section 5.1 will allow the deployment of NGSO-FSS receivers in COSMOS along with multiple 5G BS and UEs. Further, the radio mapping algorithm in COSMOS enabled by distributed noise injection [57, 58] allows the creation of arbitrary 5G network topologies on the testbed that correspond to real world network scenarios. Specifically, we will use the noise injection framework to generate topologies where both line of sight (LOS) and non line of sight (NLOS) paths exist between the FSS receivers and the 5G transmitters as shown in Fig. 5. The SDRs developed allow emulation of beamforming gains, angles of interference as well as control of modulation formats, transmit power and transmission bandwidth. Further, the control plane architecture in COSMOS allows the emulation of a centralized spectrum server [59] that can coordinate 5G transmissions. It also allows the realization of spectrum sharing algorithms using a distributed control plane implementation [60]. We will use both the centralized server and distributed control plane implementations to study the following.

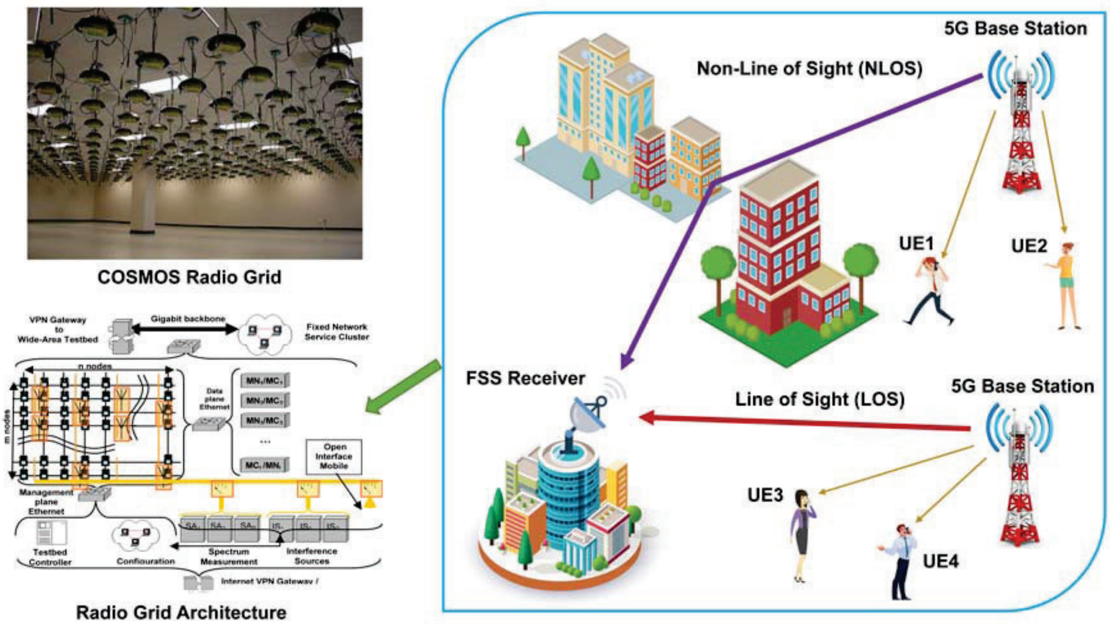


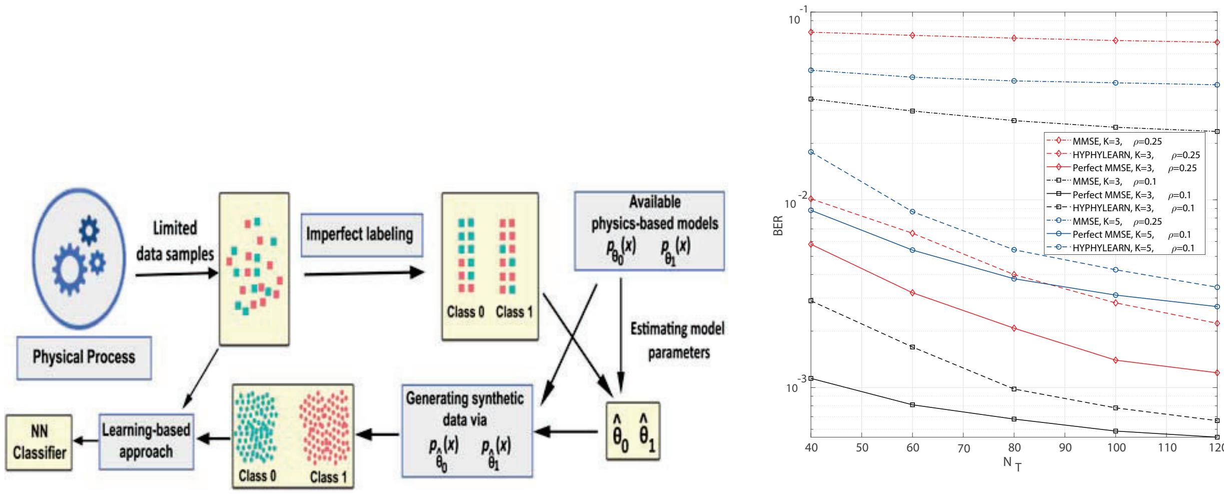
Figure 5: COSMOS GRID@WINLAB with Control Plane, Measurement Infrastructure and Radio Mapping

5.2.1 Integrated 5G Radio Resource Management and Dynamic Exclusion Zones

A key indicator of 5G and FSS coexistence is the Interference-to-Noise (I/N) ratio at the FSS receiver. We will study data-driven ML approaches for 5G transmitters by integrating beamforming with power, bandwidth and modulation control for both *deterministic* guarantees where the I/N is lower than a fixed threshold determined by FSS performance requirements as well as *probabilistic* guarantees where the I/N has a soft requirement in relation to the threshold for acceptable performance. The results will be mapped to dynamic exclusion zones that 5G transmitters will need to follow to enable coexistence with FSS. Given the body of work [18–28] that has used path loss and location based models to study 5G and NGSO-FSS coexistence, we will also consider hybrid ML approaches (see Fig. 6(a)) that integrate physics-based models with data-driven algorithms [61, 62]. These have the advantage of working well even under limited labeled data N_T as shown in Fig. 6(b) for an example of spectrum sharing with multiuser detection [61].

5.2.2 Dynamic Scheduling with Noncontiguous Orthogonal Frequency Division Multiplexing

The spatial distribution of FSS receivers as well as the temporal distribution (activity) of intended transmissions to them results in fragmented and intermittent availability of the spectrum for 5G transmissions. Knowledge of such distributions provides an opportunity to "tweak" traditional 5G NR OFDM transmissions in order to realize dynamic scheduling for efficient spectrum usage. A multicarrier design that can



(a) (b)

Figure 6: (a) Hybrid physics and data-driven ML; (b) Spectrum sharing performance with limited labeled data.

potentially enable selective (temporal and spatial) use of the available spectrum is Noncontiguous Orthogonal Frequency Division Multiplexing (NCOFDM) [63–71] where certain subcarriers are selectively nulled so as to avoid interfering with the incumbent (primary) transmissions in those spectral locations (see Fig. 7). In our earlier works [71–73], we have identified the *spectrum span* (defined as the frequency range between the outermost non-nulled subcarriers) of NCOFDM transmissions as one of the most important parameters that affects the system power consumption and resource allocation in noncontiguous spectrum access. An increase in the spectrum span of a link based on NCOFDM modulation leads to an increase in the sampling rate of ADCs/DACs, which in turn increases system power consumption. Therefore, any dynamic scheduling with NCOFDM must include constraints on the spectrum spans of these links. In addition, the developed algorithm must have the capability to quickly adapt to dynamic changes in the available spectrum. We will use both purely data-driven ML and hybrid ML and physics-based approaches to evaluate optimal scheduling of 5G transmissions to enable coexistence. Interestingly, the ratio of occupied subcarriers to the span yields a measure of the "effective" reduction in the "available" spectrum (and usage) that 5G networks incur when coexisting with FSS receivers. We will characterize such a reduction for different network topologies, interference angles and transmit powers.

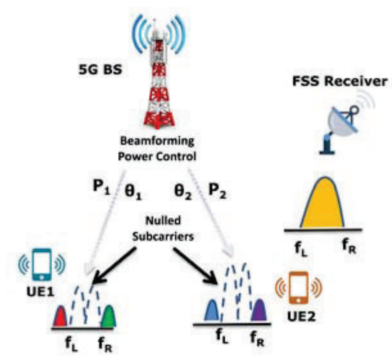


Figure 7: Dynamic NCOFDM

5.3 Thrust 3: Spectrum Coexistence of 5G Terrestrial Networks and Passive Weather Sensors in 10.6-10.7 GHz

Background and Related Work: Coexistence of 5G mmWave (FR2) and passive weather (AMSU-A [16] and ATMS [17]) sensors in the 23.8 GHz band has received a lot of recent attention. A simulation based study in [29] shows that the passive ATMS radiometer (sensor) is susceptible to even low levels of RFI, resulting in the contamination of the brightness temperature that is fed into numerical weather prediction (NWP) algorithms. Software simulation tools have also been developed in [30] for demonstrating RFI mitigation. A modeling based approach in [31] reveals that RFI levels of -15 to -20 dBW can impact NWP algorithms for prediction of temperature and prediction using the WRFDA model [74, 75] on the Super

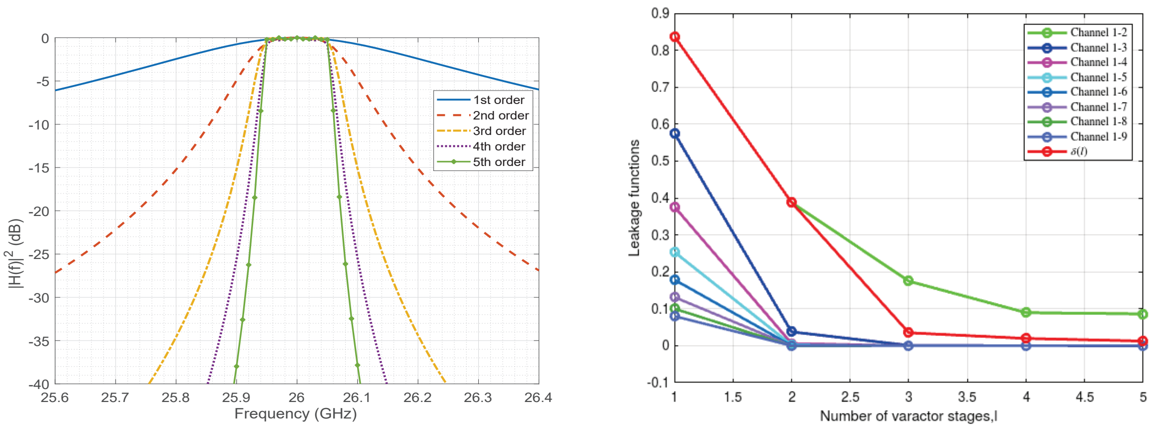
Tuesday Tornado Outbreak dataset [76]. Detailed models of antenna properties and satellite trajectories are developed in [33] to characterize RFI from 5G mmWave. Radio resource management to reduce RFI is considered in [34] using the design of filtennas [38] while [35–37] evaluates the direct impact on NWP due to the RFI resulting from projected (growth) models of 5G mmWave deployments in the continental US. These mmWave coexistence studies and reports have primarily been based on modeling and simulations. There have been testbed based 5G coexistence studies with passive sensors in the L and V bands [77, 78], but we are not aware of any in the 10.6-10.7 GHz bands.

Proposed Research- Emulation on COSMOS Sandbox: The 10.6-10.7 GHz SDR development to emulate a passive radiometer in section 5.1 will allow its deployment in COSMOS along with multiple 5G BS and UEs occupying adjacent bands, e.g. 10-10.5 GHz. The AMSR sensors in the 10.6-10.7 GHz band reside on Earth Observation Satellites that are at distances ranging from 666-812 kms from the earth's surface [55]. The RFI observed at these sensors is a function of the density of 5G terrestrial transmitters, their transmit powers, bandwidths, locations, angles of transmission, and the propagation losses from the earth's surface to the AMSR sensor. The propagation losses at these distances can be emulated on COSMOS using the noise injection mechanism that can arbitrarily dampen the signal strengths. The radio mapping algorithm mentioned earlier allows the creation of arbitrary 5G network topologies on the testbed that will be used to create aggregate levels of RFI based on transmit powers, bandwidths, locations and angles of transmission. Using this emulation framework, we will use both the centralized server and distributed control plane implementations to study the following.

5.3.1 Data-driven Modeling of Sensitivity to RFI and Identification

As identified in [29, 79] the radiometers are extremely sensitive to RFI levels and identification of RFI at extremely low "RFI-to-noise ratio" ($RFINR$) values is of paramount importance. While conventional approaches like frequency binning and kurtosis analysis can be utilized, they may however encounter some limitations for low RFI levels [80–89]. In particular, frequency binning compares power levels in each spectral bin to a baseline or expected spectrum, but it suffers from limited spectral resolution due to finite bin size. Kurtosis analysis examines the shape of the signal distribution but may not capture complete spectral characteristics or temporal patterns at low RFI levels. On the other hand, ML techniques offer the potential for automatic detection and identification of out-of-band emissions even under low RFI levels [90–92]. By training models with labeled data, these techniques can classify different emission types. However, learning-based classifiers typically require a large amount of training data from the underlying physical process. This requirement may not be feasible in practical scenarios where only limited training data is available or when actions need to be taken quickly and reliably. We propose to use hybrid physics-based statistical models and learning-based classifiers to handle scenarios with limited training data. To this end, we will first use RFI models that have been proposed [33, 34]. For example, based on a circuit simulation [93], Fig. 8(a) reproduced from [34] shows the frequency response of a Chebyshev filtenna with 100 MHz bandwidth and center frequency of 26 GHz with 0.2 dB ripple for different filter orders. With increasing filter order, the roll-off of the bandpass filtering response becomes sharper, thereby reducing the leakage to the adjacent channels. The corresponding normalized leaked powers are plotted in Fig. 8(b), where Channel 1 denotes the reference channel with a center frequency of 26 GHz and 100 MHz bandwidth, while the adjacent channels with 100 MHz bandwidth are numbered in order from 2 to 9. A polynomial fit $\delta(l)$, where l is the number of varactor stages used in the filtenna [38], is also shown that provides an analytical model for the leaked power from the reference to each adjacent channel. We will develop similar models for the 10 GHz spectrum bands and incorporate these into the the hybrid ML approach as outlined below.

The hybrid approach [61, 62] illustrated in Fig. 6(a) begins by estimating the RFI unobservable model parameters using available statistical estimation procedures, even if they are suboptimal. Then, the physics-based statistical models are utilized to generate synthetic RFI data, followed by incorporating the training



(a) (b)

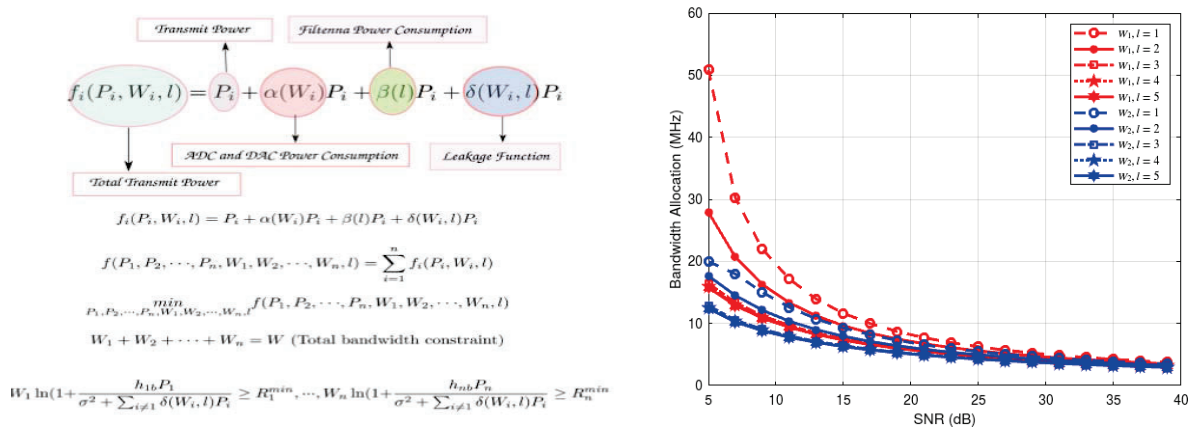
Figure 8: (a) Adjacent channel leakage spectral characteristics; (b) Normalized leaked power.

data samples with the synthetic data and feeding them into a learning-based classifier. The learning-based classifier is trained using domain-adversarial training of neural networks to address any mismatch between the training data and synthetic data. It learns a mapping relationship that aligns the training data and synthetic data to a shared feature space. Simultaneously, the classifier is trained to identify discriminative features within this common space to accomplish the classification task, which, in this case, can be leveraged for detecting and classifying RFI. By combining the strengths of physics-based models and learning-based classifiers, the hybrid approach can maximize the utilization of available data and enhance quick and reliable classification performance, even when RFI levels are low.

5.3.2 Data-driven Radio Resource Management for RFI Mitigation

We will use the data-driven RFI identification process outlined above to characterize the resulting $RFINR$ at the passive sensor as a function of 5G terrestrial network parameters such as 5G BS and UE transmit powers, bandwidths, locations and angles of transmission. We will then design data-driven RRM strategies for power control, bandwidth control and beamforming so as to keep the accepted levels of RFI within the threshold limits specified for normal passive sensor operations. We will build on our prior work on using ML for spectrum sharing [94]. An important characterization that will emerge from the studies carried out here will be the effective reduction in the "available" spectrum (and usage) that 5G networks incur so as to not cause harmful levels of RFI at the passive sensor.

We illustrate the reduction in "available" spectrum with an example from our earlier work that addresses "RFI-aware" RRM in the 26 GHz mmWave bands, where an analytical model for the RFI caused at the sensor is used and imposed as an explicit quantity in optimizing power and bandwidth allocation under minimum rate requirements for users in the mmWave (5G) network [34]. Fig. 9(a) shows the problem formulation where the RFI is explicitly accounted for via the leakage function $\delta(l)$, where a larger value of l implies a more stringent RFI reduction requirement. The problem formulation also takes into account power consumption that results from the use of RFI suppressing mechanisms such as filtennas at the 5G transmitter [38] as well as at the ADC/DAC for high bandwidth data transmission. An iterative water filling algorithm is used to solve the above problem and exemplary results are shown in Fig. 9(b) for the case of a single BS and 2 UEs (with the SNR of UE_2 being 3 dB stronger than that of UE_1). As the RFI mitigation requirement gets more stringent (increasing value of l), what is observed in Fig. 9(b) is that the resulting bandwidth allocated to both the UEs reduces. While these results based on an analytical model for RFI are very insightful, they are based on assuming that the RFI observed at the sensor is Gaussian. This is contrary to the nature of RFI caused by anthropogenic sources of RF communications into adjacent bands [95],



(a) (b)

Figure 9: (a) Optimum power and bandwidth allocation; (b) Bandwidth allocation reduction with increasing RFI.

motivating the need for data-driven approaches to modeling and mitigation of RFI which will be the focus of the emulation based approach taken here.

6 Team Management Plan and Timeline

The research conducted in this project spans multiple disciplines, requiring expertise in wireless communication, RF front-end/antenna design, radio resource management, and SDR and SDN based testbed implementation. The team members possess complementary and synergistic skills that span these areas, which are essential for the success of this endeavor (shown with thrusts and timelines in Fig. 10). PI Mandayam (NM) brings extensive experience in leading large projects and will assume the role of overall project manager as well as leading the machine learning efforts for coexistence. co-PI Seskar (IS) has extensive experience working with testbeds (he is the chief architect of the COSMOS testbed) and will lead the SDR development effort on COSMOS. co-PI Wu (CW) is an expert in RF propagation, antennas and microwaves and will lead the efforts on emulation of SAT, 5G and passive sensing.

To ensure effective collaboration and progress, the PIs and two graduate students will hold weekly meetings to discuss research directions, track progress, and address any concerns that may arise. Additionally, the team will organize workshops and invited sessions at renowned conferences in the fields of signal processing, machine learning communications, and antennas. COSMOS being a community resource, will allow the team to disseminate their research outcomes to the broader community, fostering knowledge exchange and promoting the advancement of spectrum research, in alignment with the goals of the SWIFT program.

		Year 1			Year 2			Year 3		
Thrust	**PI**	**F**	**Sp**	**Su**	**F**	**Sp**	**Su**	**F**	**Sp**	**Su**
1	NM+CW(L)+IS(L)	X	X	X	X	X	X	X		
2	NM(L)+CW+IS		X	X	X	X	X	X	X	X
3	NM(L)+CW+IS		X	X	X	X	X	X	X	X
E&O	NM+CW+IS	X	X	X	X	X	X	X	X	X

Figure 10: NM = N. Mandayam; CW = C.-T. M. Wu; IS = I. Seskar; L = Thrust Lead;
Y1 = Year 2023-2024; Y2 = Year 2024-2025; Y3 = Year 2025-2026;
Thrust 1: Software-Defined Radio-Based Heterodyne Transceiver Design for FR3 Spectrum using COSMOS Sandbox
Thrust 2: Spectrum Coexistence of 5G Terrestrial Networks in 12.2-12.7 GHz
Thrust 3: Spectrum Coexistence of 5G Terrestrial Networks and Passive Weather Sensors in 10.6-10.7 GHz
E&O: **Education and Outreach Activities**.

7 Intellectual Merit and Perspective on Proposal

Intellectual Merit: Exploring FR3 bands for emerging 5G terrestrial networks and its coexistence with SAT systems is of great interest. Further, emulation based studies and data-driven approaches are much needed in these bands. This proposal addresses the coexistence challenges of SAT-terrestrial networks in the FR3 bands by developing advanced SDR testbeds capable of emulating complex 5G network scenarios, specifically focusing on 12.2-12.7 GHz for active SAT coexistence and 10.6-10.7 GHz for passive SAT sensor coexistence. Leveraging the COSMOS platform at WINLAB, the project will establish a network of SDRs to emulate 5G radio networks, SAT transceivers, and passive radiometers in the targeted frequency bands. The research will focus on three key thrusts: (1) Thrust 1 will design SDR-based heterodyne systems to enable the emulation of 5G New Radio (NR) and SAT waveforms, including programmable metamaterial (MTM) software-defined beamforming for emulating both 5G and SAT transceivers. This will facilitate the study of coexistence between 5G terrestrial networks and active SAT systems, such as DBS/NGSO-FSS. (2) Thrust 2 will contribute to the feasibility and design of 5G terrestrial networks that can peacefully coexist with active SAT systems in the FR3 bands. Through novel SDR based network emulation on the COSMOS testbed and centralized spectrum server enabled ML algorithms, integrated radio resource management strategies for spectrum coexistence in the 12.2-12.7 GHz are developed. (3) Thrust 3 will emulate the spectrum coexistence between 5G terrestrial networks and passive sensors on Earth observation satellites. By emulating RFI from 5G networks, the team will analyze the sensitivity of passive radiometers to RFI and develop centralized spectrum server ML algorithms for RFI identification and mitigation. The project will also quantify the *loss in "available" spectrum* incurred by the 5G network due to mitigation strategies that are needed to enable peaceful coexistence with the SAT systems.

Perspective on Proposal: This proposal breaks new ground by developing an emulation based 5G-SAT coexistence study in the FR3 spectrum. While the focus is on 12.2-12.7 GHz and 10.6-10.7 GHz, the methodologies developed here will be broadly applicable in FR3. This proposal is distinct from the SWIFT project "Enabling Spectrum Coexistence of 5G mmWave and Passive Weather Sensing" (involving PIs Mandayam and Wu), in that the previous project relies on a purely modeling based effort to study the direct impact of 5G mmWave (FR2) transmissions on NWP algorithms, geographical mapping of brightness temperature, and design of filtennas and RRM for 5G transmitters to reduce the impact on passive sensors in 23.8 GHz.

8 Broader Impacts

Societal Impact The creation of the FR3 testbed as an outcome of this project will offer an invaluable open resource to the scientific community. It will enable real world emulation, and foster innovation and collaboration among researchers and industry professionals. By facilitating practical experimentation and testing, the FR3 testbed will contribute to the development of robust solutions to the ever expanding problem of meeting increasing wireless data demands. Furthermore, the project's theme is well-suited for the development of STEM projects that will captivate students at various educational levels.

URM and STEM Outreach, Undergraduate Research The team will collaborate with STEM Agents in the Department of Youth Development, and STEM Coordinators at Rutgers, to develop meaningful out-of-school time (OST) science experiences for high school students. These experiences will be delivered through summer programs and innovative activities that emphasize science research and engineering practices. One such program is the 4-H (head-heart-hands-health) initiative, which annually recruits 60 high-achieving rising 9th graders from underserved and underrepresented schools. This 5-day program aims to enhance students' interest and proficiency in STEM subjects [96]. As part of the program, students visit the Rutgers campus, where they engage with science faculty and graduate students to gain insights into scientific research, explore career paths, and get a taste of campus life. The program also trains and supports 4-H STEM Ambassadors, who share their experiences, newfound knowledge, and understanding of STEM topics with other students in their communities. Over the course of 12 years, the program has grown into a thriving initiative, with 72% of alumni expressing interest in pursuing a STEM career and 59% enrolling in STEM majors in college. The team's goal is to create a comprehensive day-long experience centered around spectrum sharing and engineering solutions. Subsequent meetings will be organized to assist the Ambassadors in developing programs to share within their urban and underserved communities, specifically targeting areas such as Trenton, Newark, and Passaic in New Jersey.

Co-PI Wu, as the vice chair of the IEEE MTT/AP chapter at Princeton Central New Jersey (PCNJ) section, will actively promote the participation of graduate, undergraduate, and high school students, including those from underrepresented minority (URM) backgrounds, in microwave and antenna research. Co-PI Wu's involvement with the McNair Scholars Program as a faculty mentor has yielded remarkable results. One of his students, Michael Edwin, received first place for his undergraduate research project at the 6th Annual Black Doctoral Network Conference in October 2018. The project focused on the application of electromagnetic waves for detecting human vital signs and human tracking.

PIs Seskar and Mandayam play an active mentoring role in the WINLAB summer internship program [97], which is now in its 20^{th} year. This program engages high school students and undergraduates from the New Jersey area, as well as other universities across the country. It has been supported by NSF REUs and we will continue that as part of this project. Participating students benefit from hands-on, team-based research experiences led by faculty mentors. They gain valuable knowledge in various cutting-edge topics related to wireless communications, develop skills in programming and technical presentations, and gain exposure to different radio and networking technologies.

Women in Graduate Research WINLAB has a strong track record of promoting women's participation in its graduate programs. Since its establishment in 1989, 42 women have successfully obtained their Ph.D. degrees through research conducted at WINLAB in the field of wireless communications. PI Mandayam has personally mentored and guided 7 women Ph.D. students, with 3 of them progressing to successful careers in academia. Presently, he supervises 3 women Ph.D. students including one jointly with co-PI Wu, further contributing to the inclusion of underrepresented groups in this project.

Education The proposed research topic also lends itself to interesting curriculum innovation with real-life case studies. co-PI Wu will design and introduce course modules on the interaction between 5G and SAT coexistence to the classes: Electromagnetic Fields and Waves [98, 99]. PI Mandayam has already incorporated "Passive Spectrum Coexistence" as a module into an undergraduate course "Wireless Revolution" [100] using the examples of 5G mmWave and weather prediction as well as 5G sub-6 GHz and aviation [101, 102]. He will add 5G-SAT coexistence in 10.6-10.7 GHz to it.

9 Results from Prior NSF Support

PIs Mandayam and Wu are collaborating on the project SWIFT-2128077; $750,000, 10/2021-9/2024, SWIFT: Enabling Spectrum Coexistence of 5G mmWave and Passive Weather Sensing. ***Intellectual Merit:*** Model based study of the effect of RFI from 5G mmWave on Numerical Weather Prediction algorithms for temperature and precipitation; Mapping of brightness (contamination) temperature in continental US using models for projected growth of mmWave deployments; Design of mmWave filtenna transmitters for reducing RFI in the 23.8 GHz band. ***Broader Impacts:*** Undergraduate, graduate and high school students including underrepresented minority groups will be engaged and trained in the coexistence of 5G with passive sensing and weather forecasting. ***Products:*** See [31, 34–38]

PI Seskar is co-PI on the project: CNS-1827923; $6,500,000, 04/2018– 03/2023, COSMOS (Cloud Enhanced Open Software Defined Mobile Wireless Testbed for City-Scale Deployment. ***Intellectual Merit:*** Design, deployment, and operation of an advanced wireless testbed in Harlem and Sandox at WINLAB, Rutgers. ***Broader Impacts:*** Provides a unique community infrastructure that allows remote experimentation with sub-6 GHz, mmWave, edge cloud, and optics. Outreach programs include a WINLAB Summer Internship REU [97]and RET program for NYC teachers [103–105]. ***Products:*** See [106–112].

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