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Software Radio with MATLAB Toolbox for 5G NR Waveform Generation

Walaa Alqwider, Ajaya Dahal and Vuk Marojevic
Dept. Electrical and Computer Engineering, Mississippi State University, Mississippi State, MS, USA
{wq27, ad2323, vm602}@msstate.edu

***Abstract*— The main resource for providing wireless services is radio frequency (RF) spectrum. In order to explore new uses of spectrum shared among radio systems and services, field data needs to be collected. In this paper we design a testbed that can generate different 5G New Radio (NR) downlink transmission frames using the MATLAB 5G Toolbox, software-defined radio (SDR) hardware and GNU Radio Companion. This system will be used as a part of a testbed to study the RF interference caused by 5G transmissions to remote sensing receivers and evaluate different mechanisms for co-channel coexistence.**

***Index Terms*—5G NR, SDR, spectrum sharing, testbed.**

I. Introduction

Radio astronomy (RA), remote sensing (RS), and other passive radio frequency (RF) sensors are indispensable in modern society. Remote sensing has many important application in the Earth science and climate studies such as for monitoring the soil moisture, which provides scientists with important information for effective agricultural decisions, as well as for forecasting weather, floods, and droughts and exploring natural phenomena happening in our universe [1], [2]. Society also increasingly depends on active wireless technologies for commerce, transportation, health, science, and defense, with emerging technologies such as the Internet of Things, unmanned aerial vehicles (UAVs), and 5G wireless further increasing this dependence. The growth of active wireless systems often increases radio frequency interference (RFI) experienced by passive systems.

Spectrum and Wireless Innovation enabled by Future Technologies (SWIFT) is an National Science Foundation program that supports research on the coexistence of passive and active wireless technologies. Our project develops different methods for the detection and mitigation of RFI from a cellular xG network to the passive receivers. We propose data-driven methods applying artificial intelligent (AI) which requires data that is labeled and includes reliable, physics-based ancillary input features during the training phase. In order to generate such data and evaluate different AI methods for RFI detection, mitigation, and avoidance, we are developing a testbed that includes 5G frame generation from ground infrastructure and UAVs as well as UAV-mounted radiometers for RS. This testbed aims to serve as a cost-efficient tool for the collection of ground truth data to enable validating spectrum coexistence techniques between 5G New Radio (NR) and RS devices. Among others, our SWIFT project proposes innovative 5G New Radio (NR) medium access control and physical layer techniques as well as new waveform generation, RFI detection, and mitigation processes using AI.

This paper presents a practical approach to 5G NR frame generation using the MATLAB 5G Toolbox together with software-defined radio (SDR) hardware and the GNU Radio framework. The rest of the paper is organized as follows: Section II introduces the enabling technologies. Section III provides the testbed architecture and the hardware and software components. Section IV present the RF measurement procedure and results. Section V concludes the paper with a brief research outlook.

II. Enabling Technologies

An SDR is a radio transceiver that is largely defined in software. It allows radio engineers and researchers to easily control the hardware and implement and configure the physical layer in software. SDRs have been used in many scientific platforms to implement, test, and study different wireless technologies and protocols. An SDR was used in [3] as a part of base station prototype for long range telemetry in a low power wide area sensor network. Reference [4] implements a practical downlink (DL) non-orthogonal multiple access system using the OpenAirInterface software. The authors of [5] evaluate the performance of low-altitude aerial nodes using SDR-based broadband wireless links. Reference [6] describes the SDR development efforts from both the hardware and the software perspectives for developing the Aerial

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Experimentation and Research Platform for Advanced Wireless (AERPAW) [7]. An SDR platform is demonstrated in [8] for the detection of human activity based on the wireless channel state information. SDRs with a system on chip are used in [9] to perform experimentation and evaluate the performance of higher order modulation schemes, adjacent channel interference, power amplifier (PA) gain compression, and effects on the bit error rate performance.

5G NR has been standardized by the Third Generation Partnership Project (3GPP) since Release 15. It is a flexible physical layer that permits many different system configurations and transmission schemes [10], [11]. Using software implementations of 5G NR allows changing the 5G protocol within the bounds of the specifications as well as beyond the specifications. The objective of this study is developing a method to customize the 5G NR transmission frames and enable RF and network performance evaluation, spectrum coexistence research, and RFI analysis, in particular. In this paper we explore the 5G waveform generation function of the MATLAB 5G Toolbox to generate different DL transmission frames. The 5G NR knobs include the bandwidth (BW), the physical resource block (PRB) allocation within the BW, the time slot occupation, the numerology, the number of layers, and the transmit (Tx) power. The generated waveform is transmitted over-the-air (OTA) using the GNU Radio software framework in conjunction with Universal Software Radio Peripheral (USRP) hardware.

The radiometer is also being custom built for this project and uses an SDR with an RF front end. The front end has a four-port microwave switch, an isolator, a tight bandpass filter (1397–1430 MHz), and a low noise amplifier. The purpose of the SDR is to record the raw data while using the full 27 MHz BW of the protected 1400-1427 MHz band for RFI analysis. The focus of this paper is on the 5G NR DL generation.

III. Hardware and Software Components

We use two SDRs to implement the transmitter and the receiver sides of the testbed. Each SDR is connected by USB 3.0 to a computer that runs GNU Radio Companion. The transmitter and the receiver GNU Radio flowgraphs have a built-in spectrum analyzer (SA) block to visualize the fast Fourier transform of the signal for spectral analysis. To validate the radiated signal we use a commercial off-the-shelf (COTS) SA. In continuation we describe the software and hardware that we use to build the testbed.

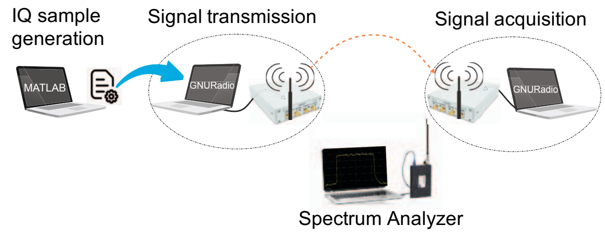

Fig. 1: The building blocks of the 5G NR waveform generation and transmission testbed.

- **MATLAB 5G Toolbox:** MATLAB is widely used by researchers for validating theoretical contributions, models, and designs through simulations. It offers the ability to create custom waveforms and protocols, as well as simulate 5G, LTE, and WLAN standards, among others. For this testbed we use the 5G Toolbox because of its flexibility to customize the uplink and DL 5G NR transmission that is compliant with the 3GPP specifications. We use another MATLAB function to convert the in-phase and quadrature (IQ) samples to binary points for use with GNU Radio.
- **GNU Radio:** GNU Radio is a free and open-source software development toolkit that provides the mechanisms and sample signal processing blocks to implement radios in software. It is compatible with low-cost SDR hardware to enable RF transmission. It has a graphical user interface—GNU Radio Companion—to assemble radios by connecting blocks. It uses C++ in the backend and when a flowgraph is created and *compiled*, it generates the equivalent Python scripts for real-time execution.
- **SDR hardware and antenna:** A USRP is an affordable device that provides the interface between the antenna and the digital signal processing on a host computer. For our testbed we use two B210 USRPs, one for the transmitter and the other for the receiver. The technical specifications of the B210 match the testbed requirements: It supports a wide RF range from 70 MHz to 6 GHz with an instantaneous BW of up to 56 MHz. It supports full-duplex transmission and 2x2 multiple-input, multiple-output (MIMO). The OTA transmission is enabled by a COTS Proxicast antenna. These antennas are low cost, have a 5 dBi gain, and are designed for operation from 698 to 2700 MHz, which covers the frequency bands of initial interest for our testbed.
- **Spectrum analyzer:** We use the Tektronix

RSA306B SA to capture our transmitted signal. It provides real time spectrum analysis, streaming capture, and deep signal analysis capabilities for signals from 9 kHz to 6.2 GHz and +20 dBm to -160 dBm measurement range with up to 40 MHz real-time acquisition BW. It uses Tektronix SignalVu-PC™ software for displaying the samples in real-time on a computer.

IV. 5G Waveform Generation

We generate a variety of 5G NR DL frames in MATLAB, including full-band, partial-band, continuous, and non-continuous. The OTA experiments are performed at 2.6 GHz where we have an FCC experimental license, whereas radiation at 1.4 GHz needs to be done in an anechoic chamber. The BW of 25 MHz is chosen based on the RS scanning requirement. Table I captures the parameters of the main experimental setup in this paper.

We first measure the Tx signal powers for different USRP gains. The test is done by connecting the Tx port of the USRP directly into the SA with a short coax cable and an attenuator as needed. Fig. 2 plots the signal power measurement results for three frequencies of interest for this project. It shows the wide range of variable and largely linear Tx gains offered by the USRP. The maximum B210 USRP gain of 89.9 dB produces a clean RF signal (Fig. 3) of nearly 1 mW at the USRP Tx antenna port. External PAs can be integrated for achieving higher transmission powers for ground or airborne advanced wireless experiments [12].

TABLE I: Experimental parameters.

Parameter	Value
System BW	25 MHz
Carrier frequency	2.6 GHz
Waveform power (MATLAB)	0 dBm
USRP Tx gain	70
MIMO configuration	1 Tx, 1 Rx antenna
Waveform sampling rate	30.72 MHz
FTT-size	2048
Modulation scheme	QPSK
Subcarrier spacing	15 kHz

In continuation we present the result for two NR DL transmission modes.

- **Continuous and full-band transmission:** The generated DL frame occupies the full 25 MHz BW with full PRB allocation for continuous transmission. Fig. 4 shows the results captured at the different stages of the signal.
- **Non-continuous and partial-band transmission:** The generated frame is sparse in time and frequency. It occupies only certain time slots and PRBs. Fig. 5 illustrates the result of this transmission captured at the transmitter, receiver, and SA.

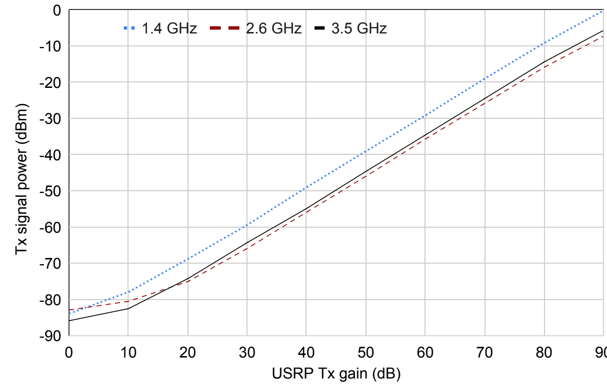

Fig. 2: Average Tx power of the 25 MHz full-PRB 5G DL frame as a function of USRP gain.

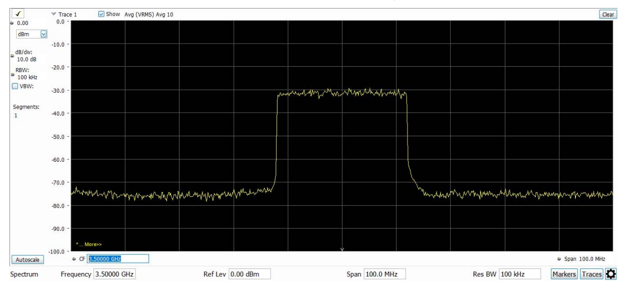

Fig. 3: Full-PRB NR DL Tx frame captured by the SA with a 10 dB attenuator for USRP Tx gain of 89.9.

V. Conclusions

The purpose of this paper is demonstrating a pragmatic process for generating different 5G NR frames for OTA transmission using COTS software and hardware. The tools can be integrated in larger systems to validate emerging technologies and advance 5G wireless procedures. One of the many uses of this testbed is to study RFI on receive-only devices. Instead of the SA used here for demonstration purposes, a radiometer is being developed as the sensing device to evaluate the RFI caused by different 5G signaling frames in a controlled radio environment, where the Tx power can be scaled to mimic real operation in the field. This testbed enables evaluating the impact of different 5G transmission options and power levels, where the transmission can be sparse, silent periods introduced, or spectrum vacated to avoid harmful RFI when the sensor is collecting data.

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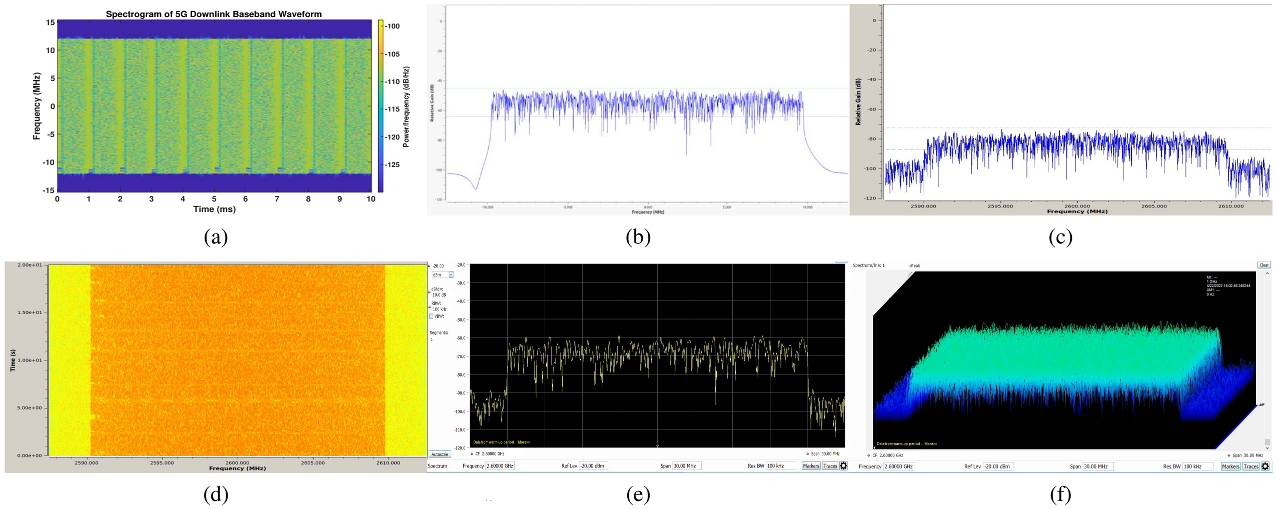

Fig. 4: Continuous and full-band transmission: Spectrogram of the generated waveform (MATLAB) (a), Tx signal magnitude (GNU Radio) (b), Rx signal magnitude (GNU Radio) (c), Rx signal spectrogram (GNU Radio) (d), signal magnitude (SA) (e), and spectrogram (SA) (f).

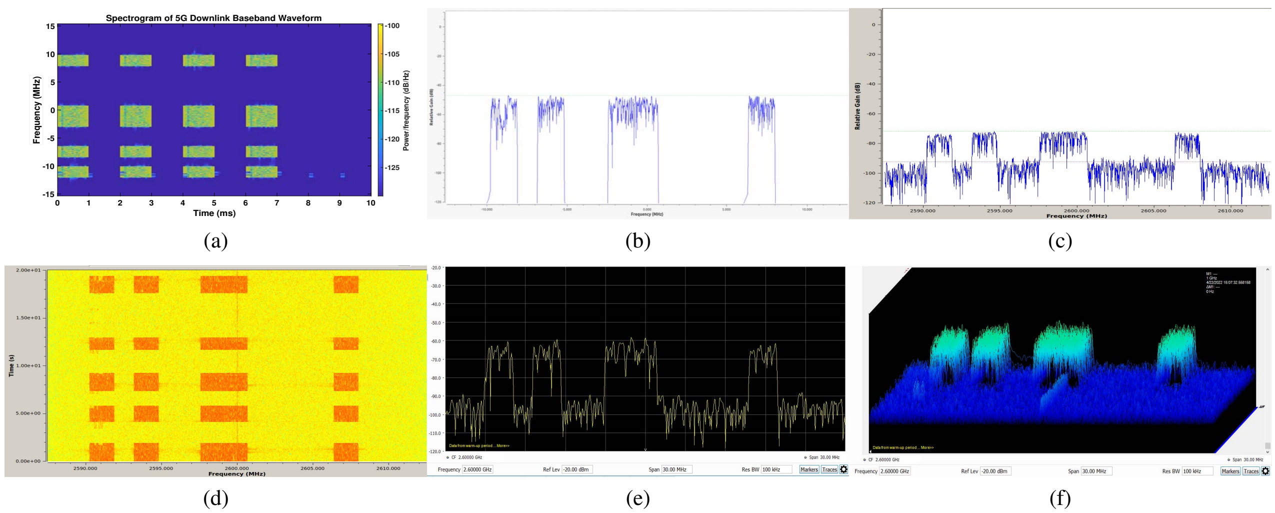

Fig. 5: Non-continuous and partial-band transmission: (a)-(f) as in Fig. 2.

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