International Journal of Engineering & Technology, 7 (3.1) (2018) 51-55

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper



A Low-Cost Software Defined Radio Based Cognitive Radio Test-Bed for LTE Networks

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Abstract

In this work, we present a low-cost implementation of a Cognitive Radio (CR) test-bed for LTE and LTE-Advanced (LTE-A) Networks. The test-bed setup is implemented using highly integrated Software Defined Radio (SDR) platforms which are well suited for wireless communication. Each transceiver can be configured to work as a primary (resp. secondary) eNodeB or a primary (resp. secondary) user in a Heterogeneous Cognitive Radio framework. In this context, we study the problem of spectrum management in an LTE based heterogeneous network and propose simple distributed algorithms which the secondary eNodeB can employ to efficiently manage the spectral opportunities that arise in such a network. Experimental validation show significant improvement in the secondary link throughput.

Keywords: *Software-defined Radio (SDR); Cognitive Radio (CR); 4G; LTE.*

1. Introduction

Software-defined radio (SDR) [1], [2] is a radio communication technology that is based on software defined wireless communication protocols instead of hardwired implementations. SDR provides an efficient and secure solution to the problem of building multi-mode, multi-band and multi-functional wireless communication devices. Flexibility in reconfiguration of baseband algorithms, software and re-programming of RF parameters has been a key requirement for a generic SDR platform. The evolution of features over several releases of 3GPP and IEEE standards, tactile and proprietary communication systems require scalable baseband algorithms and software. The RF front end requires wider band of operation aggregated over multiple bands to support high data rate communications of the future.

WaveGuru [3], [4] is a low cost SDR platform, which addresses the above needs. It can be configured to operate with different waveforms and protocols through dynamic loading of new waveforms and protocols. Radio frequency spectrum is a finite natural resource that is increasingly in demand for services which encompasses applications in communication, entertainment, security, military, space, etc. With ever increasing data demands, the available spectrum needs to be optimally utilized. Cognitive radios [5] are spectrum aware radios that enable efficient allocation and utilization of the spectrum.

Telecommunication in the 90's was dominated by voice. Early 2000 onwards, we have seen an exponential growth in data traffic. Recent years have shown a significant data explosion as we have moved into a connected sphere [6]. Moving on to the next generation networks and applications, every available spectral opportunity needs to be identified and effectively utilized. The spectrum usage data analysis indicates that a number of spectrum bands are suitable candidates for reallocation and/or sharing [7]. If we search for RF spectrum at various geographic locations [8] it is observed that i) Some licensed frequency bands by primary users are underutilized all the time ii) Some frequency bands are partially utilized iii) Some frequency bands are utilized fully and demand more. Cognitive Radio technology is a prominent technology that enables the improvement of the spectrum use in an efficient manner [9].

Mobile communication system capacity can be increased by dense deployment of small cells (Portable low power base stations with a range of few hundred meters) [11], [12]. In a heterogeneous network with Macro and small cells, the user can get quality communication by having a downlink channel from macro base station and an uplink channel to low power small cell base station. The cluster of small cells can typically communicate to a macro via a back haul. Long Term Evolution (LTE) [10] is a mature technology which has been deployed in such heterogeneous scenarios.

LTE as part of the 4G technology supports a spectral efficiency three to four times than that of the Release 6 WCDMA in the downlink and two to three times in the uplink. Multiple antennas at the base station and receiver, carrier aggregation, coordinated multi-point and user specific narrow beams are some of the features that are part of LTE-Advanced to pump in more capacity for data intensive applications. LTE and LTE-Advanced have also been touted as forerunners for next generation of wireless networks - 5G.

The spectrum access by the interested users can be visualized to constitute primary and secondary users. In a specific spectrum access scheme, secondary users may use the primary user's band avoiding any interference during use. Hence, secondary users should detect whether primary users are using the band and decide to let the band free as soon as the primary user wants to use it. This requirement leads to the inclusion of cognitive capabilities for the secondary user to sense and configure the radio.

In this context, we deploy a radio test-bed with cognitive capabilities to experiment and characterize LTE based Soft-ware Defined Radios. The radios in the test-bed are capable of sensing, reconfiguring and optimizing the overall system utility.

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An example cognitive radio based cellular network is shown in Fig. 1. Our work focuses on the management of spectrum between primary eNodeB/primary user and secondary eNodeB/secondary user. Simple distributive algorithms which the secondary network can employ to manage the spectral opportunities to efficiently utilize the spectrum are proposed. Experimental validation show significant improvements in system throughput of the secondary network.

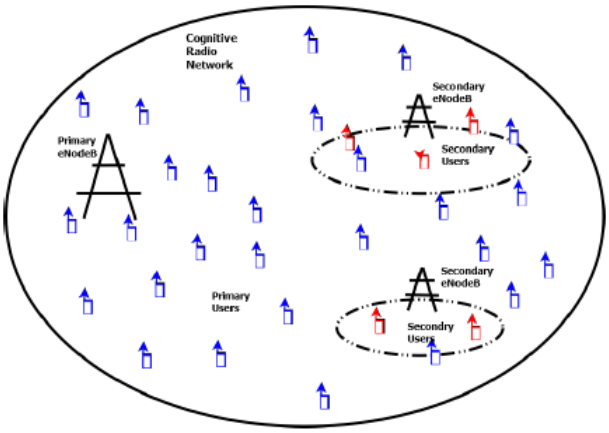


Fig. 1: A Typical Cognitive Radio Network

The remaining sections of the paper are organized as follows. Section II describes the System setup, detailing the WaveGuru Software Defined Radio and its architecture, the Cognitive radio test-bed setup, and an evaluation procedure to characterize the test-bed. Section III provides the experimental validation and concludes.

2. System Set Up

A. Wave Guru SDR: WaveGuru is a versatile and powerful Software Defined Radio which supports a multitude of wireless communication protocols and standards including LTE and LTE-Advanced. Each SDR can be configured to work as an eNodeB or an UE.

The hardware primarily constitutes a radio transceiver that can support TDD or FDD modes with a wide signal bandwidth of up to 56 MHz, and can operate over a range of radio carrier frequency bands up to 6 GHz.

The baseband signal processing, higher layers and Applica-tion Programmable Interface (API) are mapped on to a mother board which houses Field Programmable Gate Arrays (FPGA), Digital Signal Processors (DSP) and ARM cores.

It is standalone and versatile and hence is suitable for ease of deployment in a test-bed network. The architecture of the WaveGuru SDR is shown in Fig. 2

B. Cognitive Radio Test-bed Setup: The proposed cognitive radio test-bed consists of multiple WaveGuru SDRs. Graphical User Interface (GUI) based APIs allow us to configure individual SDRs in the test-bed as primary or secondary eNodeB, primary or secondary users. Unique Cell IDs and operating frequencies are assigned to the eNodeB's. One such example case is as listed in the table I.

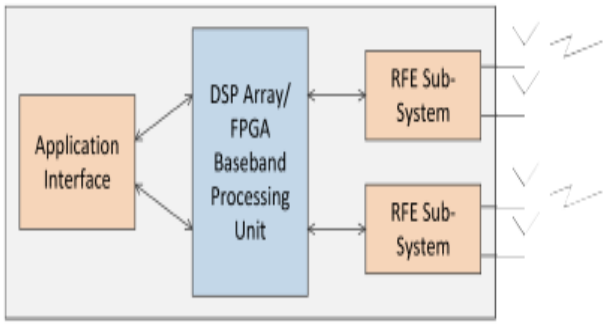


Fig. 2: Wave Guru High Level Architecture



Fig. 3: Wave Guru 4G LTE Modem (L) and Datalink Card (R)

The System view of an experimental test-bed setup is shown in Fig. 4. WaveGuru SDR 1 is assigned as a primary eNodeB and is configured to operate in an ON-OFF mode. It is assigned with a carrier frequency, cell ID and operation bandwidth and invoked to transmit LTE signal. It is ON for X seconds and OFF for Y seconds where X and Y are random numbers in units of integer seconds. This simulates spectral opportunities. Further, the ON-OFF mechanism is controlled by a system load factor which can vary between 0 and 1. WaveGuru SDR 2 is assigned as primary user and is configured to establish communication with the primary eNodeB.

WaveGuru SDR 3 is assigned as a secondary eNodeB and is configured to operate in an adjacent band. It has cognitive capabilities to sense and runs a distributed algorithm to manage the spectrum. WaveGuru SDR 4 is assigned as a secondary user and is configured to establish communication with the secondary eNodeB. It has cognitive capabilities to sense and report spectral opportunities to its serving cell.

3. Experimental Validation

With the Cognitive capabilities for the secondary eNodeB and UEs as discussed, there are multiple configurations and experiments possible.

Mode 1: Secondary eNodeB senses the spectrum, decides to switch or not if spectral opportunities arise, indicates to the UEs to follow suit

Table 1: Primary and secondary eNodeB TX Parameters

Parameter	Primary	Secondary
Cell ID	250	7
RF	2.4 GHz	2.3 GHz
BW	10 MHz	1.4 MHz

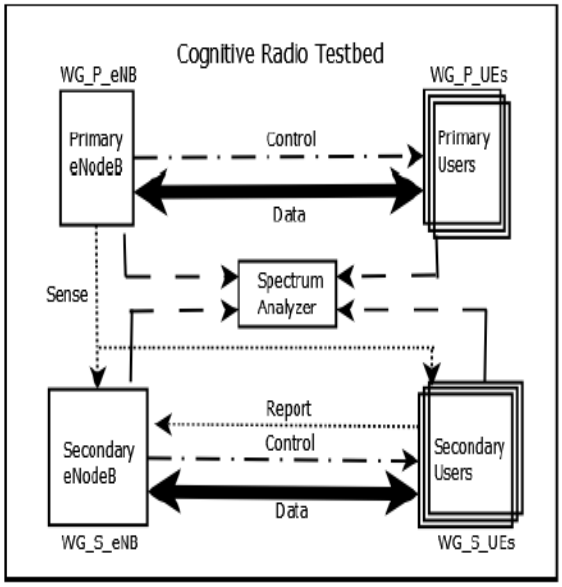


Fig. 4: System Overview of the Test bed

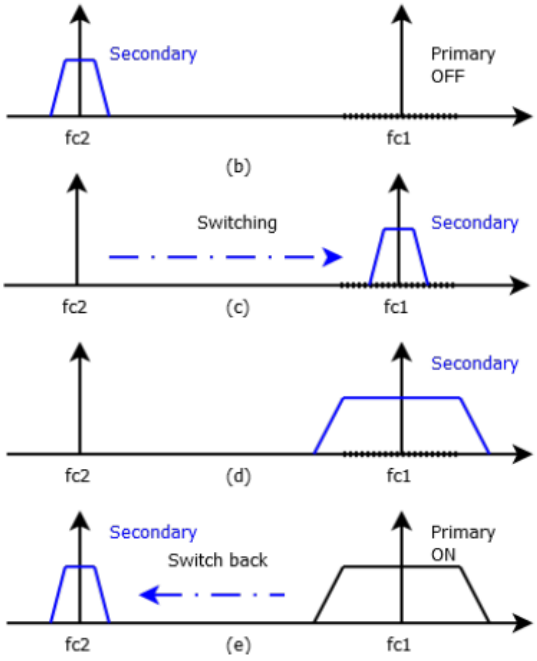


Fig. 5: Switching illustration

- Mode 2: Secondary UEs sense the spectrum, periodically reports to serving eNodeB. Secondary eNodeB analyzes the report, makes decisions to switch or not, indicates the UEs to follow suit.
- Mode 3: Both the secondary eNodeB and UEs can sense. The eNodeB can improvise switching decisions by combining its own observation and the report available from the UEs.

Sensing can be further optimized if a central server can indicate to all the eNodeBs in the network on the available carrier and bandwidth allocations. The secondary eNodeBs can use this information if they sense (Mode 1) or pass on the information to the secondary users to optimize the search space (Mode 2).

Irrespective of the above modes, the secondary eNodeB/UEs ensures periodic sensing of the spectrum for primary transmissions when utilizing the primary spectrum in order to enable primary transmissions to resume smoothly, while conforming to latency constraints put forth by the system. We rig the experimental testbed for Mode 2.

When the primary eNodeB enters the OFF state, the secondary UE senses the same and reports it to the secondary eNodeB. The secondary eNodeB analyzes the received report and if spectral opportunities exist, makes a decision to switch to the primary carrier and informs the secondary UEs to follow suit.

If larger BW options are available, the secondary eNodeB indicates the same and hence can offer better Quality of Service to the secondary UEs. The secondary UE which is sensing the spectrum regularly can detect the onset of primary transmissions and indicates the same to the secondary eNodeB. Now, the secondary eNodeB switches back to its assigned carrier and continues with its communication with the connected secondary UEs. The mechanism of switching is illustrated in Fig. 5.

For experimental validation, a spectrum analyzer as part of the setup is used to record signal transmissions across various components of the CR test-bed setup.

An overview of the sensing algorithm at the secondary UE and the switching algorithm at the secondary eNodeB is illustrated.

Algorithm 1 Algorithm Pseudocode running at the Secondary UE

```
Every N Frames
1: Scan Spectrum
2: Send Report
```

Algorithm 2 Algorithm Pseudocode running at the Secondary eNodeB

```
1: switch_flag = FALSE
2: Every N Frames
3: BEGIN_LOOP:
4: Analyze Report
5: if primary_carrier_free then
6:     switch to primary carrier
7:     switch_flag = TRUE
8: else
9:     if switch_flag then
10:        switch to secondary carrier
11:        switch_flag = FALSE
12:    else
13:        stay
14:    end if
15: end if
16: END_LOOP
```

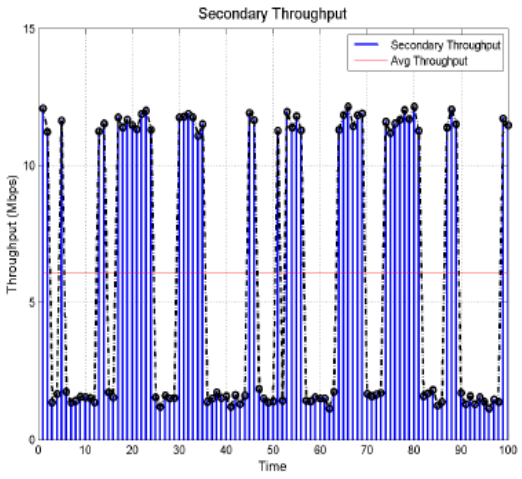


Fig. 6: Link Throughput at Secondary eNodeB - Primary load factor 0.5

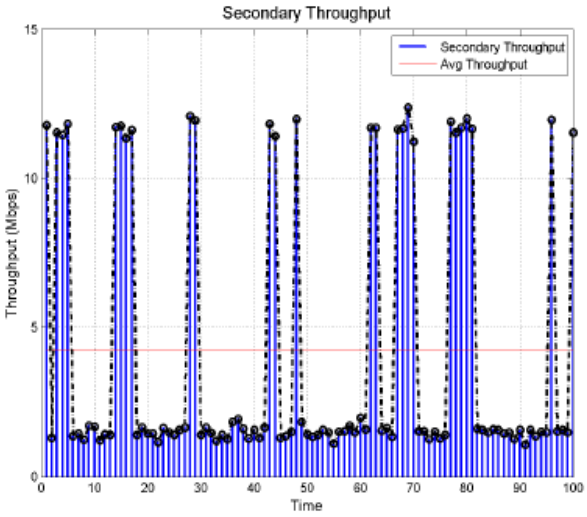


Fig. 7: Link Throughput at Secondary eNodeB - Primary load factor 0.75

Note: Each frame in an LTE network is 10 milliseconds. The scanning performs cell search and synchronization procedures across carriers and bands of interest. Generation of reports could take significant number of frames, especially during initial cell search. Subsequently to this, the spectrum sensing eNodeB/UEs can maintain a database of likely bands and carrier frequencies to search for based on its own scan reports or with aid from the serving cell or backhaul.

Running these algorithms as described, we log the actual link throughput at the Secondary eNodeB for various Primary BS load factors. As described, the primary eNodeB has a random load factor controlled ON-OFF protocol to mimic a real-time network. The secondary eNodeB system throughput is monitored over a period of 100 seconds.

In the usual mode, we assume that the Secondary eNodeB has access to a limited amount of spectrum at an adjacent band (e.g, 1.4 MHz). During the OFF period, the secondary UE senses the spectral opportunity and reports to its eNodeB, which in-turn switches its carrier to the primary carrier and to a higher available bandwidth (e.g., 10 MHz).

The link throughput with a 16-QAM, rate 1/2 MCS (Modulation and Coding Scheme) is shown corresponding to the primary ON-OFF periods for a lightly loaded primary system (50%) in Fig. 6 and in Fig. 7 for a moderately loaded primary system (75%). As can be seen, the CR algorithm which can switch efficiently and scale its bandwidth sees an increased throughput in the order of 3-4 times, depending on the load.

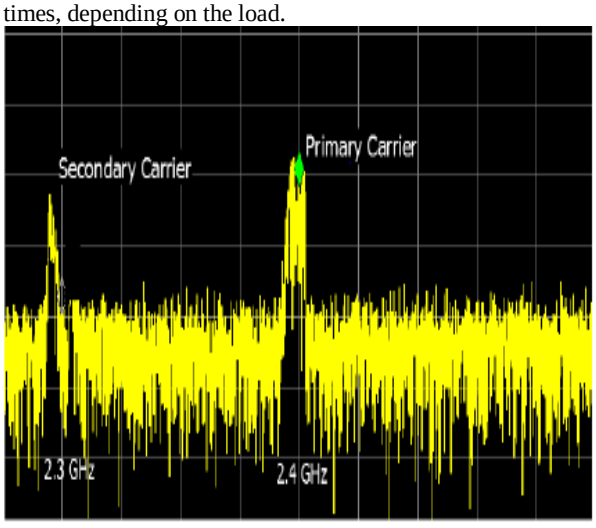


Fig. 8: Primary Carrier at 2.4 GHz and Secondary Carrier at 2.3 GHz

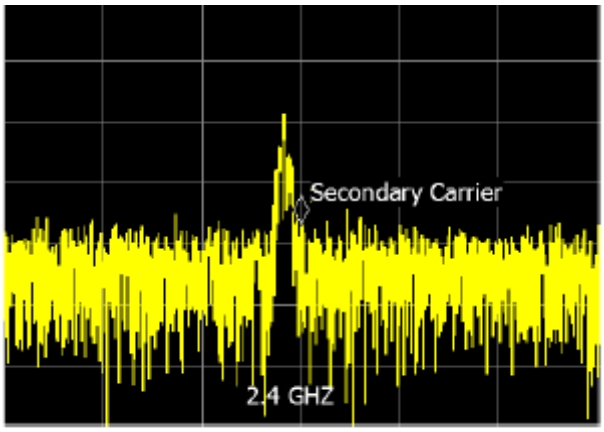


Fig. 9: Secondary Carrier switched to 2.4 GHz

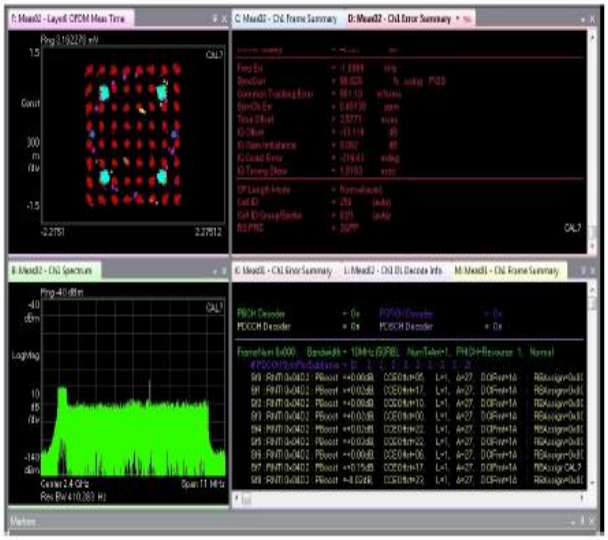


Fig. 10: Recovered Constellation and Measurements at the Secondary Receiver at 2.4 GHz

Few sample Spectrum Analyzer screens shots are captured and illustrated in Fig. 8, 9 and 10, respectively. Fig. 8 shows the primary and secondary LTE carriers at 2.4 GHz and 2.3 GHz, when the primary is ON. When primary goes OFF, the secondary switches to 2.4 GHz as shown in Fig. 9. The receiver signal is decoded by the secondary UE at 2.4 GHz and the constellation with some measurement data is captured in Fig. 10.

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A. Perspectives and Future work: The deployment and study of the Cognitive Radio test-bed leads to interesting possibilities for the network operator. The operator can distribute the available spectrum among primary and secondary network, depending on users choices and revenue models. Users who opted for a cost-effective network option (secondary users) can still benefit with spectral opportunities when demand from the primary users are light or moderate. Not only does the distributed CR algorithm help to sense and switch, it can also offer better Quality of Service to its users utilizing the excess bandwidth that is available when the primary is not utilizing the spectral resource. Further, when there are multiple secondary networks sensing and competing for the same resource (as illustrated in Fig. 1), one can formulate the underlying scenario as a game problem to optimally distribute the available spectrum or schedule the same, as appropriate. In such a case, a backhaul link should exist among the secondary eNodeBs for information exchange and spectrum management for efficient and optimal use of spectral opportunities. The authors are currently working on a theoretical frame-work to characterize and analyze the performance of such a system.

5. Conclusion

In this paper, we present a low-cost implementation of a Cognitive Radio (CR) test-bed for LTE based heterogeneous network. The test-bed setup is implemented using highly integrated Software Defined Radio (SDR) platforms which are well suited for wireless communication infrastructure. Transceivers are configured to work as a primary/secondary base station or primary/secondary user in a Heterogeneous Cognitive Radio framework. The problem of spectrum management in a LTE based heterogeneous network is addressed by proposing simple distributed algorithms which the secondary eNodeB can employ to efficiently manage the spectral opportunities that arise in such a network. Experimental validation show an increased secondary link throughput in the order of 3-4 times, utilizing the spectral opportunities that arise when the primary network is light to moderately loaded. Framework of a network which could use interesting revenue and game models to arrive at theoretical characterization of such systems are discussed as future work.

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