Proof of Concept of a Database-Driven Dynamic Spectrum Access Framework Enabled by a Network of IoT Spectrum Sensors

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Abstract
This work presents a proof of concept (PoC) of a spectrum sensing module designed for integration with an Internet of Things (IoT) device and its connection to a spectrum management database (SMDB). The solution demonstrates the viability of implementing a spectrum sensing dynamic spectrum access (DSA) testbed using commercially available transceivers and hardware components. The signal processing module for multiple secondary users (SUs) is implemented on a field-programmable gate array (FPGA), utilizing the modified Pietra-Ricci index detector (mPRIDe). The data obtained from spectrum sensing populates the SMDB, which governs spectrum management and enables a spectrum trading market (STM) to establish a self-regulated spectrum environment. The IoT sensors employed consist of ESP32 microcontrollers, while the SMDB is modular, with the STM as an additional module.
Keywords: Cognitive Communications; Dynamic Spectrum Access; FPGA; Internet of Things; Spectrum Sensing.

1. Introduction

The increasing demand for wireless spectrum in emerging communication systems, such as 5G and 6G, has heightened interest in dynamic spectrum access (DSA) solutions. Traditional static spectrum allocation methods lead to inefficient use of available resources. Cognitive radio (CR) and spectrum sensing technologies enable opportunistic spectrum access by secondary users (SUs) without interfering with licensed primary users (PUs). However, practical implementation remains a challenge due to hardware limitations, regulatory concerns, and appropriate business models. This work presents a proof of concept (PoC) of an IoT-based spectrum sensing system integrated with a spectrum management database (SMDB), which facilitates a dynamic and market-driven spectrum allocation mechanism.

The PoC aims at proofing one of the main concepts coined in Guimarães et al. (2021), where a complete solution for DSA is proposed. The solution is depicted in Figure 1. The spectrum sensing task is performed by spectrum sensing IoT (SSIoT) devices instead of SUs. An SSIoT is simply a device formed by connecting an ordinary IoT node to a spectrum sensing (SS) module, through a standard wired interface, while not all IoT devices must become SSIoTs within the IoT network. The IoT device and the SS module are equipped with their own antennas, distinguishing themselves through practical characteristics, primarily their bandwidth and central operating frequency. The SSIoTs are responsible for scanning the radio-frequency (RF) spectrum and relaying the acquired sensing information to an IoT gateway. The

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gateway gathers IoT-related data from a group of closely positioned IoT devices to publish the data in the SMDB.

Whenever requested, the spectrum occupancy database accesses the spectrum sensing IoT network to refresh the pool of accessible channels for DSA purposes. Additionally, the database has the capability of analyzing ongoing and historical activities within the primary network. This enables the provision of spectrum usage predictions and other pertinent information, enhancing the effectiveness of the quest for unoccupied frequency bands. The database management function is responsible for managing all tasks related to the spectrum market. The database-driven IoT-enabled DSA solution just described takes advantage of the high density and large coverage area of typical IoT networks, such as smart grid, smart city and wireless sensor networks (WSN), allowing for the construction of a fine-grid spectrum occupation database that can be updated in an approximate real-time fashion.

2. Methods

The method applied for designing the PoC architecture was a theoretical study based on Guimarães et al. (2021), followed by the practical interconnection of hardware building blocks. The work has also received the contribution of Prof. Rahul Shrestha from IIT Mandi, India, where one of the authors realized an internship to enhance and cement the knowledge about FPGA and application-specific integrated circuit (ASIC) designs.

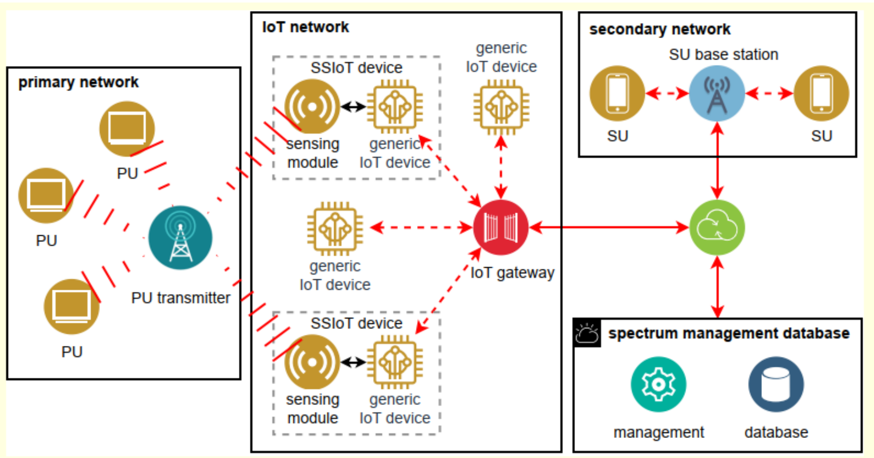

Figure 1. Architecture of the database-driven IoT-enabled DSA solution.

The resultant PoC architecture consists of three main entities, each with specific functions within the cooperative spectrum sensing (CSS) framework. The first entity is the front-end SSIoT (SSIoT-FE) device, responsible for collecting samples from the primary transmitter. The second entity is the data processing SSIoT (SSIoT-DP) device, which was an extension to the model of Guimarães et al. (2021). The SSIoT-DP is made up of an FPGA processing module, which employs the modified Pietra-Ricci index detector (mPRIDe) detector devised in Guimarães et al. (2023), along with an IoT device. This entity acts as a fusion center (FC) and the master device that coordinates clusters formed by multiple units of the first entity within the IoT network. The third entity is the SMDB, which is designed to manage spectrum and facilitate a spectrum market based on the information provided by the SSIoT devices. Figure 2 provides an overview of the PoC, with seven markers placed to represent the flow of spectrum sensing for better understanding, as explained in the following items, which have been numbered accordingly.

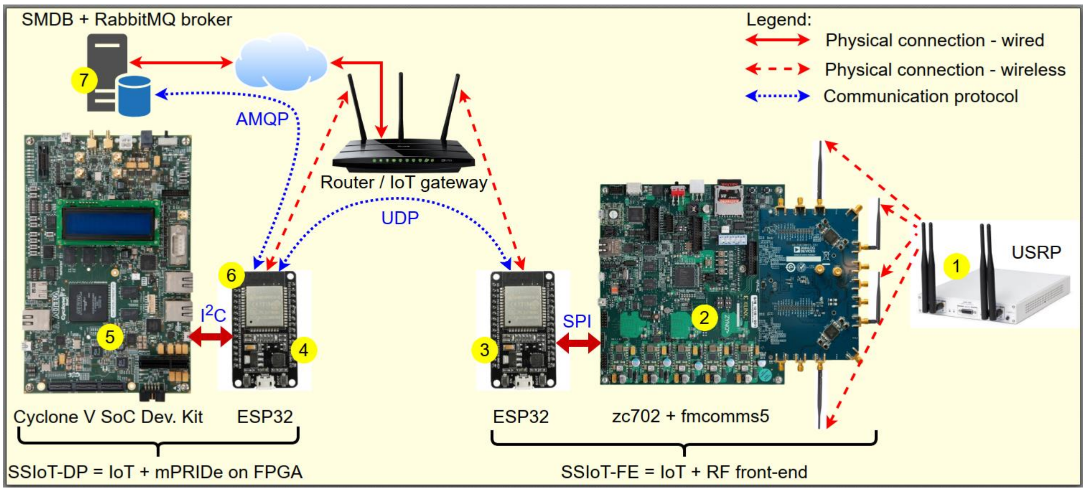

Figure 2. Overview of the proof of concept and its hardware components.
Source: Manuscript submitted by the authors to the *IEEE Internet of Things Journal*.

1. A universal software radio peripheral (USRP) acts as a signal generator to emulate a primary user (PU) transmission. The received signal is sampled by an RF front-end implemented with the Analog Devices, Inc. (ADI) FMCOMMS5 board, which incorporates two AD9361 transceivers arranged in a 4T4R configuration (four transmitters and four receivers). In this setup, only the receiver functionality is employed to collect the received signal samples. The reason for using a 4-channel board is to simulate the behavior of four SSIoT devices within a single system.

2. Signal samples are processed by the Zynq FPGA SoC from the zc702 board, which supports managing FMCOMMS5 board transceivers, as described previously. The FPGA enables the simultaneous processing of the four channels, performing tasks such as digital low-pass filtering (LPF), noise whitening (critical for accurate test statistic operation), sample re-quantization to signed 6-bit fixed-point format, and encoding. Although these operations can be implemented in hardware, they were executed in software for this PoC, due to the availability of the Python library for Analog Devices industrial I/O (PyADI-IIO), which allows for rapid development of RF applications using ADI transceivers in a Linux environment on the FPGA's processing unit. The signal processing workflow is based on the model proposed in Guimarães et al. (2021). This hardware setup may be excessive for a single-channel front-end implementation, where more cost-effective and discrete hardware solutions can be adopted. However, the use of a 4-channel board brings the advantage of not requiring additional synchronization methods, as all channels are contained within a single board and are

synchronized by default. When the sensing network consists of multiple devices, each one connected to single-channel front-end modules, these modules must support a synchronization method. A possible approach for establishing synchronization in single-channel receivers is to use the global navigation satellite system (GNSS) constellation.

3. As previously mentioned, the ESP32 microcontroller has been chosen as the IoT device in the PoC. It is used for wireless fidelity (Wi-Fi) communication with a wireless router, universal asynchronous receiver-transmitter (UART) communication with a computer host, and inter-integrated circuit (I^2C) communication with an FPGA board. Primarily, the ESP32 serves as the IoT device to which the spectrum sensing module is connected. It establishes a connection with the module through a serial peripheral interface (SPI) interface and is responsible for reading the sample buffers from the module. The ESP32 then forwards the contents of the sample buffer to the main IoT device, which is coupled to the mPRIDe core responsible for processing the samples. The data transfer is facilitated via a raw user datagram protocol (UDP) connection. In this configuration, a single ESP32 manages the sample buffers from four receivers, effectively emulating the behavior of four SSIoT devices. The code for this functionality, written in MicroPython, sends the buffer contents corresponding to each channel as separate UDP messages. The SSIoT-FE device is formed by connecting the second and third items.

4. Another ESP32 serves as the main IoT device, with its code also implemented in MicroPython. This main IoT device is responsible for receiving UDP messages containing signal samples from the sensing front-end devices. The SSIoT-DP device is formed by connecting the IoT device in this item with the processing module reported in the sequence. In a full deployed scenario, the SSIoT-DP must use multiplexing techniques and coordination to manage how the SSIoT-FEs report their data. In the PoC implementation, a single SSIoT-FE with four receiving channels is considered. In this case, one device sends four consecutive messages, each corresponding to a separate channel. Upon receiving all samples transmitted through the UDP messages, the ESP32 loads the samples into the mPRIDe processing module via the I^2C interface. This interface has been selected due to its low implementation complexity. Communication between the SSIoT devices is established using a local Wi-Fi router.

5. The cooperative spectrum sensing processing module employs an Intel Cyclone V SoC Development Kit. In addition to the mPRIDe detector detailed in Guimarães et al. (2023), other essential components were integrated, including a control module for managing the reading of input first-in first-out (FIFO) queues and an I^2C interface controller within the programmable logic of the FPGA. The mPRIDe core, implemented on FPGA, operates at a clock frequency of 75 MHz and processes windows of 128 samples per channel. The process of loading samples into the buffers and reading the decision of the mPRIDe test statistic is carried out through simple read and write operations on addressable registers.

6. After the main IoT device loads the samples into the mPRIDe processing module within the FPGA, it retrieves the decision on spectrum occupancy from the module's I^2C control register. Additionally, parameters such as device identification, geolocation, and time information are incorporated into a JavaScript object notation (JSON) message. This message is then assembled and transmitted to the database through the IoT broker, which is a middleware component that facilitates communication and data exchange between IoT devices and applications, in the case ensuring the proper transfer of the spectrum sensing data to the SMDB.

7. The SMDB receives real-time spectrum utilization information from the sensing network. This data can be obtained either through active requests by the SMDB or passively, with the sensing network periodically transmitting the information without any request. Once the SMDB has compiled a spectrum availability map, secondary users can opportunistically access the spectrum by querying the database. Alternatively, they can temporarily acquire usage rights through the STM module, functioning as a spectrum marketplace where primary users can actively participate in leasing or trading their spectrum rights.

3. Results and Discussion

The PoC depicted in Figure 1 confirms the feasibility of an mPRIDe-based spectrum sensor in accurately detecting spectrum occupancy. The implemented system successfully integrates real-time sensing data with a database-driven spectrum management approach, demonstrating a potential solution for enabling DSA frameworks in future wireless networks.

4. Conclusion

This proof of concept validates the feasibility of an IoT-enabled, database-driven DSA framework. The integration of an FPGA-based spectrum sensing module with an IoT network and SMDB provides a practical solution for real-time spectrum monitoring and management. Future work will focus on refining the spectrum trading mechanisms within the STM.

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