A Frequency Hopping Software-Defined Radio Platform for Communications and Sensing in the Upper Mid-Band

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***Abstract*—The upper mid-band spectrum, or FR3, from 6-24 GHz, is a vital range of frequencies for emerging applications including next-generation cellular networks, satellite, RADAR, and localization services. These frequencies offer a good balance of coverage and spectrum to enable high-data rates, low latency, spectral resiliency, and high-resolution sensing. Development of adaptive systems in the frequencies requires platforms that can support wideband operation, beamforming, and fast frequency hopping. This paper describes a novel software-defined radio (SDR) platform which has been designed to facilitate such experimentation and rapid prototyping. The SDR consists of four antenna arrays with fast frequency hopping to cover the full upper mid-band. RF up-conversion and down-conversion is then built with CoTS parts to provide a baseband interface for fully digital multi-array processing. Potential applications for channel measurements, beamforming, MIMO, and full-stack communications are described.**

I. Introduction

Cellular wireless systems up to the fourth generation (4G) had largely operated in a range of microwave frequencies below 6 GHz. Given the severe spectral shortage in these bands, 5G systems introduced new capabilities in the millimeter wave (mmWave) frequencies, notably at 28 and 37 GHz. The wide bandwidths available in the mmWave spectrum, combined with spatial multiplexing capabilities, have now enabled massive multi-Gbps peak rates. However, recent field tests demonstrated that practical performance is often intermittent [1]–[3], due to the inherent limited range of mmWave signals and their high susceptibility to blockage [4]–[6].

Against this backdrop, the upper mid-band — roughly from 6 to 24 GHz — is a new potential spectral frontier for cellular systems that provides a long-needed balance of coverage and bandwidth [7]. The frequencies have the potential to overcome the spectral shortage of the sub-6 bands while having favorable propagation and penetration relative to the mmWave bands – see Fig. 1. For this reason, the frequency region has attracted considerable interest from industry as a leading contender for 5G-Advanced and 6G networks [8], [9]. Indeed, 3GPP has begun discussions on these bands, calling them frequency range 3, or **FR3** [10], [11]. Additionally, the FCC has recently considered two 500 MHz bands for cellular service: 12.2-12.7 GHz [12], and 12.7-13.2 GHz [13]. While the first band has been rejected, it is widely recognized that there is a need for opening the upper mid-band for cellular services. For example, the FCC Technical Advisory Committee (TAC) has recently published a comprehensive survey of spectrum from 7.125 to 24 GHz [14] as well as a 6G working paper [15]. Finally, the World Radiocommunication Conferences (WRC)-23 set the agenda for the next WRC-27 with a clear roadmap for future IMT spectrum allocations, which involves the identification of several frequency bands, including 7.125-8.4 GHz and 14.8-15.35 GHz, for the potential use of IMT.

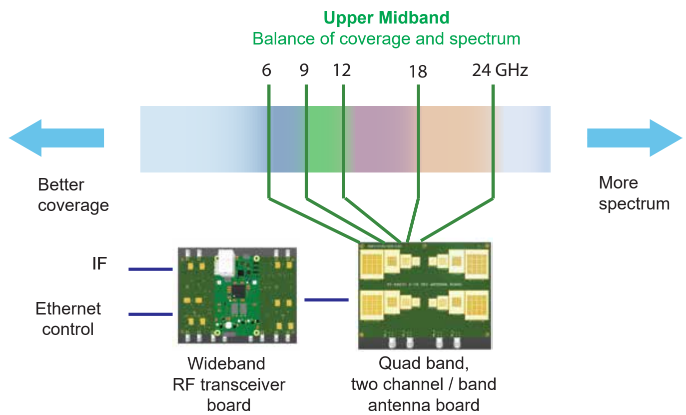

Fig. 1: The **upper mid-band**, or FR3, is emerging as an increasingly critical band for applications in cellular, satellite, and RADAR [7]. We propose a novel SDR for these bands consisting of a quad-band antenna board and wideband RF transceiver board with fast frequency switching.

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TABLE I: Challenges of existing experimental platforms and solutions.

Challenge	Limitations of existing solutions for the upper mid-band	Proposed solution
Frequency range	Most systems do not cover bandwidth and carrier frequencies for the upper mid-band.	A wideband, multi-antenna system for the full 6-24 GHz band.
Spectral agility	Most SDRs have slow frequency re-tuning and high interface latency the host.	High speed RF control interface and FPGA micro-controller-based software for ultra low-latency control.
Array count	Large numbers of antenna elements necessary for beamforming and MIMO experimentation are often not available at reasonable cost.	A fully digital system with up to 8 channels leveraging a compact RF design.
Cost	Commercially-developed systems are often at too high cost.	Low-cost design with CoTS parts enabling SDRs at moderate cost.

A. The Need for Adaptive and Spectrally-Aware Radios

While most commercial efforts have focused on relatively narrow individual bands in the FR3 range, there can be significant value for wideband systems that operate across the entire FR3 spectrum. For example, a capacity analysis in [7] based on ray tracing in Manhattan demonstrated that adaptive systems that can dynamically select one of several bands in the FR3 range offer significantly improved performance over systems in any individual band. Essentially, bands in the high frequency offer high data rates, but are often not available due to blockage and poor indoor penetration. In these cases, dynamically adaptive systems can switch to lower frequencies for more uniform converge. The study [7] demonstrated that dynamically adaptive systems offered similar peak rates as high freuqency systems and similar cell edge as low frequency systems.

However, developing adaptive systems that can dynamically use the entire FR3 band with fast dynamic switching presents significant challenges:

- *Incumbents and vital existing services:* The FR3 bands will likely need to be shared by incumbents. Most importantly, commercial satellite services already widely use these bands [16], [17], and have been interested in increased bandwidth allocations, particularly for broadband rural access. Several vital military and defense systems also use these frequencies for RADAR.
- *Frequency range and spectrum agility:* The upper mid-band is a vast range of spectrum – well beyond the span of most commercial cellular front-ends that typically operate over a small percentage of the carrier frequencies. The need to support a wide spectral range is combined with the fact that likely allocations may be fragmented over many narrow bands.
- *Spectrum security:* Cellular wireless infrastructure has become vital to the economy, life and prosperity of society. Jamming, signal disruption, channel overloading, and denial of service are all avenues for rogue actors to undermine critical communication services. The FR3 bands have the potential to unlock new opportunities to provide resilient services through frequency hopping and directional sensing.

B. Limitations of existing SDR platforms

Fundamental to addressing these open problems and realizing the full potential of the upper mid-band are experimental platforms operating in these frequencies. As shown in Table I, current systems present significant limitations in frequency range, array count, spectral agility, and cost. For example, the NI USRP X410 [18] only covers frequencies up to 7.2 GHz with a 400 MHz bandwidth, and it does not include the antennas. The TMYTEK UD 6-20 GHz module [19] is a single-channel system with 3 ms switch time. Similarly to the USRP, it does not provide any antennas.

II. Proposed FR3 Software-Defined Radio

A. Overview

To address these challenges, we propose a novel SDR platform for FR3. We will describe a two channel system meaning two TX and two RX chains. However, an eight channel system has also been designed. We focus on the two channel system as it lower cost and will be ready earlier. The basic components of the proposed upper mid-band SDR platform can be summarized as follows:

- **Quad-band antenna board:** It consists of a miniature panel that supports 2 TX and 2 RX channels over the entire 6-24 GHz range. An RF switch selects the antenna arrays with sub micro-second switching delay. Within each band, the arrays have 2 elements with separate feeds to provide support for up to 2×2 MIMO. The elements are designed from a novel metasurface structure.
- **RF transceiver board**: The antenna board mates with an RF transceiver board that performs the up and down-conversion to 2 TX and 2 RX IF streams. This two-stage up- and down-conversion is used to meet the out-of-band (OOB) and adjacent channel rejection ratio (ACLR) requirements and strict spectral masks. The transceiver board is built from commercial off-the-shelf (CoTS) parts. Importantly, LO inputs are included to tile the boards for higher array counts and support wide aperture designs.
- **Digital baseband board**: The FR3 front-end can be plugged via SMA cables to any sub-6 GHz SDR, e.g., USRP, Xilinx RFSoC, Pluto, etc. This allows to use any existing software tools and workflows, such as Vivado, Matlab, LabView, OAI, srsRAN, and so forth.

TABLE II: Key parameters for the Pi-Radio SDR system.

Parameters	Value	Remarks
Frequency range	6-24 GHz	Four bands: 6-9, 9-12, 12-18, and 18-24 GHz, based on VCO [20].
Num TX channels	2	Higher cost 8×8 system also being designed.
Num RX channels	2	
Instantaneous BW	1 GHz	
IF frequency	1 GHz	Tunable.
Output power	18 dBm / channel	Based on PA $P_{1\mathrm{dB}}$ point [21].
Noise figure	4 dB	Based on LNA [22].
Freq accuracy	0.2 ppb	Based on OCXO [23].

B. Front-end Transceiver (TRX) Board

Transceiver: As shown in Fig. 2, the TRX board accepts IF signals with a bandwidth of 1 GHz, and a center frequency of 1 GHz. A two stage up-conversion is used where the IF signal is first down-converted to baseband IQ and then up-converted to RF. The two stage conversions provides easier reduction of sidebands. The RF frequency can be adjustable with a tunable LO that supplying the mixer. Similarly, the receiver reverses this process, first down-converting the signal to baseband I/Q and then up-converting to IF. Both the IF and RF signals connect via standard SMA cables. The TRX is entirely built with commercial off-the-shelf (CoTS) parts, as illustrated in Table II.

Control Plane: As shown in Fig. 3, the TRX board has a Micro-Zed mounted on its bottom side. This module runs Linux and acts as an SPI/GPIO breakout for the TRX board. The Micro-Zed can either run in stand-alone mode or be connected to a host computer for Control (ex: configure RF frequency, filter banks, various gain levels, clocking tree, etc.). This module can optionally run Precision Time Protocol (PTP) for fine-grained control of time-gated control operations.

Clocking and LO Subsystem: The TRX board also has local oscillator (LO) sub-systems that are used for all up- and down-conversion operations. One LO subsystem is used for all conversions between baseband and IF, while the other LO subsystem is used for all conversions between RF and baseband. The key design feature is that all transmit channels and all receive channels are perfectly phase synchronous with respect to each other. The internal LO is an oven-controlled crystal clock (OCXO) [23] with $0.2\,\mathrm{ppb}$, which enables long integration periods for channel sounding even without any TX-RX synchronization. The TRX board also has a carefully designed clocking subsystem that allows it to operate with other baseband systems with tight phase coherence. The clocking subsystem also allows for clocks to be daisy-chained, so that larger channel counts can be achieved for use-cases pertaining to distributed beamforming or massive MIMO.

C. Antenna Board

As shown in Fig. 4, the antenna system is implemented as a single PCB. It supports 2 TX and 2 RX channels that span the entire 6-24 GHz frequency band. Each channel connects to a 4x4 *metasurface* antenna, sized $\lambda/2$ at each center frequency, as depicted in Fig. 5. Each channel can be switched across 4 such antennas: 6-9, 9-13, 13-18, or 18-24 GHz, with < 1us switching time. The gain per unit-cell is 5dBi. Importantly, these antennas provide 40% fractional bandwidth, which is key to enable 6-24 GHz operations. In fact, regular microstrip-fed patch antennas provide only $2-3\%$ fractional bandwidth.

A metasurface unit-cell [24] is an aperture-coupled antenna, with stacked and replicated patches, and capacitive via-walls. A shown in Fig. 5, each unit-cell is implemented on a 4-layer PCB. On the bottom later (L4), there is a microstrip feed line, open-terminated with a radial tuning stub. On the layer above (L3), there is a tuned aperture slot. The layer above (L2) has one set of replicated patches; the top layer (L1) also has a set of replicated patches.

III. Potential Research in the Upper Mid-Band

The proposed SDR platform can enable several valuable experiments for research in the upper mid-band:

Channel modeling and measurements: Channel measurements have been conducted extensively in various frequencies in the upper mid-band in both indoor and outdoor settings. However, key to developing wideband systems with fast frequency hopping is the need to model the *joint* statistics across bands. Such models are needed, for example, to evaluate the probability of outage in one band, conditional that a different sub-band is in outage. Critically, the proposed FR3 SDR is capable of near simultaneous channel measurements enabled by rapidly switching between bands. Since multiple front-end radios can be tiled together to form a multi-band fully-digital array, the system can accurately capture spatial characteristics of each path.

Spectrum sharing and cognitive radio: A critical challenge in the upper mid-band is that systems will likely need to sense and share spectrum with incumbent services including satellites, RADAR, and radio astronomy. An important feature of the proposed platform in this regard is the fast frequency hopping that will enable various spectral search and frequency selection algorithms. Additionally, the eight channel system (at higher cost) can enable experimentation for fully digital beamforming for directional spectral sharing.

Full-stack experimentation: Since the proposed platform uses a generic IF interface, in principle any full-stack baseband system could be used with the transceiver. For example, the widely-used open-source 5G impementation such as OAI [25] could be connected to the transceiver via a USRP. The main challenge is to connect the frequency selection controls. In this regard, since the platform supports precision timing protocol (PTP), all controls can be performed at precise times, which is critical in full-stack communication.

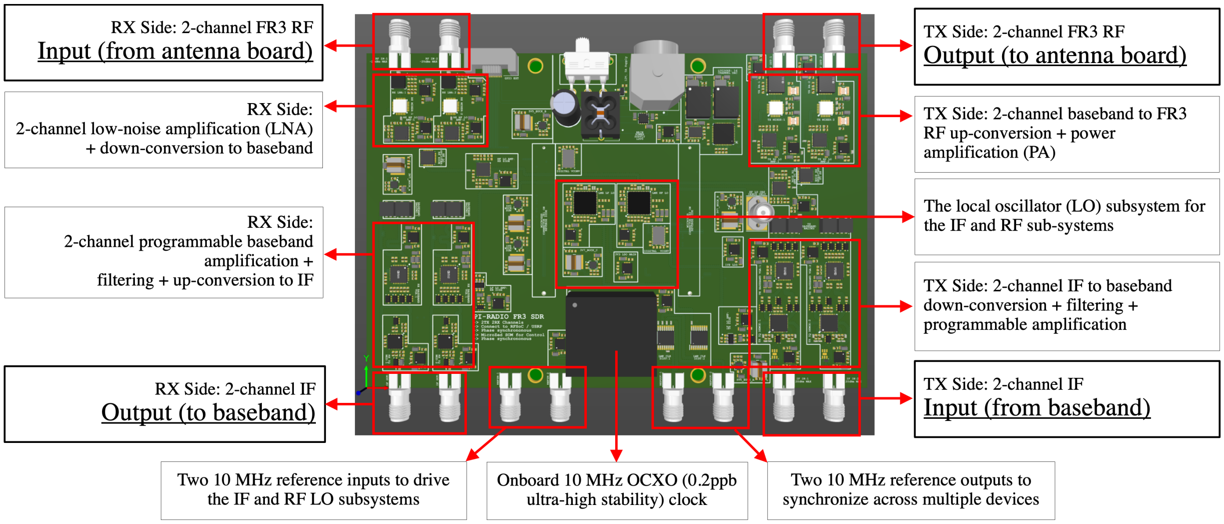

Fig. 2: The Pi-Radio TRX board supports 2 TX and 2 RX channels. Each of the TX chains uses a 2-stage conversion process to adhere to spectral masks. Each of the RX chains also uses a 2-stage conversion process to mitigate against neighboring channel interference.

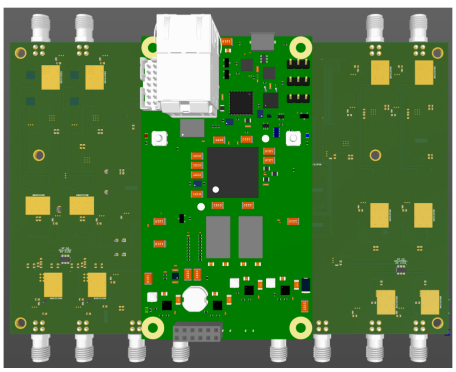

Fig. 3: On the bottom side of the Pi-Radio TRX board, a MicroZed SOM and its built-in Ethernet port allows to perform control operations such as configuring RF frequency, filter banks, various gain levels, clocking tree, etc.).

IV. Conclusion

The upper-mid band offers a favorable combination of coverage and spectrum characteristics, facilitating high-data rates, low latency, spectral resilience, and high-resolution sensing capabilities. Realizing the full potential of these frequencies demands agile systems equipped with spectral intelligence, adaptive beamforming, and rapid frequency hopping capabilities. The paper presents a novel SDR platform tailored for experimentation and swift prototyping within the upper mid-band. Featuring four antenna arrays with rapid frequency hopping, this SDR system integrates CoTS components for RF up-conversion and down-conversion, facilitating a baseband interface for fully digital multi-array processing. The platform's versatility extends to various applications, including channel measurements, beamforming, MIMO systems, and comprehensive communications protocols, thus laying a robust foundation for continued exploration and innovation in this critical frequency range.

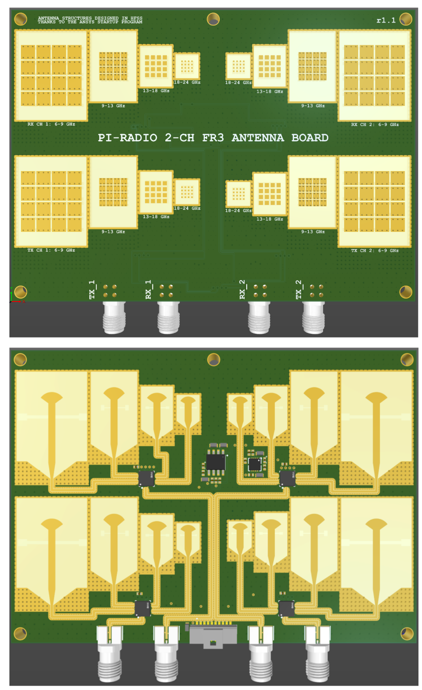

Fig. 4: Front face (**top**) and back face (**bottom**) of the Pi-Radio antenna board. This miniature panel supports 2 TX and 2 RX channels over the entire 6-24 GHz range.

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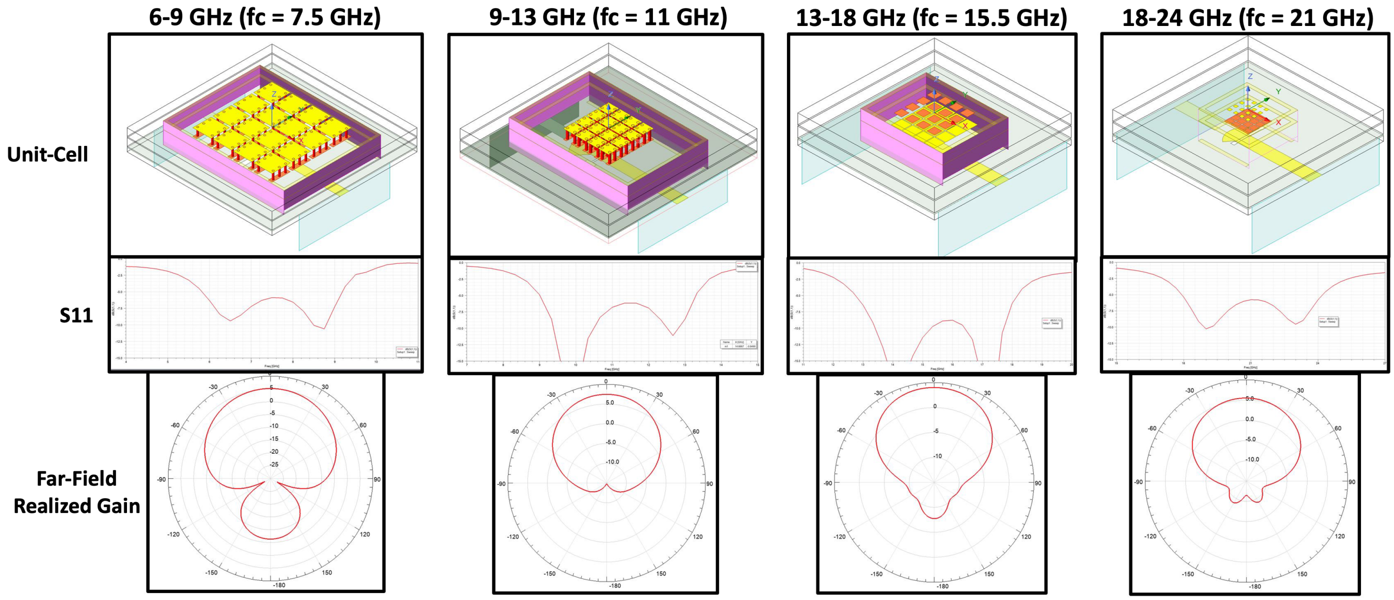

Fig. 5: HFSS simulations of the four metasurface unit-cells. Left to Right: 6-9 GHz, 9-13 GHz, 13-18 GHz, and 18-24 GHz. Top to Bottom: Stackup and physical metasurface structure; S11 of the antenna; and the far-field antenna realized gain ($\phi = 90\,\text{deg}$).

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