Cognitive Radio System On Chip

Students: Andrew Law, Calum Armstrong, Frank Conway, Jakub Czarny, Joseph Kromer

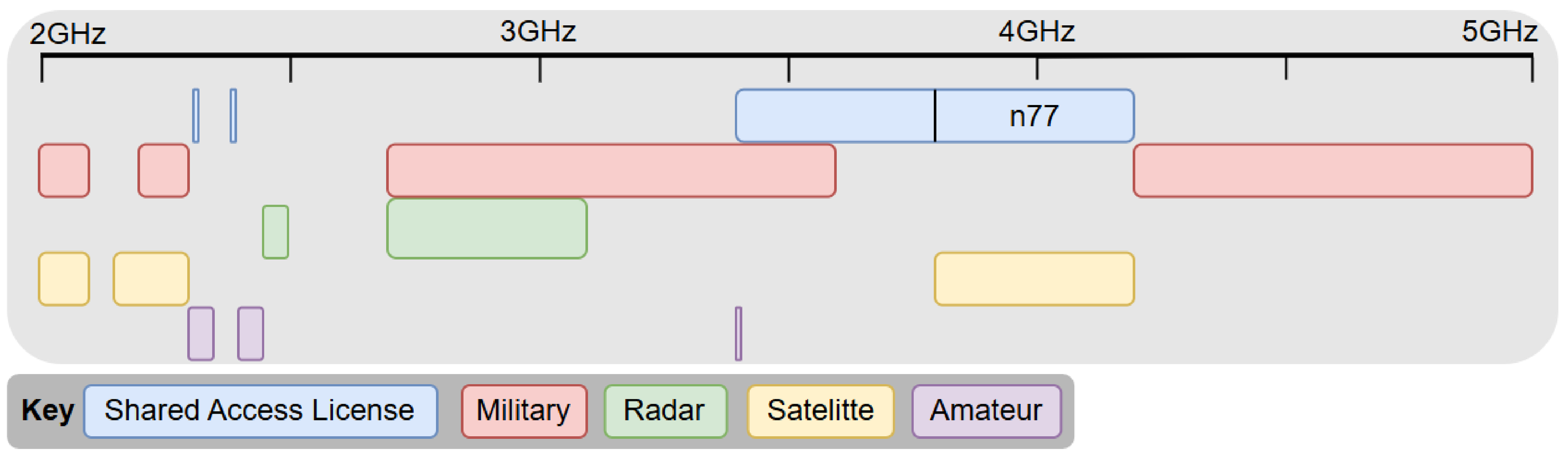
Proposer: Dr Louise Crockett Mentor: Dr Yashar Javadi

Introduction

Cognitive radios can dynamically switch the broadcast frequency based on the current RF environment, helping alleviate overuse and inefficient frequency spectra allocation existing within wireless networks. This project aims to implement a proof-of-concept cognitive radio to be used on RFSoCs. The design aimed to analyse and transmit on four 4MHz channels in the n77 band. The project also aimed to take advantage of the RFSoC RF front-end. Objectives are to explore the efficiency and robustness of different spectrum sensing techniques on the PL, and to obtain 90% accuracy within a 0 dB environment.

Spectrum Crunch

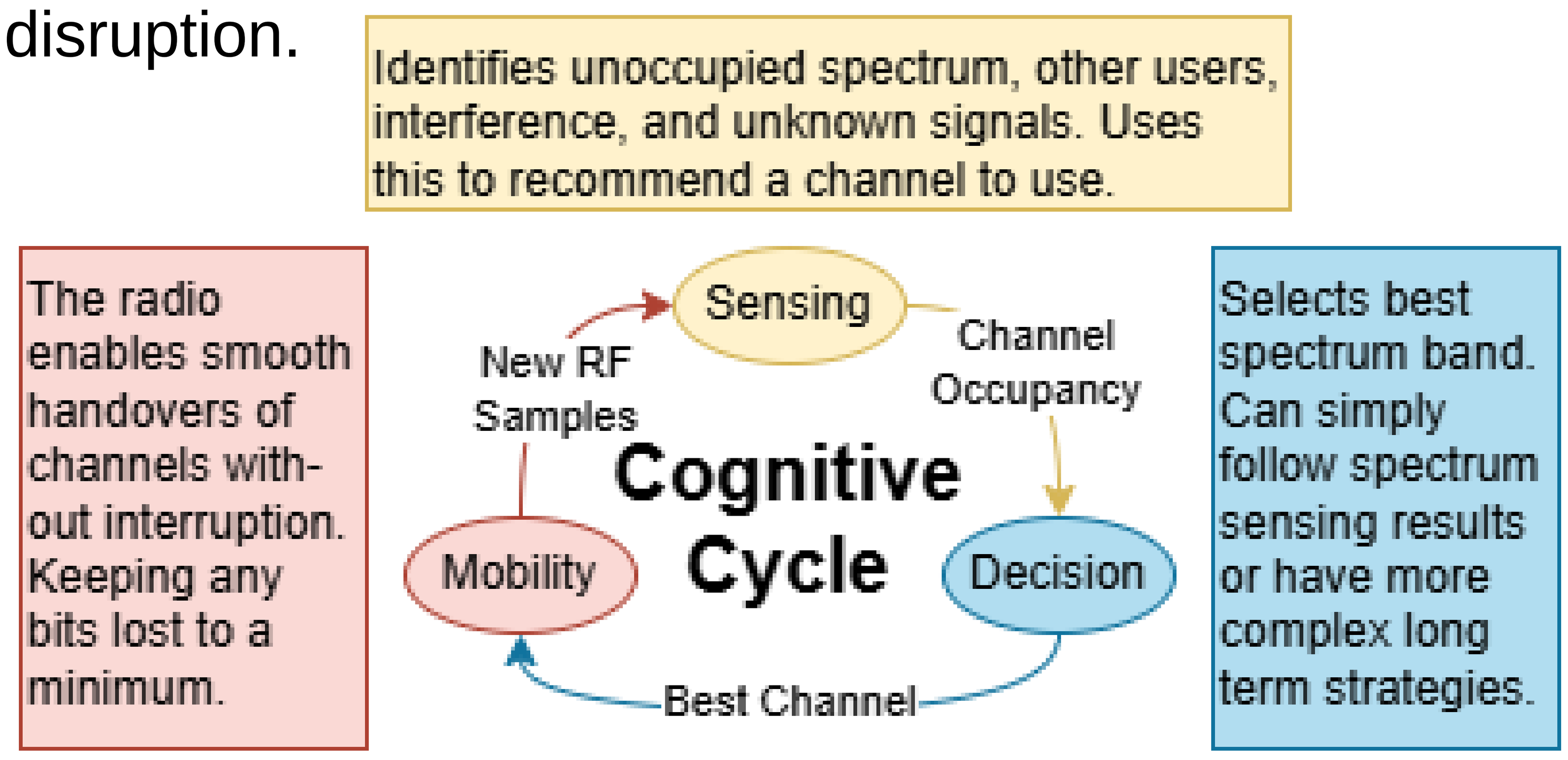
Frequency spectrum is a precious resource for comms, and we are running out due to a mixture of overuse and inefficient allocation. Solutions that enable efficient spectrum usage allow faster networks for more people, at a cheaper price. One solution that is being pushed by Ofcom is shared access licenses, where multiple users share the same spectrum. However, they must manage which channels they broadcast on themselves.



https://static.ofcom.org.uk/static/spectrum/map.html https://static.ofcom.org.uk/static/spectrum/fat.html
https://www.ofcom.org.uk/spectrum/frequencies/shared-access/

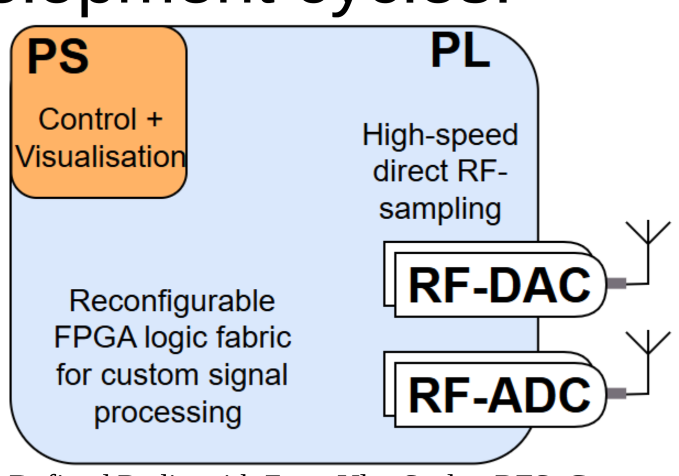
Cognitive Radios (CRs)

CRs analyse the RF environment to select the optimal transmission channel, minimizing interference by dynamically adapting to environmental conditions. This enables opportunistic spectrum access and increased utilisation, especially in dynamic environments, ensuring users maintain adequate access without disruption.



RFSoC Architecture

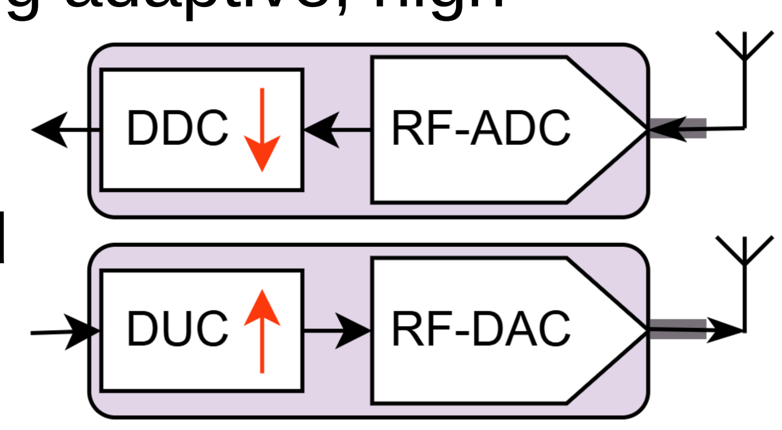
Radio Frequency System-On-Chip (RFSoC) integrates giga-sample-per-second data converters (RFDCs), programmable logic (PL) of FPGA, and a processing system (PS) with embedded ARM cores onto a single monolithic chip. Heterogenous architecture enables highly parallel, low-latency RF signal processing with high data throughput, significantly reducing need for discrete components in traditional radio systems. This simplifies overall system design, minimizes power consumption, and accelerates development cycles. Reconfigurability makes it ideally suited for 5G, electronic warfare, and advanced digital RF systems requiring real-time adaptability and rapid prototyping.



Software Defined Radio with Zynq UltraScale+ RFSoC

RFSoC Radio Front End

The RFSoC RF front-end features tightly integrated high-speed analog-to-digital and digital-to-analog data converters (ADCs/DACs), enabling direct RF-sampling removing need for traditional analogue circuitry. Reduces system complexity and provides wideband signal acquisition and generation. Architecture supports multi-gigahertz bandwidths and delivers deterministic, low-latency signal paths, essential for real-time digital signal processing in software-defined radio (SDR) systems, with easier configuration. Hence highly efficient for implementing adaptive, high -performance RF-applications across domains like CR, advanced sensor systems and satellite communications.



Software Defined Radio with Zynq UltraScale+ RFSoC

Spectrum Sensing

Spectrum sensing is an integral part of cognitive radios, and was the main focus of this project. Several different methods were implemented to test how well they would perform on the RFSoC and how many resources they would require.

	Method	Benefits	Drawbacks
Traditional	Energy Detection	Extremely low computational requirements	High false alarm rate & poor at low SNR
	Matched Filter	Works well at low SNRs	Requires prior knowledge of other users
Machine Learning	MLP	Performs better than traditional methods even with shorter buffer length	Computationally intensive and struggles with low SNRs compared to CNNs
	CNN	Provides an extremely high accuracy	Computationally intensive

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Matched Filter

Matched filtering (MFD) is achieved using a set of pre-loaded FIR filters with coefficients that correspond to a preset template. Due to the complex nature of the input signal, it is necessary to split filtering to four convolutions:

$$x[n] = a[n] + j(b[n]),$$
$$h[n] = c[n] + j(d[n])$$

$$x[n] * h[n]$$
$$= (a[n] * c[n] - b[n] * d[n]) + j(a[n] * d[n] + b[n] * c[n])$$

To save resources, the input data was interleaved and two filters with two sets of coefficients each were implemented.

Energy Detection

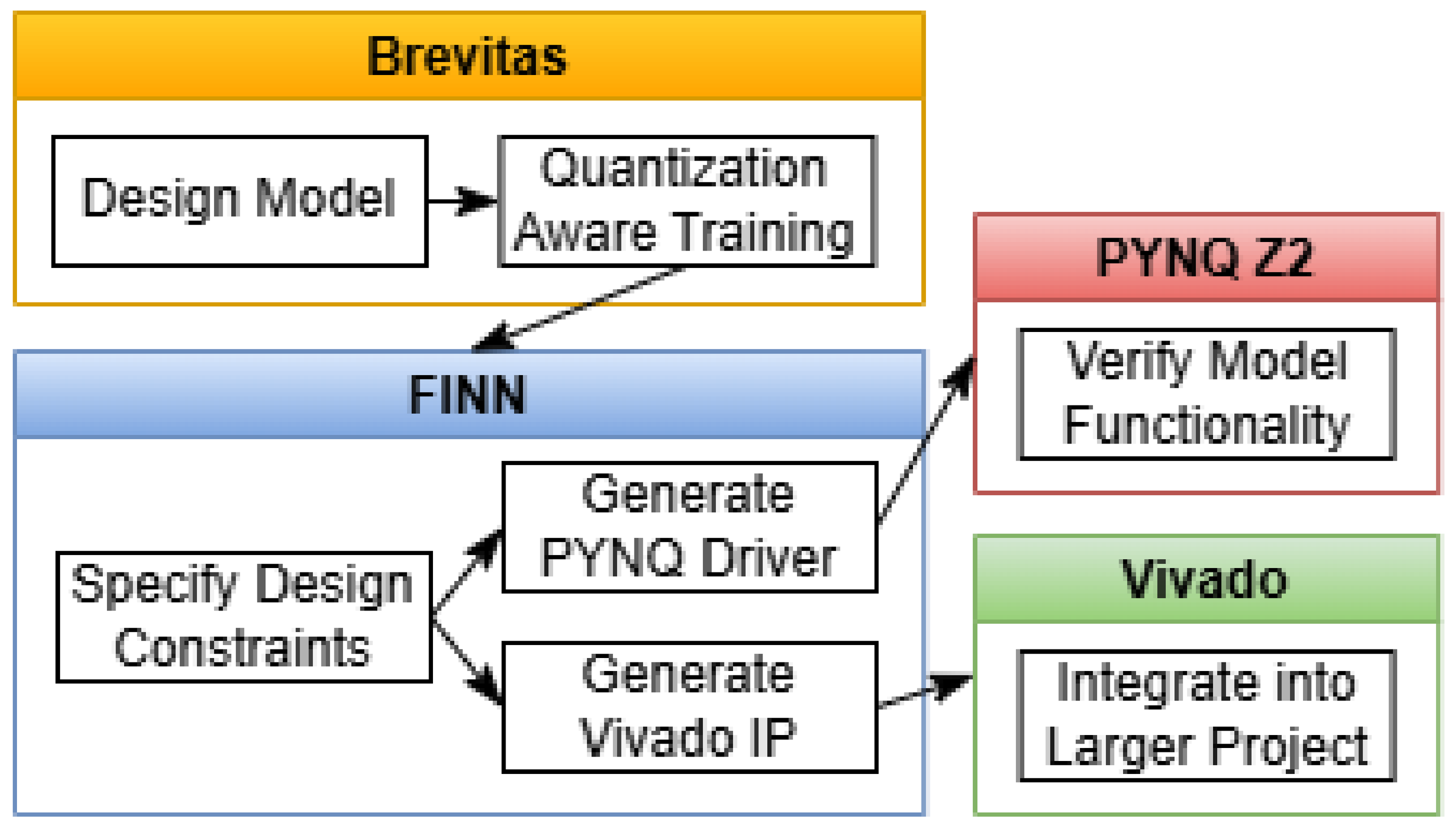
The energy detector (ED) measures the energy input to a channel and compares it to a threshold set by the user. This is achieved by implementing the following equation on the PL:

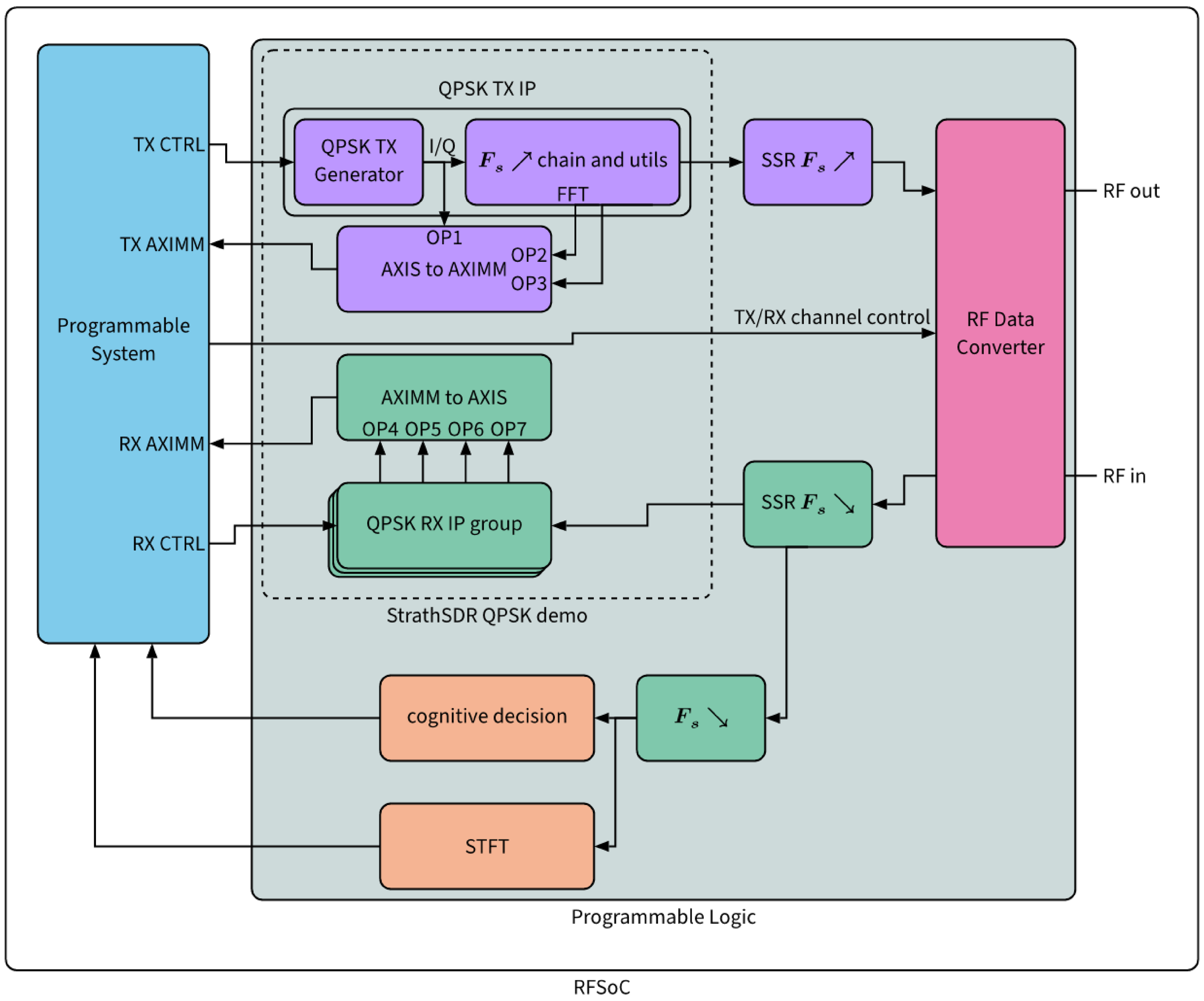
$$E = \sum_{n=0}^{N-1} |x[n]|^2$$

As well as the energy detector, a set of filters were implemented before the detectors to split the input data into the four separate channels to measure each separately.

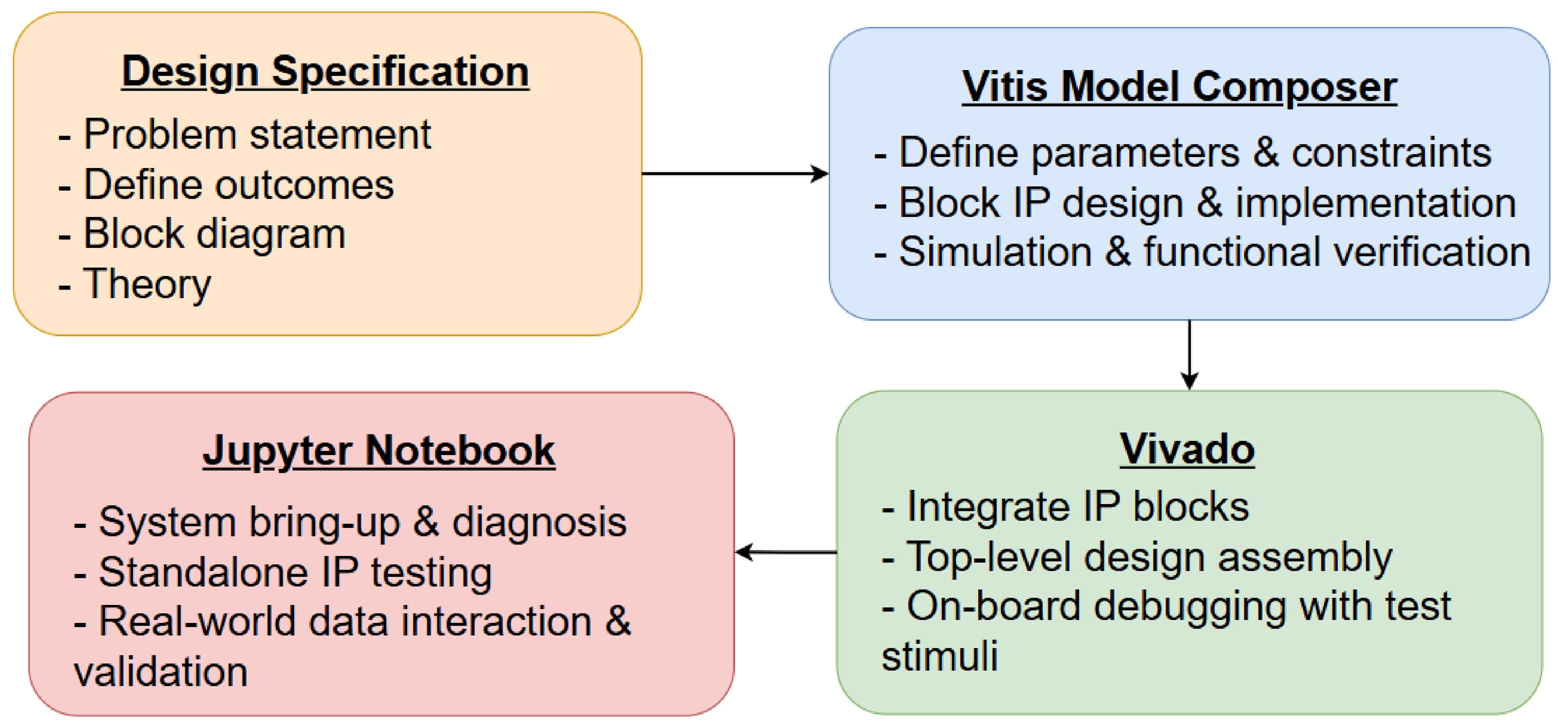
NN Implementation

To implement a neural network on the RFSoC's PL it needs to be significantly reduced in size. This was done by quantizing the model's weights and activations using some experimental programs called Brevitas and FINN. Smaller models could then be run on the PYNQ-Z2 to check they were working as expected.



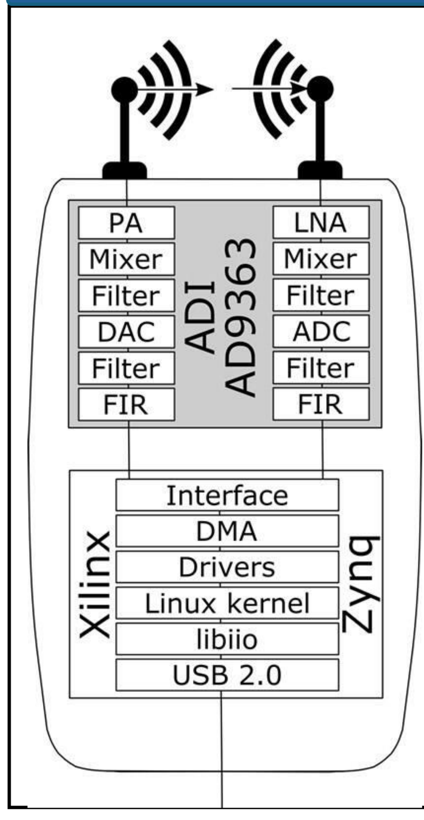


Design Philosphy



GitHub Repository

ADALM-PLUTO



PlutoSDR Used for Tx/Rx of QPSK signal at [0 -5 -10 -15 -20] dBm

Datasets

DeepSense: Publicly available Wi-fi dataset. Four 5 MHz channels

Pluto SDR dataset: QPSK transmission four 4 MHz channels, recorded as part of this project

STFT

Spectrums visualize dynamic RF environments. Short-Time Fourier Transform (STFT) time-localizes frequency analysis via FFT of time windows, creating spectrograms to show evolving spectral content

Transceivers

Adapted QPSK demo for 4 channels at ~3.8GHz. SSR interpolators and decimators to bridge RFDC with rest of system. Dynamic cannel selection via runtime NCO update.

https://github.com/strath-sdr/rfsoc_qpsk

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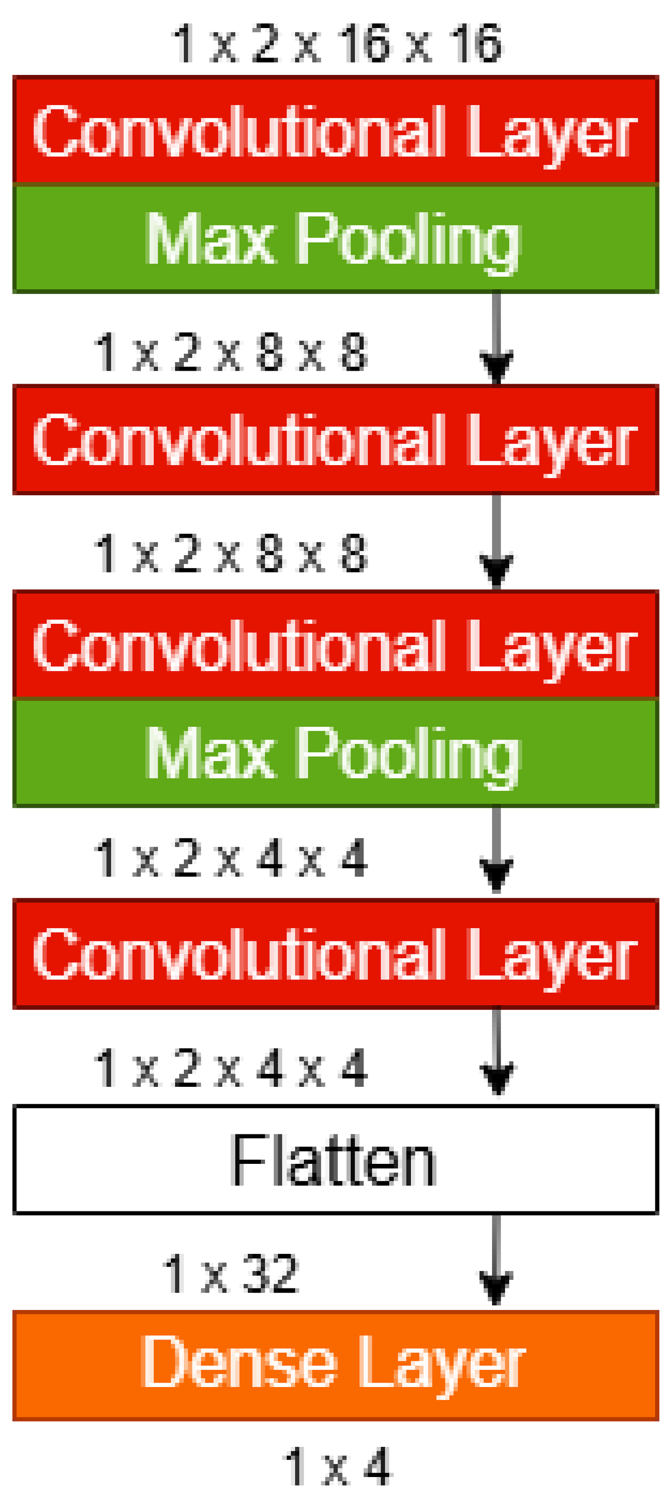
Neural Network Design



Various designs were tested in Brevitas to achieve the optimal one shown on the left. Models were trained with PlutoSDR dataset recorded for this project with data transmitted at 0 to -20 dBm. A model with smaller input buffer sizes and bit widths was better for hardware. So, these factors were balanced against the associated loss of accuracy, with a bit width of 4 and a buffer size of 256 IQ samples being settled on.

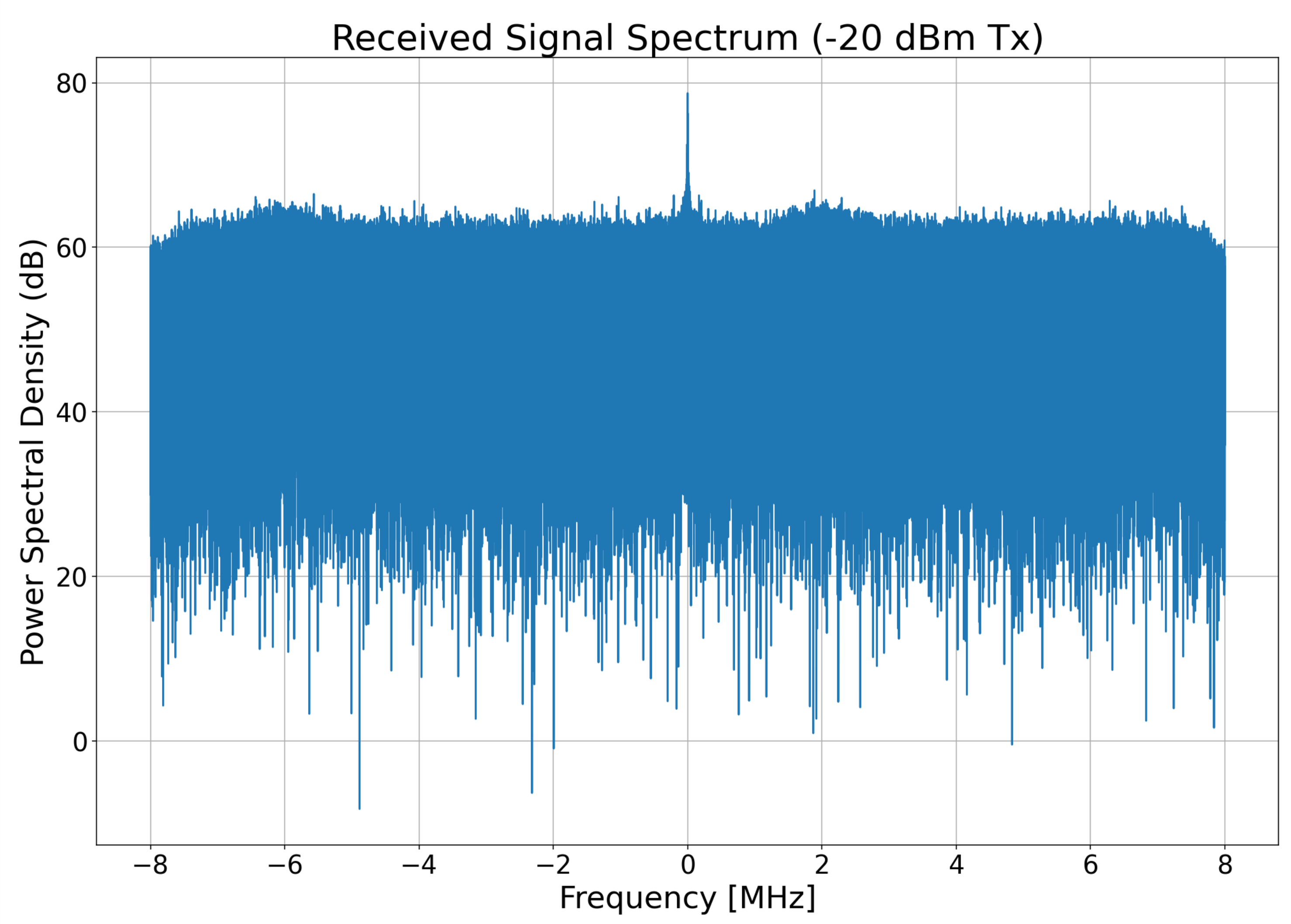
Spectrum Sensing Results

Type	Dataset	Accuracy	Recall	Precision	F1 Score
Energy Detection	0 dB	82.06%	76.6%	85.96%	0.810
	-20 dB	61.45%	47.9%	65.71%	0.554
Matched Filter	0 dB	81.25%	70.8%	77.28%	0.739
	-20 dB	69.44%	50%	72.50%	0.592
Machine Learning	0dB	99.97%	99.97%	99.97%	0.999
	-20dB	66.79%	83.10%	63.37%	0.7147
	[0:-20]dB	90.30%	90.2%	92.5%	0.884

All the implemented spectrum sensing methods were tested using a subset of the PlutoSDR dataset recorded for this project (separate from the data used for training). Testing whether they could determine which channels were free. As expected, the machine learning approach was the best all round performer, however the matched filter-based sensing did demonstrate its aptitude in lower SNR situations.

Challenge

Below is a plot of the FFT of a signal transmitted at -20 dBm and received using the PlutoSDR. This demonstrates why many systems struggle to get high accuracy for spectrum sensing, as it is difficult to distinguish data from noise.
[Channels 1 and 3 are occupied].



PL Resource Usage

IP	Utilisation				
	DSP	LUT	LUTRAM	BRAM	FF
RF	549	39648	10797	74	67509
STFT	19	6598	818	12	8852
Matched	1326	19980	14297	2	42426
Energy	490	12999	7717	2	37439
CNN	0	91730	4170	35	93215
Available	4272	425280	213600	1080	850560

IP	Utilisation (%)				
	DSP	LUT	LUTRAM	BRAM	FF
RF	13%	9%	5%	7%	8%
STFT	0.4%	2%	0.4%	1%	1%
Matched	31%	5%	7%	0.2%	5%
Energy	11%	3%	4%	0.2%	4%
CNN	0%	22%	2%	3%	11%

RFs DSP usage reflects its signal processing demands, while BRAM supports data buffering and streaming. STFT's efficient algorithm results in minimal logic and memory usage. MFD dominates DSP usage due to its computational complexity of correlation. ED performs basic power analysis hence minimal footprint. CNN relies on LUTs and FFs instead of dedicated DSPs, with BRAM likely used for weight storage. Its shallow, logic-based design explains the relatively low resource usage compared to expectations. This distribution highlights strategic and efficient IP selection and integration.

Conclusion

- Transmitting and receiving QPSK data in loopback
- STFT produced RF environment
- Implemented multiple traditional spectrum sensing methods on the PL
- Implemented neural networks for spectrum sensing running directly on the PL

Future Work

- Have multiple cognitive radios working together by communicating which channel each radio should use
- Adapt models to determine exact sections of free spectrum
- Implement more complex spectrum decision methods with long term strategies on PL