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Rapid Prototyping and Validation of FS-FBMC Dynamic Spectrum Radio With Simulink and ZynqSDR

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ABSTRACT This article presents the research carried out in developing and targeting a novel real-time Dynamic Spectrum Access (DSA) Frequency Spread Filter Bank Multicarrier (FS-FBMC) transmitter prototype to programmable 'ZynqSDR' Software Defined Radio (SDR) hardware, and introduces a series of experiments used to validate the design's 'cognitive' DSA capabilities. This transmitter is a proof of concept, that uses DSA techniques to enable Secondary Users (SUs) to access the band traditionally used for FM Radio broadcasting (88-108 MHz), and establish data communication channels in vacant parts of the FM Radio Primary User (PU) spectrum using a multicarrier modulation scheme with a Non Contiguous (NC) channel mask. Once implemented on the hardware, the transmitter is subjected to various FM Radio environments sampled from around Central Scotland, and it is demonstrated that it can dynamically adapt its NC transmitter mask in real time to protect the FM Radio signals it detects. A video is presented of this dynamic on-hardware spectral reconfiguration, and the reader is encouraged to view the video to appreciate the responsiveness of the design. An investigation into potential FBMC guardband sizes is carried out, with initial findings indicating a guardband of 200 kHz (either side of an FM Radio station) is required in order to prevent interference with the PUs. This article also demonstrates the capabilities of the MATLAB and Simulink Model Based Design Zynq-Based Radio workflow, and provides a case study and reference design that we feel other researchers working in this field can benefit from.

INDEX TERMS Dynamic spectrum access, filter bank multicarrier, FBMC/OQAM, FS-FBMC, FM radio, PHYDYAS, non contiguous, shared spectrum, software defined radio, USRP, ZynqSDR.

I. INTRODUCTION

THE EXPLOSION of *wireless everything* in recent years has placed a strain on the Radio Frequency (RF) spectrum, and has led to the so-called 'spectrum crunch,' where the spectrum is described as being nearly at capacity. Upon inspection however, many bands appear to be underutilized or not in use at all. This paradox is well understood to primarily be the result of spectrum allocation practices used by regulators around the world, rather than a shortage of physical RF resources.

Static spectrum management policies see bands of spectrum allocated for a particular type of use across a large geographical area, e.g., nationally, regardless of whether Primary Users (PUs), the license holders, are actively using all of the channels in them, in all locations. This is an inefficient approach, and results in wasted spectrum. To give an example, rural areas of the U.K. often suffer from poor cellular coverage, despite operators owning licenses to broadcast at cellular frequencies nationwide. When there is no 'business case' to deploy basestations, none are deployed;

resulting in (a) the underutilization (and 'wastage') of valuable spectral resources, and (b) unhappy communities with no cellular coverage.

The spectrum is a (non-depleting) finite resource, so ideally, it would be used as efficiently as possible. Escalating pressure on the limited number of free-to-use bands has led to a new, complementary access method being developed, that could allow Secondary User (SU) radios to utilize unused parts of the spectrum. This is called Dynamic Spectrum Access (DSA).

DSA is a method of spectrum sharing whereby SU nodes and networks are able to access the spectrum, and establish communication channels on an unlicensed (or light-licensed) basis. Subject to a new regulatory framework, DSA would see licensed PUs encouraged to share bands they are not using, allowing the spectrum to be used more efficiently. DSA-enabled SUs would ideally be spectrally aware, meaning that they are capable of identifying bands they may access without generating unacceptable levels of interference to incumbent PUs [1]. After identifying suitable bands, these SUs would be able to establish communications channels within them using a MultiCarrier Modulation (MCM) scheme.

To date however, regulators have not permitted this type of widespread, cognitive, sensing-based DSA. With the introduction of geolocation databases in 2014, controlled spectrum sharing was made possible in white space channels in the TV band (so named TV White Space, TVWS [2]). Here, SU radios contact a database to discover what channels (and transmit powers) they may use at their particular location. They cannot use sensing to identify vacant channels. A number of TVWS networks have been established around the world in recent years, mostly focused on providing Internet access in areas where it was not already available. The University of Strathclyde's Centre for White Space Communications (CWSC) was involved in the design, installation and operation of three such networks in Scotland. These were on the Isle of Bute in 2011, in Glasgow city center in 2014, and on the remote Orkney Islands in 2016. These networks (which are SUs) have seen fixed, broadband-speed Internet access provided to rural communities where there is no fiber available, and the POTS (Plain Old Telephone Service) network was not capable; and even 'nomadic' access on inter-island ferries out at sea.

Building on this work, the team at Strathclyde designed, developed, and with the help of partners, deployed a full shared spectrum 4G/5G cellular network across 360 km^2 of the Orkney Islands in 2018-2019 as part of the 5G RuralFirst project [3]. The software defined carrier-grade basestations were the first in the U.K. to operate in the new flagship 5G bands (700 MHz and 3.5 GHz), and standard commercial smartphones such as the *Google Pixel 3* or *Xiaomi Mi Mix 3 5G* could connect when using a 5GRF SIM card. One of the key deliverables of the project was a whitepaper addressing the need for introducing shared spectrum to cellular bands, in order to allow third party community operators to build and run SU mobile networks in rural areas with PU market failure, where no service was being provided [4]. *(It should be noted, this is NOT the same as the "Dynamic Spectrum Sharing" (DSS) or "Ericsson Spectrum Sharing" (ESS) concepts supported by some basestation vendors. Confusingly named, DSS/ESS simply sees some resources in 4G LTE cells re-allocated for 5G NR, allowing LTE and NR cells to coexist in the same RF channel; reducing, however, the overall basestation capacity, due to the increase in control signalling [5]. This is not spectrum sharing in the traditional sense.)*

FIGURE 1. Photographs of shared spectrum mobile basestations from the 5G RuralFirst project. (Left) a trailer mounted generator-powered pneumatic mast system with 5G cell and on-board core network, and (right) close-up of a 700 MHz radio head and 5 GHz microwave backhaul at a remote rural site.

Following the release of the 5GRF whitepaper, Ofcom (the U.K.'s RF spectrum regulator) opened a series of consultations focused on the upcoming 5G spectrum auctions and the topics of shared spectrum, local licensing and PU coverage obligations. New shared bands in cellular spectrum were proposed, along with a new licensing model that would support SUs. The outcome of this is that all vacant spectrum throughout the U.K.'s licensed cellular bands has now become available to SUs via the new *local access* framework, and parts of three cellular bands have been re-categorized as dedicated *shared access* bands [6], [7].

Various regulator-approved trials that have taken place around the world have demonstrated that SUs can peacefully coexist with PUs in a number of different real RF environments. While TVWS spectrum is 'open for business' in several countries, and parts of the U.K.'s mobile spectrum are now available for 'light-licensed' sharing, the movement towards spectrum sharing could go far further. Many bands across the RF spectrum are underutilized, and permitting unlicensed or light-licensed shared access to them could bring a raft of benefits to the economy, rural communities and emerging smart city technologies.

A. THE FM RADIO BAND

Over the last 90 years, there has been significant investment in FM Radio technology, in terms of standardization, broadcasting infrastructure and FM receiver equipment. This is an old and spectrally inefficient analogue modulation scheme; and while the peak 'popularity' of FM has almost certainly passed due to the rise of Internet and on-demand radio streaming services, it still plays a key role for state and commercial broadcasting operators around the world.

Research in the USA has shown that, in regions with populations between 100,000 and 1 million, around 75% of the channels in the band are expected to be unallocated [8], [9], [10]. The authors note 'unallocated' does not directly equate to 'vacant,' as consideration must be given to the geographical frequency guardbands that protect PU transmitters; but even then, the findings suggest that a significant portion of this spectrum is 'vacant' in many areas across the USA. (A similar study was conducted exploring the occupancy of the band in Central Scotland, the results of which will be presented and discussed in Section V-E).

There have been attempts by various countries to switch away from FM to a digital radio solution, such as DAB (Digital Audio Broadcasting). To date, Norway is the only country to have ended FM broadcasting [11]. One region in the North of Italy has also begun turning off FM transmitters, having installed DAB+ equipment at transmitting stations [12]. The only other country with a set date to transition away from FM is Switzerland, and they intend to switch to digital between 2020/2024 [13]. In contrast, Sweden and Denmark have both cancelled their plans to switch to digital services, stating that FM currently provides a better service to the consumer [14], [15]. A recent statement by the BBC (the British state broadcaster) said that it would be "premature to shut down analogue," and that "radio is better served by a mixed economy" [16]. With many nations so reliant on it, this likely means the world will be living with FM Radio services for the next few decades; and living with the inefficiencies, and wasted and fallow spectral resources that go with it. There is a strong motive, therefore, to explore secondary reuse of vacant parts of the band. Subject to regulatory permission, vacant spectrum in the FM Radio band should be considered a prime candidate for dynamic spectrum SU access.

Signals broadcast at these frequencies have excellent long distance propagation characteristics (when compared to the WiFi bands, for example). They are able to diffract around objects such as hills and human-made structures, and have high levels of penetration through buildings. This band would be perfectly suited for use as a SU IoT Wide Area Network (WAN) broadcast channel; either downlink only, used for applications such as Demand Side Management (DSM) for energy smart grid balancing; or for regional transmit/ receive IoT communications, operating in Time Division Duplexing (TDD) mode with 'resource blocks,' similar to how a TDD LTE/NR basestation operates. The band is very fragmented, and PU utilization varies geographically (depending on PU transmitter locations). It is, however, 'clean,' unlike the congested 868 MHz/ 2.4 GHz unlicensed bands used for LoRA/ Bluetooth, ZigBee (+ WiFi). Any SU looking to operate in vacant parts of the FM band must use a highly dynamic modulation scheme that is capable of aggregating enough fragments together to meet its bandwidth requirements, and it must have sufficiently low OOB leakage to prevent interference with PU broadcasters.

B. PROOF OF CONCEPT SU DEVELOPMENT

In our previous work, [17], a novel DSA-enabled radio design was proposed that could facilitate SU communication in the FM Radio band using a Frequency Spread Filter Bank Multi-Carrier (FS-FBMC) technique. As no geolocation database existed for the FM Radio band, the radio was designed to be capable of scanning recorded FM spectrum signals, identifying available frequencies and developing a Non Contiguous (NC) channel mask that would allow the SU to transmit in gaps whilst protecting PU signals. The NC FBMC transmitter was developed in Simulink, and was compared with an equivalent NC OFDM transmitter in 'field test' simulations. Unlike the OFDM-based transmitter, the FBMC-based transmitter was shown to cause minimal interference to the PUs, suggesting that it would be capable of coexisting in the FM Radio band.

The next stage of this research was to target (i.e., implement) the design on programmable Software Defined Radio (SDR) hardware, enabling a practical RF co-existence investigation to take place with genuine RF signals generated in real-time. The radio prototyping platform chosen for this was the *ZynqSDR*, which comprises a Xilinx Zynq based development board, and an Analog Devices AD9364 SDR front end. Zynq is a heterogeneous processing system that combines both a dual core Arm processor and a high speed Xilinx FPGA on a single piece of silicon. The AD9364 is a widely used SDR front end that features a 12-bit ADC/DAC (Analogue-to-Digital Converter and vice versa) pair, both of which operate across the frequency range 70 MHz to 6 GHz. Combined, these two hardware elements can be used to implement powerful and wideband Tx/Rx (Transmit/Receive) SDR systems with a significant amount of programmable resources. This flexible radio platform is an excellent candidate for prototyping new DSA-radio designs.

This article presents the work carried out in targeting the novel FS-FBMC transmitter to programmable ZynqSDR hardware using various tools provided by MathWorks and Xilinx software, and introduces a series of experiments used to validate the design's DSA capabilities. Firstly, real time simulations are carried out on the hardware to confirm that the generated FPGA bitstream was functioning as expected. Here, the radio is subjected to recordings of different FM Radio environments, and the spectra of the generated FBMC signals are examined. Next, an investigation is carried out to explore what SU guardband size is required in order to prevent interference with the PU. Finally, the transmitter design is modified to allow it to run in live 'cognitive' mode, and tests are conducted to confirm that the radio can adapt its mask in real time, based on information obtained from the live ‘off the air’ FM environment.

C. PAPER ORGANIZATION AND ACCOMPANYING RESOURCES

The remainder of this article is organized as follows. A brief literature review is presented in Section II. Section III provides an overview of the FS-FBMC transmitter design, and Section IV, the Zynq-Based Radio targeting workflow. A method for real time simulation using the hardware is presented in Section V; and an investigation into SU guard-band sizes is documented in Section VI. In Section VII the SU radio design is modified to enable live ‘cognitive’ mode, and tests are carried out to demonstrate its capabilities. Some applications of the proposed SU radio are discussed in Section VIII. Finally, a conclusion, future work and outlook are presented in Sections IX, X and XI.

A companion video is presented with this article. It provides information on the system design and the tests described herein, and allows the reader to see the radio dynamically reconfiguring its spectral mask in real time as it adapts to the changing RF environment. Links to this are provided below.

http://dx.doi.org/10.15129/607b5dd7-1ab6-4efb-8a55-18876919714c

https://www.youtube.com/watch?v=AZoS_-n-SsY.

II. RELATED WORKS AND RELEVANCE OF WORK

Otermat was the first to propose the secondary reuse of spectrum in the FM Radio band [8], [9], [10]. In his research, he models the amount of ‘unallocated’ and ‘vacant’ FM spectrum across the USA, and carries out some field measurements to validate occupancy predictions. This work provides strong evidence that the spectrum is not used as effectively as it could be, and an argument is made that the band could be targeted by SU devices. Our work builds on Otermat’s research, and an SDR prototype of a novel DSA-enabled radio transmitter is presented that enables SU access to this vacant spectrum. To the best of the Authors’ knowledge, the FS-FBMC radio discussed in this article is the first to address the opportunity (and challenge) of enabling SU communication in the FM Radio band.

Ernesto [18] and Capela [19] discuss the propagation benefits of low frequency bands for Cognitive Radio (CR) applications. Ernesto presents a CR for voice communication in disaster recovery situations, that accesses vacant spectrum in the AM and FM Radio bands; while Capela demonstrates an NC OFDM based CR targeted at Maritime Mobile Service (MMS) frequencies (156–174 MHz) for data applications. Radios using a NC OFDM PHY layer for SU spectrum access have been presented by many other researchers; e.g., Bindiganavile [20], Bobrowski [21], Iyer [22], Rajbanshi [23], Recio [24] and Sanker *et al.* [25]. This scheme is the clear favorite in the literature for NC-MCM applications, however, it is not suitable for the application in question. The spectral leakage issues are identified by Recio, and suggestions are made in his work that either FBMC or Filtered MultiTone (FMT) based PHY layers may be more suitable alternatives for DSA scenarios. These findings are in line with those of Farhang-Boroujeny [26], Mahmoud *et al.* [27] and Weiss *et al.* [28].

Much of the material published around FBMC/OQAM (Offset Quadrature Amplitude Modulation) for SU access focuses on system architecture proposals and the simulation and evaluation of FBMC waveforms, such as the work of Velamala [29] and Zhang [30]. They present PPN-FBMC radios suitable for general SU coexistence, with implementations limited to simulations. Of the few published FBMC hardware implementations, most of the focus has been on PPN-FBMC. Berg *et al.* [31] proposes the use of NC PPN-FBMC for accessing vacant TVWS bands, and presents an implementation of a transmitter on the T-Flex FPGA platform, and analyses the hardware resource requirements and utilization after the place and route processes. Nadal *et al.* [32] presents a low complexity FPGA implementation of the PPN based approach that uses FFT pruning to reduce hardware processing requirements. Shaheen and Zekry [33] discusses an FPGA implementation of a PPN-FBMC transmitter and receiver pair, with a focus on the resource utilization and power consumption of the design. Initial comparisons between PPN-FBMC and the alternative architecture, FS-FBMC, are provided by Bellanger [34]. Varga and Kollár [35] and Keerthana and Rajaram [36] compare the computational requirements of the two architectures, and more general comparisons of hardware resource requirements between various NC modulation schemes are presented in [37] by Gerzaguet *et al.*. Carvalho *et al.* [38] and Ferreira and Ferreira [39] perform analysis of the resource requirements and FPGA utilization for a generic dynamic FS-FBMC transmitter using a ZedBoard. Ferreira goes on to implement and compare reconfigurable OFDM, FS-FBMC and Universal Filtered MultiCarrier (UFMC) transmitters on Zynq FPGA hardware [40], [41].

Kaushik *et al.* [42] and Wunsch *et al.* [43] present an SDR FPGA demonstrator of a PPN-FBMC transmitter on a USRP, that uses energy and preamble detection algorithms to prevent it interfering with PU signals. Their work is similar to that by Dziri *et al.* [44] and Horváth and Bakki [45]. Font-Bach’s work [46] compares hardware implementations and coexistence capabilities of PPN-FBMC and LTE OFDM transmitters using the Xilinx ZC706 FPGA and Analog Devices FMCOMMS 3 AD9361 SDR front end, for the application of SU access to PMR bands (Professional Mobile Radio). Drozdenko presents an 802.11a SDR-WiFi implementation targeted to the same hardware in [47], [48], [49], [50], using the MathWorks Model-Based Design workflow for SDR targeting featured in this article. The only other publications discovered that make use of the workflow are by Dang [51] and Cai *et al.* [52], which review the QPSK transmitter/receiver examples created by MathWorks engineers to demonstrate

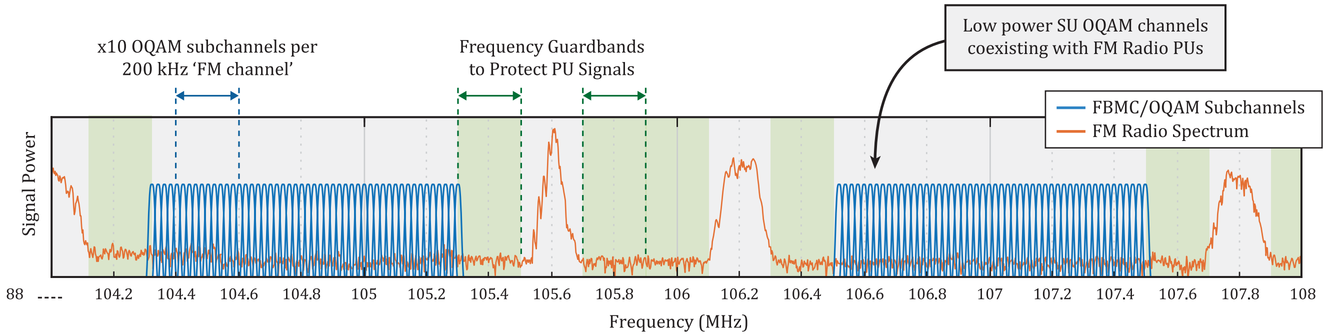

FIGURE 2. SUs using an FBMC scheme with appropriate subchannel masks and guardbands are able to make use of vacant spectrum in the FM Radio band.

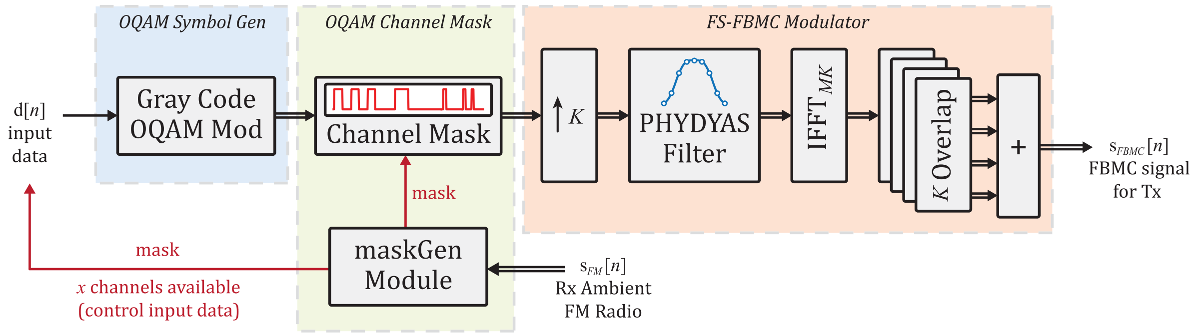

FIGURE 3. Block diagram of the FS-FBMC/OQAM transmitter PHY as previously proposed in [17], with the addition of a 'maskGen' module that dynamically updates the FBMC subchannel mask to protect detected PU signals in the FM Environment.

their tools [53], [54], [55]. Finally, a state of the art SDR prototyping platform using the Xilinx RFSoC ZCU111 is discussed by Goldsmith in [56]. This is a single-chip SDR device that has direct support for all frequency bands across the range 0-6 GHz, with RF-ADCs and RF-DACs (RF Analogue-to-Digital and Digital-to-Analogue Converters) operating at 4096 Msps and 6554 Msps respectively. With the addition of appropriate RF signal conditioning stages, it could be argued that this new platform is a key enabler and solution for future DSA radios.

This article is one of few published works that present an FS-FBMC FPGA hardware implementation, and one of even fewer that is targeted to SDR hardware.

Building on our previous work [17] where the radio was proposed and a simulation model developed, in this article we present a real-time, cognitive DSA-enabled radio transmitter PHY that is fully implemented and targeted to programmable SDR hardware. The transmitter PHY is tailored for the application and target hardware, with a custom FS-FBMC modulator architecture (and FBMC parameters) developed to meet the design constraints for ZynqSDR targeting. We also demonstrate the capabilities of the ZynqSDR workflow, providing a case study and reference design that we feel other researchers working in this field can benefit from.

The 'maskGen' module initially developed in [17] is modified to support real time operation. It is shown to be capable of automatically constructing a subchannel mask complete with guardbands, based on detected PU activity, in a period of 320 ms. This is the first such mask generator for SU access to the FM Radio band reported in the literature.

Further to the simulation-based quantitative and qualitative SU to PU interference investigations carried out in [17], an investigation is carried out using the targeted SDR hardware and a commercial off-the-shelf (COTS) FM Radio receiver to explore the interference effects the FBMC frequency guardband size has on the quality of PU FM Radio signals.

III. SU ACCESS TO FM BAND WITH FS-FBMC/OQAM

The DSA-enabled SU transmitter developed in [17] sees the 20 MHz-wide FM Radio band split up into a number of OQAM subchannels, such that 10 (overlapping) OQAM subchannels fit inside each standard 200 kHz wide 'FM channel,' as highlighted in Fig. 2.

When the transmitter is activated, a channel mask (complete with guardbands to protect the detected FM Radio stations) is automatically generated by the 'maskGen' module, which is shown in Fig. 3 (as part of the overall system design). This mask will contain x active, and $M-x$ disabled subchannels. Next, x bits of binary data (and $M-x$ null bits) are acquired from a data buffer, and are fed (according to the channel mask) into a Gray coding and OQAM modulation stage, shown in blue in Fig. 3. This creates complex OQAM symbols [57]. The mask is applied to the symbols, which then enter the FS-FBMC modulator. Here they are upsampled by a factor of K=4, and convolved with the frequency domain coefficients of the PHYDYAS (PHYsical layer for DYnamic

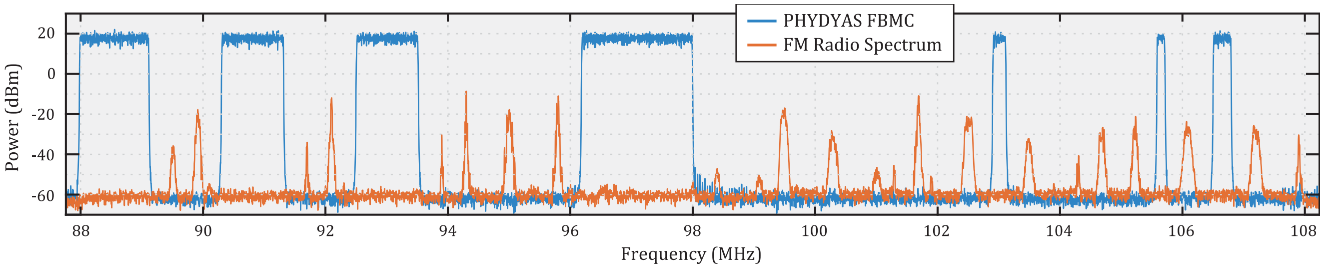

FIGURE 4. Simulink Spectrum Analyzer window showing the FBMC SU signal coexisting with ambient FM Radio stations in Glasgow city center.

AccesS) prototype filter [58], [59]. The *MK* filtered samples pass through an IFFT to generate time domain FBMC symbols, and *K* of these are then 'overlapped and summed' in the time domain prior to being output to the radio front end. The roll-off of the PHYDYAS filter means that the power of the Out-Of-Band (OOB) leakage in spectrum holes (i.e., in disabled parts of the mask) will be 80 dB below the in-band level [59]. (For a fuller review of the FS-FBMC/OQAM modulation process, please see [17, Secs. 3 and 4]).

If every subchannel was found to be available for use, the data throughput rate of the transmitter would be just under 20 Mbit/s (due to the use of 4-OQAM modulation). This is never likely to occur however, as the throughput is a function of the number of FM stations being broadcast in the local area, the frequencies they are using, and the size of the frequency guardband used in the mask. Even if the same number of stations were being broadcast in two different locations, it is unlikely that their center frequencies would be the same, so there will almost certainly be different throughput rates. Based on the findings from the USA [9], in regions with a population between 100,000 and 1 million, there is on average around 6 MHz of available spectrum; meaning a rate of 6 Mbit/s could be possible with this radio. While this throughput would not be suitable for streaming 4K video, it would be more than sufficient for an IoT application.

Initial 'field test' simulations, as presented in [17], provided promising evidence that the SU radio could coexist with FM Radio PUs. Further FM Radio spectrum datasets have since been harvested from around Central Scotland, and it was confirmed by subjecting the radio to different FM environments in simulation, that it was capable of adapting its channel mask (and therefore output spectrum) 'on the fly.' The radio produced FBMC signals with spectra such as the example shown in Fig. 4.

In our previous work [17], the floating and fixed point 'field test' simulations of the transmitter were performed in Simulink, on a powerful workstation. Because of the sheer volume of operations simultaneously being carried out, the simulation (even on the workstation) could not be performed in real time. FPGAs are better suited to the parallel processing requirements of communications systems, and as such, the decision was made to target the design to a ZynqSDR. This would allow real time simulation on the hardware, and for various (cabled) transmit tests to be carried out.

IV. ZYNQ-BASED RADIO MODEL BASED DESIGN ENVIRONMENT

MathWorks have developed an ecosystem whereby it is possible to take a floating point Simulink model, readily convert it to fixed point implementation, and then automatically generate Hardware Description Language (HDL) and/or C code (with the *HDL Coder* and *Embedded Coder* toolboxes). The generated code can be used to program the FPGA and processor of a device such as a Zynq, respectively [60]. This is an incredibly powerful prototyping environment that can rapidly speed up development times.

The hardware support package for Zynq-Based Radio [61] enables support for ZynqSDR in Simulink, making it possible to target block-based designs onto the programmable radio hardware. The base radio design features a 'user logic' module on the FPGA (connected in-line as part of the transmit and receive paths), as well as the option to run software on the Arm processor.

A. ZYNQ-BASED RADIO RECEIVER CHAIN

When using the ZynqSDR as a receiver, the AD9364 downconverts arriving signals from RF to baseband by mixing them with a complex local oscillator. After passing through a programmable analogue filter stage, the signals are sampled by an ADC. Decimation takes place, and the signals (now sampled), are transferred to the Zynq device. Once the samples enter the FPGA of the Zynq, they pass through a user logic area, as shown in Fig. 5. When the FPGA is configured with the default MathWorks bitstream, this simply acts as a passthrough, meaning that the samples are not modified in any way. The user has the option, however, to target this area with their own receiver designs. While some design constraints must be followed, the user otherwise enjoys full flexibility when implementing a radio design in the user logic area. Eventually, the IQ samples work their way to the Arm processor (which is running the Linux Busybox Operating System, OS). Here they are acquired by the MathWorks SDR driver, optionally processed with custom software, and passed out over the Ethernet interface back to the host computer.

The user has the option of adding programmable registers to their user logic design, which can be used to change the way in which the design functions; for example, to swap between demodulator 'A' and demodulator 'B' in the receiver. These registers can be programmed in real-time

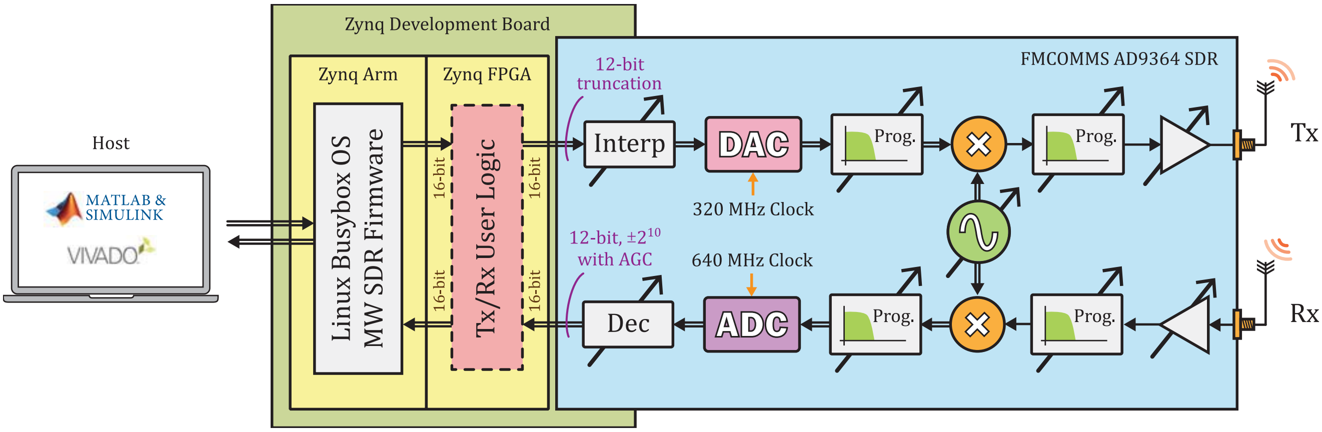

FIGURE 5. High level diagram of the ZynqSDR, featuring numerous tunable components and a 'user logic' area on the FPGA that can be targeted with transmitter and receiver HDL designs.

via COM or SSH Terminal connections, or from a Simulink model running in 'external mode.'

B. ZYNQ-BASED RADIO TRANSMITTER CHAIN

The transmit process is similar to the receive process, but in reverse. Complex samples are passed down to the FPGA via the Arm processor from the host computer. The samples pass through the user logic area, which can again be targeted with a transmitter design. Next, the samples enter the AD9364 and are interpolated up to the DAC rate. The samples are converted to an analogue signal, which is filtered, mixed with a complex local oscillator and transmitted.

C. ZYNQ-BASED RADIO DESIGN CONSTRAINTS AND HARDWARE CONFIGURATIONS

As the MathWorks tools provide a base design that contains a 'targetable' user logic module, there are a few design constraints that must be met.

The wordlengths of the I and Q input and output ports must all be signed 16-bit, despite the wordlength of the ADC/DAC pair only being 12-bits. On the receive side, when the Automatic Gain Control (AGC) of the AD9364 is in use, arriving samples will have an average value of around $\pm 2^{10}$. This is convenient, as it means that the approximate range of input samples will always be known during the design process. The full 16-bit interface may be used between the FPGA and the Arm processor on both the receive and transmit paths. On the transmit side, 16-bit signals are truncated to 12-bits prior to the AD9364.

The overall sampling rate of the user logic areas must match the baseband sampling rate configured in the AD9364 front end. The rate can be changed inside the user logic designs, however the rate at all ports must be consistent with the SDR. The number of FPGA resources (flipflops, lookup tables, DSP48 slices etc.) available for use is also dependent on the Zynq development board used. Design optimizations or partitioning may be required in order to fit the user's design into the available resources.

There are three main modes this hardware can be used in: Tx only, Rx only, and Tx/Rx. There is a function called `TransmitRepeat()`, where a contiguous burst of data can be repeatedly broadcast; and there are options of FPGA or AD9364 internal loopbacks in addition to using the external RF interfaces. Finally, there is a feature called 'Burst Mode,' which can be used to ensure that contiguous bursts of data are transferred between the Zynq and host computer (i.e., with no dropped samples). These many configuration options make it a very attractive platform for SDR prototyping.

V. REAL TIME SIMULATION ON ZYNQSDR

This section discusses how the Zynq-Based Radio workflow was leveraged to enable real-time simulation of the FBMC transmitter design, on hardware, in a 'closed' environment. The transmit user logic area was targeted, and the loopback functionality activated to feed samples of the generated FBMC signal back to the receiver and host computer, for examination in Simulink (release R2018b with associated toolbox and hardware support package versions).

A. SYSTEM OVERVIEW

The transmitter design in Fig. 3 requires complex samples of the FM band to be input to the maskGen module. These are provided using the Zynq-Based Radio `TransmitRepeat()` function. A recording of FM samples is loaded into the transmit register, and the function activated; meaning that samples are passed into the user logic area at the appropriate sampling rate. An FBMC mask is created, and the transmitter activated. Samples of the FBMC signal are then output to the SDR front end, looped back, and passed through the (untargeted) receiver user logic area. These are then fetched by the driver, and are sent back to the host computer over Ethernet, as shown in Fig. 6.

Once the design is deployed and `TransmitRepeat()` enabled, the host computer can run a simple model with `AD936x Receiver` (ZynqSDR Receiver) and `Spectrum Analyzer` blocks. This allows for visualization of the 'transmitted' FBMC signal.

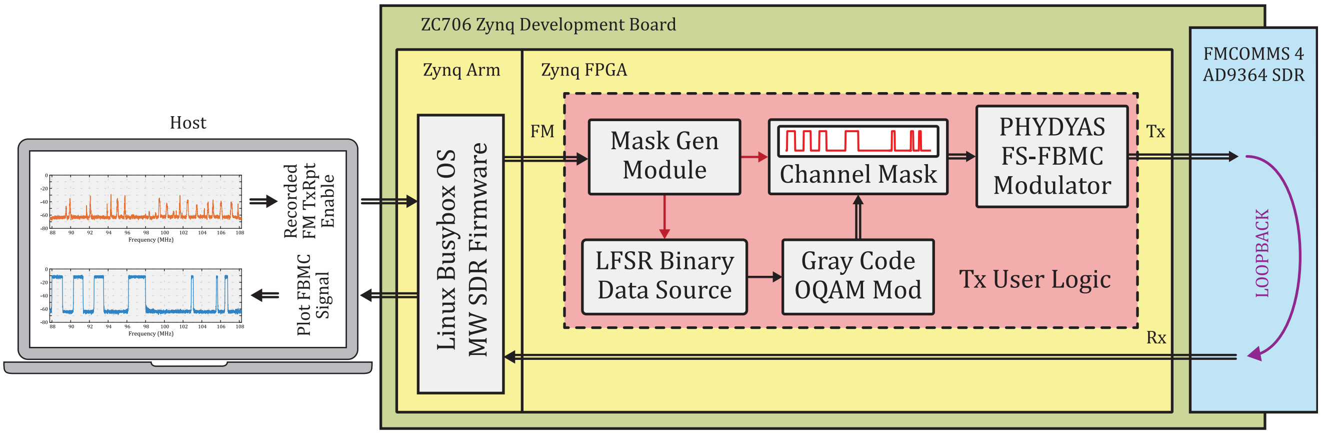

FIGURE 6. Transmitter design configuration for real time simulation on ZynqSDR. An FM Radio environment is input to the ZynqSDR from the host computer. The output FBMC signal is looped back inside the AD9364 so that the 'transmitted' signal can be received and examined on the same device.

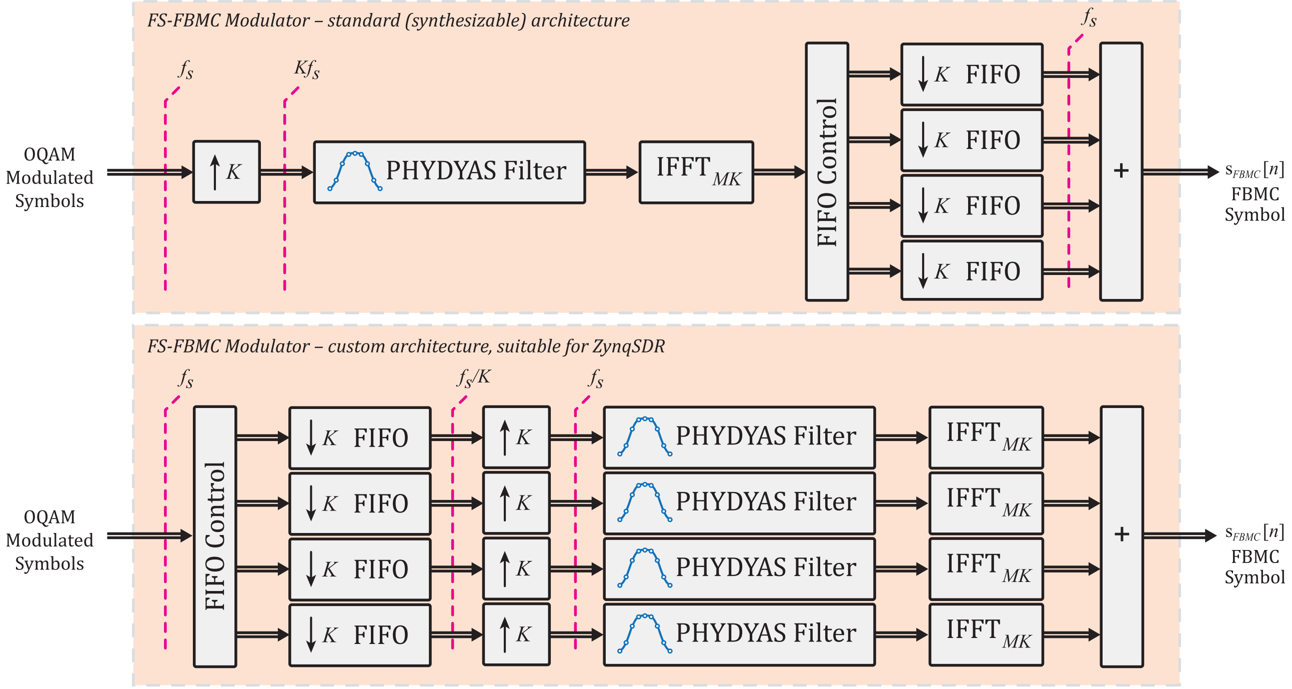

FIGURE 7. A comparison of the standard (synthesizable) FS-FBMC modulator architecture (top) and the custom, sample rate limited configuration developed in this work, for compatibility with the ZynqSDR (bottom).

B. MODIFICATIONS TO PREPARE FOR TARGETING

While many of the Simulink blocks used in the initial design in [17] were suitable for the HDL targeting process, some had to be replaced with their HDL counterpart from the HDL Coder Library. One major design modification required was to reconfigure the FS-FBMC modulator to trade off FPGA resources for system clock rate; due to limitations associated with the targeting process. A custom FS-FBMC modulator architecture had to be developed, as presented in Fig. 7.

To elucidate on this, the sampling rate of the design was $f_S = 20.48$ MHz. As discussed in [17], the upsampling process increases the rate to K times the OQAM symbol rate, resulting in the filter stage, IFFT and FIFO (First-In First-Out) memory blocks running at a rate of 81.92 MHz, before the overlap and sum operation reduces the rate back to f_S. This did not meet the design constraints for targeting, so the design was split into K parallel processing branches using a series of FIFOs, and each branch was fed a contiguous burst of M OQAM symbols at a rate of $f_S/4$. When these parallel modulators upsampled by K and generated FBMC time domain symbols, they each output at the original rate, f_S. By their parallel nature, these modulators were already 'overlapping' in time, so a final summation acted to combine them and generated the output FBMC time domain signal.

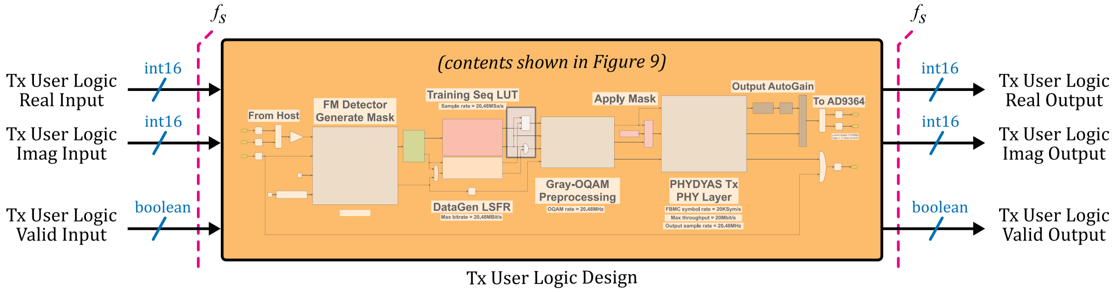

FIGURE 8. This is the top level block for the transmitter user logic, used to target the ZynqSDR user logic area. It features *I*, *Q* and *Valid* input and output ports, and runs at a sampling rate of *fs* = 20.48 MHz.

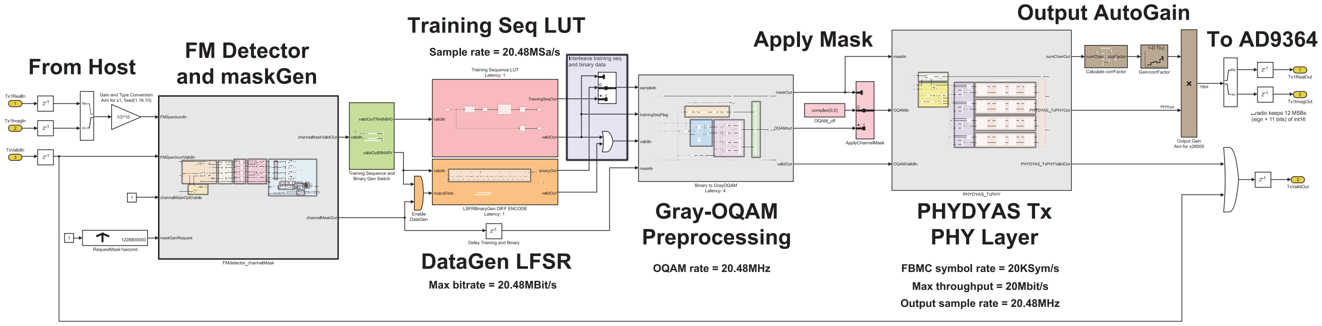

FIGURE 9. This Simulink model shows the components inside the transmitter user logic top level block. (Zoom into high resolution PDF to see full detail). On the left are the *I*, *Q* and *Valid* input ports; followed by a series of subsystems including the maskGen block–that generates an FBMC subchannel mask based on the FM Environment–and the custom implementation of the PHYDYAS FS-FBMC/OQAM modulator. The output FBMC signal, complete with spectral holes and guardbands to protect PUs, is output from the *I*, *Q* and *Valid* ports on the right.

It was confirmed via simulation that this alternate architecture generated exactly the same signal. While the physical resource requirements of the modulator component increased by a factor of K, the design performs almost the same number of operations per second; and hence the designs are essentially computationally equivalent.

C. TRANSMITTER USER LOGIC DESIGN

The top level block of the Tx user logic design is shown in Fig. 8. Here there are I, Q and *Valid* input and output ports. The I and Q ports have a datatype of int16 (i.e., 16-bit signed integer format), and the *Valid* is boolean (1-bit binary). The sampling frequency of all of these ports is $f_S = 20.48$ MHz. This Simulink block is essentially what is substituted directly into the transmit user logic area.

Fig. 9 presents a vector printout of the next level in the Simulink hierarchy. FM samples input to the Tx user logic enter the maskGen module. This contains a matched detector, and is able to scan the entire (baseband) FM spectrum and generate a channel mask complete with guardbands in 0.33 seconds. The output mask is used to control a Tx data buffer, ensuring that none of the random binary data generated by the LFSR (Linear Feedback Shift Register), which models the FBMC data signal, is lost. Next, the binary stream undergoes Gray coding, and OQAM preprocessing, creating OQAM symbols. The mask is reapplied in a binary fashion (on/off), to ensure that no data has been mapped into a subchannel that should be disabled, and the symbols enter the modulator of Fig. 7.

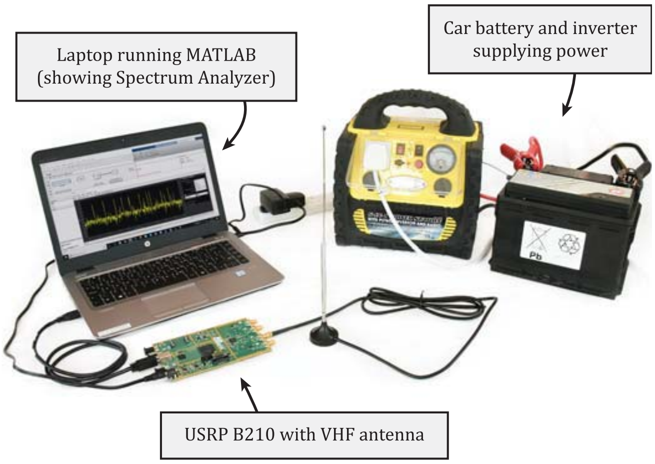

FIGURE 10. Annotated diagram showing the experimental setup used for FM Radio spectrum harvesting.

In order to ensure that the FBMC symbols are generated to the highest accuracy, the wordlength of the modulator stage is allowed to grow to 27 bits with 16 fractional bits. Scaling is therefore required to reduce the wordlength back to 16-bits prior to the output, in order to make use of the full dynamic range of the 12-bit DAC. This is made more complex by the fact that the amplitude of the FBMC samples is non-linearly related to x, the number of subchannels in use at any point in

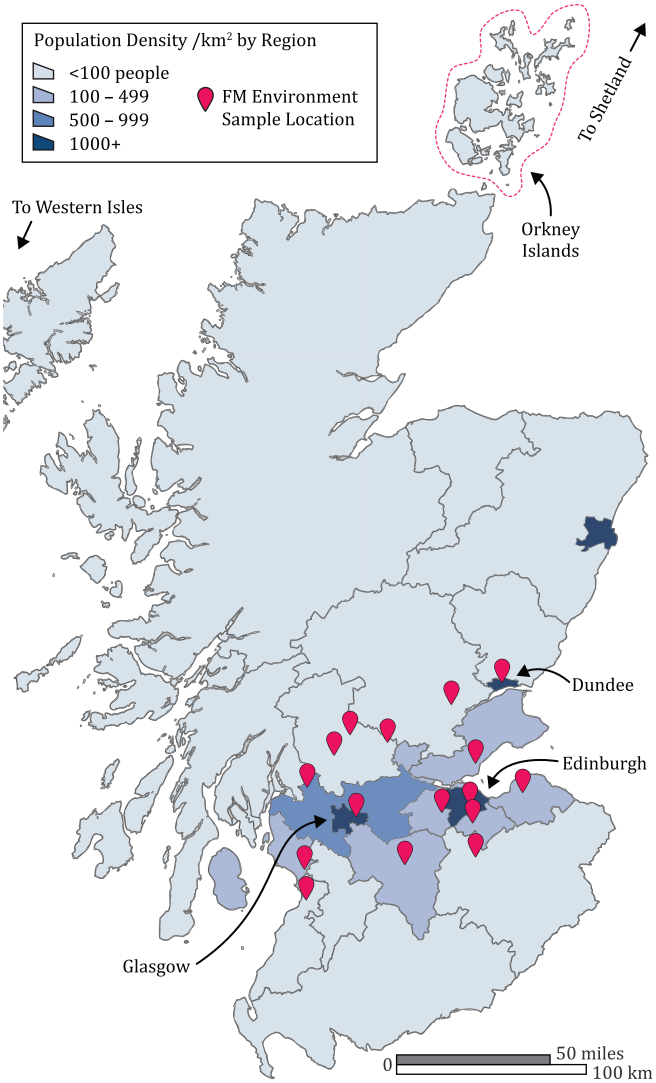

FIGURE 11. Population density map showing the main landmass of Scotland [62], with highlighted (red marker) FM Environment sample locations.

time. An 'AutoGain' module was developed to calculate and apply an appropriate gain, such that the average value of the samples output is always around ±26000 (FBMC has a high peak to average power ratio; so this allows for some large peaks with amplitudes up to ±32767 before saturation will occur). This maximized the achievable dynamic range of the SDR, and would lead to an output signal with a reduced noise floor. (It should be noted that, due to the limited wordlength of the FMCOMMS SDR, it is not possible to output a 'clean' PHYDYAS FBMC signal with an 80dB dynamic range, i.e., the power difference between 'on' and 'off' subchannels, as shown in Fig. 4. The 12-bit DAC can theoretically achieve a range of ~66 dB.)

D. TARGETING PROCESS

Once the design was ready to be targeted, the HDL Workflow Advisor tool was initiated. This guides the user through the process of compiling the model, generating HDL code, packaging this as an IP (Intellectual Property) core and launching a Xilinx Vivado shell window to build the project. Once the build is complete, a Xilinx bitstream is created. For this particular research, the Xilinx ZC706 development board/ Analog Devices FMCOMMS 4 ZynqSDR configuration was selected.

TABLE 1. FM radio environments, sampled from central Scotland.

Location	Area Population (2011 census)	Number of FM stations (num unique)	Unallocated Spectrum (MHz)
Edinburgh	510,000	35 (15)	13.0
Livingston	66,000	31 (14)	13.8
Kirkcaldy	50,000	27 (14)	14.6
Ayr	47,000	23 (9)	15.4
Glasgow	1.2 million	22 (16)	15.6
Callander	3,200	20 (12)	16.0
Balloch	24,000	20 (10)	16.0
Haddington	9,200	19 (12)	16.2
Perth	47,500	19 (9)	16.2
Dunblane	9,000	18 (12)	16.4
Dundee	150,000	18 (12)	16.4
Lanark	8,200	16 (12)	16.8
Aberfoyle	900	16 (10)	16.8
Penicuik	16,000	15 (12)	17.0
Kilmarnock	47,000	14 (8)	17.2
Peebles	8,900	14 (8)	17.2

Using MATLAB commands from the Zynq-Based Radio support package, the ZynqSDR's FPGA was programmed with the full design. This comprised the base MathWorks project (complete with various data movers, clock generators and Analog Devices IP that control the AD9364), and the targeted Tx user logic area.

E. FM RADIO ENVIRONMENT TEST DATA

In order to test the design, recordings of the FM Radio spectrum were required. A portable radio spectrum harvesting solution was developed to obtain this data, which featured an omni directional 'VHF' antenna, a USRP B210 and a laptop running MATLAB; with power provided by a car battery and inverter. *(The Ettus Research USRP B210 is another SDR based on an Analog Devices front end radio).*

FM Radio environments were harvested from 16 different locations around Central Scotland (a mixture of cities, towns and villages), as highlighted in Fig. 11. Details about each of these FM Radio environments are presented in Table 1. This is the first comparable study to Otermat's work that has been published for Scotland. (Note, the number of unique FM stations in each location is presented along with total number received. Many of the duplicate stations were very noisy, and of bad quality. If these duplicates were discounted, a greater amount of the spectrum could be considered 'unallocated').

F. REAL TIME SIMULATION RESULTS

Prerecorded samples of the FM Radio spectrum were loaded into the transmit register using `TransmitRepeat()`, and a simple receiver design was developed that contained `AD936x Receiver` and `Spectrum Analyzer` blocks.

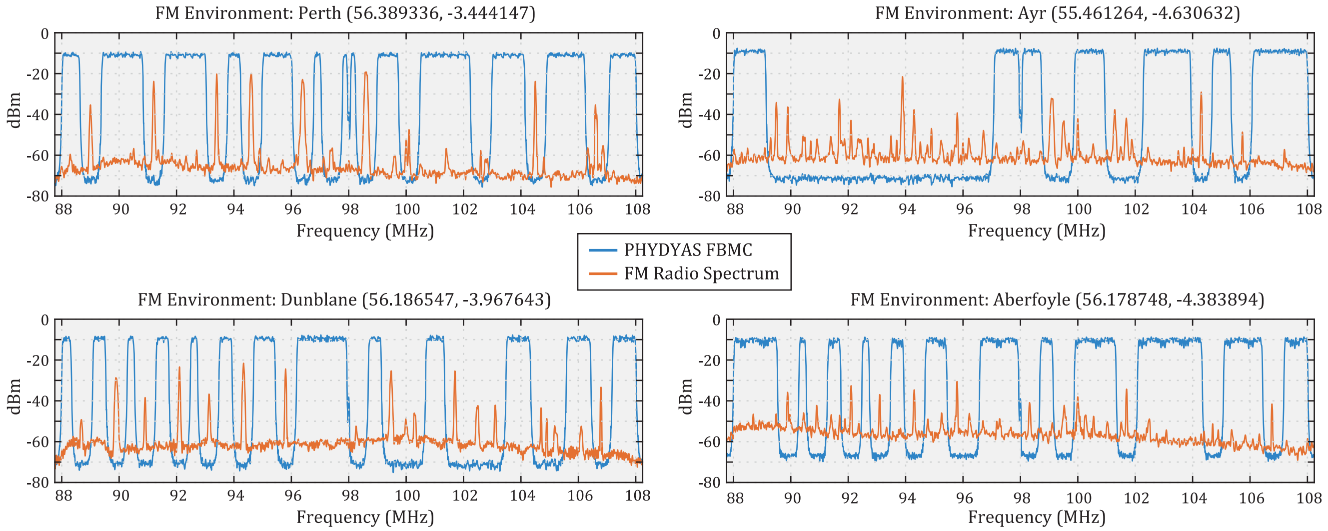

FIGURE 12. **Real time simulation using ZynqSDR hardware: results from four different FM Radio environments from Central Scotland–Perth, Ayr, Dunblane and Aberfoyle. It is clear to see that the FBMC signals (blue) have successfully adapted to mold around the FM Radio PUs (orange). Note–the power levels used here are arbitrary, as the SU signal is not output to calibrated amplifier components, and simply looped back inside the SDR.**

The transmitter was enabled, and the receiver was run. The targeted design began generating FBMC signals, which were looped back to the receiver, and passed to the host computer. The spectrum of the generated FBMC signals could then be examined in Simulink, all in real time!

From reprogramming the `TransmitRepeat()` register to seeing signals arriving in the `Spectrum Analyzer` windows, each of these real time simulations took around 30 seconds to complete. In comparison, they would have taken around 30 minutes each if the full design was running in a compiled Simulink model on a workstation. This significant time saving is one of the main benefits that ZynqSDR targeting can bring when prototyping communications system designs.

The resulting spectra for four different FM Radio environments are shown in Fig. 12. (Note, the power levels used here are relative). As can be seen, the transmitter design has successfully adapted its mask to prevent PU interference. The eagle-eyed reader may notice that, in the Aberfoyle environment for example, some high energy peaks in the FM spectrum (e.g., 100.1, 100.3 MHz) have not been classified as FM Radio stations by the maskGen module. This is because the SNR of the signals is so poor that there is no audible audio signal present on these carriers; just high energy noise. These were found to be duplicate stations, which are not intended to serve the locations in question.

The guardband used in the FBMC mask for these on-hardware simulations spanned 300 kHz either side of an active FM Radio channel. This was an initial estimate, as it was not known what would ultimately be required in order to prevent interference with COTS FM Radio receivers. With this setting, the throughputs presented in Table 2 were possible for each of the 16 central Scotland FM Radio environments tested. It is clear that the throughput is not directly proportional to the number of FM stations received at a particular location (for the reasons discussed in Section III); however there is a general trend that the throughput increases as the number of stations decreases.

TABLE 2. **4-OQAM PHYDYAS FS-FBMC throughput rates.**

Location	*Number of FM stations*	Possible PHY Throughput (Mbit/s)			
		300 kHz Guard	200 kHz Guard†	100 kHz Guard†	0 kHz Guard†*
Edinburgh	*35*	4.78	7.32	10.70	14.80
Livingston	*31*	6.70	8.72	11.90	15.60
Kirkcaldy	*27*	5.42	7.82	11.10	15.30
Ayr	*23*	7.38	8.88	11.18	15.38
Glasgow	*22*	5.50	8.30	11.42	15.60
Callander	*20*	8.98	11.48	14.18	16.90
Balloch	*20*	11.10	13.10	15.18	17.48
Haddington	*19*	9.90	12.10	14.40	17.00
Perth	*19*	9.60	12.0	14.50	17.10
Dunblane	*18*	8.30	10.90	13.70	16.60
Dundee	*18*	6.92	8.92	12.18	15.78
Lanark	*16*	11.90	13.70	15.50	17.50
Aberfoyle	*16*	9.68	11.88	14.28	17.00
Penicuik	*15*	11.38	13.48	15.58	17.68
Kilmarnock	*14*	11.40	13.20	15.00	17.40
Peebles	*14*	11.22	13.10	15.30	17.50

† Results for Section VI
* Differs to Table 1 'unallocated' values as the received station quality is considered by the maskGen module

It is interesting that such throughput rates are possible, even in Glasgow, Edinburgh and Dundee, three of the four largest cities in the country. In line with the findings of [9], in rural areas (such as Balloch, Lanark and Peebles), the amount of usable vacant spectrum—and therefore throughput rate—increases dramatically.

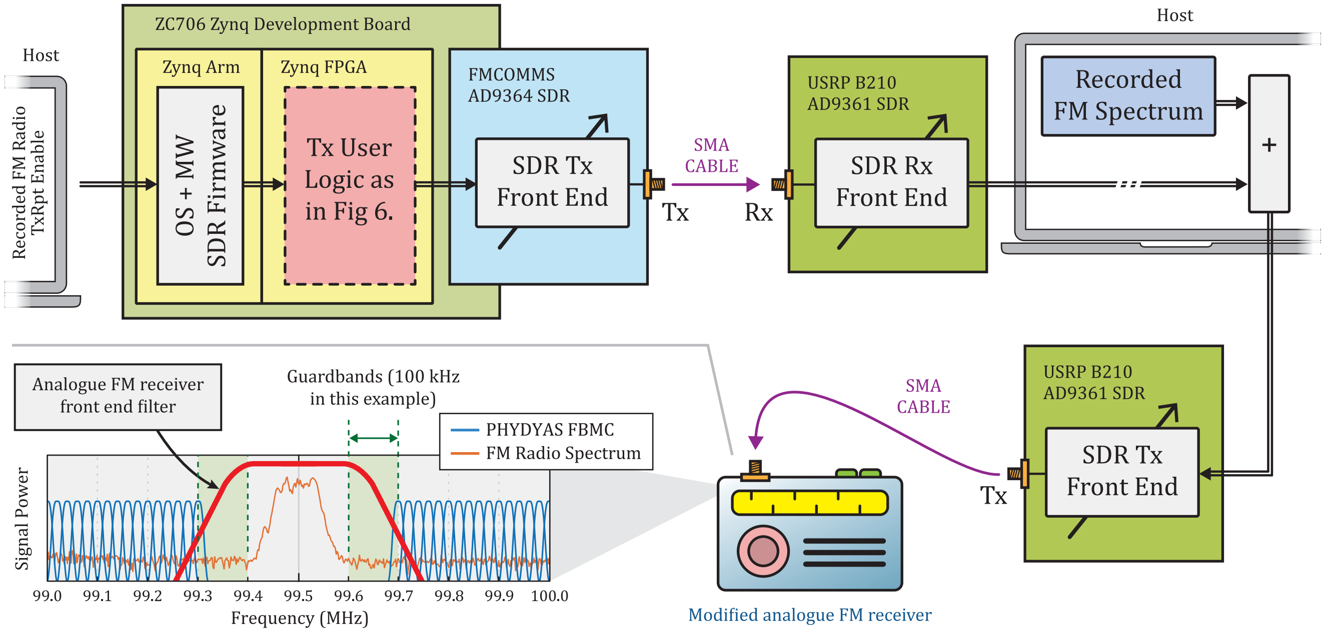

FIGURE 13. This is the hardware configuration used to investigate SU to PU interference for various FBMC frequency guardbands. An FBMC signal is generated on the ZynqSDR based on an FM Environment, and output from the AD9364 front end. This analogue signal is transmitted through a cable to a USRP, which receives the signal and mixes it to baseband. The FM Environment is then added to the received FBMC signal, and rebroadcast via another USRP to an analogue FM Radio receiver. Additionally, a plot demonstrating the speculated frequency response of the analogue FM Radio receiver's front end filter is presented.

VI. FBMC GUARDBAND SIZE INVESTIGATION

The throughput achievable with the radio is linked to the number of active channels; and therefore, the size of the frequency guardband used to protect the PU signals. A narrower guardband will lead to higher rates; however, reducing it could result in interference being caused to commercial off-the-shelf FM Radio receivers.

By design, the superheterodyne demodulators in FM receivers contain a filter which passes a narrow band of frequencies, centered around the FM carrier. This is highlighted by the red band sketched in the plot of Fig. 13. The passband of the filter could be very narrow (e.g., ±100 kHz either side of the carrier frequency), or it could be much wider; the characteristic of the analogue filter is an unpublished design parameter of individual FM Radio receivers, and is therefore unknown. It is likely that the filter characteristic will also vary between different FM Radio receivers.

Normally, FM Radio stations are spaced a minimum of 200 kHz apart; so it is expected that the filter will begin to attenuate frequencies past ±100 kHz (although the transition band must be considered too), in order to prevent station intermodulation. This is in line with the FM Radio protection ratios presented in ITU-R BS.412-9 [63]. The wider the passband is, the larger the FBMC transmitter's guardbands will have to be. An interesting research question, then, is what size of guardband is required in order to prevent noticeable interference?

A. HARDWARE CONFIGURATION

Due to RF spectrum emission regulations (at the time of writing), it would be illegal to transmit RF signals in the FM Radio band for these tests using the prototype SU radio. *(Details on the U.K.'s Wireless Telegraphy Act and other radio spectrum emission laws can be viewed on the Ofcom website [64])*. The ZynqSDR also lacks a suitable 'RF front end' (containing power amplifiers, analogue filters and duplexers) that would ensure unwanted harmonics and OOB spectral images do not cause interference to neighboring bands–i.e., ensuring the device would not be an "RF Jammer" as classified by Ofcom, use of which would also be illegal. (Developing such a front end would require extensive analogue engineering and expense). The solution, therefore, was to perform tests in a controlled and legal environment by transmitting through RF coaxial cables. The hardware implementation from Fig. 13 was therefore used during the guardband size investigation.

The ZynqSDR internal loopback was disabled, and a USRP B210 was connected directly to the Tx output port. The transmitter was enabled as before (with recorded FM data passed to the ZynqSDR to allow the transmitter to generate the mask). The modulated FBMC signal was output, received by the USRP, and then saved to the computer. In a second Simulink model, the FBMC recording was added to the recording of the FM spectrum, and the power level was adjusted to make sure that the noise floor of the FBMC signal was below the floor of the FM spectrum. This ensured that the FBMC OOB leakage played no part in these tests.

An old analogue FM Radio receiver was sourced, and its antenna (and internal wiring) was removed and replaced with an SMA port and shielded RF cable. The USRP was cabled directly to the FM Radio, and the combined (FBMC + FM) signal was re-transmitted directly into the FM Radio receiver. The receiver was tuned to the center frequencies of the locally re-transmitted FM stations, and the signals were demodulated and output to the device's speaker.

B. EXPERIMENTAL RESULTS

With 300 kHz guardbands, no perceptible interference was detected in the audio outputs of the demodulated FM Radio signals, for any of the FM environments tested. This was expected, because the 400 kHz 'gap' between the FM center frequency and the edge of the FBMC signal was greater than the expected passband of the FM receiver's front end filter. Tuning to parts of the band where the FBMC signal was transmitting, a buzzing noise was heard from the speaker of the FM receiver. Because the energy at these frequencies was considerably greater than the standard 'white noise' floor normally found between FM Radio stations, the buzzing audio output was quite loud.

Parameters of the transmitter design were adjusted to change the width of the guardbands from 300 kHz to 200 kHz, 100 kHz and 0 kHz, and new FPGA bitstreams were created for each configuration. Repeating the previous steps, the signals with the narrower guardbands were generated and transmitted to the FM receiver. No noticeable interference was caused from the FBMC signal with the guardband configured at 200 kHz. With the 100 kHz guardbands, a slight degradation in audio quality was noted for some stations that were received with a (relative) low power. Very surprisingly, around half of the FM Radio signals could still be demodulated successfully with a good quality audio output when there was no guardband in place at all (0 kHz). A strong crackling noise could be heard on the weaker stations, likely to be the result of some of the FBMC subcarriers passing through the FM receiver's front end filter and being demodulated, as highlighted by the plot in Fig. 13.

From these initial results, it would appear that the front end analogue filter in the FM receiver used in these tests passes frequencies past ±200 kHz. An FBMC guardband of 200 kHz (i.e., ±300 kHz from the FM center frequency) would therefore be a safe choice—as long as every FM receiver in the world met this minimum filter characteristic. Reducing the guardband to 200 kHz results in an increase to the FBMC throughput rates, on average by 2.17 Mbit/s, as presented in Table 2.

It is unlikely, however, that all FM receivers will have the same characteristic. Further research with a series of different FM Radio receivers (a mixture of analogue and digital devices) will be required in order to state conclusively what guardband must be used to prevent interference to the existing FM Radio equipment in use across the country, some of which may be several decades old. In order to perform these tests, the FBMC + FM Radio signals will need to be broadcast through the air to a range of devices inside an RF-shielded anechoic chamber.

VII. TESTING DSA CAPABILITIES WITH LIVE FM RX/FBMC TX ON ZYNQSDR

The ultimate aim of this work was to develop a 'cognitive' DSA radio that was able to automatically reconfigure its channel mask (without the need for a SU geolocation database), and transmit in empty channels of the FM Radio band whilst ensuring the protection of PUs. To achieve this goal, the radio must regularly receive and process the ambient FM Radio environment, and update the mask as soon as changes are detected in the PU spectrum.

Transmitting and receiving in the same frequency band at the same time is an engineering challenge, as the receiver will detect signals being output from the transmitter. Additional RF hardware such as a duplexer would have to be used to help prevent the receiver's SDR front end from becoming saturated. As discussed in Section VI-A, all transmit tests at this time must be cabled; so this removes the cross-talk issue from the equation.

After some modifications to the user logic design, it was possible to use the hardware configuration of Fig. 14 to test the radio's cognitive capabilities. Live FM Radio signals can be acquired from an antenna, and fed into the maskGen module to allow for real time reconfiguration. The remainder of this section describes the modifications and hardware setup required to complete this last set of tests, and reviews the results obtained.

A. USER LOGIC DESIGN MODIFICATIONS

Additional ports were added to the Tx user logic design in Simulink to enable simultaneous transmit and receive (thus making it into a TxRx user logic design). The existing transmitter input ports were terminated, as these were no longer required; and the receiver input ports were looped round and connected to the input of the maskGen module, as shown in Fig. 14. This means that live FM Radio signals received by the ZynqSDR front end would be used when the mask was being generated.

The 'maskUpdate' strobe (a feature of the maskGen module) was configured to force the radio to automatically perform a new scan and generate a new mask once every second. This would permit near real time reconfiguration of the FBMC signal's mask, and allow for a more interactive test to be carried out.

B. HARDWARE CONFIGURATION

A USRP was connected via an SMA cable to the ZynqSDR Tx output port, and a VHF antenna was attached to the Rx input port. A Simulink model was created, and a `AD936x Receiver` block was placed in it with 'Bypass user logic' mode enabled. This would output the received FM Radio spectrum, as presented to the maskGen module in the targeted TxRx user logic design (as shown in Fig. 14). `USRP Receiver` and `Spectrum Analyzer`

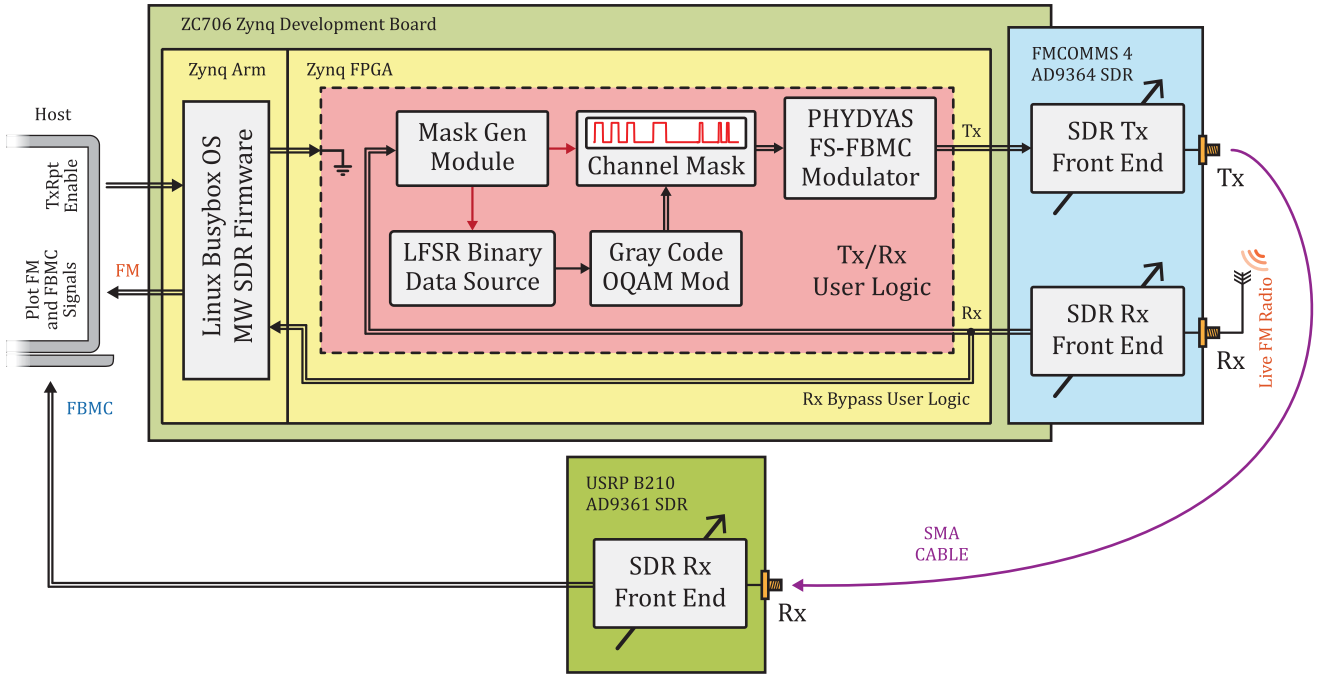

FIGURE 14. Finally, this is the hardware configuration used for ‘cognitive’ DSA radio tests. Here the ZynqSDR is configured to receive live off-the-air FM Radio signals, and automatically adapt its spectral mask based on detected PUs. The FBMC signal output from the AD9364 is received by a USRP to allow visualisation of the generated signal on the host computer.

blocks were added, and these were connected to enable simultaneous viewing of the received FM Radio spectrum, and the generated, transmitted and received FBMC signal.

C. EXPERIMENTAL RESULTS

The radio equipment was tested in a room where it was possible to receive strong ambient FM Radio signals. `TransmitRepeat()` was enabled (to activate the transmit path of the FMCOMMS), and the receiver model was run. When the first frames of data arrived in Simulink, a plot that was almost identical to the one in Fig. 4 was displayed in the `Spectrum Analyzer`; meaning the design was working.

Some handheld FM Transmitters were activated (the type one would use to broadcast music from a phone via a 3.5mm headphone jack to an older car radio) in order to add more FM signals to the spectrum. Within a second, the FBMC signal adapted and new spectral holes appeared to protect these newly detected FM signals.

Next, the center frequencies of the handheld transmitters were varied. Shifting the carriers up and down through the FM band, the FBMC signal kept adapting, with the spectral holes following the FM carriers as they moved.

A video demonstrating the responsiveness of the design was made, and this should be available to view on the paper’s IEEE Xplore page. A higher quality version can be found at the DOI link provided in the caption of Fig. 15.

Further tests were carried out for alternative FM Radio environments. These tests were conducted in two ways: firstly, by connecting a second USRP to the Rx input port of the FMCOMMS, and re-transmitting recorded FM data; and secondly, by performing live off-the-air tests in different cities. In all cases, the radio was found to be capable of adapting autonomously to keep PU signals protected, whilst maintaining its SU FBMC broadcast.

VIII. SU APPLICATIONS FOR THE FM RADIO BAND

The FS-FBMC SU Radio prototype and ideas presented in this article are a proof of concept, that demonstrate the potential for an SU to coexist with PUs in the FM Radio band. This unique research is still in the early stages, and is not yet at a point where it can be viewed as a completed solution. Prior to any further work developing this transmitter and a receiver, consideration needs to be given to the SU radio’s ultimate application, as this will have a significant impact on the remainder of its PHY configuration, and on the requirements of the supporting communications stack and protocols. A few potential applications are considered in the sections below.

A. TDD TX/RX BASESTATION

If a full TDD Tx/Rx stack was developed on top of the transmitter and receiver low level PHY layers, these SU radios could operate in a manner similar to a TDD LTE/NR basestation. Resources in the FM Radio band that are available for SU use would alternate between downlink and uplink channels, meaning client nodes (10s/100s/1000s depending on the use case) would be able to attach to each basestation and transmit and receive data.

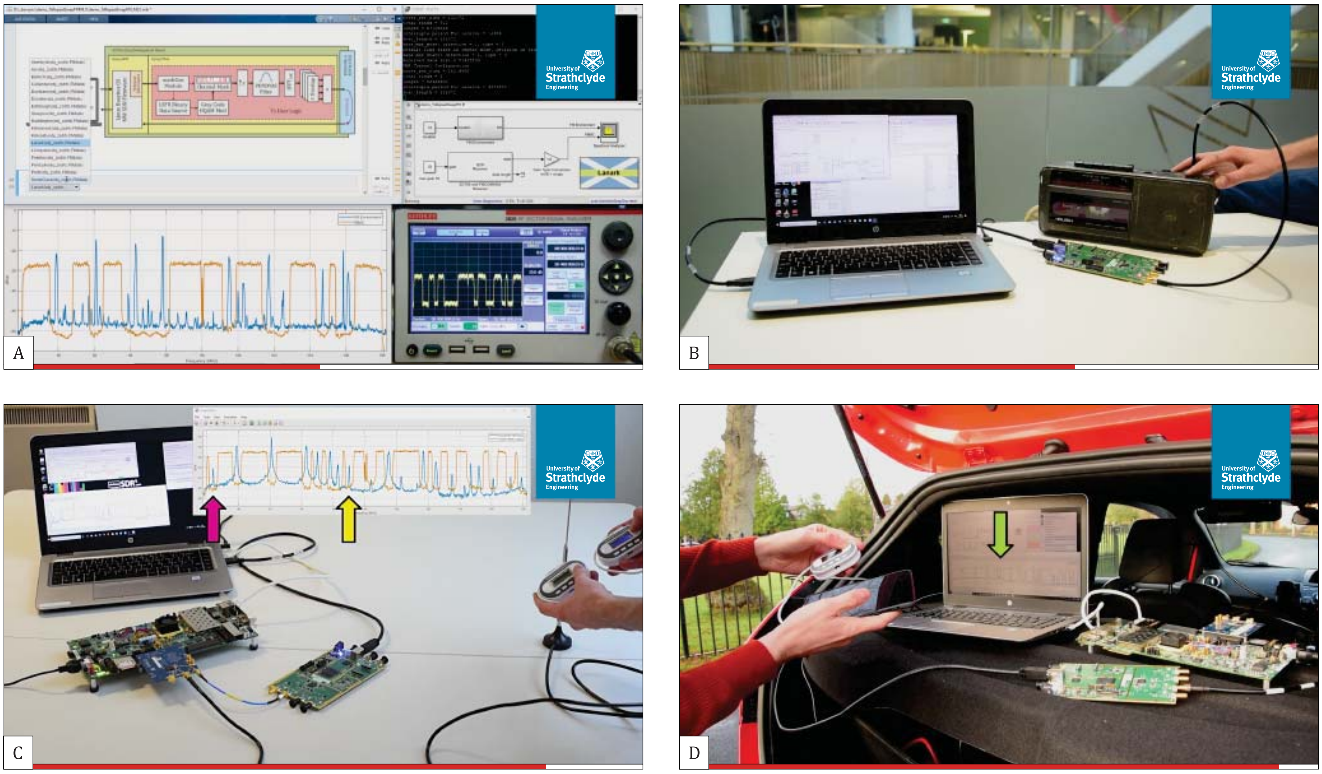

FIGURE 15. Stills from the companion video (http://dx.doi.org/10.15129/607b5dd7-1ab6-4efb-8a55-18876919714c) demonstrating: (A) - Real time simulation of the FS-FBMC SU radio on the ZynqSDR. The `TransmitRepeat()` function is used to pass assorted FM Environments captured from around Central Scotland to the ZynqSDR. On receiving the new FM Environment, the maskGen module reconfigures the FBMC subchannel mask to suit the environment, disabling subchannels and adding guardbands to protect detected PU signals. The Simulink Spectrum Analyzer window (and Keithley 2820 RF Vector Signal Analyzer) demonstrate the output of the FBMC modulator. At this particular instance in the video, the FM Environment being tested is from the Lanark location. https://youtu.be/AZoS_-n-SsY?t=343. (B) - Investigations into the SU frequency guardband size. After generating and capturing FBMC signals that are suited for the various Central Scotland FM Environments, a USRP B210 is used to transmit combined (FBMC+FM) signals into a standard FM Radio receiver. The antenna has been removed, and an SMA connector installed instead. (It would not be legal with the current regulations to broadcast from the USRP to the FM Radio receiver through the air, hence the test is cabled). When listening to the video, it is possible to hear that no interference has been caused by the SU to the PU FM Radio signals, with the guardband configured to 200 kHz. https://youtu.be/AZoS_-n-SsY?t=444. (C & D) - The FBMC SU dynamically adapting to the changing FM Environment in real time on the ZynqSDR when it is configured to run in 'cognitive' mode. Here the prototype SU is receiving live FM Radio signals off the air and dynamically adapting its spectral output to ensure it does not interfere with detected PU signals. Handheld FM Radio transmitters are used to add additional FM signals to the bands, and the frequencies of these are varied. Spectral holes can be seen to follow the FM carriers up and down through the band as they are shifted. Video still (C) demonstrates 'cognitive' mode tests in a building at the University of Strathclyde in Glasgow City center; and (D) highlights the further testing being carried out from the back of a car in the town of Uddingston (near the famous Teacake factory). https://youtu.be/AZoS_-n-SsY?t=568.

Neighboring basestations would operate in the same band, probably using exactly the same FBMC subchannel mask, as the basestations are geographically close to one another and therefore are likely to be in the same FM Radio environment. In real world cellular networks, neighbor cells for a particular operator will tend to broadcast on exactly the same frequencies as each other, as operators have limited access to spectrum. Higher layer techniques have been developed to allow support for overlapping neighbor cells. By lowering the client cellular node's Modulation Coding Scheme (MCS) and ensuring neighboring cells' Physical Cell Identity (PCI) and Root Sequence Index (RSI) do not conflict, it is possible for the client node to remain attached to a basestation, transmitting and receiving, in areas where cells overlap. The neighbor can be thought of as background noise in this scenario. Applying a similar stack and techniques to the hypothetical TDD FBMC basestation, it would be possible to deploy neighboring FBMC basestations in the same FM Radio environment. There are two ways these basestations could be deployed.

1) SINGLE OPERATOR ROLLOUT

If a single operator were to deploy the basestations, thorough network planning would ensure cells are appropriately configured to coexist with their SU neighbors. One business model for this might be a nationwide IoT Tx/Rx channel, where client FBMC SU nodes connect and authenticate with the network using subscriptions, as cellphones do. As discussed in Section I-A, the propagation properties of this VHF band are favorable for wide area coverage, and signals that are broadcast here should penetrate deep into buildings. A subscription network with these characteristics could have great benefits for evolving smart city applications.

2) THIRD PARTY FREE-FOR-ALL

An alternative is where basestations are deployed by third parties randomly, as happens with WiFi, ZigBee and Bluetooth. The basestations could be configured to listen for neighbors on initial switch-on, and then configure their PCI/ RSI appropriately. The downside to this is the hidden node issue, as is well documented for WiFi deployments [65].

Additional collision avoidance schemes have been developed for WiFi too, and these could be considered.

B. TX ONLY BASESTATION, SINGLE OPERATOR ROLLOUT

Instead of using the FBMC radio as a traditional Tx/Rx basestation, it could be configured for Tx mode only; and deployed city- or nation-wide by a single operator. This would allow the vacant spectrum in the FM Radio band to be used as a broadcast signalling channel. Low cost receiver-only nodes could then be developed. A similar service currently exists in the U.K. called the Radio Teleswitching Service (RTS). (The switch-off is imminent due to the rapidly depleting supply of thermionic glass valves worldwide). One of the U.K.'s energy grid operators, SSE, encodes digital information alongside the BBC Radio 4 long wave AM Radio carrier to control, in pseudo real-time, the remote switching of electric radiators in the north of Scotland. This technology has been in use since the early 1980s, and can be considered a very basic form of load balancing [66].

The FBMC radio could be used for a similar type of broadcast service, enabling all sorts of value-add use cases in the smart city, such as traffic light sequencing and localized load balancing; by broadcasting time signals and a series of codes from a standardized dictionary. As the Tx-only basestations would be deployed by a single operator, either a Time Division Multiplexing (TDM) system between neighbors could be used (similar to the transmit backoff system used in WiFi), or a PCI/RSI scheme as discussed above could be developed to enable simultaneous broadcast.

IX. CONCLUSION

This article has presented the practical work carried out in targeting the novel FS-FBMC SU Radio prototype, initially presented in [17], to programmable ZynqSDR hardware, using various tools provided by MathWorks and Xilinx software.

Real time on-hardware simulations were performed to confirm that the radio was able to adapt to the different prerecorded FM Radio environments presented to it. The results were in line with the findings of simulations presented in [17], providing more evidence that this PHYDYAS FBMC based SU radio would be capable of coexisting with the FM Radio PUs. Achievable SU throughput rates with the proposed 4-OQAM FS-FBMC radio design for 16 locations across Central Scotland were presented, highlighting that a significant portion of the band is suitable for SU access. In line with the findings of [8], in smaller towns and rural areas (such as Kilmarnock, Lanark and Peebles), the amount of usable vacant spectrum—and therefore achievable throughput rate—was shown to increase dramatically.

An investigation into the required FBMC SU guardband size was carried out, where SU signals were transmitted (via cable) into a COTS FM Radio receiver. By design, FM Radio receivers contain a filter to pass a narrow band of frequencies centered around the FM carrier; however, the analogue filter characteristic is unknown, and is likely to vary between different FM Radio sets. Initial results indicate that a FBMC guardband of 200 kHz (i.e., ±300 kHz from the FM center frequency) would prevent interference; however, further research with a series of different FM Radio receivers (analogue and digital) would be required to state conclusively the guardband size required.

The design was modified to operate in 'cognitive' mode, and was shown to be capable of automatically reconfiguring its channel mask in real time to prevent interference with PU FM Radio stations detected live off-the-air. Low power handheld FM transmitters were activated to add additional PU signals to the spectrum, and their center frequencies were varied to confirm that the SU subchannel mask dynamically reconfigured itself. A video was presented that demonstrates this real time reconfiguration, highlighting the flexibility and suitability of the FBMC scheme for DSA applications.

X. FUTURE WORK

To date, the prototype SU FBMC radio PHY described in this article has been targeted to ZynqSDR hardware, and tests have been carried out to explore whether it causes interference to PU FM Radio channels. A Simulink based receiver (that has not been discussed), and a corresponding low level PHY layer protocol (with preamble/ data symbols and an FBMC burst structure) have also been developed; and used to explore interference caused by the PUs to the SU radio. This work, presented in the lead Author's Ph.D. Thesis, will latterly be published on the University of Strathclyde open access research portal [67]. The transmitter and receiver currently do not incorporate a communications stack; meaning that further work would be required to realize a fully functional communications link between A and B. As discussed in Section V-C, a LFSR is currently used to generate random 'data' for broadcast. Future upgrades would see an appropriate stack developed at each end.

The ZynqSDR is an excellent prototyping device for the lab environment, however it is not suitable for real world broadcast tests with a high RF output power. An alternative SDR solution that features an appropriate analogue RF front end (containing power amplifiers, analogue filters and duplexers) would be required for the next stages. This would ensure the radio did not broadcast unwanted harmonics and aliased spectral images, which are a feature of all SDR front ends.

In Section II the Xilinx RFSoC and its applicability for DSA applications was mentioned. One of the primary benefits this device offers is its ultra-wide sampling rates. It is possible to massively oversample at the RF front end, which in turn means aliased spectral images output from the SDR could be positioned 10s, 100s or 1000s of MHz away from the band of interest by design. In turn, lower cost analogue RF filters and wideband amplifiers could then be used, massively reducing the cost and complexity of the analogue RF front end. The RFSoC is a highly attractive platform for the next stages of implementation.

As mentioned, a Simulink based receiver has been developed and used for PU to SU interference simulations; i.e., interference caused by the incumbent to the SU. The next stages of the receiver implementation will see synchronization systems completed, and the receiver design itself targeted to SDR hardware. This would likely begin again with the MathWorks Zynq-Based Radio ecosystem, as, for all the reasons discussed in this article, it is an excellent prototyping platform.

Due to U.K. radio spectrum laws, any real world broadcast trial (i.e., not transmitting through cables) would require regulatory consent and stakeholder consultation. Proof would need to be provided that the radio design would not cause unwanted interference to neighboring bands, and in all likelihood (considering the way in which TVWS trials were approached), channel masks and guardbands would initially be set by the regulator. An intermediate step might be to explore transmission inside an RF shielded anechoic chamber. This would allow an initial chance to experiment with the simultaneous broadcast of FM Radio and FBMC signals without the chance of legal repercussions, to explore interference effects and receiver synchronization systems further.

XI. OUTLOOK

With the demand for wireless connectivity exponentially increasing, innovative new shared and dynamic spectrum access techniques will be required in order to use the finite resources of the radio spectrum in more efficient ways. In light of this, regulators are beginning to adopt new shared spectrum strategies. Ofcom was one of the first to implement sharing for TVWS, and has recently granted third parties shared access to all vacant spectrum in licensed cellular bands.

The FM Radio band, it should be remembered, is only one of many RF bands that are underutilized. There are vacant channels all throughout licensed RF spectrum. With the adoption of a more localized (as opposed to a national) spectrum licensing approach, regulators will be able to unlock these available resources for SU sharing. The spectrum revolution is just beginning, and DSA-enabled radios such as the prototype presented in this article will become key tools to drive it forward.

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