# Implementation Aspects of a DSP-Based LTE Cognitive Radio Testbed

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**Abstract.** One of the key issues of designing radio communication systems is to enhance the efficiency and flexibility of the available radio spectrum. In this context, reconfigurable implementation of the different system layers such as Media Access Control (MAC), Physical (PHY), and RF layers with optimal cross-layer design is driving nowadays research on designing reliable and robust mobile communication systems. This paper presents the software and hardware implementation aspects of a DSP-Based cognitive LTE testbed and addresses the design, the implementation and the realistic verification of the key components of the system.

**Keywords:** Cognitive Radio · LTE · Testbed · DSP

## 1 Introduction

In order to meet the increasing requirements of data throughput and the number of interconnected devices, the cellular communication are developing mainly in two directions. First, the spectral efficiency has been improved from 2G era's about 1 bps/Hz to today's 4G LTE Advanced (LTE-A)'s over 20 bps/Hz. The large spectral efficiency requires sophisticated and power-consuming signal processing which seems to be approaching a practical limit when considering the feasibility in practical implementations, such as the number of active antennas in mobile terminal, the interference mitigation techniques within both single device and from network perspective. The limitation in achievable spectral efficiency has pushed the research/development (R&D) and regulation into the other direction, thus enabling the utilization of more radio spectrum with dynamic sharing with the cognitive radio (CR) [1] technology. During the past 15 years, several CR standards have been defined, such as the IEEE 802.22, IEEE 802.11af and ECMA-392. However, they are alternatives to the mainstream cellular technologies and lack of the endorsement by both large network operators and vendors. As a result, despite of the promising concept of CR, it is still far from commercial success. In order to bridge the gap between CR and the cellular technologies, in


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the project kogLTE [2], we are enhancing the LTE system with the CR functionalities to enable the flexible dynamic spectrum access, especially for accessing the significant underutilized TV band. In this paper, the flexible architecture of the cognitive LTE system is presented in Fig. 1. The main component in this architecture is the dual TI C6670 DSP platform which is used for LTE physical layer (PHY) base band processing, spectrum sensing (SSM) and to run the cognitive engine (CE). The ARM processor runs a full LTE protocol stack (PS) implementation and communicates with LTE PHY through an ethernet interface. The baseband platform communicates with the RF front-end (RF-FE) through the common public radio interface (CPRI). The key implementation aspects of spectrum sensing, cognitive engine, RF control and the integration of hardware and software components are introduced in this paper. The architecture and implementation of the testbed makes it particularly suitable for the fast deployable eNodeB system based on tethered aerial platform which is proposed in the FP7 ABSOLUTE project [3]. The organization of this paper is as follows: The Spectrum Sensing Module (SSM) is described in Section 2. The Cognitive Engine Module is illustrated in Section 3. Section 4 gives a brief description of the RF Control Module, and Section 5 describes the integration of the complete system, while Section 6 concludes the paper.

## 2 Spectrum Sensing

The *spectrum sensing module (SSM)* is an essential component to enable the cognitive functionality of the LTE cognitive testbed. It performs periodic and event based spectrum sensing and provides the cognitive engine (CE) with the knowledge about the spectrum environment. Based on the cognitive engine requirements, SSM can perform either blind detection of the signal (e.g. energy detection) or it can also classify the signal (e.g. cyclostationarity-based sensing) [4]. Signal classification is important to distinguish primary and secondary users which helps the cognitive engine to allocate available spectrum resources properly. SSM is implemented on one core of the Texas Instruments (TI) Digital Signal Processor (DSP) (TMS320C6670) [5] and communicates with the cognitive engine which runs on the same core through shared memory. There are three procedures defined for the spectrum sensing module (SSM). The initial procedure is the initial sensing where a simple energy detector based on a TI DSP library function is implemented. This function will return the calculated power for each of the channels to be sensed (the channels to be sensed are provided by the cognitive engine) as shown in Fig. 2 below. The power measurement can be repeated several times to get the mean power of the sensed channel. After the sensing is done a task status flag is set to inform the cognitive engine that the sensing task is finished. The other two procedures are the in-band sensing and out-of-band sensing. The in-band sensing procedure is triggered periodically (each 1-160 ms [6]) to ensure that the operating channel is still free. Energy detection is used to detect any interference in the operating channel. If an interference is detected, the interference flag is set to alarm the cognitive engine that shall select a new

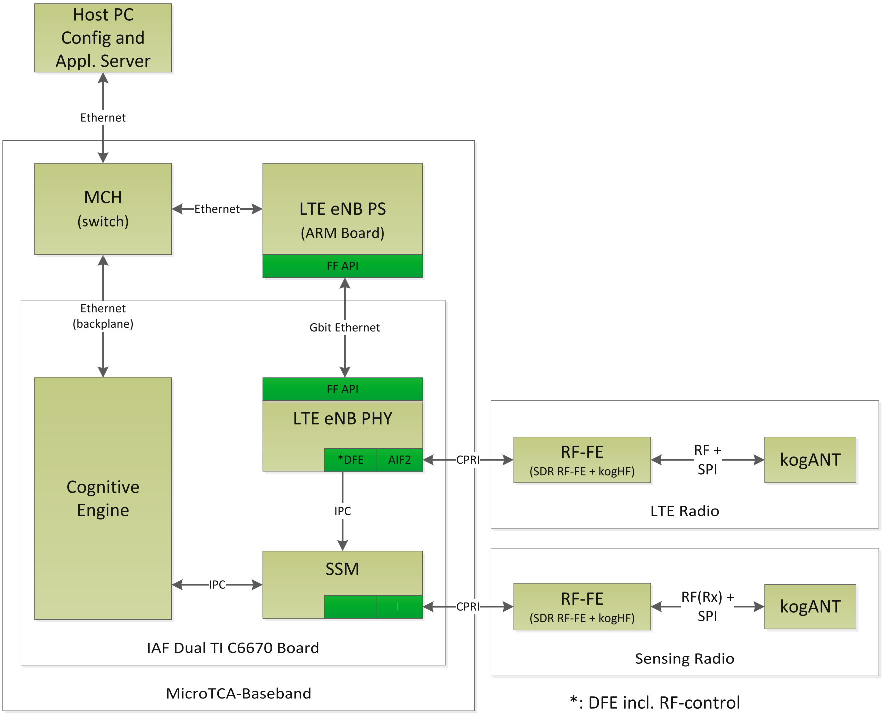


**Fig. 1.** Block diagram of the cognitive LTE Small Cell Base Station

operating channel based on the information in its data base or *radio environment map (REM)* which contains sensing results of other possible operating channels. The out-of-band sensing procedure is also carried out periodically (each 0.1 - 60 sec [6]) to sense one or several channels around the operating channel. If the classification flag is set, the SSM performs an advanced sensing algorithm to classify the type of the signal (DVB-T, LTE etc.), otherwise a simple sensing algorithm like energy detection is sufficient. If an increased interference in one of the sensed channels is detected the interference flag is set to alarm the cognitive engine.

## 3 Cognitive Engine

In this section we describe the SW architecture of the cognitive engine which is depicted in Fig. 3. From the figure it can be seen that the cognitive engine and the spectrum sensing module constitute the cognitive extension. The overall goal in designing the architecture in the logical sense was to keep the cognitive extension as modular as possible to attach it to a commercially available 3GPP LTE Protocol Stack. In the following the cognitive engine modules are highlighted.

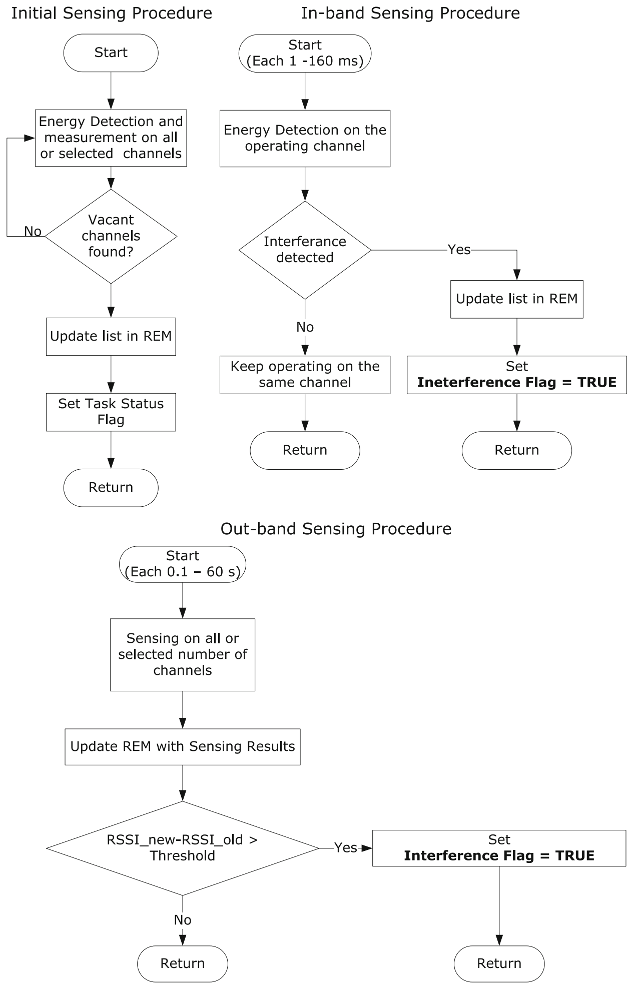


**Fig. 2.** Sensing Procedures

## 3.1 Cognitive Manager

The *Cognitive Manager - CM* is the central part of the architecture and is responsible for the information exchange between the internal and external entities. In particular, it acts as a master to manage the procedures carried out by the slave modules such as the Optimization & Decision Unit or Cognition Unit which perform specific functions. Further, inspired by the architecture in [6] we have defined for the cognitive manager the state machine shown in Fig. 4. When the cognitive BS is turned on, it goes first into the initialization state to find an operating channel. During this procedure, the cognitive devices (BS and UEs) perform spectrum sensing to gather information about the radio environment. The process of gathering information about the radio environment can be further assisted by a database access or in other words with a *REM - Radio Environment Map*. The retrieved information is then stored in the *Cognitive Database*. Next, this information is then used by the *Optimization & Decision Unit - ODU* to execute the core channel selection algorithms. After a suitable channel is found, the CM configures the LTE protocol stack, to be more specific the carrier frequency and the maximum transmit power for the DL and UL are passed to the *Radio Resource Control - RRC* layer. Then, the CM goes into the operating state and is ready for data transmission. During the operating state, the CM carries out two main periodic tasks. One of them is the regular updating of the local REM residing in the cognitive database controlled by a timer $T_{refresh\_REM}$. The other one characterized as background procedures in Fig. 4 is the periodic execution of spectrum sensing tasks. Both of these procedures serve the purpose of keeping the radio environmental information up-to-date. Moreover, in case the interference in the used channel increases above a predefined threshold the *CM_channel_move* flag is set to TRUE and the channel evacuation procedure is executed. This procedure involves notifying the cognitive UEs to stop any transmission and wait for a new channel assignment.

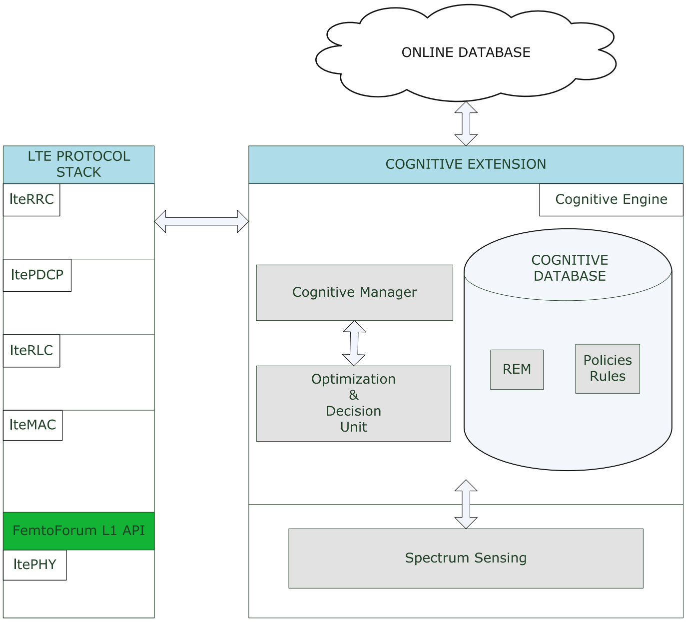


**Fig. 3.** SW Architecture of the Cognitive Extension

## 3.2 Optimization and Decision Unit - ODU

The ODU is as already mentioned responsible for dynamically allocating resources for the cognitive devices. In particular it selects an unused channel

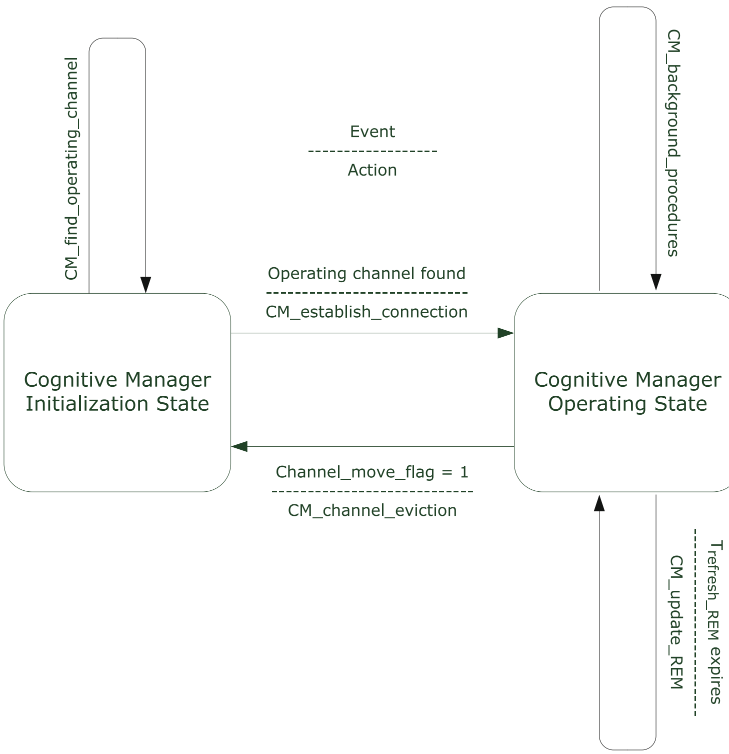


**Fig. 4.** Cognitive Manager as a state machine

and configures the transmit power in order not to cause harmful interference to primary (licensed) users i.e. in case of the *TV White Spaces - TVWS* according to the rules defined in [7]. This access rule allows a secondary access to the licensed TV bands based on a predefined degradation of the outage probability in the reception of the TV signals i.e 1%. Due to space limitation we omit here the detailed description of how to accomplish the channel selection and transmit power configuration and refer for the interested reader to [8]. Specifically, based on the fact that the optimization problem to be solved is non-convex with a combinatorial aspect due to the channel selection, we made use of a meta-heuristic method called *Ant Colony Optimization.*

### 3.3 Cognitive Database

The cognitive database has the task of storing the spectrum sensing results and a location specific copy of the REM retrieved through an online database. Within the external database access procedure, the CM sends to the online database its geolocation coordinates and the external database calculates the received primary signal levels at the position of the cognitive device with the usage of path loss models and information about the TV transmitters which can be gathered from the national institute for broadcasting services in Germany [9]. We used the *Okumura-Hata* path loss model for urban areas and implemented the database on a PC running the C code. The target platform from TI (TMS320C6670) communicates with the database running on the PC through an ethernet interface.

## 4 RF Control

The RF control module (part of the digital front-end DFE in Fig. 1 above) is implemented to control the RF front-end (RF-FE), including RF parameter configurations (e.g. carrier frequency, bandwidth, automatic gain control (AGC), etc.). To enable the reliable transmission of RF control commands between the baseband DSP (the master node) and the RF front-end (the slave node), a two-layer protocol is defined, namely data link layer (DLL) and physical layer (PHY). In the DLL layer, the basic RF control commands and procedures are defined. In order to adapt to the flexible RF control commands in cognitive radio, a frame structure as shown in Fig. 5 with variable length is applied, the end of which is marked by the special symbol "END" for the purpose of frame synchronization. Additionally, a finite state machine with three states, i.e. "RFctrl Initial", "RFctrl Config" and "RFctrl Failed", is defined as shown in Fig. 6. The PHY layer of the RF control can apply the existing RS232 or the common public radio interface (CPRI) in which the fast control and management (C&M) channel is used to convey the RF control commands. The parity check in the PHY layer is used to detect errors in the received command frame based on which the slave node can configure the RF units successfully and reply the acknowledgement (ACK) to the master node or just reply the negative acknowledgement (NACK).


**Fig. 5.** Command frame structure

## 5 Integration Aspects of the Cognitive LTE Testbed

In this section, the hardware and software implementation aspects of the cognitive small cell base station testbed will be described. The software partitioning is planned such that the PHY, CE, and Spectrum sensing are running on a dual

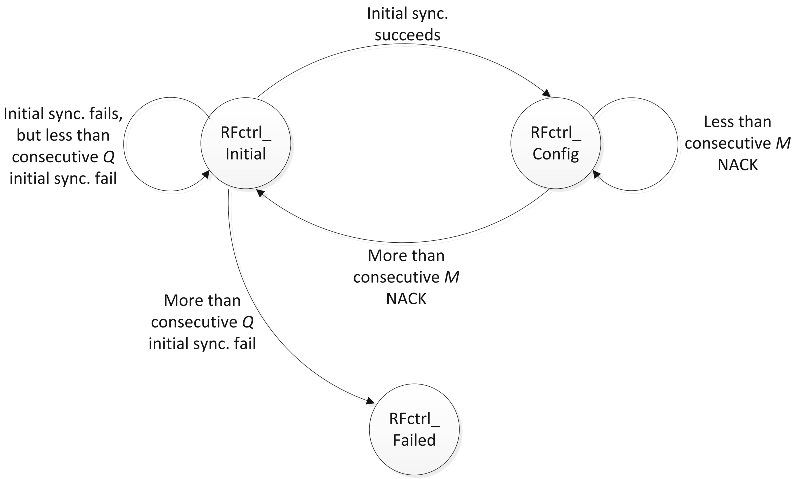


**Fig. 6.** Finite state machine in the master node

C6670 board which has two TI (TMS320C6670) DSPs with 4 cores each [10]. The board has optical connectors (SFPs) towards the RF boards and a Gigabit Ethernet interface (GbE) to the ARM board. The physical layer implementation is following LTE 3GPP specification and is adapted for small cell operation. The protocol stack (PS) including Media Access Control (MAC) is running on a Qseven (Q7) compatible i.MX6 CPU-Module ARM board [11]. The ARM board has two Gigabit Ethernet interfaces for high bandwidth connection to the dual C6670 baseband processing platform and to the Evolved Packet Core (EPC) which is running on a separate linux PC. Fig. 7 illustrates the dual C6670 board and the partitioning of the software components on the different cores.

For the implementation of the cognitive LTE system, only one 4 core-DSP of the dual TI C6670 board is used (The other DSP might be used if more complex algorithms are needed in future). Core0 is used for initialization of the different software modules and also the resource management of the system. Cognitive Engine and Spectrum sensing modules are running on Core1. Core2 is used for the complete LTE PHY baseband processing, while Core3 is used as an interface to the PS running on the ARM board. This interface is used to allow the communication between PHY and PS based on a Gigabit Ethernet (GbE) communication. It follows the Small Cell Forum specification [12], and provides an API towards both Layer 1 and Layer 2 that allows both to communicate with each other through a platform specific transport layer. In this case, the transport layer is the TI Ethernet driver and network coprocessor (NETCP) [13]. The RF boards used include two components: the converter module (kogHF) to allow the

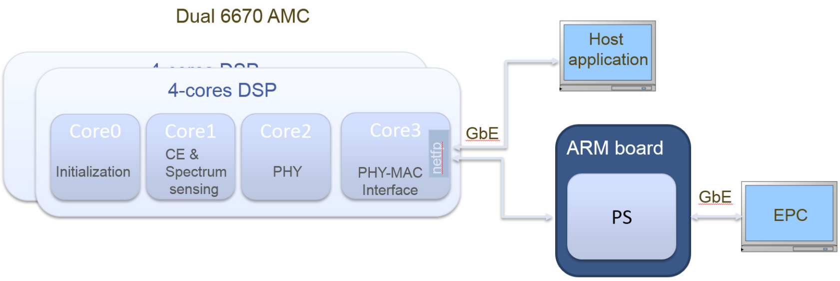


**Fig. 7.** Software partitioning on the DSP

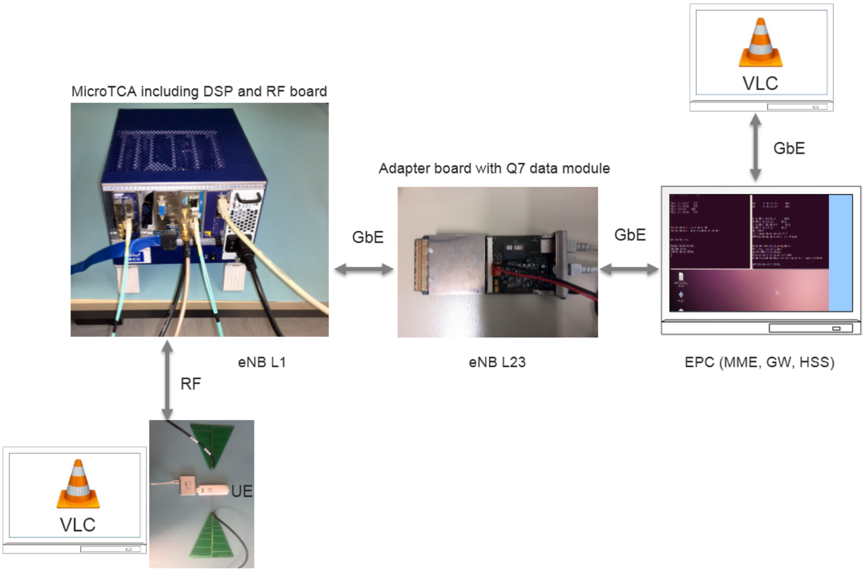


**Fig. 8.** The different hardware components of the cognitive LTE testbed

system to work in TV white space. It is used as an up/down converter between TV whitespace frequency range (470 - 790 MHz) and LTE radio-frequency (e.g. 2.6 GHz). The second component is the software defined radio RF front-end (SDR RF-FE) [14], which is used as a reconfigurable LTE RF front-end. It has a common public radio interface (CPRI) [15] towards the baseband DSP board with a data rate of 2457.6 Mbit/s, Xilinx Spartan-6 FPGA and 2-antenna duplex operation with variable RF signal bandwidth. Fig. 8 shows a picture of the testbed and its different components.

A commercial UE dongle with a test SIM was used for the test. It communicates with the eNB via antennas. At the eNB side, the DSP (PHY) is connected to the SDR RF board via CPRI interface to exchange the baseband IQ signal,

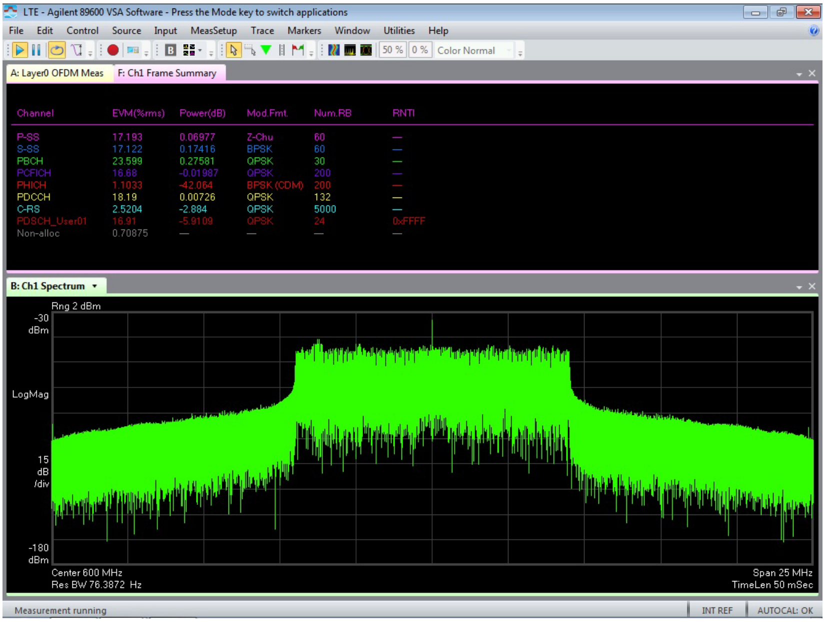


**Fig. 9.** The LTE spectrum and the EVM of the different downlink channels at 600 MHz carrier frequency

and connected to ARM board (eNB L23) via GbE. eNB L23 is connected to the EPC (MME, GW, HSS) with a GbE. An access-net system which is used for data and video streaming is connected on the other side of the EPC. PHY is executed after compiling and loading the binaries to the DSP using Code Composer Studio (CCS). Protocol Stack (PS) binary is loaded to the ARM board. On a Linux PC, HSS, GW and MME are executed. After running the PS, the message exchange between PHY and PS starts, and the broadcasting stage begins. On a separate PC, the UE is controlled and the attach procedure with the eNB is initiated. After RACH, connection and authentication stages, UE is attached to the eNB. Further more, the responsibility of the cognitive extension which is running on the DSP is to sense the environment and choose the right channel available for transmission without affecting the primary users by controlling the RF unit and the PS configuration.

Measurement results of the downlink decoded information at 600 MHz carrier frequency are shown in Fig. 9 and Fig. 10. Agilent MXA spectrum and signal analyzer was used for capturing and decoding the downlink signal.

For video streaming test, an access net machine has been attached to the GW on which a VLC software runs as a media server to stream video to the UE. A DL video streaming with about 8 Mbps throughput has been verified at the UE side with 10 MHz bandwidth. Fig. 11 shows a screen shot of the video received at the UE side.

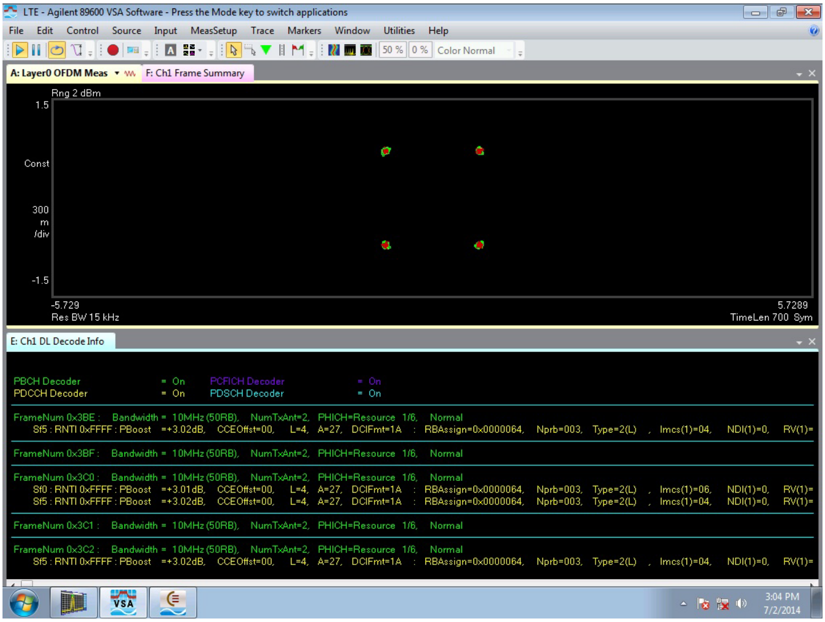


**Fig. 10.** Constellation and downlink decoded information

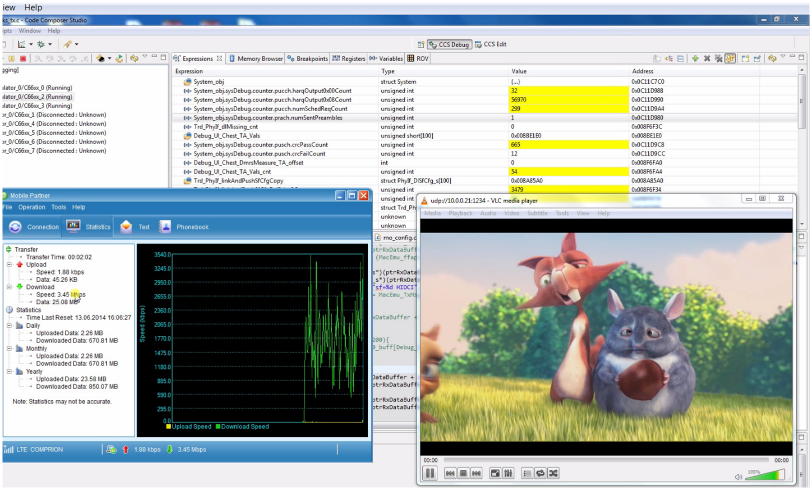


**Fig. 11.** Screen shot of video streaming

## 6 Conclusion

This paper presented the implementation aspects of a cognitive LTE testbed working in TV white space spectrum. It focuses on the implementation and the features of the main components of the system such as LTE PHY, spectrum sensing, cognitive engine, and RF control. The software and hardware integration of the testbed was discussed, and measurement results of the downlink decoded information in TV white space spectrum were presented.

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