A PHY LTE- Advanced analysis and a Software Defined Radio implementation

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Abstract

The capacity, reliability and services demand at high bit rates on cell phone communications are constantly demanding better performance, and together with the RF spectrum limitations force radio systems to achieve great spectral efficiency. In this article we analyze the physical layer (PHY) of the Long Term Evolution Advanced (LTE-A) standard that the workgroup 3GPP (3rd Generation Partnership Project) proposes as a solution to accomplish the 4G (Fourth Generation) compatibility requirements defined by the ITU-R (International Telecommunication Union) including up to 1 Gbps for downlink and 500 Mbps for uplink bit rates [1]. We describe the processes perfomed at the PHY layer in the uplink, and those stages where a free implementation is allowed to full fill the 4G requirements.

Keywords: LTE-Advanced, 4G, SC-FDMA, uplink

1. Introduction

One of the keys to achieve higher bit transmission rates is the implementation and use of antena arrays, which allows spatial multiplexing commonly known as MIMO (Multiple Input Multiple Output) and can be reinforced by the use of relays technique which consists in the transmission-reception of signals from-to users located into the cells to reduce the transmitter-to-receiver distance and thereby allowing for higher data rates [2].

Another key technique for achieving higher throughput in new generation networks is the so called OFDM (Orthogonal Frequency Division Multiplexing) air interface, which is based on the use of orthogonal subcarriers for data transmissions, where every symbol is transmitted in one subcarrier, minimizing multipaths effects in the radio channel, achieving a better performance in joint with an efficient technique like MIMO.

A modification that has been done in the downlink access method is called OFDMA (Orthogonal Frequency Division Multiple Access) which allows to assign different number of subcarriers to the mobile users (according to the needed transmission rate). Furthermore, SC-FDMA (Single Carrier - Frequency Division Multiple Access) has been proposed for the uplink. SC-FDMA allows a full orthogonal scheduled system (multiple users using a part of available carriers) with a low PAPR (Peak to Average Power Ratio) [3]. In the same way, a new technique is implemented on the PHY layer called Carrier Aggregation, which enables to transmit data at very high bit rates in a group of narrow bandwidth carriers, jointly achieving a higher capacity [4].

2. MAC and physical layer technologies (PHY)

2.1. Medium access methods (OFDMA and SC-FDMA)

The OFDMA technique was originally introduced as an air interface technology in the fixed wireless network IEEE802.16d standard in 2004; the IEEE802.16e standard was implemented in 2005 in order to allow users mobility in wireless networks. The adoption of the OFDMA technique on the PHY layer by 3GGP was done in 2005 as an evolution of WCDMA (Wideband CDMA) based on UMTS (Universal Mobile Telecommunications System). such modification is included in the standard refereed as 3GPP LTE Release 8 and it was finished in 2008. The new release of 3GPP standard is known as LTE Advanced Rel 10, which is actually being developed.

OFDMA permits the allocation of time/frequency resources to specific users, these divided on logical basic resource units which consist of subbands in frequency and one or more OFDM symbols in time domain. A subband comprises several subcarriers. The basic resource units are then mapped to the physical OFDMA frame, there exist two permutation schemes, the first one consist in distributing the data to transmit on noncontiguous subcarriers using the frequency diversity, achieving to reduce the error probability due to frequency selective fading or channel interference. In the second scheme, the data is sent in contiguous carriers, to allow multiuser diversity and frequency selective scheduling.

The PHY layer OFDMA implementation involves complications, like PAPR, which is particularly high in OFDM/OFDMA systems, because the OFDM symbol waveform in time domain is the superposition of sinusoids where the frequency is n times the lowest subcarrier. A high PAPR requires power amplifiers with a lineal output over a big frequency range. It is a factor that decreases the battery life and increases the cost in OFDMA mobile devices.

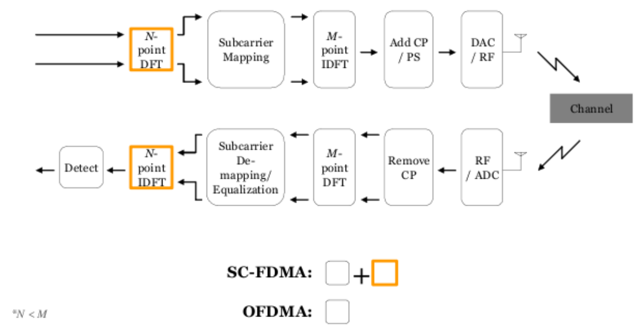

Figure 1. Block diagram of a OFDMA-SCFDMA system.

3GPP LTE-Advanced proposes to use a technology called SC-FDMA or DFTS-OFDM (Direct Fourier Transform Spread - OFDM) in the uplink, which among their main characteristics is the presence of a low PAPR. SC-FDMA technique consist in precoding the data symbol with a discret Fourier transform stage, as shown in Figure 1, and the samples obtained of the precoding stage are parallely transmitted over a subcarriers group. The resulting time domain waveform have the characteristics of a single carrier waveform, with a low PAPR although the waveform is not a single carrier waveform [5].

The SC-FDMA transmitter handles blocks of size N, which contain the samples (complex values) of the digital modulated symbols, the N-point DFT stage generates a frequency domain representation of the input symbols. The samples are mapped in some of the M subcarriers available in the M-point IFFT stage, where $M > N$, transforming the subcarriers amplitude in a complex signal in the time domain. The value of N depends on the amount of users or the expansion factor Q and the amount of available subcarriers M, $(N = M/Q)$.

The samples obtained from the DFT stage are mapped in the corresponding subcarriers through two methods: distributed mapping of subcarriers and localized mapping of subcarriers. In the distributed mode (also known as DFDMA, Distributed Frequency Division Multiple Access), the DFT output is distributed over the subcarriers of all the available bandwidth, that is, on all necessary orthogonal subcarriers, and completing with zeros those subcarriers not utilized. In the localized mode (LFDMA) the DFT output is assigned to contiguous subcarriers, filling with zeros the higher and/or lower subcarriers.

In DFDMA, if the condition of $M = Q \times N$ is accomplished, which means that, the occupied subcarriers are equidistant between them, the scheme is known as interleaving mode (IFDMA). It can be observed in Figure 2 why IFDMA is a special case of SC-FDMA, the implementation of the IFDMA technique becomes very

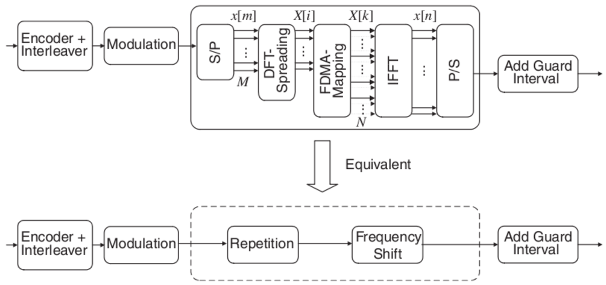

Figure 2. Equivalence of SC-FDMA and DFTS IFDMA in the uplink.

efficient because the SC-FDMA transmitter can modulate the signal strictly in time domain without the DFT and IFFT stages.

Depending on the mapping method, the modulated symbols of SC-FDMA can be different in time domain. For IFDMA, the modulated symbols in time are a repetition of the original input symbols, simply with a scaling factor of $1/Q$ and some phase rotation. DFDMA and LFDMA have the same symbol structure in time and have exact copies of the symbols in time domain with a scaling factor of $1/Q$ in the N positions of the samples and the intermediate values are the sum of all the symbols in time with different complex weight. For this reason there are more expected fluctuations and peaks in the amplitude of DFDMA and LFDMA [6].

2.2. Carrier Aggregation

The Carrier Aggregation technique allows to get together various LTE Carrier Components (CC) with an individual bandwidth of 20 MHz, until achieving a group with a 100 MHz bandwidth (up to 5 CC), and it can be observed as a separate CC of 100 MHz in the spectrum. The objective of grouping is to guarantee the compatibility with LTE devices, which requires a bandwidth of 20 MHz (LTE 8).

There are three configurations of Carrier Aggregation (CA): Contiguous CA, noncontiguous CA in the same band, and noncontiguous CA in different bands. The contiguous CA assigns to a LTE-A user a group of CC as a single CC, although a LTE user only see every CC individually. In case that several contiguous CC are not available, the noncontiguous CA configuration allows a LTE-A user to get the bandwidth required for the transmission. Due to the presence of two LTE users, the available CC are not contiguous, but the amount of all the CC unused in the band allows the bandwidth allocation required by the LTE-A user.

Also, in case that not enough CC exist to fullfill the bandwidth required by the LTE-A user, the CC available in other frequency band can be used, it is known as noncontiguous CA in different bands. In noncontiguous CA in different bands scheme, a LTE-A user can present many different channel conditions due to the use of multiple bands with different frequencies, as well as different propagation delays between bands because of that it is connected to different base stations simultaneously [7].

2.3. Virtualization

The LTE-A transmitter includes the capacity to increase the diversity gain trough a transmission scheme of 8 antennas with only 4 physical antennas in the device. In this case, 4 virtual antennas may be added. In case of a 6×6 array be desired, and just 4 physical antennas are available, two virtual antennas may be appended. This is possible with precoding and a small delay for mapping every diversity flow in a unique subgroup of physical antennas to conform a virtual antenna.

The LTE-A uplink transmitter can transmit two TB simultaneously. Besides it allows the transmission with a MIMO 4×4 scheme through virtualization by the same way like the downlink transmitter, with precoding and a small delay for mapping every diversity flow in a unique subgroup of physical antennas to conform a virtual antenna.

3. Transmission structure

The transmission structure for downlink between the base station and users is defined by [8], where OFDMA is the medium access method technique. Due to the mobile device limitants (in both power and size), the uplink transmitter is designed with SC-FDMA as medium access method (MAC) technique. There are three types of logic channels for data transport, the broadcast channel (PBCH) used for transmitting the basic system configuration information; the multicast channel (PMCH) used for transmission services, like TV over a LTE infrastructure and the downlink shared channel (PDSCH) that is the main data channel, used to transmit data blocks known as transport blocks (TB), they are obtained from the MAC layer (Medium Access Control). In this standard, up to two TB can be transmitted simultaneously by an LTE-A user and downlink and uplink structure subframe using RB.

In the carrier aggregation case, the transmission over multiple subcarriers corresponds to multiple and diverse transport channels, and even to independent process on the PHY layer, like multiple transmitters in the same device to send data into multiple frequency bands.

According to [9], the PHY layer process includes the next stages:

1. 24 bits CRC insertion.
2. Channel coding: Turbo codes based on internal interleaving QPP (Quadratic Polynomial Permutation) with trellis termination.
3. PHY layer ARQ-hybrid process.
4. Channel interleaving.
5. Scrambling.
6. Digital modulation.
7. DFT precoding.
8. Layer mapping and precoding.
9. Mapping to antennas.

3.1. Code Block Segmentation and CRC attachment

A transport block (TB) is first segmented into multiple codeblock segments. There exists three CRC attachment schemes, in CRC attachment scheme 1, a CRC is computed for and attached to each segment independently. In scheme 2, CRC computation for the first codeblock segments is different from that for the last one. For the first segments, CRC is computed for and attached to each segment independently. The CRC bits attached to the last segment are computed based on all information bits of that transport block. In scheme 3, a TB-level CRC computed based on all information bits of that transport block is attached to the TB. The entire transport block along with the TB-level CRC is then segmented into multiple codeblock segments. A CRC is then computed for and attached to each segment independently . The two cyclic generator polynomials for $L = 24$ referred to as gCRC24A (D) and gCRC24B (D) for transport block CRC and codeblock CRC respectively are given as:

$$\begin{aligned} gCRC24A(D) = D^{24} + D^{23} + D^{18} + D^{17} + D^{14} \\ + D^{11} + D^{10} + D^{7} + D^{6} + D^{5} \\ + D^{4} + D^{3} + D + 1. \end{aligned} \tag{1}$$

$$gCRC24B(D) = D^{24} + D^{23} + D^{6} + D^{5} + D + 1 \tag{2}$$

The first polynomial gCRC24A is used for transport block CRC calculation on UL-SCH, DL- SCH, PCH and MCH. The second polynomial gCRC24B is used for codeblock CRC calculation.

In LTE-A a minimum and maximum code block size is specified so the block sizes are compatible with the block sizes supported by the turbo interleaver, the minimum code block size is set to 40 bits and a maximum code block size equals to 6144 bits, if the length of the input block is greater than the maximum code block size the input block is segmented.

3.2. Turbo coding

The turbo coding used is a parallel concatenated convolutional code (PCCC) with two 8-state rate 1/2 constituent encoders and a “contention-free” Quadratic Permutation Polynomial (QPP) interleaver, The transfer function for each constituent encoder is given by:

$$G(D) = \left[1, \frac{g_1(D)}{g_0(D)}\right], \tag{3}$$

where

$$g_0(D) = 1 + D^2 + D^3, \tag{4}$$

$$g_1(D) = 1 + D + D^3. \tag{5}$$

The rate 1/3 turbo code generates a stream of systematics bits, a stream of parity bits from the first convolutional code (parity 1 bits) and a stream of parity bits from the second convolutional code (parity 2 bits).

The role of the interleaver in the second convolutional code input is to spread the information bits such that in the event of an error, the two codes are affected differently allowing data to still be recovered. The relationship between the output index i and the input index (i) satisfies the following quadratic form:

$$\Pi(i) = f_1 \cdot i + f_2 \cdot i^2 \mod K, \tag{6}$$

where K is the number of input bits to the turbo code internal (QPP) interleaver, $0 < i$ and $f_1,\ f_2 < K$. The common values of f_1 and f_2 are that the greatest common divisor of f_1, and K should be 1 and any prime factor of K should also divide f_2.

3.3. PHY layer ARQ-hybrid process

The bits input to the block interleaver are the bits for each of systematic, parity 1 and parity 2 streams. The interleaving is achieving by writing row-wise in a 32 column rectangular matrix, applying matrix columns permutations and finally reading from the matrix column-wise. The inter-column permutation for the matrix is performed based on the bit-reversal-order pattern, this is, for column 0001, the reversed bit number is 1000.

An additional interlacing is only performed between parity 1 and parity 2 bits, The systematic bits are not interlaced, This is to guaranteed an equal amount of parity 1 and parity 2 bits transmission.

3.4. Channel Interleaving

This subblock consists in a simple interleaver where bits are written to a rectangular matrix row-by-row and read out column-by-column .

3.5. Scrambling

The code bits delivered by the hybrid-ARQ functionality is multiplie (exclusive-or operation) by a bit-level scrambling sequence which consist in a unique ID cell. By applying different scrambling sequences for neighboring cells, the interfering signal after descrambling is randomized, ensuring full utilization of the processing gain provided by the channel code .

3.6. Digital modulation

The set of modulation schemes supported includes QPSK, 16QAM, and 64QAM, corresponding to two, four, and six bits per modulation symbol respectively.

3.7. DFT precoding

The modulation symbols, in blocks of M symbols, are fed through a size-M DFT, where M corresponds to the number of subcarriers assigned for the transmission.

The DFT size should be constrained to a multiple of 12, from 12 up to 204, where the DFT can be implemented as a combination of relatively low- complex radix-2, radix-3, and radix-5 FFT processing. The DFT sizes of 60, 84, 120, 132, 156, 168, 180 and 204 will not be allowed .

3.8. Layer mapping and precoding

The complex symbols are mapped to one, two or four layers sequentially, this is, un case of two layer the even symbols are mapped to the first layer and the ood symbols are mapped to the second layer. In single mode, the symbols are mapped to one layer; in diversity mode, the symbols are mapped into two or four layers, depending on the number of transmit antennas used; in spatial multiplexing mode, the symbols are mapped into two, three or four layers, in this case the number of layers is always less or equal to the number of antennas used.

There exists three types of precoding, spatial multiplexing, transmit diversity and single antenna port transmission. Within spatial multiplexing there are two schemes; precoding with large delay Cyclic Delay Diversity (CDD), also known as open loop spatial multiplexing and precoding without CDD also known as closed loop spatial multiplexing.

For transmission over a single antenna port no processing is carried out over the symbols, for transmit diversity its employed an Alamouti scheme space-frequency for two and four antennas, for spatial multiplexing its employed a codebook configured by the eNodeB and user equipment when is required.

3.9. Mapping to antennas

The transmission scheme is based on a conventional OFDM transmitter. 7 OFDM symbols make a slot with a duration of 0.5 ms, a subframe is conformed by two slots, it corresponds to a TTI (Transmission Time Interval) with a duration of 1 ms. A radioframe takes 10 ms, so that, this is formed by 10 subframes or 10 TTI with a duration of 10 ms. The space between OFDM subcarriers is 15 kHz, where 12 subcarriers constitute a resource block (RB). The RB can contain from 6 up to 110 blocks. There are two kinds of cyclic prefix for the 7 OFDM symbols, the normal prefix of length $160 \times T_s$ (for the first OFDM symbol), another one $144 \times T_s$ (for the rest of OFDM symbols); and the extended prefix of $512 \times T_s$ (for all OFDM symbols) where $T_s = 1/(2048/15kHz)$ which is the space between subcarriers. The system bandwidths are between 1.08 MHz (6 RB) up to 19.8 MHz (110 RB).

4. Transmission modes

LTE and LTE-A include the layer concept, which consists on assigning the transport blocks to the corresponding antenna for the transmission; it is worth to mention that the quantity of modulated symbols is the same, and equals the sum of the symbols to transmit in every antenna. There exist many transmission modes in LTE-A that indicate the way in which one or two transport blocks, after digital modulation, are mapped and processed to the different device antennas.

The transmission modes are:

Transmission mode 1: Single-antenna transmission.

Transmission mode 2: Transmit diversity.

Transmission mode 3: Open-loop codebook-based precoding in the case of more than one layer, transmit diversity in the case of rank-one transmission.

Transmission mode 4: Closed-loop codebook-based precoding.

Transmission mode 5: Multi-user-MIMO version of transmission mode 4.

Transmission mode 6: Special case of closed-loop codebook-based precoding limited to single- layer transmission.

Transmission mode 7: Release-8 non-codebook-based precoding supporting only single-layer transmission.

Transmission mode 8: Release-9 non-codebook-based precoding supporting up to two layers.

Transmission mode 9: Release-10 non-codebook-based precoding supporting up to eight layers.

These transmission modes are only applicable for sending DL-SCH.

In transmit diversity mode, the transmitter as well as the receiver use all the antennas to mitigate the multi-path fading efects. This scheme is based in the Alamouti's space frequency block code (SFBC) and support two and four antennas.

When using transmit diversity mode, only a transmit TB per user is allowed, this is because the way the symbols are sent by the Alamouti's scheme, as shown in equation (7), the values for x_n are complex samples from a DFT precoding stage. The ith row is transmitted from the ith antenna, and each kth column is transmitted in the corresponding kth subcarrier. Subcarrier k_n is assigned by the IFFT stage inside an OFDM block.

$$\begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix} \tag{7}$$

For the configuration of four antennas, the Alamouti's code is defined by equation (8), where all the subcarriers are adjacent (columns).

$$\begin{bmatrix} x_1 & x_2 & & \\ & & x_3 & x_4 \\ -x_2^* & x_1^* & & \\ & & -x_4^* & x_3^* \end{bmatrix} \tag{8}$$

The spatial multiplexing mode, including both open-loop and closed-loop, are permitted by LTE-A, allowing every antenna to have an independent data flow. It must be mentioned that this mode is not standardized in 3GPP LTE Advanced Rel 10, allowing the free implementation of any algorithm for spatial multiplexing.

The basic procedure for codebook-based precoding consist in mapping the modulated symbols corresponding to one or two transport blocks in multiple layers. The quantity of layers are from one to the quantity of antennas presented in the device. The open-loop spatial multiplexing is intended for high mobility users, where the transmitter does not have knowledge of the channel. The precoding scheme used in this mode is based on CDD (Cyclic Delay Diversity), where a series of defined precoded matrices are applied in every RE (Resource Element); as a result, a frequency domain diversity is obtained, by the delay applied in every RE, even if the channel over the RE doesn't need it, as in a flat fading case [10].

The maximum possible throughput by LTE-A is obtained in spatial multiplexing closed-loop mode, but this technique requires the feedback of the channel state information at the transmitter (CSIT) and the user must have a low to medium mobility as well as a channel with medium to high SNR.

When the channel is perfectively known by the transmitter, the optimum scheme for spatial multiplexing is precoding by singular value decomposition (SVD) [11], which spatially decomposes the MIMO channel into virtual channels orthogonal among themselves.

5. Development in an USRP testbed with GNU Radio

The transmission capacity of LTE-A can achieve up to 3 Gbps; however, since we are using an USRP based testbed, the maximun data rate is restricted by the USB 2.0 interface. Actually, the USRP cards can sustain a 32 MBps data rate via USB 2.0. All samples sent over the USB interface are in 16-bit signed integers with IQ format; this means, 16-bit in-phase and 16-bit in- quadrature data where the data size is 4 bytes per complex sample. This results in a 8 MSps across the USB obtained from 32 MBps / 4 Byte. Since complex processing is used, this provides a maximum effective total spectral bandwidth of about 8 MHz, according to the Nyquist criteria [2].

GNU Radio is a free open source project of SDR for Python programming language, like a communication control plane, which allows the implementation of new Digital Signal Processing (DSP) blocks written in C++ programming language for critical and high performance processes in the data plane, it will allow to develop several routines that are not included in the actual GNU Radio project libraries. The stages like OFDM modulator, digital modulation and DFT spreading are performed with the available functions in GNU Radio libraries.

5.1. DFTS-OFDM Implementation

Figures 3 and 4 show a GNU Radio based implementation, the transmitter block diagram shows the bits generation, the CRC attachment, the header and payload bifurcation, their corresponding digital modulation (QPSK for header and 16-QAM for payload), the 192-points DFTS stage and the OFDM transmitter. The receiver shows a OFDM symbol detection stage based on Schmidl and Cox technique, when a symbol is detected the demux stage split the data flow into the header and payload stream, after the header is detected, the receiver has a channel state knowledge and performs the payload

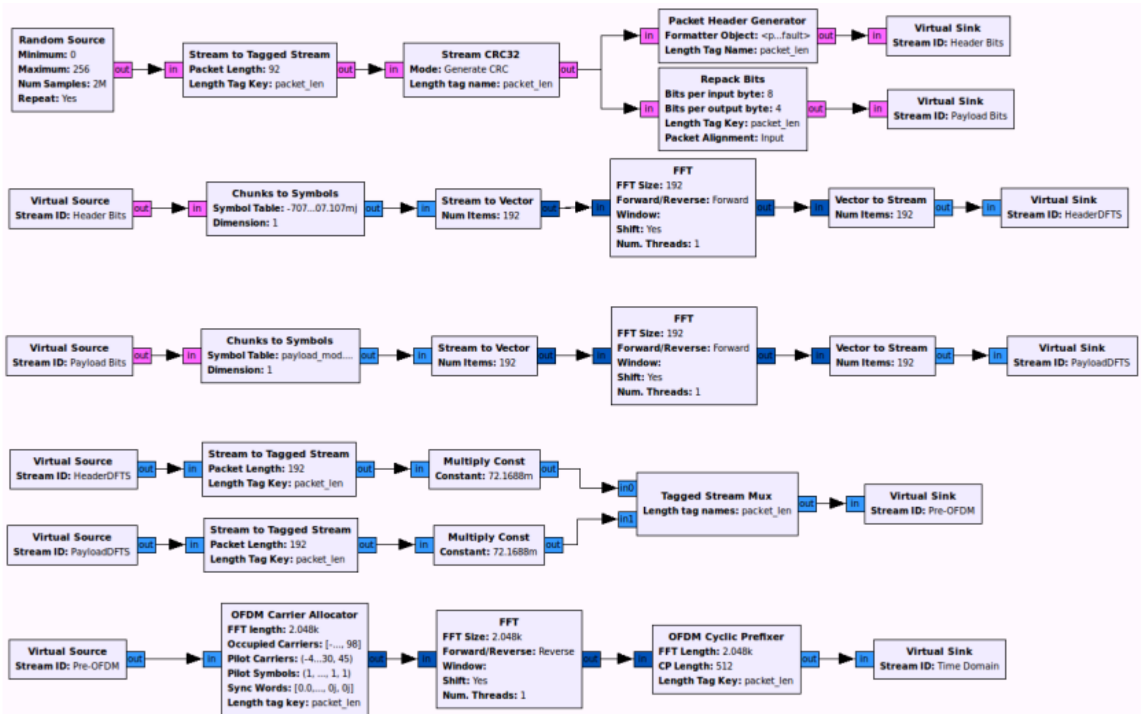

Figure 3. Block Diagram of a DFTS-OFDM SDR transmitter implementation.

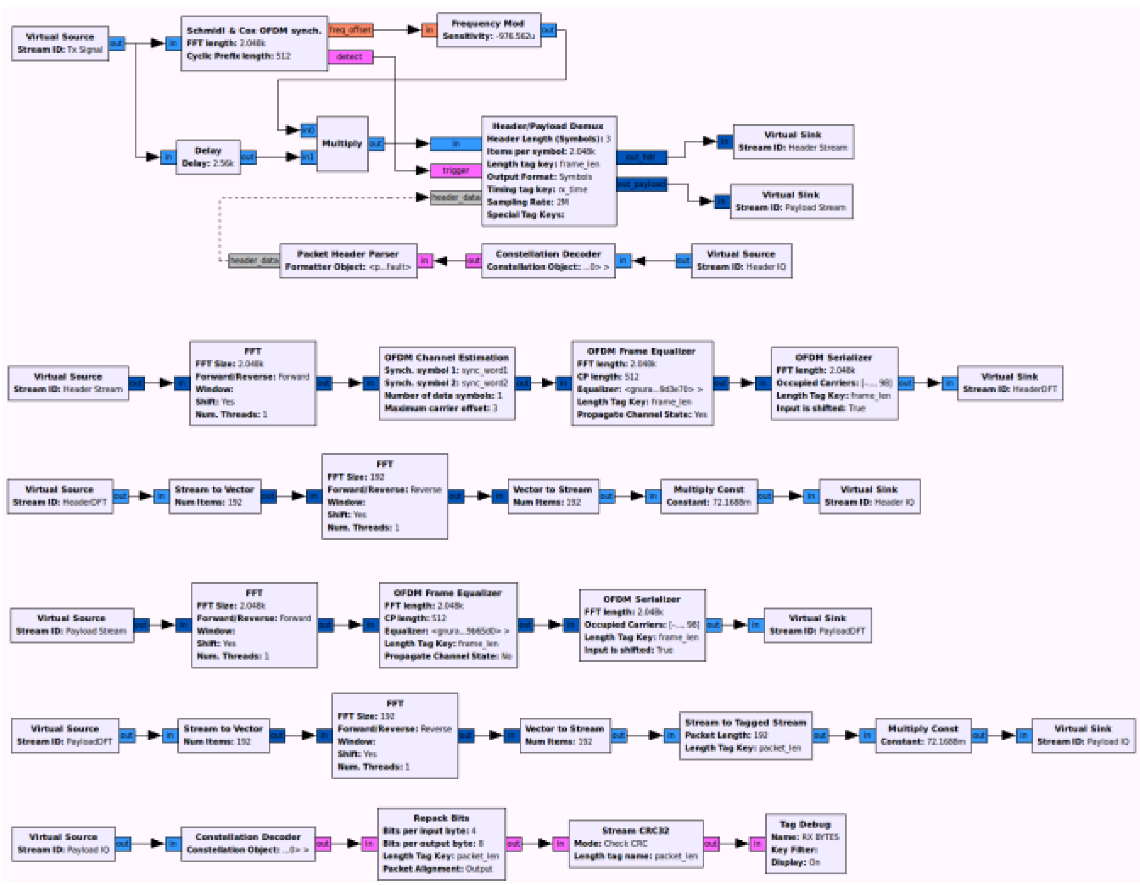

Figure 4. Block Diagram of a DFTS-OFDM SDR receiver implementation.

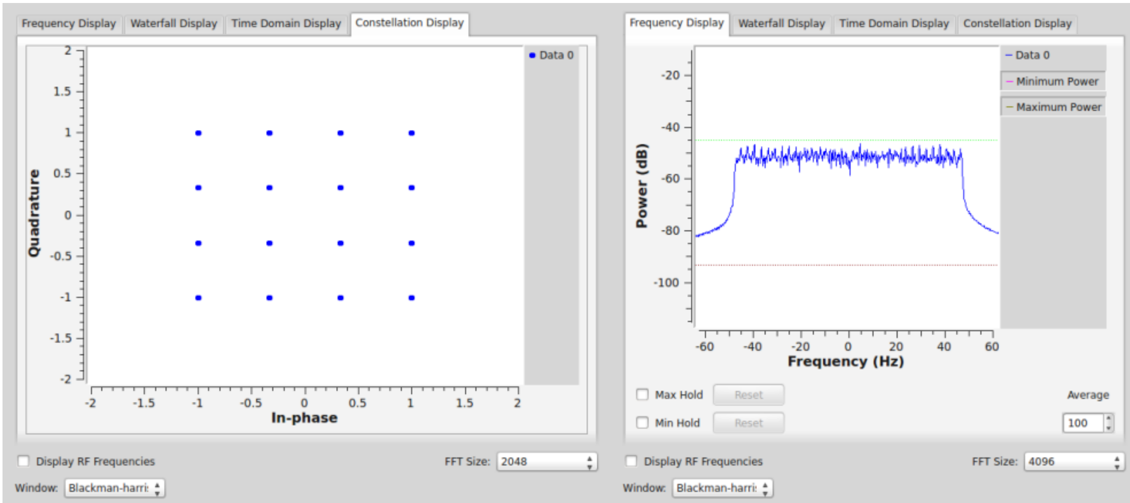

Figure 5. Implementation results.

recovery process, equalizing the OFDM symbol, applying a DFTS inverse process and finally demodulating the received signal. We can observe in Figure 5 an OFDM transmitted symbol and the payload constellation diagram at the receiver.

6. Conclusions and Future Work

This article is an overview of the stages that are part of the PHY layer of 3GPP LTE-A, where the implementation of SC-FDMA in mobile devices allows great battery power savings; the LTE-A standard also allows the use of a single OFDM symbol by many users at same time, by means of the OFDMA and SC-FDMA techniques for downlink and uplink respectively. The Carrier Aggregation technique (CA) offers to the mobile devices a bigger bandwidth (up to 100 MHz) by grouping different carrier components (CC). And the implementation of antenna virtualization (by precoding and a small delay) increases the transmissions modes up to 8x8 antenna array, which yields the freedom to implement multiple diversity techniques in the spatial, frequency and time domain.

Actually, we are developing a SDR project which allows an implementation of LTE-A PHY layer stages in a software environment called GNU Radio. The next step consists in developing the channel coding stages and perform a MIMO based communication between two or more USRP devices, to improve performance analysis with the aid of measurements.

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