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Performance analysis of a fourth generation wireless communication system developed on a software defined radio environment.

Tesis
para cubrir parcialmente los requisitos necesarios para obtener el grado de
Doctor en Ciencias

Presenta:

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Resumen de la tesis que presenta Víktor Iván Rodríguez Abdalá como requisito parcial para la obtención del grado de Doctor en Ciencias en Electrónica y Telecomunicaciones.

Análisis de desempeño en la implementación de un sistema de comunicación inalámbrica de cuarta generación en una plataforma de radio definido por software.

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En los sistemas de comunicación de 4ta y 5ta generación se propone el uso de técnicas que aumenten la capacidad de canal al máximo, tales como el uso de múltiples antenas combinado con altos esquemas de modulación y un gran número de subportadoras ortogonales entre si, permitiendo explotar eficientemente el espectro limitado disponible. La dimensión espacial permite aumentar la capacidad de canal, el uso de múltiples antenas propicia la diversidad de información y el uso de receptores sencillos para la estimación de símbolo. En cambio, las técnicas de multicanalización permiten transmitir a altas tasas de transmisión con receptores mas complejos en la estimación del símbolo.

El incremento de dispositivos conectados a la red celular y el aumento de aplicaciones que requieren un ancho de banda mayor han provocado un cambio en la forma como se estructura la red celular. Tendencias como densificación de red, comunicación dispositivo a dispositivo y la presencia masiva de antenas obligan a usar arreglos virtuales para poder gozar de estas tecnologías. El uso de protocolos cooperativos permite la virtualizacion de arreglos de antenas y la comunicación con dispositivos que se encuentren en el límite de la cobertura de la célula, con ayuda de nodos repetidores fijos o móviles.

En esta tesis se desarrollaron las simulaciones para la implementación de la codificación de Alamouti en la segunda fase de los protocolos cooperativos dividiendo el código de diversidad espacial en cada nodo relay; además se desarolló una tecnica de estimación de símbolo para multicanalización debido a los cambios de dominio tiempo-frecuencia-tiempo al momento de agregar Direct Fourier Transform Spread (DFTS) en un receptor DFTS - Orthogonal Frequency Division Multiplexing (OFDM).

En las plataformas de radio definido por software (SDR) se desarrolló un sistema de comunicación basado en DFTS-OFDM punto-a-punto, así como la implementación de una estimación ciega de SNR para OFDM en el receptor el cual se usó para el cálculo de las curvas de desempeño. Finalmente, se implementaron los nodos relay para AF, DF y EF de dos saltos en un arreglo de tres plataformas de SDR.

Palabras Clave: **SDR, DFTS-OFDM, USRP, Protocolos cooperativos.**

Abstract of the thesis presented by Víktor Iván Rodríguez Abdalá as a partial requirement to obtain the Doctor in Sciences degree in Electronic and Telecommunications.

Performance analysis of a fourth generation wireless communication system developed on a software defined radio environment.

Abstract approved by:

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Dr. Jaime Sánchez García
Thesis director

The 4th and 5th generation wireless communication systems propose the use of techniques that provide a maximum increase in the channel capacity, like the use of multiple antennas in combination with high modulation schemes and a large number of orthogonal subcarriers allowing to efficiently exploit the limited available spectrum. Exploiting the spatial domain allows to increase the channel capacity, the use of multiple antenna arrays allows to transmit in either the diversity . Diversity techniques allow to get low bit error rates in the channel with simple receivers for the symbol estimation. On the other hand, multiplexing techniques allow to exploit the low noise channel condition to generate independent data flows, but increases the complexity of the receiver.

The increase of both, the number of devices connected to the cellular networks and the amount of applications that require wider bandwidths, have induced a change in the way the cellular network is structured. Trending topics like network densification, device-to-device communication and the massive antennas presence force to use virtual arrays to facilitate the access to these technologies. The use of cooperative protocols allows the virtualization of antenna arrays and the communication with devices at the edge of the cell, with the support of fixed or mobile relay nodes.

In this dissertation we developed several simulations for Alamouti coding in phase two of cooperative protocols, dividing the space - time code in every relay node for their implementation; additionally, a symbol estimation technique for multiplexing due to the time-frequency-time domain switching introduced by the addition of the Direct Fourier Transform Spread (DFTS) stage in a DFTS - Orthogonal Frequency Division Multiplexing (DFTS-OFDM) receiver was developed.

In the software defined radio (SDR) boards, a point-to-point DFTS-OFDM wireless communication system was developed, including a SNR blind estimation for OFDM at the receiver which was used for Bit Error Rate (BER) performance estimation. Finally, the AF, DF and EF relay nodes for two hopes in a three SDR hardware array were developed.

Keywords: **SDR, DFTS-OFDM, USRP, Cooperative Protocols.**

Dedicatory

To my parents

Víctor Manuel Rodríguez Félix

Ana Rosa Abdalá Román

For being who they are, for showing me that in life you can achieve what you wish to do and with no restrictions that can stop us. For the confidence and support they showed me during these years I was away and being there for me at any moment I needed them.

To my uncle and aunt

Aureliano Rodríguez Félix

Marta Reynoso

For accepting me into their family and helping me endure times of loneliness.

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1. Introduction

1.1 Fourth and fifth generation systems physical layer techniques

The communications industry has experienced a tremendous growth in areas of research and development of SDR technology, however the development of SDR prototypes require specialized tools and knowledge in the management of programming languages and digital signal processing. These tools can have an educational and research impact as they allow a fast implementation of different communication systems. SDR is an emerging technology that increases the capacity of research and development at low cost, because it allows software modifications which are not possible in conventional radio systems (González *et al.*, 2009).

The SDR technology is a radio-communication technique where the components previously implemented in hardware are now implemented in software modules, mainly using embedded systems like FPGAs (Field Programmable Gate Arrays) and/or microprocessors. Although the SDR concept is old, the new digital technology evolution has made it possible to implement many functions through software, instead of hardware, that previously were proposed from just a theoretical point of view.

The PHY layer implementation in a SDR platform allows great flexibility in adapting information signals to different transmission channels (spectrum availability or interference changes) at the execution time, techniques such as cognitive radio can automatically adapt the wireless devices during the transmission. Platforms such as GNU Radio (radio libraries open source software) allow SDR to manage devices such as USRP (Universal Software Radio Peripheral) (Kindratenko *et al.*, 2005).

USRP is a basic platform of SDR, it implements the application functionality and ADC and DAC functions. But this device assumes that the PHY layer processing will be performed by the computer to which it is connected. GNU Radio is a software toolkit designed to run software radio in computers in combination with a hardware testbed, that allows the construction of software radio devices. GNU Radio signal processing block libraries include modulation, demodulation, filtering and I/O operations such as file access to its transmission data. It also offers communication blocks for USRP devices, and allows clear and simple manipulation of these devices (Dhar *et al.*, 2006).

The fourth generation concept includes high performance radio techniques like MIMO (Multiple Input Multiple Output) and OFDM (Orthogonal Frequency Division Multiplexing), two terms that define the 3G evolution. The ITU (International Telecommunication Union) requirements and 4G standards specify the following characteristics: for the radio channel access to abandon CDMA (Code Division Multiple Access) UMTS (Universal Mobile Telecommunications System) access technique and adopt OFDMA (Orthogonal Frequency Division Multiple Access) and SC-FDMA (Single Carrier - Frequency Division Multiple Access), which is a traditional OFDM transmitter with a DFT (Direct Fourier Transform) spread; To implement SDR (Software Defined Radio) looking for the optimization of the PHY layer stages; To have an all IP (Internet Protocol) network; Maximum peak rate up to 100 Mbps in downlink and 50 Mbps in uplink (with a bandwidth of 20 MHz in both links and 40MHz in some configurations) (Wu *et al.*, 2011).

The fifth generation involves a new concept in network design, mainly due to a massive increase in traffic volume and a huge growth in connected devices with several requirements for a wide range of applications like video calls, VoIP (Voice over IP), cloud storage and synchronization with other devices; as a consequence, more bandwidth and frequency range is required. Its proposal covers massive MIMO, device-to-device (D2D) communication and network densification, that implies a new way to use the spectrum and acquire new frequency ranges (Saravanan and Ravi, 2011).

The 4th and 5th generations of wireless communications have in common the high transmission rates and increased capacity on their mobile devices. Among the key improvements is the solution through multiple antennas enabling spatial multiplexing with up to 8 transmit and 8 receive antennas, so in the case of LTE, CoMP (Coordinated Multipoint) is added in the transmission and reception of signals to/from users which are located in multiple cells (Parikh and Basu, 2011).

The main focus of the wireless technology has been geared towards the delivery of rich multimedia content, transmitted over links with high spectral efficiency, low latency and proper QoS (Quality of Service). Among the changes compared to previous generations, it is the OFDM air interface, which allows techniques such as MIMO to be efficient and provide high gain independent data streams. Another change was the implementation of SC-FDMA in the uplink, this allows a scheduled orthogonal system (multiple users using a portion of the available subcarriers) with low PAPR (Peak to Average Power Ratio) based on DFTS-OFDM transmitters (Nagaraj *et al.*, 2009).

MIMO specifically refers to the way the radio waves are handled in the transmission and reception stages through multiple antennas. In traditional wireless transmission systems, the signal is affected by the channel because of the multipath propagation, which causes phase changes and thus data errors. MIMO exploits the multipath propagation phenomenon to increase the transmission rate and reduce the error rate, so it increases the spectral efficiency of a wireless system through the use of the spatial domain. MIMO technology has been used in wireless communications systems, like 802.11n and 802.16m, achieving a significant increase in the rate of information transmission through different channels via spatial multiplexing (Kadhim and Ismail, 2011).

Space Frequency (S-F) coding is a wireless communications technique for achieving maximum diversity gain when transmitting through an antenna array. The transmitted waves suffer from fading in the wireless channel, and since each copy follows a different path, some copies will be more damaged than others. It is possible to use the redundancy to more accurately estimate the transmitted signal. S-F codes combine all copies of the received signal in a way that it is possible to extract as much information from each of them, even though the received signal is a sum of all signals transmitted in each of the antennas.

Modulation schemes of higher degree in combination with an array of antennas allow transmission rates to increase significantly. Communication between a node and a mobile device may have delays in transmission, but the use of two or more nodes for simultaneous data transmissions would reduce these delays and greatly increase the transmission capacity with virtual antenna arrays. A cooperative communication system based on the use of STNC codes (Space-Time Network Codes) was proposed to achieve time and frequency synchronization with each node. For a network of N client nodes, R relay nodes and a base node, the STNC offers a diversity of order (R+1) for each transmitted symbol with (N+R) time slots, resulting in a reduction of 2N time slots compared to a traditional cooperative systems which has N(R+1) time slots. STNC codes also allow the client nodes to act as relay nodes for other customers to increase the transmission performance (Lai and Liu, 2011).

Although the cooperative communications capacity has been studied for decades (Cover and Gamal, 1979), 4G and 5G wireless networks take advantage of the presence of relay nodes to extend the capacity of cellular networks, at the cost of increasing the system complexity and the signalling overhead required for supporting device cooperation; however, the costs related with site acquisition and backhaul are lower than those of a base station (Hoymann *et al.*, 2012). The presence of relay networks concept allows, inside a cell, to coordinate among distributed antennas and achieve a macro diversity gain similar to MIMO diversity gain through a technology called cooperative, distributed or virtual MIMO, where the antenna array is conformed by several relays or mobiles in the cell (Sendonaris *et al.*, 2003; Wang *et al.*, 2010; Zhang *et al.*, 2015).

The use of relay stations to implement pico-cells allows the densification-over-space concept inside a cell, with the advantage of low power consumption. Since the macro-cell signals will be received with higher power at the mobile, they may have preference over the pico-cells signals, however the goal is to keep the mobile connected to the pico-cell to achieve better quality of service (Nunes *et al.*, 2014).

Network densification is the key mechanism for wireless evolution. It includes densification over space and frequency. Large-scale cost-effective spatial densification is facilitated by self-organizing networks and inter-cell interference management. Full benefits of network densification can be realized only if it is complemented by backhaul densification, and advanced receivers capable of interference cancellation (Bhushan *et al.*, 2014).

Clearly, the signal bandwidth can be increased by using additional spectrum, which leads to a linear increase in data capacity. The data load can be decreased through cell splitting, which involves deploying a larger number of base stations, and ensuring that user traffic is distributed as evenly as possible among all the base stations. Spatial multiplexing can be increased using a larger number of antennas at the base station and user devices (Iosifidis *et al.*, 2014).

Cell splitting has the favourable side-effect of reducing the path loss between a user device and base stations, which increases both desired and interfering signal levels. As a result, interference mitigation is paramount for link efficiency improvement in modern cellular systems. This requires a combination of adaptive resource coordination among transmitters and advanced signal processing at the receivers.

Network densification is a combination of spatial densification and spectral aggregation. Spatial densification is performed by increasing the number of antennas per node, and increasing the density of base stations deployed in the given geographic area, while ensuring nearly an uniform distribution of users among all base stations. Spectral aggregation refers to using larger amounts of electromagnetic spectrum, spanning all the way from 500 MHz into the millimetric wave bands (30–300 GHz) (Swindlehurst *et al.*, 2014).

1.2 Problem statement

The existence of projects based on both SDR and USRP in the area of wireless communications is scarce or deals with previous generation systems, such as OpenBTS (Natalizio *et al.*, 2010) (which is a cellular communications SDR based on GSM technology), Hydra (Mandke *et al.*, 2007) (a project that emulates a communication system according to the IEEE802.11n standard), or WimaxScanner (Alshaalan *et al.*, 2010) (a project that seeks to implement the IEEE802.16e PHY layer). The proposed research aims to the implementation of a DFTS-OFDM wireless communication system and its performance analysis; it considers the design and programming of different PHY layer stages (such as spatial diversity codes, QAM digital modulation and OFDM modulation) using the SDR platform. The performance will be measured in a multipath channel environment, with and without considering a line-of-sight (LOS).

1.2.1 General objectives

To design and implement a DFTS-OFDM SDR architecture system in the USRP card including all stages that comprise the PHY layer communication standard, to analyse its performance in real environments. Then to proceed to modify their space-time coding and the modulation scheme, implementing these changes on the SDR card; the results will be compared with those obtained with the original version.

1.2.2 Particular objectives

To study the requirements for implementing wireless communication systems in SDR platforms. To design software modules that emulate hardware stages of a communication system.

To study the current wireless communication standards for developing PHY layer functions with a simulation tool and then proceed to emulate these PHY functions on a SDR platform.

To study the different types of space-time codes and space-time network codes for implementation in SDR platforms and analyse their performance regarding wireless network requirements.

The evaluation will be done in terms of bit error rate (BER) versus signal to noise ratio (SNR).

1.3 Thesis outline

The organization of this thesis is as follows:

In Chapter 2, we provide some background material which will be used in developing our main contributions and results contained in this thesis. We begin with a brief description of SDR and GNU Radio, where we show how several software libraries and new software modules with original codes can be included into our project.

In Chapter 3, we briefly review the concept of DFTS-OFDM, the main difference with a traditional OFDM transmitter and how it achieves a low PAPR. We also describe OFDMA and SC-FDMA with the interleaved and contiguous operation modes as well as basic configurations.

In Chapter 4, we show the most common techniques used in MIMO for both diversity and multiplexing in spatial domain.

In Chapter 5, we discuss diversity techniques for cooperative protocols in wireless communications. Also, a general overview on amplify-and-forward, decode-and-forward and equalize-and-forward is given.

In Chapter 6, we define how the DFTS-OFDM transmitter will work in both simulation and emulation environment, their basic requirements and settings. We also describe the link from the source to the destination node, passing through the relay node, according to the cooperative protocol implemented. Finally, we present a description of the modifications made to the transmitter, for both diversity and spatial multiplexing, due to the presence of the DFTS stage.

In Chapter 7, we propose some scenarios conforming its capabilities to perform a transmission with cooperative protocols. We discuss several considerations like channel estimation for amplify-and-forward in spatial diversity and frequency domain equalization for spatial multiplexing.

In Chapter 8, both performance simulation and emulation results of the proposed scenarios will be presented and examined.

Finally, Chapter 9 contains some concluding remarks and discussion on future research on this topic.

2. Software Defined Radio

2.1 Introduction

Based on projects like (Zheng *et al.*, 2008; Mandke *et al.*, 2007), the development of several wireless communications technologies with general purpose programmable radio testbeds is a reality; this allows the free development and modification of software for different PHY layer stages in a single testbed without hardware settings because these settings will be defined by a programming line code (Reddy and Lakshmi, 2014). This paradigm known as Software Defined Radio (SDR) allows to resolve many hardware problems at the RF stage by means of software algorithms. The SDR main advantage is that it does not require RF laboratories or special equipment, only a computer and a SDR test-bed to deploy a radio communication system (Mitola, 1995; Mitola III, 1993).

The open source toolkit GNU Radio (Barros *et al.*, 2012) allows the user to access signal processing block libraries oriented to communications, this toolkit is developed in Python programming language, allowing to monitor the system development through an easy control panel with the high precision and critical operations performed by libraries in C++ programming language in a kind of data panel. In this way, C++ performs only the mathematical operations and Python controls all the system parameters (Marwanto *et al.*, 2009; Tucker *et al.*, 2009).

Although GNU Radio (Rondeau, 2015) includes several and diverse functions related to communications, it is possible to add new functions both in Python and C++ as libraries included as part of GNU Radio project. In Figure 1 we can observe the way how GNU Radio, being a Python library, can interact with C++ libraries through SWIG, which is a C++ to Python interpreter; furthermore, through CMAKE, GNU Radio allows to add C++ libraries not previously included in the project.

2.2 Development of GNU Radio projects

A way to develop projects in GNU Radio is through a graphic user interface called GNU Radio Companion (GRC), which allows to use the GNU Radio libraries and functions in a graphical mode. GRC facilitates the development of signal processing systems for communications without having Python programming skills, since it just interprets the blocks and translate them to a Python programming code (Beazley *et al.*, 1996); so GRC is just an interpreter, not a compiler.

An example of a GNU Radio application is the digital modulator shown in Figure 2; this consists of a random bit generator, a binary to decimal converter and a digital modulator at the transmitter, a Gaussian noise channel and the corresponding stages at the receiver. As analysis tools, an oscilloscope and a bit error rate (BER) block are included.

The communication among signal processing blocks is made through data flows. A data flow is composed by single elements, where all elements have a particular data type. GNU Radio performs a strict data verification, namely, the input data type will be the same as output data type in the signal processing block link connection, otherwise, the application will generate an error.

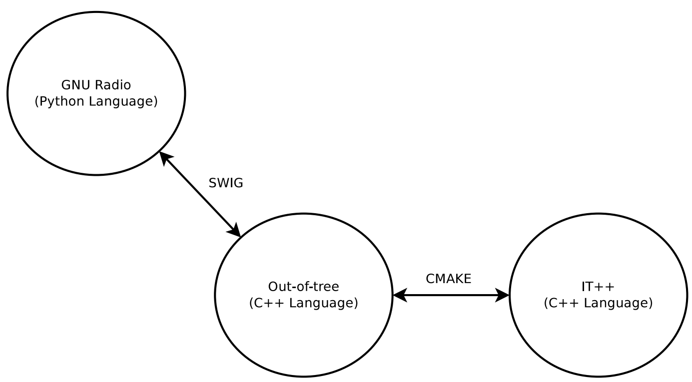


Figure 1: Interaction among C++ and Python with GNU Radio.

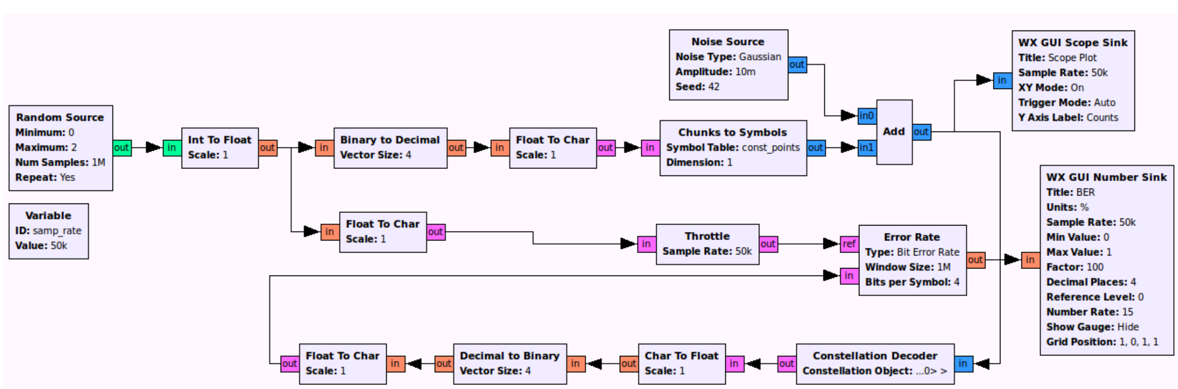


Figure 2: Digital Modulator with GNU Radio.

The data type may be bytes, shorts, int, floats and complex, which are selected according to the information that will be manipulated, for an OFDM symbol and FFT samples the type used is complex; byte type is used in channel coding because the presence of ones and zeros in the data. Also, a data type can be byte, short, int, float or complex vector which is different from flow type because a vector is a kind of data grouping in a determined length, the group or vector is determined by a flag inside the data flow, although for GNU Radio, a regular data flow is just a vector whose length is the total flow.

The data type characteristics are:

1. Byte. It is conformed by a data byte, namely, 8 bits by element.
2. Short. It consists in an integer conformed by 2 bytes.
3. Int. This data type is conformed by a 4 bytes integer
4. Float. It allows a floating point through 4 bytes
5. Complex. It is an 8 bytes array, actually two float data type.

For their integration in GNU Radio, the processing blocks are conformed by 4 type files:

1. xml files. Therein are defined the block settings like data type (float, int, short or complex), and the set of functions which it belongs to. This file is used by GRC for the graphical representation.
2. h files. Are the libraries of the developed blocks.
3. cc files. Therein are the programming line codes that will be perfomed by the block, the programming language is C++.
4. i files. Also known as swig files, allow the SWIG tool to obtain the parameters to the communication among C++ block files and Python interface.

For custom blocks or block developing with new processes, GNU Radio includes a function called gr_modtool for ”out-of-tree” projects; that is a script that automatically generates all the files required to develop a new signal processing block.

The directory structure of an out-of-tree is:

1. apps: These contain the test and example applications.
2. cmake: These contain several setting files and they are not configurable.
3. docs: These contain the documentation files that are automatically generated by Doxygen.
4. grc: These contain the xml files for the graphical blocks included in GRC.
5. include: These contain the h files, that are the header files of out-of-tree modules.
6. lib: These contain the cc files, that are the programming code in C++ of signal processing blocks.
7. python: These contain Python scripts.
8. swig: These contain the i files or swig files with the interpreter settings for C++ and Python.

All these folders, including the project root, contain ”CmakeLists.txt” with data setting at the compiling time of signal processing blocks through CMAKE program.

gr_modtool is a Python script with parameters like create or add, which through a simple interface allows the user to create, modify or delete modules and blocks of the out-of-tree projects (Schroeder *et al.*, 2004); also include all the folders and files required for their development.

According to the processing requirements, GNU Radio considers several block types:

1. Sink: Only input data.
2. Source: Only output data.
3. Sync: The input data elements are the same amount that output data elements, M=N.

4. Decimator: The relationship between input data and output data is M/1.
5. Interpolator: Inverse decimator block, relationship is 1/N.
6. General: The relationship between input data and output data is M/N.
7. Hiercpp: Hierarchical block conformed by a C++ blocks set.
8. Hierpython: Hierarchical block conformed by a Python blocks set.

Also, in GNU Radio there are environment variables that help the programming at the different processes, such as:

1. noutput_items. It is the element amount that the block can handle.
2. in[i]. It is the block input variable, it is an array with an i index.
3. out[i]. It is the block output variable, the data resulting from the signal processing block is assigned to this variable.

Finally, to add an out-of-tree module to GNU Radio project, it is required some commands in a Linux terminal.

```
$ mkdir build
$ cd build
$ cmake ../
$ make
$ sudo make install
$ sudo ldconfig
```

2.3 IT++ and GNU Radio.

IT++ is a C++ library with signal processing and communications classes and mathematical functions. It is used mainly to help research through simulation, evaluating communication systems performance in the communications area. The IT++ library kernel is conformed by generic vector and matrix classes and a set of routines that allows the use of vectors and matrices in the programming code.

IT++ library is developed by the Information Theory Department in Chalmers University of Technology, Gothenburg, Sweden; under the terms of the GPL license (GNU General Public License). IT++ is commonly used by communication area researchers and developers, from both industry and university. In 2005, 2006 and 2007, IT++ was developed as part of NEWCOM (European Network of Excellence in Wireless Communications).

IT++ makes an extensive use of open source and commercial libraries to increase functionality, speed and precision. In particular BLAS, LAPACK and FFTW libraries, also optimized libraries for a specific platform, such as:

- ATLAS (Automatically Tuned Linear Algebra Software). Include BLAS optimized routines and a limited LAPACK set.
- IMKL (Intel Math Kernel Library). Include all BLAS, LAPACK and FFT routines (FFTW is not required).
- ACML (AMS Core Math Library). Include BLAS, LAPACK and FFT routines (FFTW is not required).

It is possible to compile and use IT++ without the previous libraries, but the functions performance seems to be diminished (Boeglen, 2007); without compromising the data integrity in the communication system simulation.

In order that GNU Radio may interact with external libraries developed for C++, they must be included during the signal processing block developing in the out-of-tree modules. To include external libraries a searcher module in CMAKE must be added, which will determine the library path location and change the flags for the installation path of the C++ library (Rodriguez and Sanchez, 2014).

According to (Rondeau, 2015), it is possible to show CMAKE the external libraries for the integration in the project, thereby at the installation moment, CMAKE will locate required libraries and allowing the out-of-tree installation. The external libraries integration of C++ and Python will allow to expand the functions and scope of GNU Radio.

Figure 3 shows two digital signal processing blocks using IT++ called convolutional encoder and convolutional decoder; they are added to GNU Radio as an out-of-tree project.

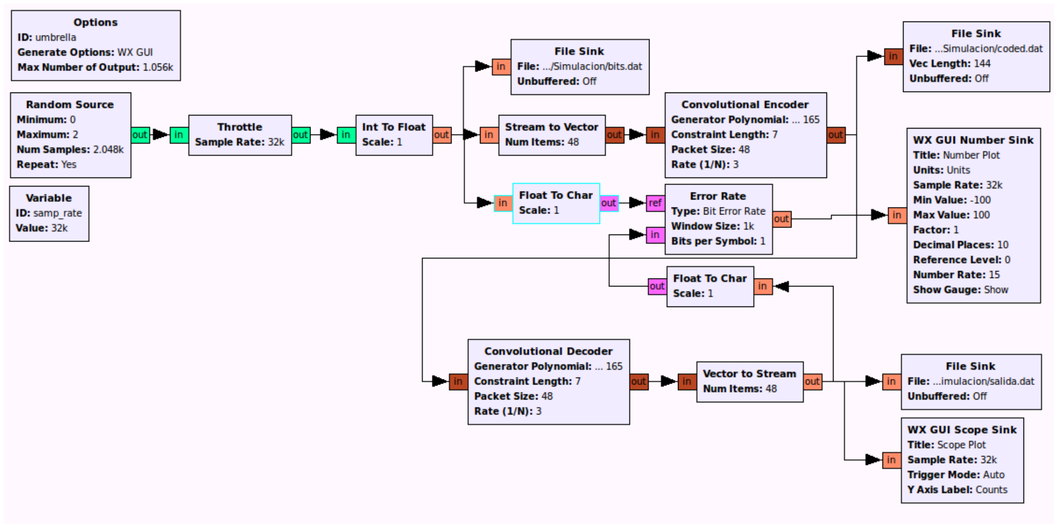


Figure 3: Convolutional encoder with GNU Radio and IT++.

2.4 USRP and GNU Radio

The universal software radio programmable cards, like USRP, allow GNU Radio the data transmission and reception through hardware, which is represented by a signal processing block in the programming code.

USRP cards require a host (computer) that performs the signal processing, this mean, GNU Radio manipulates the data and perform the PHY layer operations, both transmitter and receiver, and sends the processed data to the USRP card through an USB or Ethernet port that will be transmitted through the wireless channel, interpreting the received data (digital) and converting to a modulated signal in a frequency carrier specified by GNU Radio. In other words, in an OFDM modulator, the FFT and cyclic prefix are performed by GNU Radio in the computer and the USRP hardware prepares the OFDM symbol received to their transmission in the wireless channel (Abirami *et al.*, 2013).

Transmission rate is defined by the bus, in USB 2.0, the USRP card can transmit at a bit rate of 32 MBps, all the samples sent by USB are 16-bits integer with sign in IQ format, these means, 16 bits for phase and 16 bits for quadrature, therefore data size is 4 bytes by complex sample. This results in a data rate of 8 MMps through the USB obtained from 32 MBps / 4 Bytes. According to Nyquist criterion, the maximum effective bandwidth in the spectrum is 8 MHz (Ettus, 2005); similar estimations can be performed for USB 3.0 and Ethernet.

3. Direct Fourier Transform Spread - Ortoghonal Frequency Division Multiplexing

3.1 Introduction

One of the keys to achieve higher bit transmission rates, for next generation wireless networks is the implementation and use of OFDM (Orthogonal Frequency Division Multiplexing) air interface, which is based on the use of orthogonal subcarriers for data transmission, where every symbol is transmitted in one subcarrier, minimizing multipaths effects in the radio channel, along with a multiple antenna transmission technique. As a result of the reliability and versatility of the OFDM technique, it has been proposed as a wireless access method, achieving a better performance when combined with an efficient multiple antenna array (Capozzi *et al.*, 2013).

OFDM is a technique that reduces the fast fading channel effects among narrow band orthogonal subcarriers, allowing them to be handled as flat fading channels. A problem with OFDM is that when many sub-carriers are set to zero or are not being used, the symbol PAPR increases, which implies that conventional amplifiers need to work at the saturation point increasing the power consumption. This is not a problem in the base station, but, in the user device this causes a decrease in the battery life (Myung *et al.*, 2006b,a).

The 4th generation LTE standard for cellular networks has included a downlink access method 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 group of available carriers) with a low PAPR (Nagaraj *et al.*, 2009). Both OFDMA and SC-FDMA are OFDM transmitters, the difference is the presence of a DFT stage previous to the IFFT stage in SC-FDMA; the Single Carrier prefix in SC-FDMA is related to the signal characteristics that are too similar to a single carrier signal waveform, even though it is an OFDM signal (Parkvall and Astely, 2009).

3.2 OFDM transmitter

A traditional OFDM transmitter consists primarily of two stages: IFFT and Cyclic Prefix (CP) addition. In the first stage, the OFDM signal is generated at baseband by taking the IFFT of Quadrature Amplitude Modulated (QAM) or Phase-Shift Keyed (PSK) symbols $c_k = a_k + jb_k$, generating an OFDM symbol conformed by a digitally modulated symbol mounted on each subcarrier. The CP is added to the time samples of the OFDM symbol to avoid the Inter-Symbolic Interference (ISI); a copy of the last OFDM symbol samples, whose length is greater than the channel impulse response, is added at the beginning of the OFDM symbol. The frequencies of the complex exponential are $f_k = k/T$, and the useful part for $2N + 1$ sub-carriers is given by:

$$u(n) = \sum_{k=-N}^{N} c_k \exp\left(j2\pi f_k t\right),\ 0 \leq t \leq T \tag{1}$$

Previous to the OFDM stage is the digital modulator, this modulator converts the data bit (ones and zeros) into complex values according to a symbol constellation, if the modulator is Quadrature Phase Shift Keying (QPSK), it deals with two bits per symbol. In the case of a QAM modulator, the number of bits per symbol is log_2 of the QAM constellation size.

For a DFTS-OFDM transmitter it is necessary to add a DFT stage between the digital modulator and the IFFT, in this way the IFFT will transform the DFTS samples and not the modulated digital symbols (Ghosh *et al.*, 2010). The DFT size will depend on the number of the subcarriers needed by the source, the remaining sub-carriers $(N - M)$ will be set to zero by the transmitter to accomplish the IFFT size. The two ways in which the DFTS samples can be mapped into the IFFT stage are localized or distributed, depending on the subcarriers available at the receiver side; this is because an OFDM symbol can be shared by multiple users. The DFTS-OFDM symbol is given by:

$$\tilde{x} = \mathbf{C}\,\mathbf{F}_N^{-1}\mathbf{D}\,\mathbf{F}_M x \tag{2}$$

where $\mathbf{F}_N^{-1}$ and $\mathbf{F}_M$ are the N-point IFFT and M-point DFT matrices, respectively. **D** denotes the sub-carrier mapping. **C** represents the CP insertion matrix (Priyanto *et al.*, 2007).

At the receiver side, the useful symbols for a particular terminal are obtained after the FFT, and the equalization should be done before sending them to the IDFT stage. This way, the equalizer must be implemented in the frequency domain over signals that can not be related to any modulation constellation. Then, the common Decision Feedback Equalizer (DFE) can not be used in this case, because DFE estimates the received symbols according to the constellation used by the digital modulator (Zhang *et al.*, 2010; Noune and Nix, 2009; Wang *et al.*, 2008).

3.3 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) defined by the UMTS (Universal Mobile Telecommunications System). Such modification is included in the standard referred as 3GPP LTE Release 8, which was finished in 2008 (Yuan *et al.*, 2010). The 3GPP standard release 10, known as LTE-Advanced, also includes these media access methods, while the 5th generation foresees a combination of these two techniques and single carrier modulation, due to the presence of millimeter wave communications (Bhushan *et al.*, 2014).

OFDMA enables the allocation of time/frequency resources to specific users, named 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 consists in distributing the data to transmit on noncontiguous subcarriers, taking advantage of the frequency diversity, aiming to reduce the error probability due to frequency selective fading or channel interference. In the second scheme, the data is sent in contiguous subcarriers, to allow multiuser diversity and frequency selective scheduling, as shown in Figure 4.

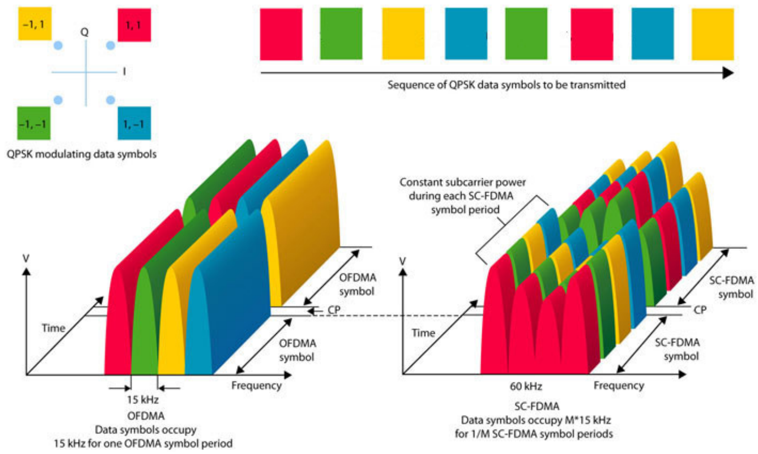


Figure 4: OFDMA vs SC-FDMA.

The PHY layer OFDMA implementation involves complications, dealing with the 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 linear response over a big frequency range. It is a factor that decreases the battery life and increases the cost in OFDMA mobile devices (Berardinelli *et al.*, 2008; Ciochina and Sari, 2010).

The 4th generation cellular standard 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 (Temi *et al.*, 2009). The SC-FDMA technique consists in precoding the data symbol with a discrete Fourier transform stage, as shown in Figure 5, and the samples obtained from the precoding stage are simultaneously transmitted over a subcarriers group. The resulting time domain waveform has the characteristics of a single carrier waveform, with a low PAPR although the waveform is not a single carrier waveform (Maeder and Zein, 2010).

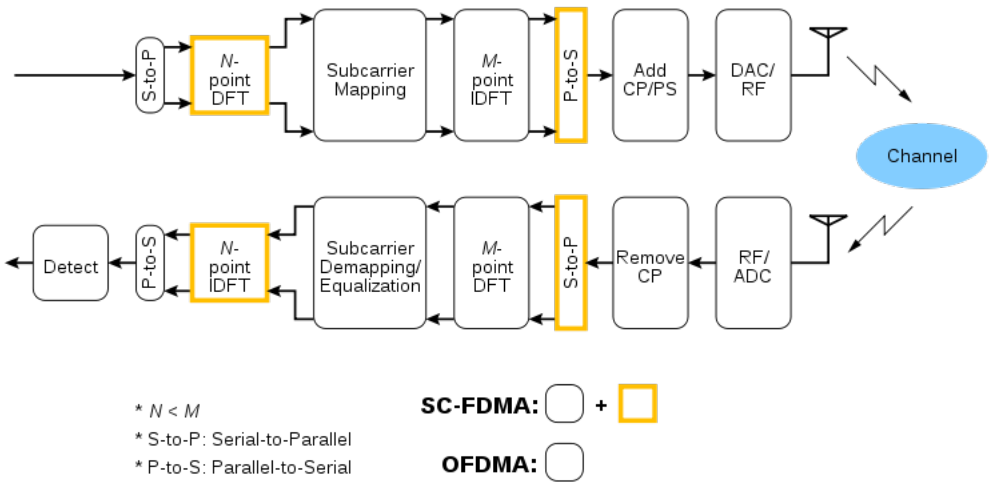
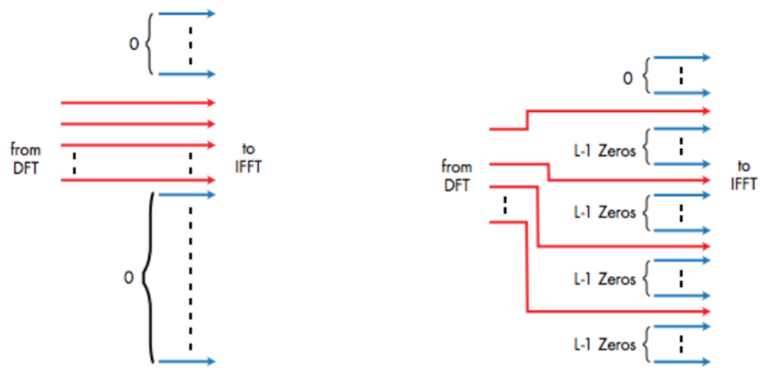


Figure 5: Block diagram of an OFDMA-SCFDMA system.

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 as show in Figure 6.

In DFDMA, if the condition of M=Q*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 7 why IFDMA is a special case of SC-FDMA, the implementation of the IFDMA technique becomes very efficient because the SC-FDMA



(a) Local FDMA. (b) Distributed FDMA.

Figure 6: LFDMA vs DFDMA.

transmitter can modulate the signal strictly in time domain without the DFT and IFFT stages.

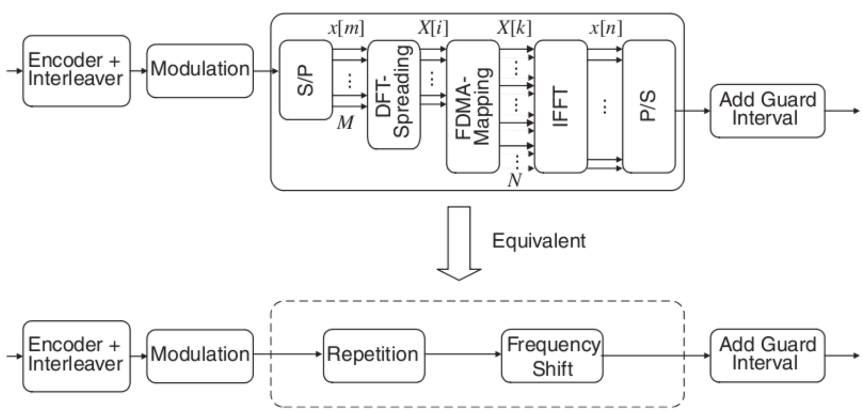


Figure 7: Equivalence of SC-FDMA and DFTS IFDMA in the uplink.

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 (Myung, 2007).

3.4 Transmission structure

In LTE-A, 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 constraints (in both power and size), the uplink transmitter is designed with SC-FDMA as a medium access method (MAC) technique.

According to Sesia *et al.* (2009), a DFTS-OFDM transmitter can include in the PHY layer process the following 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.

3.4.1 DFT precoding

The digital modulated symbols from a QAM or QPSK modulator are grouped in blocks of M symbols and 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 192, 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 and 180 will not be allowed.

It can be observed that although an OFDM symbol can be conformed by 2048 sub-carriers, the DFT size represents only close to 10% of throughput symbol, leaving the remaining subcarriers with a value of zero, this characteristic allows that multiple users share an OFDM symbol.

4. MIMO: Diversity and multiplexing

4.1 Introduction

Due to the limitations in traditional wireless links, the research community was looking for an alternative to design very high speed wireless links that offer good quality-of-service and greater range capability in non-line-of-sight (NLOS) environments. The use of multiple antennas at the transmitter and receiver increases the channel capacity gain, compared to one-antenna links, by exploiting spatial domain.

There exist several configurations of antenna arrays according to the pattern in both transmitter and receiver, as shown in Figure 8; if the transmitter and receiver have one antenna it is called single input, single output (SISO); if there are multiple antennas at the transmitter and one antenna at the receiver the configuration is called multiple input, single output (MISO); one antenna at the transmitter and multiple antennas at the receiver it corresponds to single input, multiple output (SIMO); finally, when there are multiple antennas at both the transmitter and the receiver, the configuration is called multiple input and multiple output (MIMO) (Yellin and Weinstein, 1994; Goldsmith *et al.*, 2003; Akyildiz *et al.*, 2010).

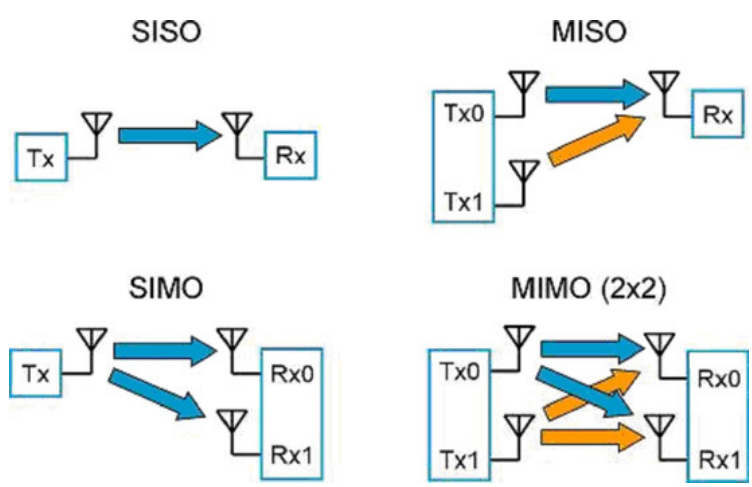


Figure 8: MIMO configurations.

No matter what the antenna array, there is a trade-off among diversity and multiplexing, the multiple antenna presence can help to get diversity in the transmitter (MISO), receiver (SIMO) or both (MIMO), in this way the signal detection at the receiver will be an operation with low computational complexity and a resulting low BER in low SNR channels in comparison with SISO; or the antenna array can be used to generate multiple flow streams independent among them, where each stream can be modulated with different schemes, this kind of transmission requires high SNR and low correlation channels to avoid interference among the streams, the signal detection at the receiver is more complex and requires all the streams to cancel the interference, because each stream produces interference to the other streams (Li *et al.*, 2010).

Recently the research was focused on Massive MIMO (Larsson *et al.*, 2014; Rusek *et al.*, 2013), this technique consists in highly increasing the number of antennas in the transmitter and receiver arrays, looking for the limits in the MIMO channel capacity exploiting the spatial domain. The presence of massive antenna arrays increases the complexity of signal detection at the receiver, in this way, the use of efficient algorithms to estimate the received symbol without error is required.

4.2 Space-time and space-frequency block coding based transmit diversity

The estimation of the CSI for a frequency selective channel with many taps is a complex task; several works have addressed the problem of exploiting available spatial and frequency diversities, when neither the transmitter nor the receiver knows the CSI. In order to achieve the time and frequency diversities several schemes were proposed in (Tarokh *et al.*, 1999; Tarokh and Jafarkhani, 2000; Hughes, 2000; Hochwald and Sweldens, 2000; Tao, 2006; Borgmann and Bolcskei, 2005; Ma *et al.*, 2005; Zhu and Jafarkhani, 2005; Himsoon *et al.*, 2006; Hong *et al.*, 2006; Zhu and Jafarkhani, 2006; Li *et al.*, 2008; Fazel and Jafarkhani, 2008; Jafarkhani and Seshadri, 2003).

The diversity mode allows to exploit the spatial domain, decreasing the BER by sending copies of the symbol through the channel, in this way, the receiver has several copies of the symbol proportional to the number of antennas in both arrays. According to the orthogonal block code, the transmission rate can be affected, but this is not a priority because it is exploiting the diversity. This kind of block codes are suggested to be used in channels with a low SNR, where it is required to help the receiver in the symbol estimation.

The implementation of an Alamouti encoder is shown in Figure 9.

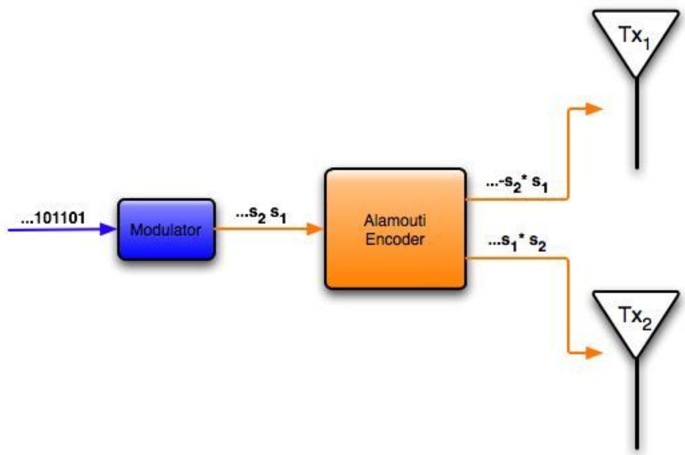


Figure 9: Alamouti encoder.

There are three ways to exploit MIMO diversity: space-time (S-T), space-frequency (S-F) and space-time-frequency (S-T-F) codes. Space-time block codes require as many time intervals as antennas at the transmitter to transmit the symbols (Tarokh *et al.*, 1999); for example, to transmit two symbols with two antennas two times intervals to a successful transmission is required. S-F block codes use frequency domain in the same way as space-time block codes use time domain, thus, when MIMO is combined with OFDM (for the case of two transmission antennas and an orthogonal S-F block code designed for 2 antennas) one antenna transmits the QAM symbols without modifications, while the other antenna transmits the OFDM symbol with the QAM symbol interleaved and modified according to the block code. Finally, space-time-frequency block codes exploit both time and frequency domains to offer diversity in the link, S-T-F codes are a combination of space-time block codes and space-frequency block codes (Jafarkhani, 2005), as shown in Figure 10.

4.2.1 Alamouti block code

The most common S-T block code is the one proposed by Alamouti (Alamouti, 1998), which consists in simultaneously send the first symbol in the first antenna and the second symbol in the second antenna; then (in the second transmission time), send the negative complex conjugate of the second symbol in the first antenna and the complex conjugate of symbol one in the second antenna, as shown in Table 1.

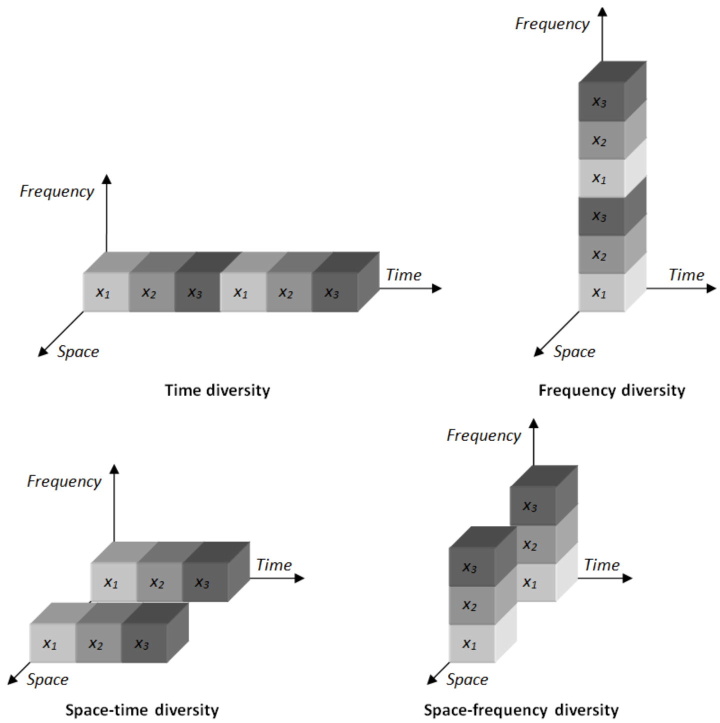


Figure 10: Diversity at time and frequency.

Table 1: Alamouti space-time block code.

Time slot	Antenna 1	Antenna 2
τ_n	x_1	x_2
τ_{n+1}	$-x_2^*$	x_1^*

At the receiver, the combination of the symbols transmitted by the antenna one and the symbol from the antenna two arrives at time slot one, while the combination of the complex conjugated of the symbol from antenna one and the symbol from antenna two arrives at time slot two, as shown in equation 3.

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ -h_2^* & h_1^* \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{3}$$

The receiver performs the next operation to recover the original symbols:

$$\begin{bmatrix} \widetilde{s}_1 \\ \widetilde{s}_2 \end{bmatrix} = \begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix} \begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} \tag{4}$$

Substituting 3 in 4, we obtain:

$$\begin{aligned}
\widetilde{s_1} &= h_1^* r_1 + h_2 r_2^* \\
&= h_1^*(h_1 s_1 + h_2 s_2 + \eta_1) + h_2(-h_1 s_2^* + h_2 s_1^* + \eta_2)^* \\
&= h_1^* h_1 s_1 + h_1^* h_2 s_2 + h_1^* \eta_1 + h_2(-h_1^* s_2 + h_2^* s_1 + \eta_2^*) \\
&= |h_1|^2 s_1 + h_1^* h_2 s_2 + h_1^* \eta_1 - h_2 h_1^* s_2 + |h_2|^2 s_1 + h_2 \eta_2^* \\
&= |h_1|^2 s_1 + |h_2|^2 s_1 + h_2 \eta_2^* + h_1^* \eta_1 \\
&= (|h_1|^2 + |h_2|^2) s_1 + h_2 \eta_2^* + h_1^* \eta_1 \qquad (5)
\end{aligned}$$

In the same way, we can obtain $\widetilde{s_2}$ from equation 4.

4.2.2 Alamouti based space-frequency block code

In LTE-A (Lee and Williams, 2000), to perform in diversity mode, the transmitter uses all the antennas to mitigate the multipath fading effects according to a block code. This scheme is based on the Alamouti's space-frequency block code (SFBC) and can support two or four antennas as shown in Table 2 and Table 3 respectively.

Table 2: Two antennas diversity scheme.

Antenna	Subcarrier k_1	Subcarrier k_2
1	x_1	x_2
2	$-x_2^*$	x_1^*

Table 3: Four antennas diversity scheme.

Antenna	Sc k_1	Sc k_2	Sc k_3	Sc k_4
1	x_1	x_2		
2			x_3	x_4
3	$-x_2^*$	x_1^*		
4			$-x_4^*$	x_3^*

In the case of DFTS-OFDM, the values for x_n are complex samples from a DFT pre-coding stage. The sub-carrier k_n of the OFDM symbol is assigned by the IFFT stage inside an OFDM block. For the configuration of four antennas the four sub-carriers are adjacent. The receiver performs a similar symbol estimation that space-time block codes but in the frequency domain in one time slot.

4.3 MIMO Multiplexing

The presence of multiple antennas at the transmitter in combination with multiple antennas at the receiver allows to increase the peak data rates. This is because multiple data streams transmission is enabled by using MIMO spatial multiplexing, which exploits the MIMO channel gain. A MIMO channel consists of a set of transfer functions, one for each link between all transmit and receive antennas, this feature in addition to larger bandwidths and high-order modulations allows to achieve the peak data rate targets.

When the channel is perfectly known by the transmitter, the optimum scheme for spatial multiplexing is precoded by singular value decomposition (SVD) (Goldsmith, 2005), which spatially decomposes the MIMO channel into virtual channels orthogonal among themselves.

There are some techniques that allow multiplexing in the transmission: open-loop and closed-loop. Open-loop leaves the receiver alone to decode the received streams, the transmitter does not have previous knowledge of the channel state information (CSI), it selects the best precoder from a codebook and sends the precoded symbols to the receiver. Otherwise, a closed-loop requires a delay in the transmission, in this way, the receiver sends the CSI to the transmitter, which performs a precoding in the symbols to help the receiver in the symbol estimation. An open-loop requires a complex signal estimator, this is because it does not know the CSI, contrary to the closed-loop case, where the receiver and transmitter has a previous acknowledgment of the channel state.

In Sesia *et al.* (2009), LTE-A proposes for the open-loop a codebook for one antenna ports consisting of four precoders for rank-1, while for two antenna ports there are three precoders for rank-2 as given in Table 4. The four rank-1 precoders correspond to single columns of a second and third rank-2 precoder matrices. The second and third rank-2 precoders are DFT matrices W_0 and W_2 respectively, where W_0 and W_2 are defined as:

$$W_0 = \frac{1}{\sqrt{2}} \begin{bmatrix} e^{j0} & e^{j0} \\ e^{j0} & e^{j\pi} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{6}$$

$$W_2 = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ e^{j\pi/2} & -e^{j\pi/2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix} \tag{7}$$

An important criterion in open-loop precoding is that the selection of the codebook for up to two antenna ports was restricted to precoders that use QPSK alphabets $\{\pm 1, \pm j\}$; the codebook of Table 4 meets this criterion. The rationale for limiting the codebook alphabet to $\{\pm 1, \pm j\}$ was the reduction of the mobile device difficulty in calculating channel state information (CSI), by avoiding the need for computing matrix/vector multiplication. The first rank-2 precoder is a 2 x 2 identity matrix that enables a simple transmission of two layers from the two antenna ports. This precoder is only used for open-loop MIMO spatial multiplexing without the need of CSI feedback. Also, there are no rank-1 precoder vectors corresponding to the 2 x 2 identity matrix; this is because each 2 x 2 identity matrix column represents a physical antenna port that leads to a non-constant modulus transmission scheme, because the power from the two antenna ports cannot be used for rank-1 transmission.

Table 4: Codebook for transmission over one and two antenna ports

	Number of layers	
Codebook Index	$\nu = 1$	$\nu = 2$
0	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix}$	$\frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ j \end{bmatrix}$	$\frac{1}{2}\begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -j \end{bmatrix}$	

This kind of transmission mode is recommended for channels with high SNR and low correlation, in this way it can be assured that each flow is independent and can be recovered at the receiver side. Unlike diversity mode, BER is high and its efficiency is measured with channel capacity vs SINR graphs.

4.3.1 Symbol estimation at the receiver

The efficiency of the symbol estimation at the receiver highly depends on a good channel estimation and the technique employed to dismiss the channel effects. Linear signal detection methods like ZF (Zero Forcing) and MMSE (Minimum Mean-Square Error) techniques handle all transmitted signals as interference except for the desired stream from the target transmit antenna (Foschini, 1996; Golden *et al.*, 1999; Wolniansky *et al.*, 1998). These methods nullify the interference with their corresponding weight matrix denoted by W:

$$\mathbf{W}_{ZF} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H \tag{8}$$

$$\mathbf{W}_{MMSE} = (\mathbf{H}^H\mathbf{H} + \sigma_z^2\mathbf{I})^{-1}\mathbf{H}^H \tag{9}$$

where H is the wireless channel matrix with complex values, σ^2 is the ZMCS (Zero Mean Circularly Symmetric) Gaussian noise power, I is an identity matrix and $(\cdot)^H$ denotes the Hermitian transpose operation, in other words, it cancels the channel effects as follows:

$$\begin{aligned} \widetilde{\mathbf{x}}_{ZF} &= \mathbf{W}_{ZF}\mathbf{y} \\ &= \widetilde{\mathbf{x}} + (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H\mathbf{z} \\ &= \widetilde{\mathbf{x}} + \widetilde{\mathbf{z}}_{ZF} \end{aligned} \tag{10}$$

where $\widetilde{x}$ is the estimated symbol, **y** is the received symbol and **z** represents the noise, using the MMSE weight in equation (9), we obtain the following relationship:

$$\begin{aligned} \widetilde{\mathbf{x}}_{MMSE} &= \mathbf{W}_{MMSE}\mathbf{y} \\ &= (\mathbf{H}^H\mathbf{H} + \sigma_z^2\mathbf{I})^{-1}\mathbf{H}^H\mathbf{y} \\ &= \widetilde{\mathbf{x}} + (\mathbf{H}^H\mathbf{H} + \sigma_z^2\mathbf{I})^{-1}\mathbf{H}^H\mathbf{z} \\ &= \widetilde{\mathbf{x}} + \widetilde{\mathbf{z}}_{MMSE} \end{aligned} \tag{11}$$

The SIC (Successive Interference Cancellation) method uses a bank of linear receivers, each of which detects one of the parallel data streams, with the detected signal components successively cancelled from the received signal at each stage. More specifically, the detected signal in each stage is subtracted from the received signal so that the remaining signal with the reduced interference can be used in the subsequent step.

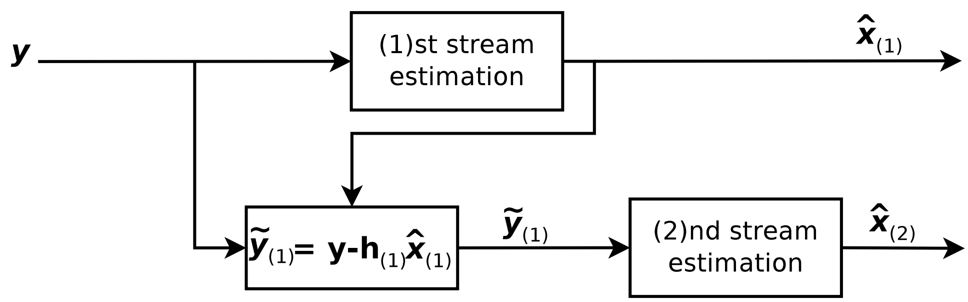


Figure 11: Successive interference cancellation for two spatial streams.

Figure 11 shows the SIC symbol detection procedure, that in combination with ZF or MMSE (ZF-SIC and MMSE-SIC respectively) can detect two or more spatial streams. Let $\hat{x}_{(i)}$ denote a sliced value of $x_{(i)}$ (the term "sliced" refers to a value adjusted to the nearest symbol in the constellation table of a digital modulation) the symbol estimated using ZF or MMSE methods. The first stream is estimated with the first row vector of the weight matrix in equation (8) or (9). After estimation and slicing to produce $\hat{x}_{(1)}$ the remaining signal in the first stage is obtained by subtracting it from the received signal, that is:

$$\widetilde{\mathbf{y}}_{(1)} = \mathbf{y} - \mathbf{h}_{(1)}\hat{x}_{(1)}$$
$$= \mathbf{h}_{(1)}(x_{(1)} - \hat{x}_{(1)}) + \mathbf{h}_{(2)}x_{(2)} + \mathbf{z} \quad (12)$$

if $x_{(1)} = \hat{x}_{(1)}$, then the interference is successfully cancelled in the course of estimating $x_{(2)}$.

5. Cooperative Protocols

5.1 Introduction

Although this topic has been researched many years, it is actually considered as a way to develop network densification and its interest has grown in recent years. It is based on deploying micro-cells and femto-cells by the user and operator to increase the macro-cell capacity as shown in Figure 12. A cooperative protocol consists in relay nodes helping a source node (which can be a base station or an user device) to deliver a signal at a specific destination. It can be conformed by a single relay node or a group of them, every node will perform a signal processing that may be a simple signal amplification or a complex signal decoding, as it is determined by the protocol implemented at the relay node.

The presence of relay nodes in modern cellular networks implies the study of topics related to network densification, because these relay nodes will be pico-cells with low power consumption, allowing the macro-cell to be received with a higher power, having preference over other devices, but the goal is to keep the device connected to the pico-cell for better quality of service (less traffic and resources consumed by other devices) in comparison with the resources offered by the macro-cell (Kishiyama *et al.*, 2013).

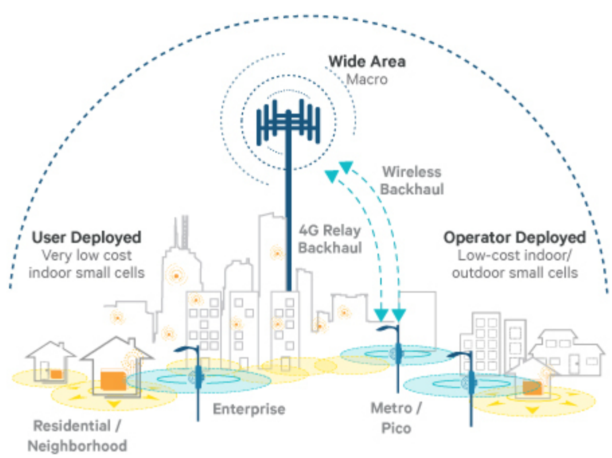
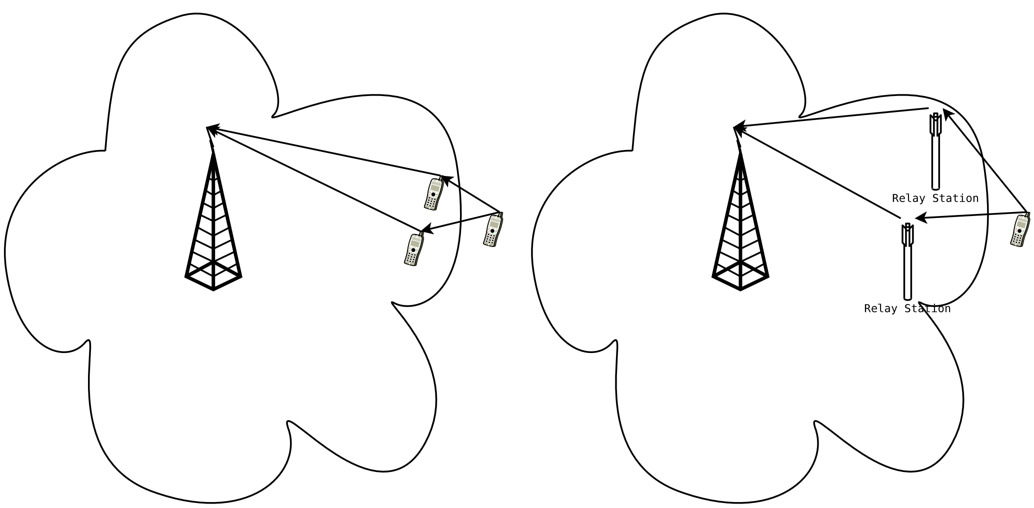


Figure 12: Network densification.

A relay network could be a group of fixed or mobile nodes acting as relay nodes, which means that it could be from a simple user device to a complex relay station, where each relay node will be managed by the device who will transmit the information as shown in Figure 13.

According to the way in which the signal is processed in the relay node, there are two main types of relay transmission schemes: amplify-and-forward (AF) and decode-and-forward (DF) (Su *et al.*, 2008). AF is the easiest kind of repeater because it introduces little delays and has low deployment cost. Depending on the received SNR, the signal is proportionally amplified but the accompanying noise is also amplified. The operation may be described in two steps; in the first one the relay station receives the signal from the source, in the second step it amplifies the received signal and forwards it to the destination. Since at low SNR values there is a high presence of noise in the received signal, a variation of the AF protocol has been proposed, where the signal is amplified only if a SNR threshold is exceeded; otherwise the relay node does not work, because the received signal will only add noise to the entire transmission. Furthermore, the AF repeater is transparent to the destination which means that the destination node still needs to communicate back to the source.



(a) Relay network with mobiles. (b) Relay network with relay stations.

Figure 13: Relay network.

In the DF scheme, a relay station demodulates, equalizes and performs decoding over the received signal from the source at the first step, which is verified via the CRC field. If the CRC of the decoded data is correct, the relay station will perform channel coding and will forward the new signal (with new CRC) to the destination at the second step. This scheme suffers an extra delay due to the additional signal processing tasks and it is relatively expensive to deploy. Therefore, a DF relay can provide independent scheduling and link adaptation, in this way, it does not forward the interference and noise in the received signals, but only the useful data.

Additionally, we study a scheme called equalize-and-forward (EF), where the symbol is only equalized at the relay station and then forwarded to the destination. In this scheme, a relay station receives the signal from the source at the first step, then removes the channel effect of the previous step equalizing the received signal and finally forwards it to the destination at the second step.

According to the network scenario, the received signal at the destination could be modeled in many ways, for example with or without a LOS among the source and destination, as shown in Figure 14. The mathematical representation of the received signal with LOS from source to destination and from source to relay is defined by:

$$y_{s,d} = \sqrt{P} h_{s,d} x + \eta_{s,d} \tag{13}$$

$$y_{s,r} = \sqrt{P} h_{s,r} x + \eta_{s,r} \tag{14}$$

Where $h_{s,d}$ and $h_{s,r}$ are the channel responses among the source-relay and source-destination, $\eta_{s,d}$ and $\eta_{s,r}$ are the additive Gaussian noise with a zero-mean and unit variance and P the transmission power. In phase 2, the relay forwards a processed version of the source's signal to the destination and this can be represented as:

$$y_{r,d} = \sqrt{P} h_{r,d} q(y_{s,r}) + \eta_{r,d} \tag{15}$$

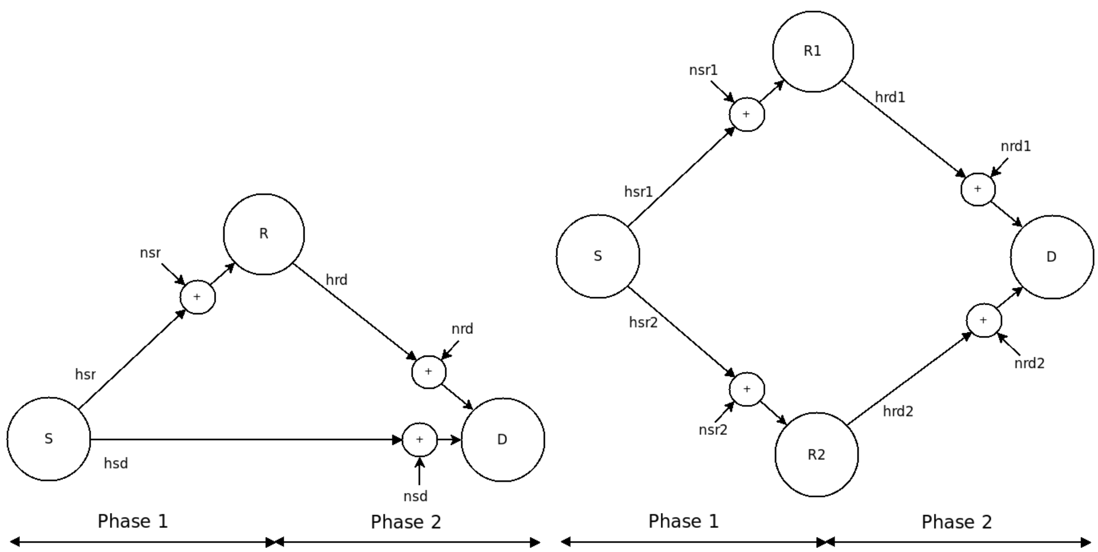
where the function q(.) depends on which processing is implemented at the relay node.

The NLOS signal in the phase 1 is defined by:

$$y_{s,r} = \sqrt{P}h_{s,r}x + \eta_{s,r} \tag{16}$$

In the phase 2, the relay forwards a processed version of the source's signal to the destination, which can be modeled as:

$$y_{r,d} = \sqrt{P}h_{r,d}q(y_{s,r}) + \eta_{r,d} \tag{17}$$



(a) Relay network with LOS. (b) Relay network without LOS.

Figure 14: Relay network scenarios.

5.2 Amplify-and-Forward

In AF, depending on the received SNR, the signal is proportionally amplified along with the noise without any kind of signal processing. The protocol consists of two phases: in the first one the relay station receives the signal from the user device, in the second phase it amplifies the received signal and forwards it to the base station.

In a scenario where the destination receives a signal from the source and relay nodes, the received signal at the destination, in the second phase, is a combination from both nodes given by:

$$y_{s,d} = \sqrt{P}h_{s,d}x + \eta_{s,d} \tag{18}$$

$$y_{s,r} = \sqrt{P}h_{s,r}x + \eta_{s,r} \tag{19}$$

In phase 2, the relay amplifies the signal from the source and forwards it to the destination to dismiss the channel fade, in this case, the relay simply scales the received signal by a factor that is inversely proportional to the received power, which is denoted by:

$$\beta_r = \frac{\sqrt{P}}{\sqrt{P|h_{s,r}|^2 + N_0}} \tag{20}$$

In this way, the received signal in the destination at the phase 2 from the relay is given by:

$$y_{r,d} = \beta_r h_{r,d} y_{s,r} + \eta_{r,d} \tag{21}$$

As previously mentioned, there is a variation of AF named selective AF, where the relay node is turned off if the received signal is not greater that a SNR threshold. The received signal at the destination for selective AF is defined by:

$$y_{r,d} = \beta_r h_{r,d} y_{s,r} + \eta_{r,d} \quad \text{if} \quad SNR > threshold \tag{22}$$

5.3 Decode-and-Forward

In the DF scheme, a relay station demodulates, equalizes (with the source-relay channel information) and performs channel decoding until the Cyclic Redundancy Check (CRC) stage is performed. If the CRC of the decoded data is correct, the relay station will perform channel coding and will forward the new signal (new CRC) to the base station at the second phase. In the case of LOS among the source and destination in addition to the relay-destination link, the received signal in first phase at the destination is given by:

$$y_{s,d} = \sqrt{P} h_{s,d} x + \eta_{s,d} \tag{23}$$

$$y_{s,r} = \sqrt{P} h_{s,r} x + \eta_{s,r} \tag{24}$$

The received signal at phase 2 in the destination is given by:

$$y_{r,d} = \sqrt{P} h_{r,d} \bar{y_{s,r}} + \eta_{r,d} \tag{25}$$

where $\bar{y_{s,r}}$ is the symbol decoded by the relay node and forwarded to the destination with a new CRC.

There may be many processes before the CRC stage. We include the following stages in the relay node for DF: 24 bits CRC insertion, turbo coding, channel interleaving, scrambling, digital modulation, DFT precoding, layer mapping and mapping to antennas.

In the case of selective DF, the received signal at destination is defined by:

$$y_{r,d} = \sqrt{P}h_{r,d}y_{\bar{s},r} + \eta_{r,d} \quad \text{if} \quad SNR > threshold \tag{26}$$

5.4 Equalize-and-Forward

In the EF scheme the symbol received by the relay node only undergoes an equalization before being re-transmitted. A relay node receives the OFDM symbol from the user device at the first phase, then removes the channel effect of the previous phase (source-relay) in the received signal and finally forwards it to the base station at the second phase.

The received signal at the destination, in the second phase, is given by:

$$y_{r,d} = \sqrt{P}h_{r,d}y_{\tilde{s},r} + \eta_{r,d} \tag{27}$$

where $y_{\tilde{s},r}$ is the symbol equalized on frequency by the relay node and forwarded without the channel effects from phase 1.

For selective EF, the received signal at destination is defined by:

$$y_{r,d} = \sqrt{P}h_{r,d}y_{\tilde{s},r} + \eta_{r,d} \quad \text{if} \quad SNR > threshold \tag{28}$$

6. System model

6.1 Introduction

Since there may be several network scenarios in a cooperative protocol implementation, it is important to know the number of relay nodes and antennas involved in the current scenario; thereby the destination node can estimate the received symbol in an appropriate manner, because the relay nodes can be used to conform a virtual MIMO array or even one relay node can have more than one antenna and can help in the MIMO array (Teodoro *et al.*, 2009b; Hassan, 2012).

Considering this, the proposed scenario is shown in Figure 15, where all the nodes, including the source and destination, make use of just one antenna for diversity mode and two antennas for a multiplexing mode.

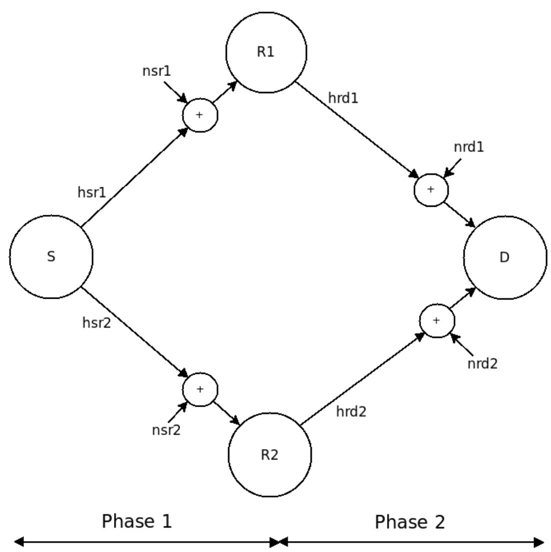


Figure 15: Relay network scenario proposed.

Furthermore, subject to the cooperative protocol being used, it is possible to deploy some network scenarios where both antennas will be used for the reception but only one antenna will be used to transmit. In this way the maximum antenna array will be set to 2x2 on both phase one and phase two.

Some additional considerations will be mentioned in the simulations and emulations, from the stages considered in the relay nodes according to the cooperative protocol up to the antenna arrays and operation details during the communication link.

6.2 Space-frequency block codes over cooperative protocols

In Laneman and Wornell (2003) it is considered a Space-Time Block Code (STBC) relay implementation, where a Medium Access control protocol is needed because requires many time slots to transmit the block code according to the code rate and the MIMO channel. A traditional block code like Alamouti uses two time slots, because it uses two antennas and it has a code rate of one (it sends two symbols in two time slots). SFBC, unlike STBC does not require two time slots, it needs two properly spaced antennas and two highly correlated channels (which in OFDM are two adjacent sub-carriers). In order to deploy a relay version of a SFBC in uplink transmission, we need to consider each single-antenna relay as an antenna directly connected to the source, and see them as a single device with multiple antennas (distributed MIMO). In this diversity mode, which is based on the Alamouti code, one antenna will have the original OFDM symbol to transmit and the other one will contain the conjugated complex symbol interleaved according to the SFBC size.

In a diversity mode, a traditional transmitter without cooperative protocol has two or more antennas to avoid the channel effects. Figure 16 shows a DFTS-OFDM transmitter with two antennas for diversity using Alamouti code. In case that a device with one antenna requires spatial diversity it would be necessary to use a virtual MIMO array with the antennas of other devices or relay nodes.

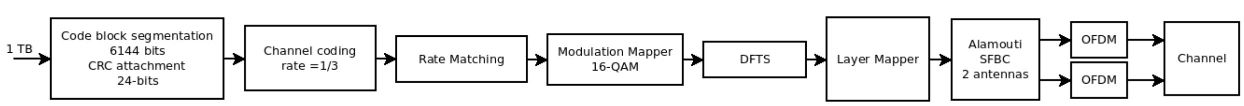


Figure 16: DFTS-OFDM transmitter with diversity.

Depending on the code being used, the device will require two or more antennas for space-frequency diversity. Based on Table 5, the MIMO array is conformed by two antennas at the transmitter.

Table 5: Two antennas S-F diversity scheme.

Antenna	Subcarrier k_1	Subcarrier k_2
1	x_1	x_2
2	$-x_2^*$	x_1^*

When using transmit diversity mode, the symbols are sent by the Alamouti scheme, as shown in Table 5, the values for x_n are complex samples from a DFT precoding stage. The sub-carrier k_n is assigned by the IFFT stage inside an OFDM block.

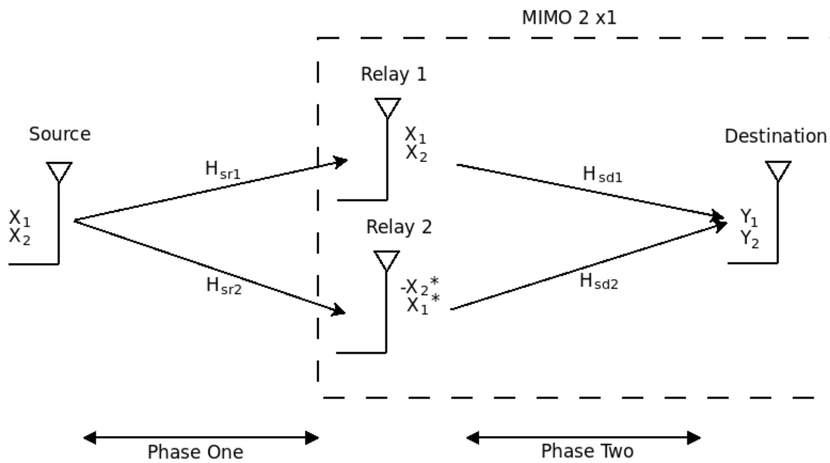


Figure 17: Network scenario for SFBC.

Making a kind of interpolation, the relay node will be acting as an antenna in the virtual MIMO array, as shown in Figure 17; Table 6 shows how the Alamouti code will be represented by the relay nodes, allowing in the phase two the presence of a 2x1 array as stated in the Alamouti code. We assume a block fading channel model (where a block has the size of an OFDM symbol) in which the channel realizations vary independently from one block to another, while within each block the channels remain constant over each sub-carrier pair. Also, we assume that each receiver knows the channels from the transmitter to the relays and its own receiving channels. In other words, the destination knows H_{sr_1}, H_{sr_2}, H_{rd_1} and H_{rd_2}.

Table 6: Two relay nodes S-F diversity scheme.

Relay node	Subcarrier k_1	Subcarrier k_2
1	x_1	x_2
2	$-x_2^*$	x_1^*

As the SFBC is only performed by the phase 2, in the phase 1 the source-relay communication is a direct link without any kind of diversity. Thus, the received signals at the relay node 1, at instant $k + T_s$, on sub-carrier n and $n + 1$, are given by:

$$
\begin{aligned}
y_n(k+T_s) &= \frac{1}{\sqrt{2}}(s_n h_{sr_i,n}) + \eta_n(k+T_s) \\
y_{n+1}(k+T_s) &= \frac{1}{\sqrt{2}}(s_{n+1} h_{sr_i,n+1}) + \eta_{n+1}(k+T_s)
\end{aligned} \tag{29}
$$

at the relay node 2, the received signals are given by:

$$
\begin{aligned}
y_n(k+T_s) &= \frac{1}{\sqrt{2}}(s_n h_{sr_{i+1},n}) + \eta_n(k+T_s) \\
y_{n+1}(k+T_s) &= \frac{1}{\sqrt{2}}(s_{n+1} h_{sr_{i+1},n+1}) + \eta_{n+1}(k+T_s)
\end{aligned} \tag{30}
$$

where s_n is the data symbol of the n^{th} sub-carrier, with unitary power, $h_{m,n}$ represents the complex Rayleigh flat fading channel on sub-carrier n, with m identifying the channel at the i^{th} relay node, and, $\eta_n(k+T_s)$ and $\eta_{n+1}(k+T_s)$ are the zero mean complex additive white Gaussian noise (AWGN) samples with variance of $\sigma^2_{n_d}$ at time $k+T_s$ on sub-carrier n and $n+1$, respectively.

6.2.1 Amplify-and-Forward

AF is the easiest kind of relay, depending on the received SNR the signal is proportionally amplified, along with the noise. The operation may be described in two phases; in the first one the relay station receives the signal from the user device, in the second phase it amplifies the received signal and forwards it to the base station (Li *et al.*, 2009). To deploy the SFBC in the phase 2, inside the relay node 1 (according to the Table 6 the relay node 1 is the first antenna and the relay node 2 is the second one) the received symbol is forwarded to the IFFT stage without modifications unlike the relay node 2 where the received symbol, which is the same as the received by the relay node 1, is processed as indicated in the antenna 2 row from Table 6. In this way, an Alamouti transmission based on single-antenna relay nodes can be performed as shown in Figure 18.

The received signal at the destination, in the second phase, is given by:

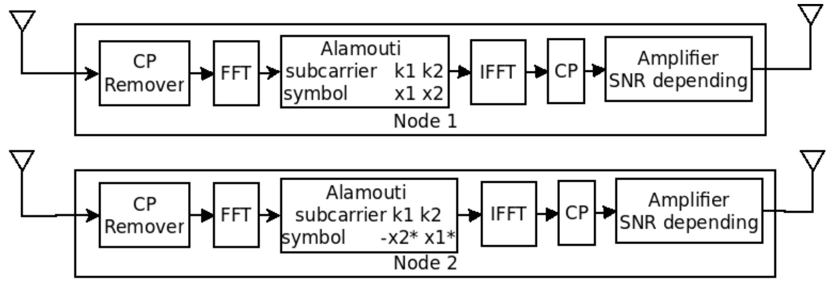


Figure 18: Relay node in amplify-and-forward.

$$y_n(k+2T_s) = \frac{1}{\sqrt{2}}(s_n h^*_{rd_i} h^*_{sr_i} + s^*_{n+1} h_{rd_{i+1}} h^*_{sr_{i+1}}) + \eta_n(k+2T_s)$$
$$y_{n+1}(k+2T_s) = \frac{1}{\sqrt{2}}(s_{n+1} h^*_{rd_i} h^*_{sr_i} - s^*_n h_{rd_{i+1}} h^*_{sr_{i+1}}) + \eta_{n+1}(k+2T_s) \quad (31)$$

6.2.2 Decode-and-Forward

In the DF scheme, a relay station demodulates, equalizes (with the source-relay channel information) and performs channel decoding until the Cyclic Redundancy Check (CRC) stage is performed as shown in Figure 19. If the CRC of the decoded data is correct, the relay station will perform channel coding and will forward the new signal (new CRC) to the base station at the second phase. Before the symbol is sent to the OFDM stage in the relay transmitter side, the respective Alamouti block code process is applied to it; this means that if the relay node emulates the antenna one in the distributed MIMO array, the relay node will perform the block code corresponding to the row one in the Table 6, in the same way, the relay node 2 is associated with the second row. This scheme could be deferred by the signal processing delay (Rong *et al.*, 2010).

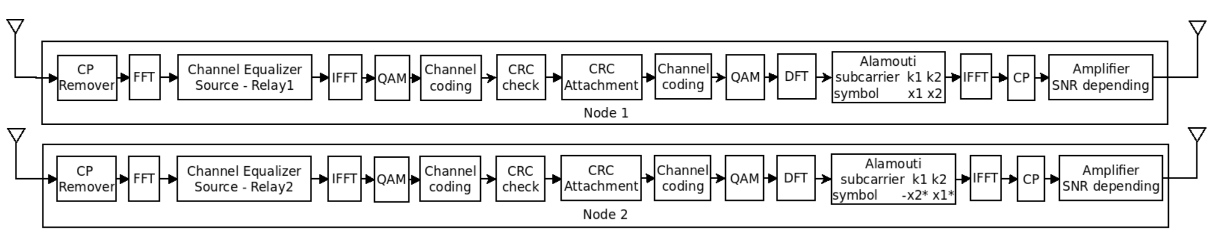


Figure 19: Relay node in decode-and-forward.

The received signal at the destination, in the second phase, is given by:

$$y_n(k+2T_s) = \frac{1}{\sqrt{2}}(\bar{s}_n h^*_{rd_i} + \bar{s}^*_{n+1} h_{rd_{i+1}}) + \eta_n(k+2T_s)$$
$$y_{n+1}(k+2T_s) = \frac{1}{\sqrt{2}}(\bar{s}_{n+1} h^*_{rd_i} - \bar{s}^*_n h_{rd_{i+1}}) + \eta_{n+1}(k+2T_s) \quad (32)$$

where $\bar{s}_n$ and $\bar{s}_{n+1}$ are the symbols decoded by the relay node and forwarded to the destination with a new CRC.

There may be many processes before the CRC stage. We include the follow stages in the relay node for DF: 24 bits CRC insertion, turbo coding, channel interleaving, scrambling, digital modulation, DFT precoding, layer mapping and mapping to antennas.

6.2.3 Equalize-and-Forward

In the EF scheme the symbol received by the relay node only undergoes an equalization before being retransmitted (Teodoro *et al.*, 2009a). A relay node receives the OFDM symbol from the user device at the first phase, then removes the channel effect of the previous phase (source-relay) in the received signal and finally forwards it to the base station at the second phase based on the 2x2 Alamouti block code as shown in Figure 20.

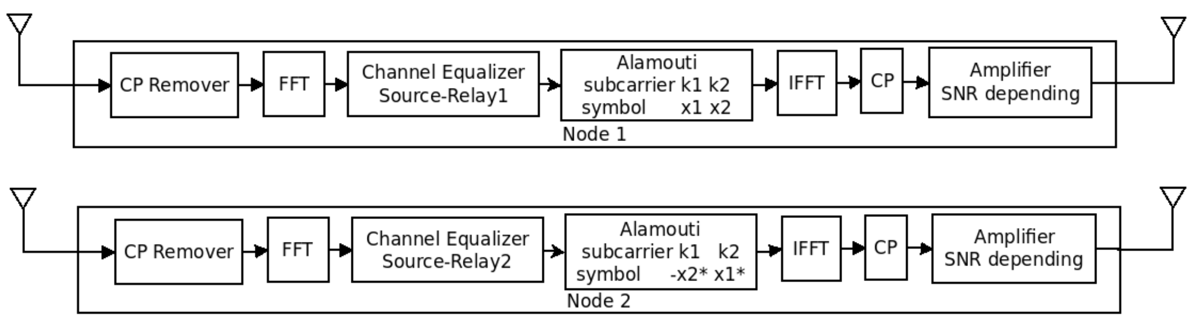


Figure 20: Relay node in equalize-and-forward.

The received signal at the destination, in the second phase, is given by:

$$y_n(k+2T_s) = \frac{1}{\sqrt{2}}(\tilde{s}_n h^*_{rd_i} + \tilde{s}^*_{n+1} h_{rd_{i+1}}) + \eta_n(k+2T_s)$$
$$y_{n+1}(k+2T_s) = \frac{1}{\sqrt{2}}(\tilde{s}_{n+1} h^*_{rd_i} - \tilde{s}^*_n h_{rd_{i+1}}) + \eta_{n+1}(k+2T_s) \quad (33)$$

where $\tilde{s}_n$ and $\tilde{s}_{n+1}$ are the symbols equalized in the frequency domain by the relay node and forwarded without the channel effects from phase 1.

6.2.4 Symbol Estimation at the Destination

It is important to remark that the symbol estimation of SFBC is only performed by the destination, the relay nodes amplify, decode or equalize according to the case, but do not perform a symbol estimation, because in phase one there is not a SFBC stage. A block diagram of the receiver according to the cooperative protocol is shown in Figure 21.

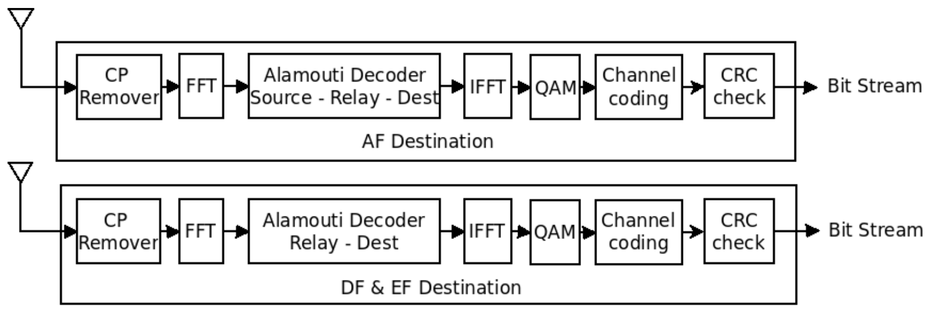


Figure 21: The receiver according to the cooperative protocol.

For the AF protocol, the destination has both channel states knowledge (from source to relay and from relay to destination), because the relay nodes only perform a complex symbol value calculation and symbol interleaving according to SFBC, keeping their channel effects.

In accordance with Alamouti (1998), where the author considers that the channel state does not change in two time slots or during the transmission of two symbols (for the case of Space-Time Block Codes), this criterion applied for SFBC requires that the Channel State Information (CSI) of a pair of consecutive sub-carriers be the same, this means $h_n = h_{n+1}$ (for further references we consider $h = h_n = h_{n+1}$) in this way the SFBC can be deployed without problems. However, for a two-hop network scenario with two single-antenna relay nodes, we can determine the estimated signals at the destination in the relay network ($\hat{s_n}$ and $\hat{s_{n+1}}$), these signals could be defined by:

$$\hat{s_n} = s_n h^*_{rd_i} h^*_{sr_i} + s^*_{n+1} h_{rd_{i+1}} h^*_{sr_{i+1}} \tag{34}$$

$$\hat{s_{n+1}} = s_{n+1} h^*_{rd_i} h^*_{sr_i} - s^*_n h_{rd_{i+1}} h^*_{sr_{i+1}} \tag{35}$$

where s_n and s_{n+1} are the signals received by the i^{th} destination node and that were transmitted by the relays in the second phase at two consecutive sub-carriers,

$$s_n = x_{i,n} h_{rd_i} - x^*_{i+1,n+1} h_{rd_{i+1}} + \eta_n \tag{36}$$

$$s_{n+1} = x_{i,n+1} h_{rd_i} - x^*_{i+1,n} h_{rd_{i+1}} + \eta_{n+1} \tag{37}$$

where η_n and η_{n+1} represent complex noise and interference at the k_n and k_{n+1} sub-carriers in the antenna receiver. The signals received by the relay nodes and transmitted from the source in phase one are defined by:

$$x_{i,n} = x_n h_{sr_i} + \eta_n \tag{38}$$

$$x_{i,n+1} = x_{n+1} h_{sr_i} + \eta_{n+1} \tag{39}$$

$$x_{i+1,n} = x_n h_{sr_{i+1}} + \eta_n \tag{40}$$

$$x_{i+1,n+1} = x_{n+1} h_{sr_{i+1}} + \eta_{n+1} \tag{41}$$

where $x_{i,n}$ is the data symbol of the i^{th} relay node at the n^{th} sub-carrier.

Substituting (36) and (37) in (34),

$$\hat{s_n} = (x_{i,n}h_{rd_i} - x^*_{i+1,n+1}h_{rd_{i+1}} + \eta_n)h^*_{rd_i}h^*_{sr_i}$$
$$+ (x_{i,n+1}h_{rd_i} - x^*_{i+1,n}h_{rd_i} + \eta_{i+1})^*h_{rd_{i+1}}h^*_{sr_{i+1}} \quad (42)$$

replacing (38), (39), (40) and (41) in (42),

$$\hat{s_n} = x_n(|h_{sr_i}|^2|h_{rd_i}|^2 + |h_{sr_{i+1}}|^2|h_{rd_{i+1}}|^2) + \eta \quad (43)$$

where:

$$\eta = \eta_n h^*_{sr_i}h^*_{rd_i} + \eta^*_{n+1}h_{sr_{i+1}}h^*_{rd_{i+1}} + \eta_n|h_{sr_i}|^2h_{rd_i}$$
$$+ \eta_{n+1}h^*_{sr_i}h_{sr_{i+1}}h_{rd_{i+1}} + \eta_n|h_{sr_{i+1}}|^2h_{rd_{i+1}} + \eta^*_{n+1}h^*_{sr_i}h_{sr_{i+1}}h^*_{rd_i} \quad (44)$$

For estimating $\hat{s_{n+1}}$, a similar process must be followed, starting at (35).

The channel estimation in the AF protocol for the two phases can be described as follow: first the destination sends the training sequence to the relay node and estimates the relay-destination channel, then the destination sends again the training sequence to the relay node and the relay node forwards that sequence to the source, the source forwards these sequence to the relay node and the relay node forwards the sequence to the destination. Once the destination has the relay-destination CSI, it can mitigate its effect leaving only the source-relay channel effects; in this way the destination can know the source-relay-destination CSI (Koyuncu *et al.*, 2008)

In both, the DF and EF cases, we can not use this process because the source-relay channel is mitigated by the relay node in phase one and the symbol presented in phase two is corrected by the node in its transmission stage, therefore the estimated signal in the destination at phase two is defined as:

$$\hat{s_n} = s_n h^*_{rd_i} + s^*_{n+1} h_{rd_{i+1}} \tag{45}$$

$$\hat{s_{n+1}} = s_{n+1} h^*_{rd_i} - s^*_n h_{rd_{i+1}} \tag{46}$$

According to the previous demonstration, the AF receiver needs the channel information from the two phases, but DF and EF receivers only need the last phase to decode the received symbol.

6.3 MIMO Multiplexing

Multiplexing is a technique that exploits the spatial domain and increases the wireless channel capacity by sending different data flows through antennas that have a separation that ensures that the channels are independent. A DFTS-OFDM transmitter with multiplexing is conformed by a precoding stage previous to the antennas, as shown in Figure 22, where a precoder is selected from a codebook based on the CSI, to perform a signal processing in the symbols to be transmitted. This precoding is defined by the transmitter with the help of the receiver in case of closed-loop, for open-loop the transmitter sends the index of the codebook to indicate which precoder is used in the transmission.

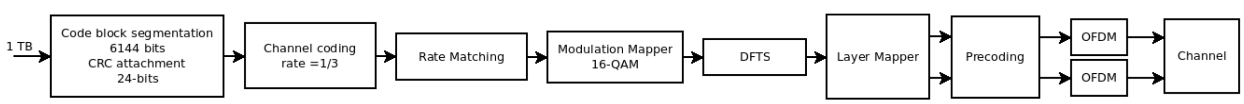


Figure 22: DFTS-OFDM transmitter with multiplexing.

To allow multiplexing with open-loop, the transmitter selects a precoder from a codebook that both transmitter and receiver had previously agreed upon. This precoder will be the best for the current channel not only for one antenna, in case an error threshold is reached the transmitter selects another precoder with a better performance. Based on Table 7, the selected precoder for the simulation is the index 0 for two antennas. This precoder is only used for open-loop MIMO spatial multiplexing without the need of CSI feedback.

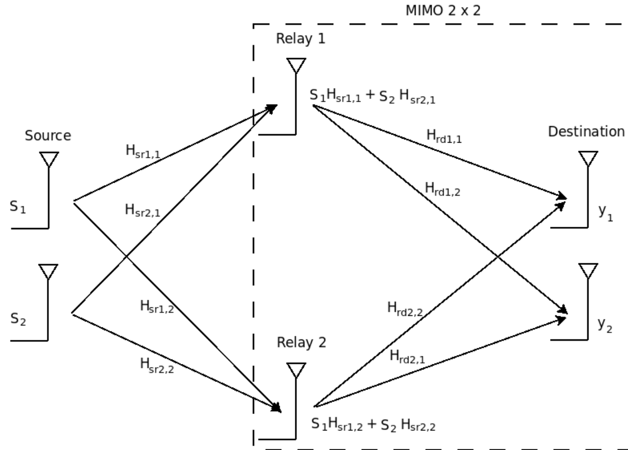
Table 7: Codebook for transmission over one and two antenna ports

Codebook Index	Number of layers $\nu = 1$	$\nu = 2$
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	

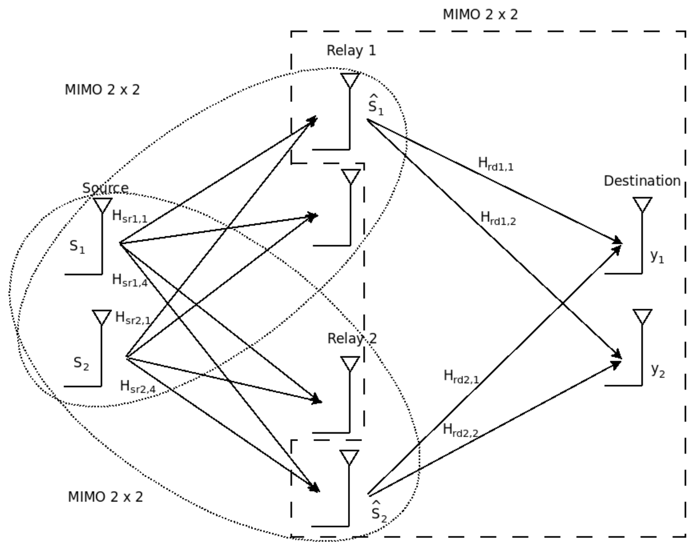
According to the network scenarios previously proposed, we consider two main scenarios as shown in Figure 23, where both source and destination nodes are conformed by a two antenna array because the scenario is for multiplexing, the changes in the network scenarios are presented in the relay nodes. The first network scenario where the relay nodes only have one antenna is to guarantee a 2x2 MIMO array among the relay nodes and destination. In the first phase there is a 2x2 channel among the source and both relay nodes, in the second phase the relay nodes conform a virtual two antenna array along with the destination. In the second network scenario the relay nodes are conformed by a two antenna array individually, in this way the source and relay nodes guarantee a 2x2 channel among the source and each relay node. The problem arises in the second phase, where the scenario has a 4x2 and not a 2x2 channel, to avoid this, the relay node disables an antenna and selects only one symbol to send to the destination. For the first scenario case, AF is the only protocol developed, because for DF and EF it is required to dismiss the phase one channel effects, which is very complex to perform in the relay node. For the second scenario case, the three protocols (AF, DF and EF) were developed, this is because the relay nodes can perform symbol estimation and get the two symbols from their two antennas.

6.3.1 Amplify and forward

This cooperative protocol is proposed in both network scenarios. It can be observed from Figure 24 the relay node is conformed by one antenna, because the relay node can



(a) Relay network with one antenna in the relay node.



(b) Relay network with antenna selection in the relay node.

Figure 23: Relay network scenarios for multiplexing.

not separate the received signals, it will send to the destination the sum of the received signals, the difference among the relay nodes will be the channel effects in their respective links. The receiver will consider the channel effects from both phases to perform the correct symbol estimation.

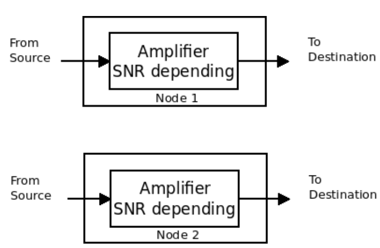


Figure 24: Relay node in amplify-and-forward with one antenna.

In the case of Figure 25, the relay node has a two antenna array. As the AF protocol performs only an amplification over the received signal in proportion to the SNR, the relay performs only the addition of the signals from the two antennas, without any kind of signal processing other than the amplification and transmission. Once the signals are mixed, the relay node will send the mixed signal through one antenna, this is why the name of antenna selection, and the destination will receive its symbols from a 2x2 channel. The channel effects detected at the destination are a sum from the wireless channels of phase one and a multiplication from the phase two.

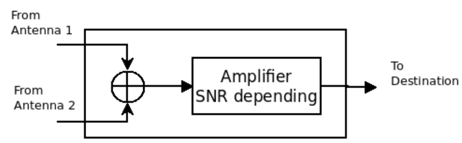


Figure 25: Relay node in amplify-and-forward with antenna selection.

6.3.2 Decode and forward

For DF, the relay node requires to estimate the received symbol and verify the CRC, this way it is necessary to have a two antenna array in both relay nodes; Figure 26 shows the stages that will perform the relay nodes. Each relay node will estimate both transmitted symbols and perform the CRC verification, but only one of the two symbols will be sent to the destination. For simplification, the relay node one will send the symbol one and the relay node two the symbol two. Since the channel effects from the phase one will be dismissed in the relay node, the destination only needs the CSI from the phase two to properly estimate the received symbols.

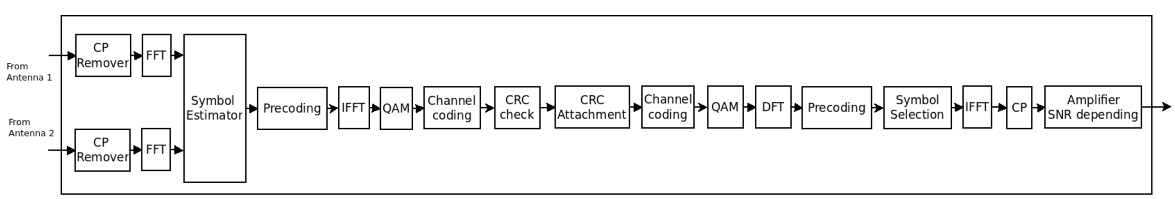


Figure 26: Relay node in decode-and-forward with antenna selection.

In DF, the stages considered for simulation are: 24 bits CRC insertion, turbo coding, channel interleaving, scrambling, digital modulation, DFT precoding, layer mapping and mapping to antennas.

6.3.3 Equalize and forward

In a similar way for DF, each relay node in EF estimates both received symbols and then proceeds to equalize them, as shown in Figure 27. When the symbols are estimated and equalized, the relay node selects one symbol to be sent to the destination, and dismiss the other one; the equalization is performed in the symbol estimation stage as part of the algorithm, after this, the relay node conforms a new OFDM symbol and sends it to the transmitter.

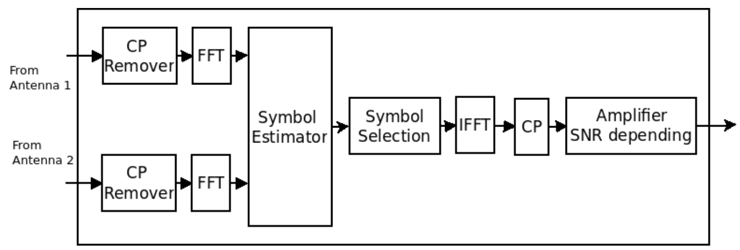


Figure 27: Relay node in equalize-and-forward with antenna selection.

6.3.4 Symbol Estimation at the receiver

Due to the presence of the DFTS stage, the symbol estimation (ZF, MMSE, ZF-SIC or MMSE-SIC) at the receiver must consider the domain change introduced by the DFT stage (time - frequency - time) to correctly estimate the received symbol. This domain change causes the estimated symbol to be a representation in the frequency domain of a digital modulated symbol, instead of known values from an alphabet, thus the slicing operation can not be performed; a block representation of the signal detection is shown in Figure 28.

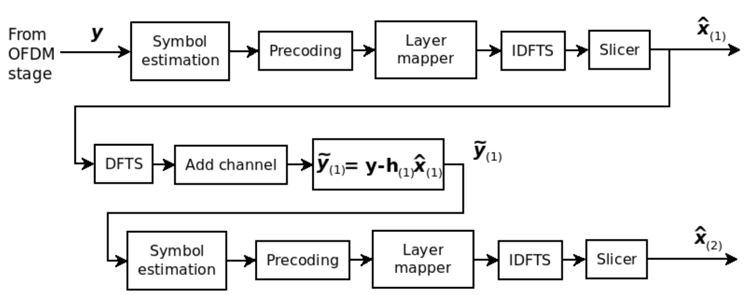


Figure 28: Illustration of SIC signal detection for two spatial streams with DFTS.

It is important to mention that, in AF, the previous channel information knowledge is required at the phases one and two, leaving to the destination node the symbol estimation task without relay nodes help. The ZF and MMSE relay version weight matrices considering two relay nodes are:

$$\mathbf{W}_{ZF} = (\mathbf{H}_{sr}^H \mathbf{H}_{sr})^{-1} \mathbf{H}_{sr}^H (\mathbf{H}_{rd}^H \mathbf{H}_{rd})^{-1} \mathbf{H}_{rd}^H \tag{47}$$

$$\begin{aligned} \mathbf{W}_{MMSE} = & (\mathbf{H}_{sr}^H \mathbf{H}_{sr} + \sigma_z^2 \mathbf{I})^{-1} \mathbf{H}_{sr}^H \\ & (\mathbf{H}_{rd}^H \mathbf{H}_{rd} + \sigma_z^2 \mathbf{I})^{-1} \mathbf{H}_{rd}^H \end{aligned} \tag{48}$$

The symbol estimation operation at the receiver considers the CSI from both hops (source - relay - destination) to estimate the data stream received at the antenna. The ZF and MMSE estimated symbols ($\tilde{x}_{ZF}$ and $\tilde{x}_{MMSE}$ respectively) with these considerations are:

$$\begin{aligned} \widetilde{\mathbf{x}}_{ZF} &= \mathbf{W}_{ZF} \mathbf{y} \\ &= (\mathbf{H}_{sr}^H \mathbf{H}_{sr})^{-1} \mathbf{H}_{sr}^H (\mathbf{H}_{rd}^H \mathbf{H}_{rd})^{-1} \mathbf{H}_{rd}^H \mathbf{y} \\ &= \widetilde{\mathbf{x}} + (\mathbf{H}_{sr}^H \mathbf{H}_{sr})^{-1} \mathbf{H}_{sr}^H (\mathbf{H}_{rd}^H \mathbf{H}_{rd})^{-1} \mathbf{H}_{rd}^H \mathbf{z} \\ &= \widetilde{\mathbf{x}} + \widetilde{\mathbf{z}}_{ZF} \end{aligned} \tag{49}$$

$$\begin{aligned} \widetilde{\mathbf{x}}_{MMSE} &= \mathbf{W}_{MMSE} \mathbf{y} \\ &= (\mathbf{H}_{sr}^H \mathbf{H}_{sr} + \sigma_z^2 \mathbf{I})^{-1} \mathbf{H}_{sr}^H \\ &\quad (\mathbf{H}_{rd}^H \mathbf{H}_{rd} + \sigma_z^2 \mathbf{I})^{-1} \mathbf{H}_{rd}^H \mathbf{y} \\ &= \widetilde{\mathbf{x}} + (\mathbf{H}_{sr}^H \mathbf{H}_{sr} + \sigma_z^2 \mathbf{I})^{-1} \mathbf{H}_{sr}^H \\ &\quad (\mathbf{H}_{rd}^H \mathbf{H}_{rd} + \sigma_z^2 \mathbf{I})^{-1} \mathbf{H}_{rd}^H \mathbf{z} \\ &= \widetilde{\mathbf{x}} + \widetilde{\mathbf{z}}_{MMSE} \end{aligned} \tag{50}$$

where **y** is the received symbol and **z** represents the noise. DF and EF do not require the source-relay channel state information, this is because the relay node estimates the symbol received after hop 1 and therefore mitigates the channel effects.

7. System Development

7.1 Simulation Setup

The modulation technique for the uplink is called DFTS-OFDM with a 16-QAM modulator, where all the nodes in the network, even the source and destination, work with this scheme. The OFDM symbol is conformed by 2048 subcarriers from which 192 are the occupied subcarriers in the OFDM symbol.

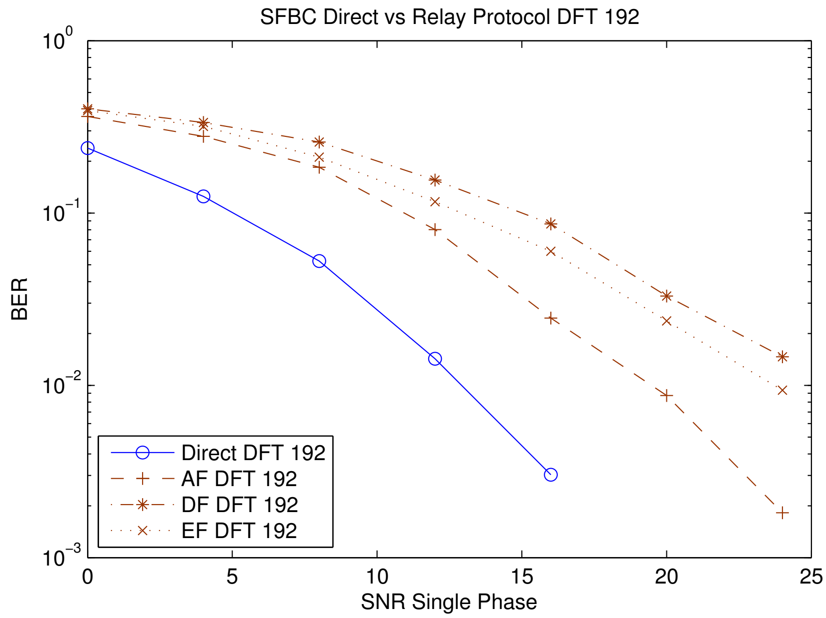
We assume a block fading channel model (where a block is an OFDM symbol) in which the channel realizations change independently from one block to another, while within each block the channels remain constant over each sub-carrier. Also, it is assumed that the receiver knows the channels from the transmitter to the relays and its own receiving channels.

7.1.1 PHY layer Setup

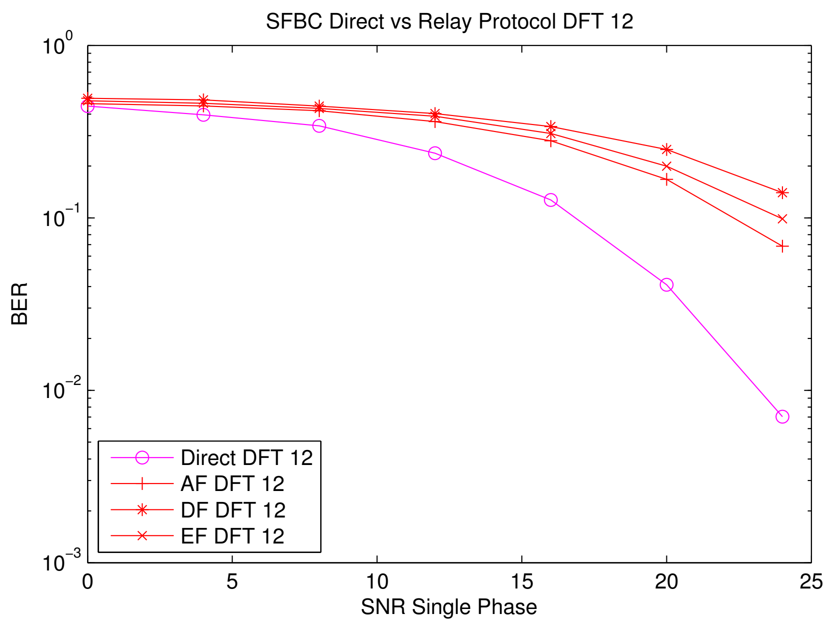
We based all our configuration setup in accordance with the LTE-A standard (Sesia *et al.*, 2009), where the uplink PHY layer has the following characteristics: the IFFT size to conform the OFDM symbol has 2048 bins, the cyclic prefix size to avoid the InterSymbol Interference (ISI) is 144 bins, the DFT size to perform the DFT spread is 192 bins, the packet size to be transmitted is 40 bits, this includes the 24 CRC bits, and the frame size is 1024 bits. The channel coding is a turbo code with rate 1/3 and the digital modulation scheme is 16 QAM.

To compare the DFT spread impact over the OFDM symbol, the simulation includes the DFT spread with 192 and 12 bins in a diversity mode, maintaining the other parameters without changes. In other words, in the first simulation only 192 sub-carriers out of 2048 have been occupied while just 12 sub-carriers were employed for the second simulation, as shown in Figure 29.

The number of occupied sub-carriers can affect the cooperative protocol BER performance, the 12-point DFT spread and 16-QAM combination has a poor BER, including the direct link case, but just changing the DFT spread size, i.e. increasing the number of



(a) BER Alamouti relay protocol comparison with a DFT 192.



(b) BER Alamouti relay protocol comparison with a DFT 12.

Figure 29: BER Alamouti relay protocol.

occupied sub-carriers to 192, with a 192-point DFT spread all relay protocol modes show a better BER performance.

The performance is evaluated in terms of Bit Error Rate (BER) versus Signal to Noise Ratio (SNR), the SNR displayed is per step, i.e. by setting SNR to 20, the source-relay (phase one) and relay-destination (phase two) SNR are both equal to 20.

Additionally, to select the better symbol estimator, a comparison among the diverse techniques employed was performed (zero-forcing (ZF), minimum mean square error (MMSE), and their combination with successive interference cancellation (SIC) like SIC-ZF and SIC-MMSE). Since we found that the DFT spread affects the BER performance, Figure 30 show both 192-points and 12-points spreads and the best response is for MMSE.

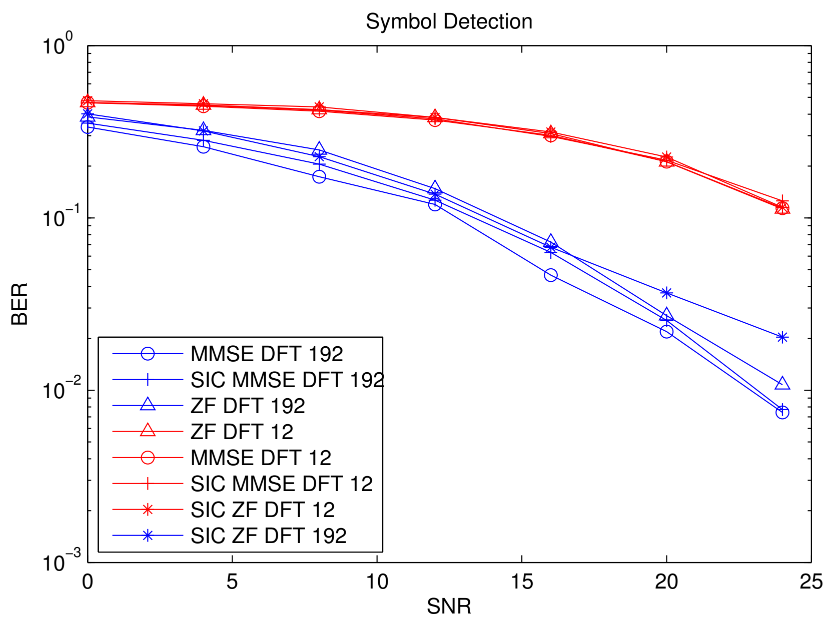
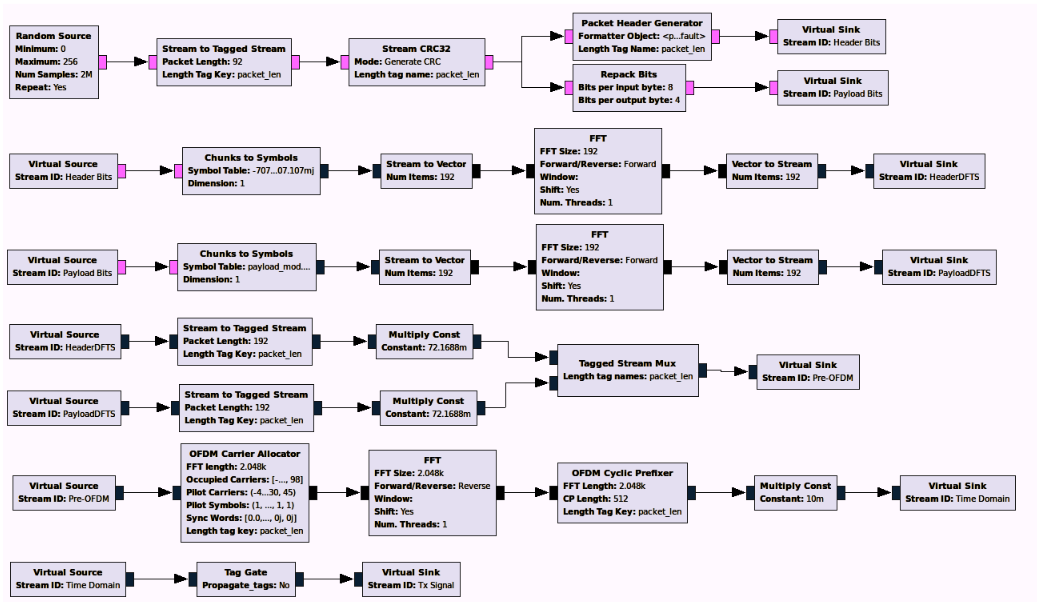


Figure 30: MIMO multiplexing symbol detection comparison.

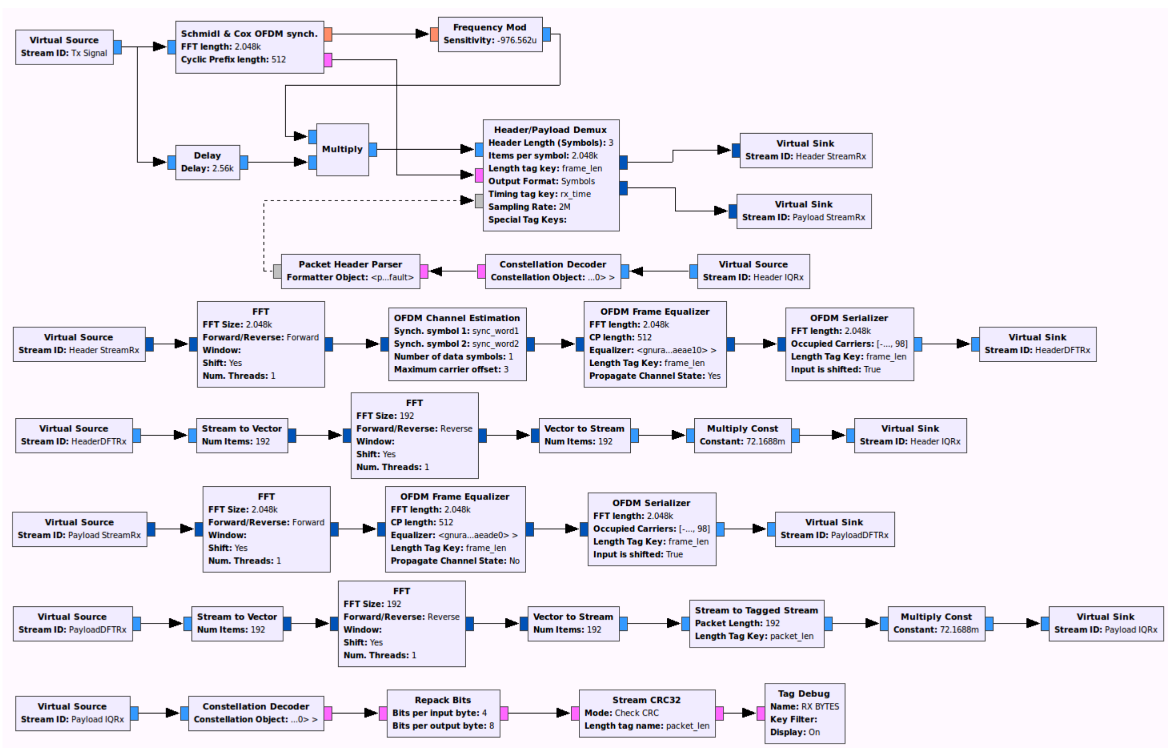
7.2 Emulation setup

The emulation is based in the OFDM transmitter and receiver proposed by GNU Radio project. The OFDM transmitter is conformed by two main procedures: header and payload transmission. The header consists of QPSK symbols where the payload characteristics (such as a sequence number, packet size, and cyclic redundancy check) are specified. One OFDM symbol is required to send this information to the destination. The payload consists of 16-QAM symbols that conform the transmitted data in one or more OFDM symbols. To perform a DFTS-OFDM system, the project needs to include a DFTS stage before the OFDM stage, Figure 31 shows the transmitter and the receiver, which are modified to include the DFTS in both header and payload flows.

Additional to the DFTS stage and its respective normalized blocks at the transmitter, the receiver includes two modifications, an IDFT block in both header and payload flows,



(a) Transmitter with GNU Radio.



(b) Receiver with GNU Radio.

Figure 31: GNU Radio project.

and an equalizer capable of handling the frequency domain samples, which is not the proposed by GNU Radio project called ”simple DFE equalizer”.

Originally the OFDM transmitter was designed for a 64 subcarriers OFDM symbol, in this case the emulation uses a 2048 points IFFT, 512 samples for CP, and a 192 points DFT, similar to the one was used on the simulation. Without loss of generalization, a setup of three OFDM preamble symbols (two for sync and one for header) and one payload symbol were arranged, this setup can easily be modified to include more payload symbols. It can be observed on Figure 32 the header and payload generation, though the header is generated from the same source than the payload, the header packet generator block replaces the bits with header information data.

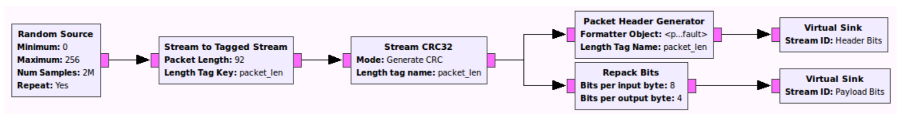


Figure 32: Header and payload generation at the transmitter.

To adapt this model to a DFTS-OFDM it is required to add the DFT stage after the header and payload digital modulator, separately as shown in Figure 33, because they will be transmitted by different OFDM symbols. The symbols received from the header and payload are different and the DFTS size could be different, in this case the DFTS size is fixed to 192-points. The samples obtained after DFTS are the frequency representation of the digital symbols group and should not be modified or split to be recovered without problems at the receiver.

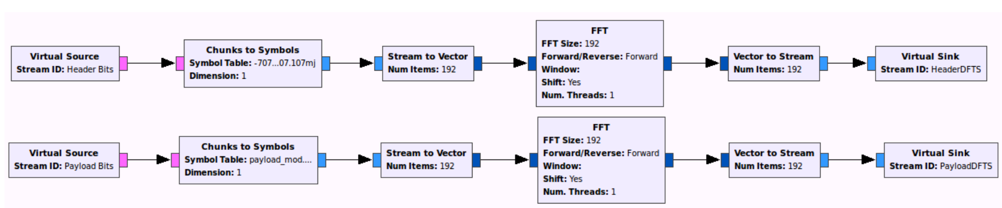


Figure 33: DFTS stage in OFDM transmitter.

The header and payload flows are coupled again in the same data flow to the OFDM transmitter, in first place goes the header data, followed by the payload symbols. The data is not mixed due to the presence of flags called ”tags”, these tags are used for the control plane, they do not affect the transmitted data and specify the frame size of the header and payload. Figure 34 shows how the header and payload flow are tagged, and how the Tagged Stream Mux block links again the data in the correct order.

Finally, the carrier allocation and preamble processes are performed in the OFDM

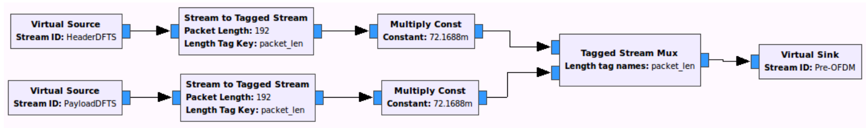


Figure 34: Header and payload at the transmitter.

stage, as shown in Figure 35; since there are 192 samples to conform the 2048 subcarriers OFDM symbol, the rest of subcarriers are set to zero. The subcarriers location is selected by an index of 2048 elements, where it is indicated if the allocation is localized or distributed; furthermore, the allocation could be in an arbitrary order for test purpose. The preamble sequence allows the Schmidl block to detect the presence of OFDM symbols at the receiver.

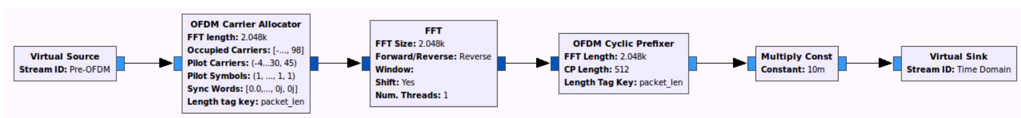


Figure 35: OFDM stage at the transmitter.

There are additional procedures at the receiver, like symbol detection and channel estimation; for implementing these procedures, two synchronization words are transmitted before the header symbol, the first one serves for the receiver to detect the OFDM symbol presence while the second one is used for the channel state estimation. The first sync word is conformed by symbols hosted only on even subcarriers, this way the Schmidl and Cox receiver (Schmidl and Cox, 1997) will detect an OFDM symbol on the air and will perform a frequency offset adjustment to the symbol. The second sync word, where all subcarriers are occupied, contains a pseudo-random sequence known by the receiver, which is used to estimate the channel state; this information is propagated to the payload equalizeline-of-sigthr in order to recover the payload without the channel effects, as shown in Figure 36.

It can be observed in Figure 37 how the receiver estimates the CSI with the sync words, in the equalizer stage the channel effects will be removed from the DFTS samples; by default, the provided GNU Radio example considers a simple DFE equalizer, this involves a digital symbol estimation based on the constellation map; this kind of equalizer is not recommended for DFTS-OFDM, since in this case the samples are not based on a constellation map, so we use a basic equalizer, which consists in a division of the received

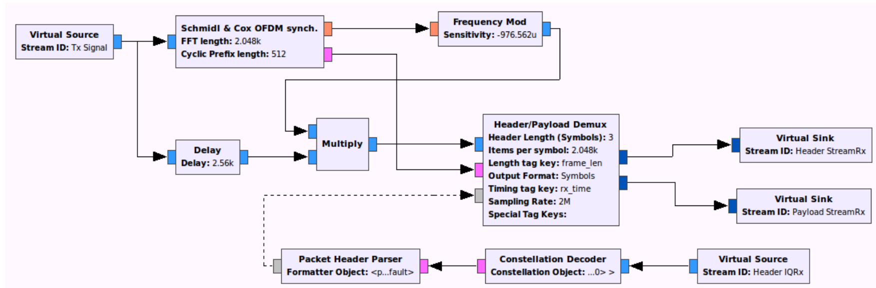


Figure 36: OFDM symbol presence detection stage.

signal by the channel estimation (on a per subcarrier basis).

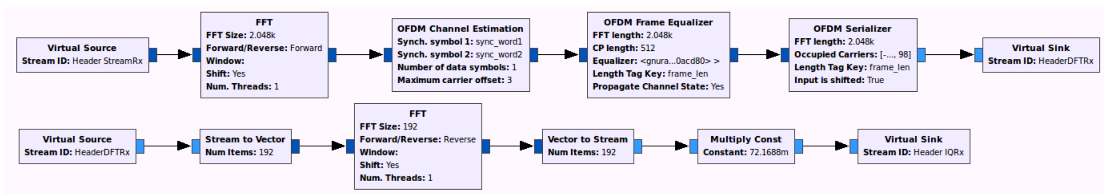


Figure 37: Header estimation at the receiver.

With the information obtained trough the header, the payload can be recovered properly, the CSI is sent to the payload equalizer and the symbols are estimated. There is not a forward error correction procedure implemented, only an error detection performed by a 32-bit Cyclic Redundancy Check (CRC) stage for the payload and an 8-bit CRC for the header as shown in Figure 38.

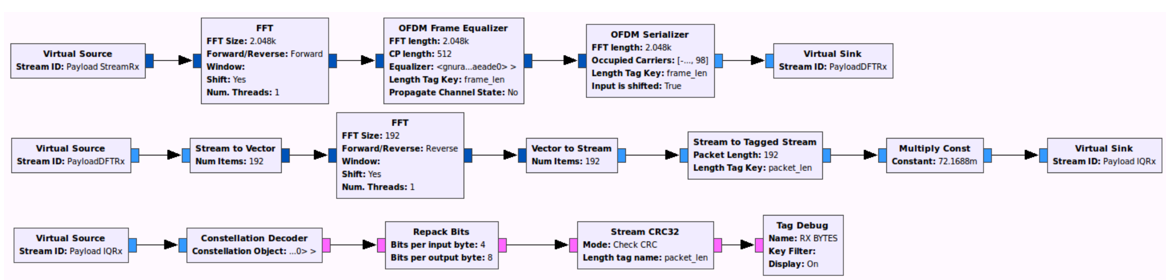


Figure 38: Payload estimation at the receiver.

To perform the SNR estimation at the receiver it is required to know the transmitted symbol, in this way the same symbol is repeated in the payload stage. The preamble symbols can not be repeated because they have random fields. The SNR estimation at the receiver is performed over the payload data, using a blind SNR estimation technique, which consists in a low-complexity algorithm for an OFDM signal transmitted over a frequency-selective channel with colored or white noise; this algorithm only uses the second moment statistics in the frequency domain without requiring training symbols or pilot subcarriers. This technique allows to estimate the SNR in each OFDM symbol or a set of OFDM symbols (Li, 2010).

7.2.1 Relay emulation setup

The network scenario is conformed by a source, a relay node and a destination with only one antenna. The OFDM symbol is conformed by 2048 subcarriers and the DFTS by 192 points, this means only 192 subcarriers are occupied in the OFDM symbol transmitted. The cooperative protocol includes in the relay node only the required PHY layer stages: a repeater for the AF case, a payload equalizer and the header stages for the EF case and all the stages for the DF case.

For AF, the relay node is conformed by the receiver and the transmitter for USRP cards, the amplifying operation is performed through a variable in the UHD block. Figure 39 shows the relay node and gain in the transmitter.

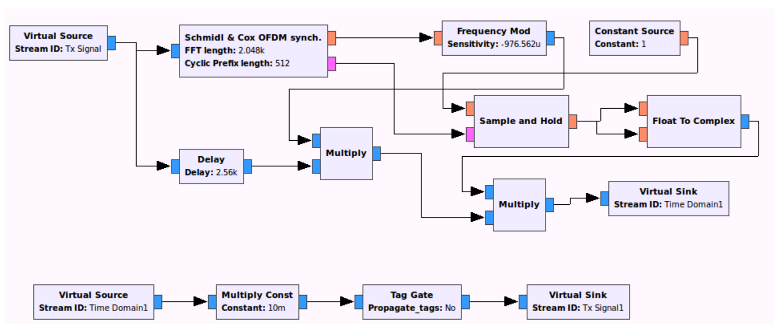


Figure 39: AF node.

It is observed on Figure 40 that DF is the cooperative protocol with the most complex relay node; to perform the CRC checksum the relay node needs to obtain the data bits after the digital modulation, once the CRC checksum is passed, the relay node generates a new header and payload flow to conform a new OFDM symbol that will be sent to the destination. In case that the Schmidl or the CRC checksum verification fails, the relay node will not generate the new OFDM symbol to send to the destination.

The EF protocol is simpler than DF but there are some considerations to know, because the header received at the relay node can not be used again and the header generator block requires data bits to create a new one, the relay node includes the header

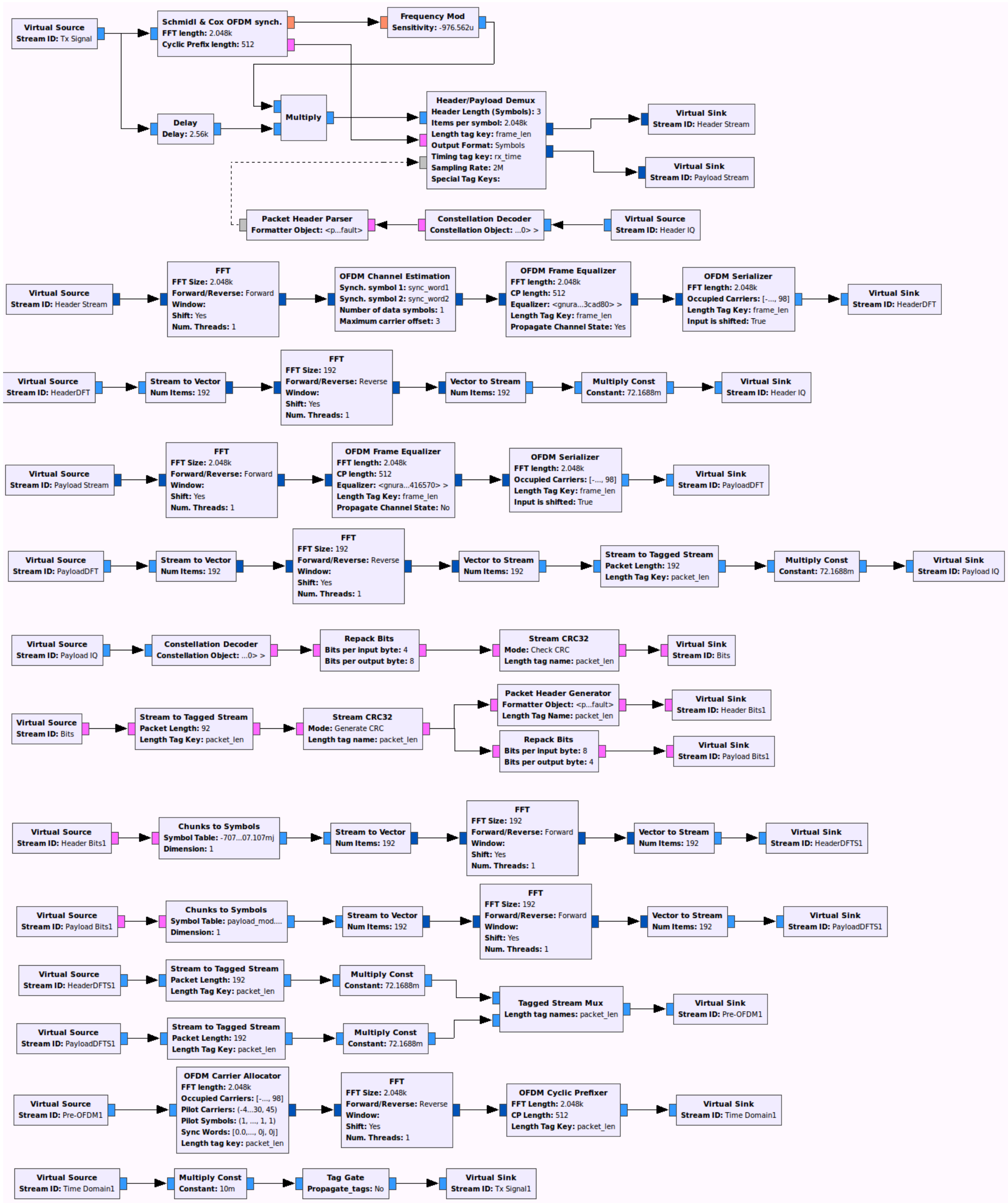


Figure 40: DF node.

generation stage at the same time that performs the equalization in the payload flow. In this way the equalized payload is sent to the destination with a new header created in the relay node as shown in Figure 41.

The cooperative protocols performed are selective, because of two stages included in the receiver: the Schmidl and header verification. If the Schmidl does not detect the

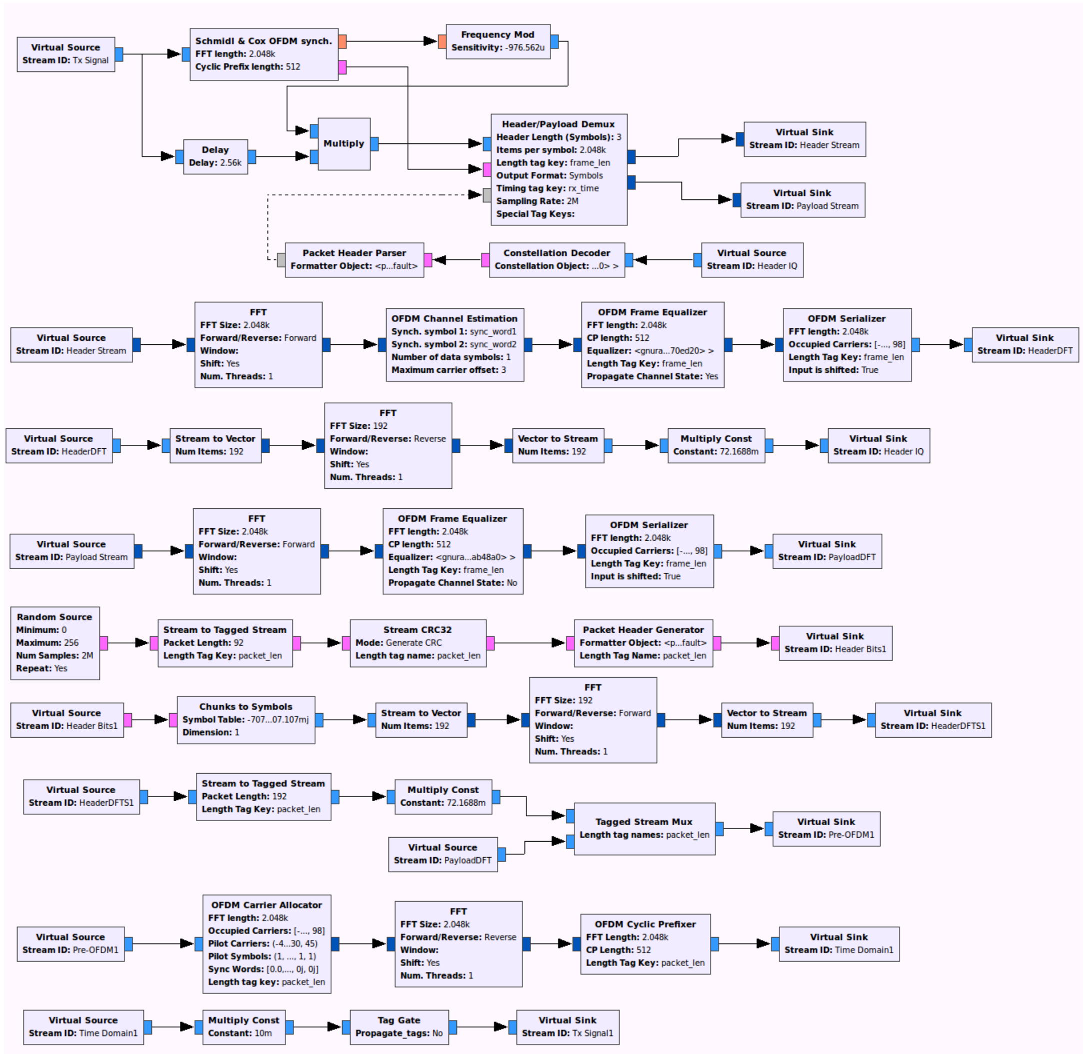


Figure 41: EF node.

presence of a good OFDM symbol all the stages of the relay node are turned off, else if the OFDM symbol is detected then it allows the header verification to be performed over the received symbols. The Header/Payload Demux block has a trigger that only enables the payload recovery when the header verification is passed. In other words, even if the OFDM symbol is received in the node, this does not guarantee that the payload will be decoded, for this to happen it is necessary to pass the header verification.

8. Numerical results

8.1 SFBC with relay protocols simulation

It can be observed from Figure 42, we can observe that AF is the worst cooperative protocol and DF has a better BER performance, because there is only one single-antenna relay node and there is not any kind of signal processing in the antenna (like in S-T block codes) only the channel coding for DF and an amplifier for AF. It also observed that EF has a similar performance to DF at high SNR; this is an advantage for EF cooperative protocol because the relay node for EF has less signal processing stages those of the DF, since it only requires a signal equalization after the OFDM stage.

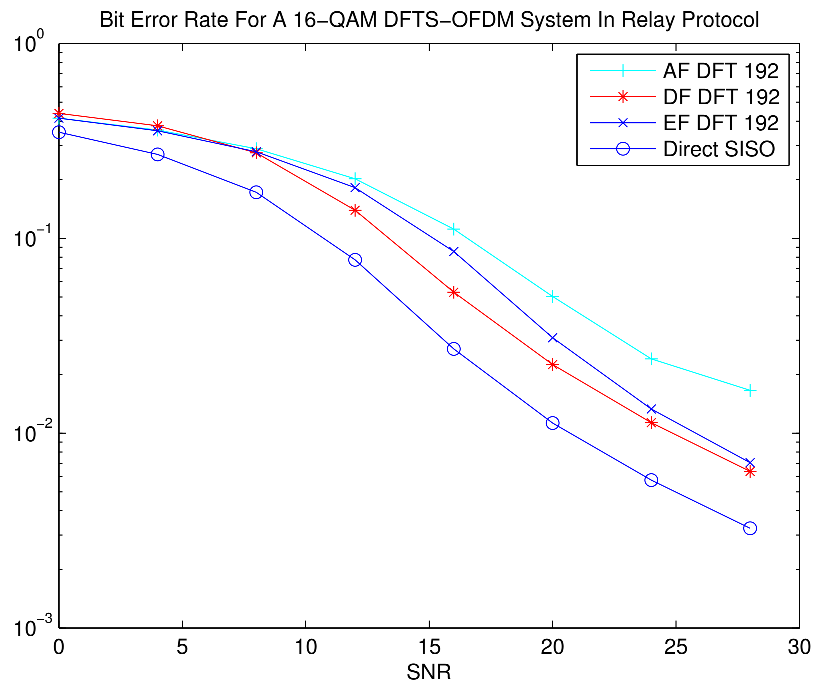


Figure 42: SISO simulation results.

Figure 43 shows the results of the BER performance for cooperative protocols in a scenario where the source has just one single-antenna, which by definition could not deploy a MIMO transmission, but with virtual MIMO technique and relay nodes it is possible to deploy a virtual array with MIMO capabilities.

The comparison between the cooperative protocols shows a better BER for AF than for the other two protocols, this is because the estimation symbol process is performed by

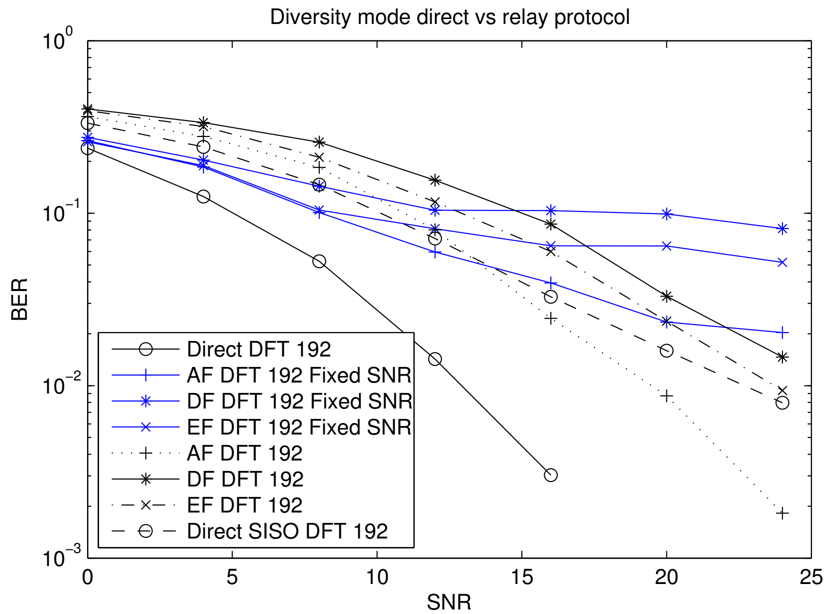


Figure 43: SFBC simulation results.

the destination node with the CSI of all phases, unlike what happens for DF and EF cases.

The EF is better than the DF protocol because an eventual phase one bit-level error is transmitted to the destination node without symbol manipulation, i.e. the relay node in EF cannot detect a bit-level error or a symbol error even though it estimates a symbol; the destination node estimates the symbol and performs the channel decoding to recover the data bit.

The DF protocol presents the most complex relay node structure, the relay node is composed by all the PHY layer stages and performs a CRC verification. But if the relay node does not recover the data correctly, there is not a symbol to send to the destination and the receiver cannot correctly decode the transmitted data because it does not match with the relay node transmitted data for Alamouti SFBC symbol estimation.

Leaving the phase two with a fixed SNR, we can observe that BER performance is affected even when there is a high SNR at the phase one, the numerical results are congruent with the expected behaviour where the best possible link is the worst of phases in the relay protocol.

The comparison with direct SISO shows an improvement of amplify-and-forward at medium to high SNR, where the relay protocol is better at a 192-point DFT spread. The use of virtual MIMO allows single-antenna user devices to have a reliable communication with diversity mode although this is not better than a MISO direct link, i.e. a relay channel will not achieve a better performance than a single channel.

The relay protocols are compared with a MISO 2x1 direct link and a SISO direct link, where the link setup is between the source node and the destination node without relay nodes in between.

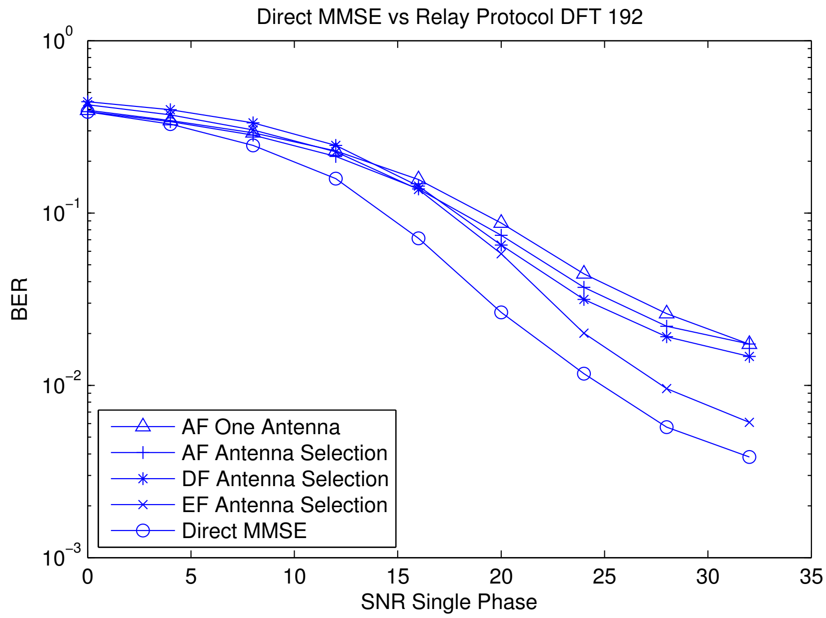
8.2 MIMO multiplexing simulation

According to the symbol detection technique comparison for both 12-point and 192-point DFT spread, in the first case we can observe that there is no difference in the technique employed, but for 192-point, the MMSE estimation technique can obtain a better bit error rate (BER) performance; this does not mean that MMSE is better than SIC-ZF or SIC-MMSE, the performance of SIC is better with the use of many antennas, but, in this scenario, we only have two antennas. The BER comparison is developed under a point-to-point scenario, not under a relay deployment.

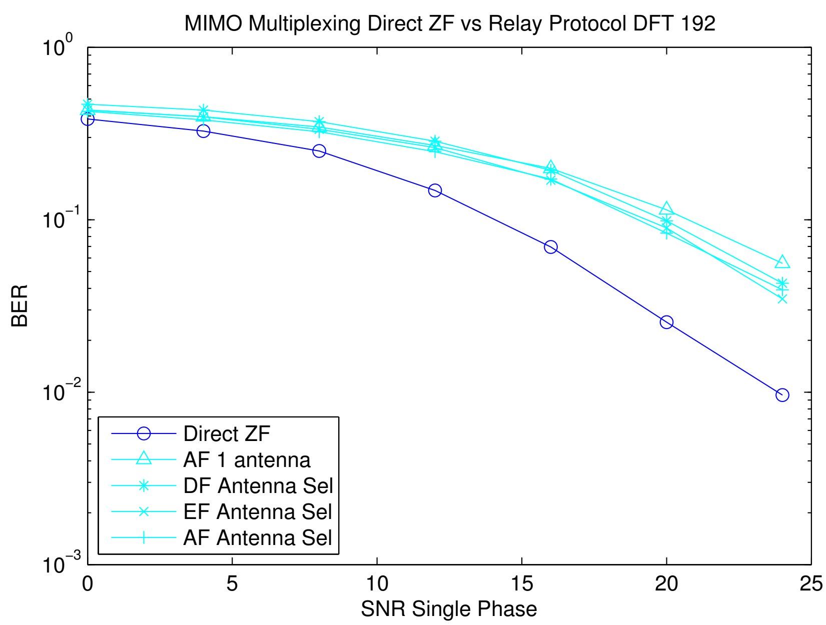
As it can be seen in Figure 44, the EF protocol performs better than the other relay protocols. The results show that EF in combination with MMSE has a better performance at high SNR but in combination with ZF the performance is affected but not enough to be overcomed by other cooperative protocol. The worst performance corresponds to the AF cooperative protocol with one antenna in the relay node, no matter the symbol estimation used.

Additionally, Figure 45 shows the BER comparison in a scenario where the SNR of the phase one was held fixed at a 15 dB value, we can observe how the slope is relatively null at high SNR for both estimation techniques.

The error rate flattens out at SNR = 15, except for direct MMSE. This is because direct MMSE does not use a relay node; in a relay scenario the error from phase one limits the performance of phase two, in other words, we can have a performance as good as the one that can be provided by the worst channel.



(a) MMSE estimation.

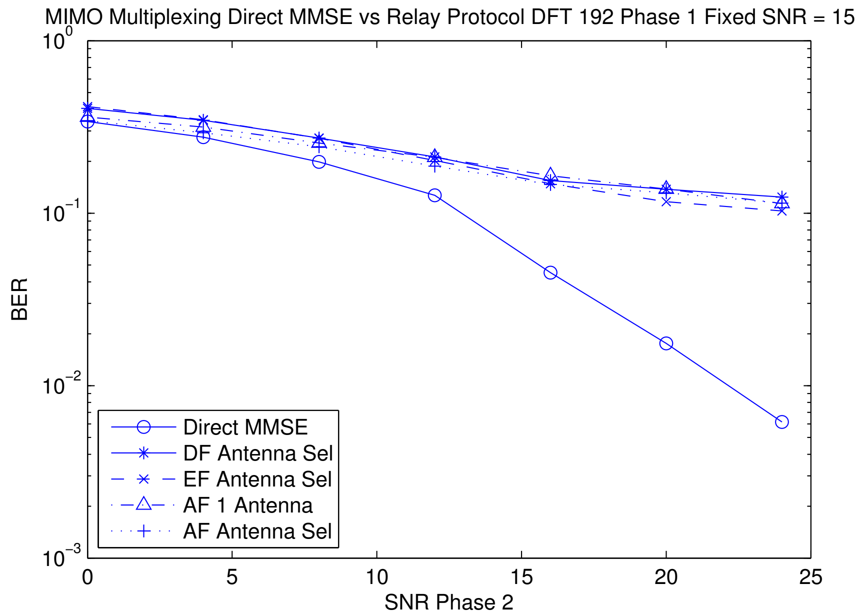


(b) ZF estimation.

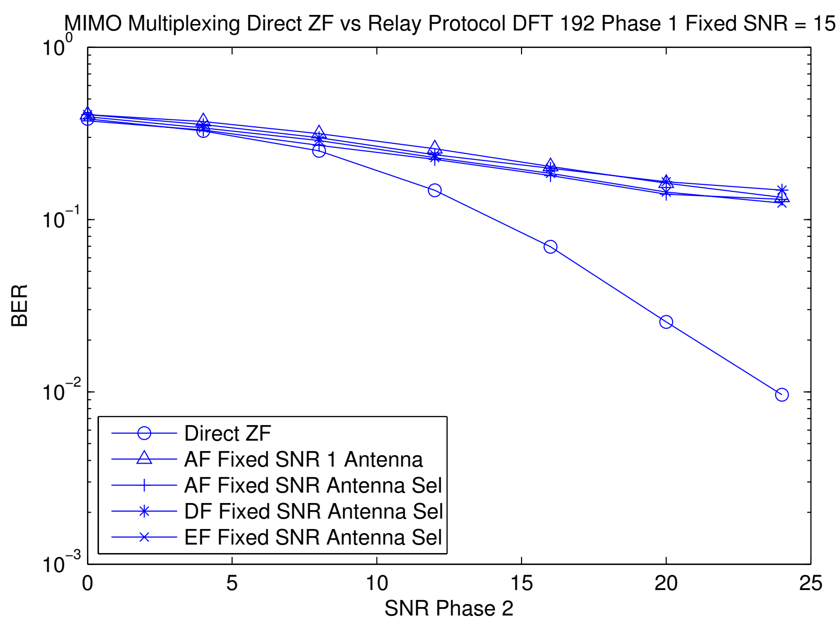
Figure 44: Cooperative protocols with DFT 192.

8.3 DFTS-OFDM emulation

GNU Radio brings a set of measurement tools that allows real time analysis, such as QT Graphical User Interfaces. Figure 46 shows the modulated symbol constellation and the spectra of the OFDM symbol, both at the transmitter and at the receiver (with the effect



(a) MMSE estimation.



(b) ZF estimation.

Figure 45: Cooperative protocols with DFT 192 and fixed SNR at phase two.

of the radio channel). With the help of File Sink blocks, we collect the data received at several SNR values and estimate their corresponding BER, PER and SER.

To demonstrate that the blind SNR estimation algorithm works correctly, a simulation of a DFTS-OFDM was performed, the estimated SNR is shown in Figure 47 and is very close to the real value in the simulation, the SNR value is in the right y axis. Considering

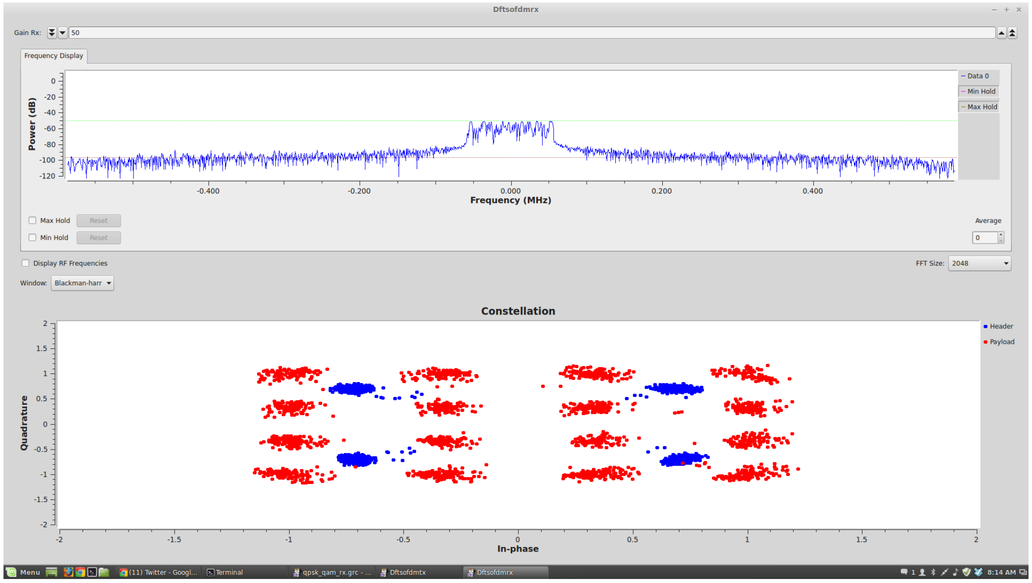


Figure 46: Received symbol and spectra.

this, we estimated the SNR in the OFDM symbols of a real transmission, calculating the BER, PER and SER and comparing with the simulation. The error rate is in the left y axis.

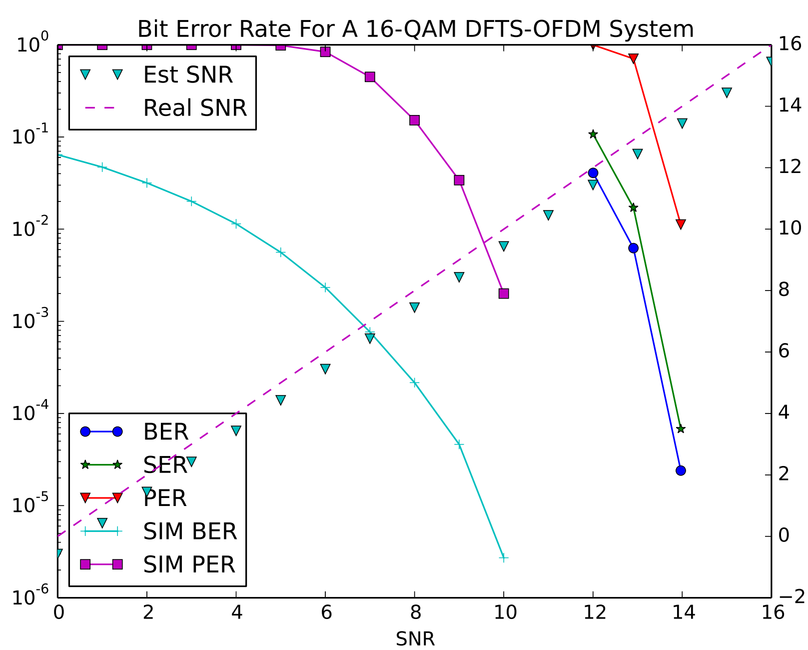


Figure 47: Emulation results.

The difference between the emulation and simulation curves denotes that simulation does not consider several issues in hardware stages like the receiver sensitivity to detect the presence of a OFDM symbol, this is the reason why the emulation curve starts at

SNR equals to 12 dB. Additionally we observe a saturation phenomenon at high transmission power, which does not allow to transmit at SNR values over 14 dB, even though we increased the transmission power and the receiver sensitivity.

8.4 Relay protocol emulation

In AF, the relay node only amplifies the received OFDM symbol. Figure 48 shows the GNU Radio interface displaying the received and transmitted OFDM symbol in real time. The OFDM symbol is received and if the SNR threshold is exceeded, the relay node sends it to the destination with an amplification, the noise added by the receiver is amplified along with the OFDM symbol. The box in the graph is for 2048 subcarriers, the OFDM symbol shows 192 subcarriers according to the DFTS-OFDM setup.

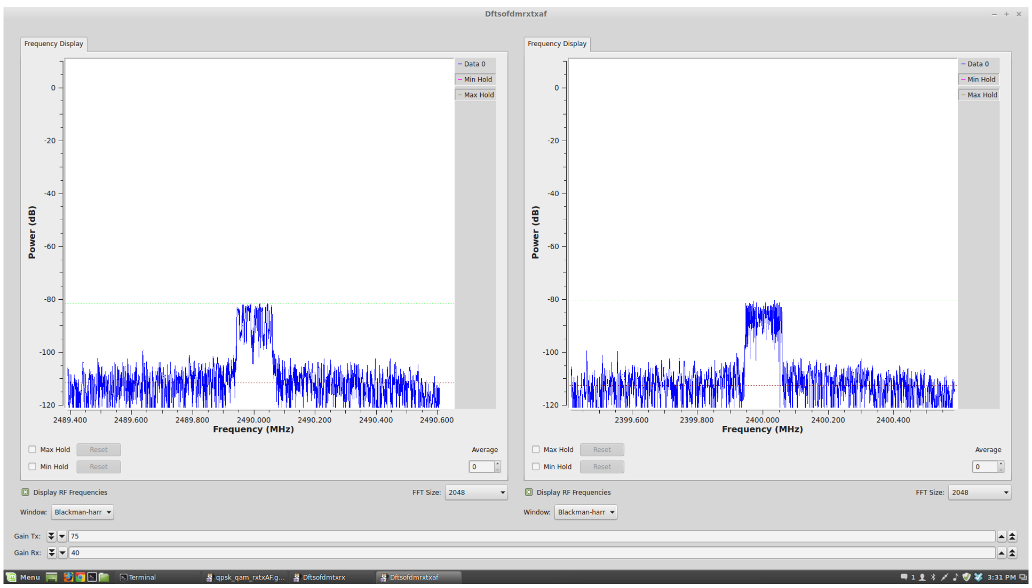


Figure 48: AF node emulation.

Figure 49 shows the relay node performance with DF cooperative protocol, where both the header and payload are recovered and demodulated. The header consists of QPSK symbols, while the payload consists of 16-QAM symbols; the transmitted symbols are set in the exact position in the IQ graph, but the decoded symbols are just near the constellation position in the graph, this is because the wireless channel effects and AWGN are not completely dismissed.

The EF relay node can only decode the header packets because the payload is only equalized as DFTS samples. Figure 50 shows the recovered headers and the spectra of

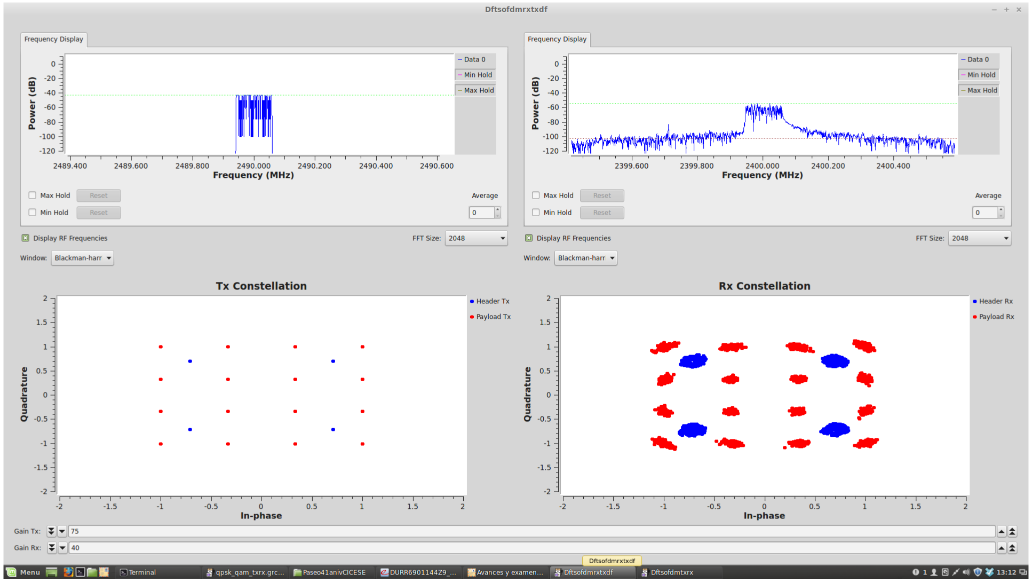


Figure 49: DF node emulation.

the OFDM symbol received, the payload cannot be displayed in a constellation graph.

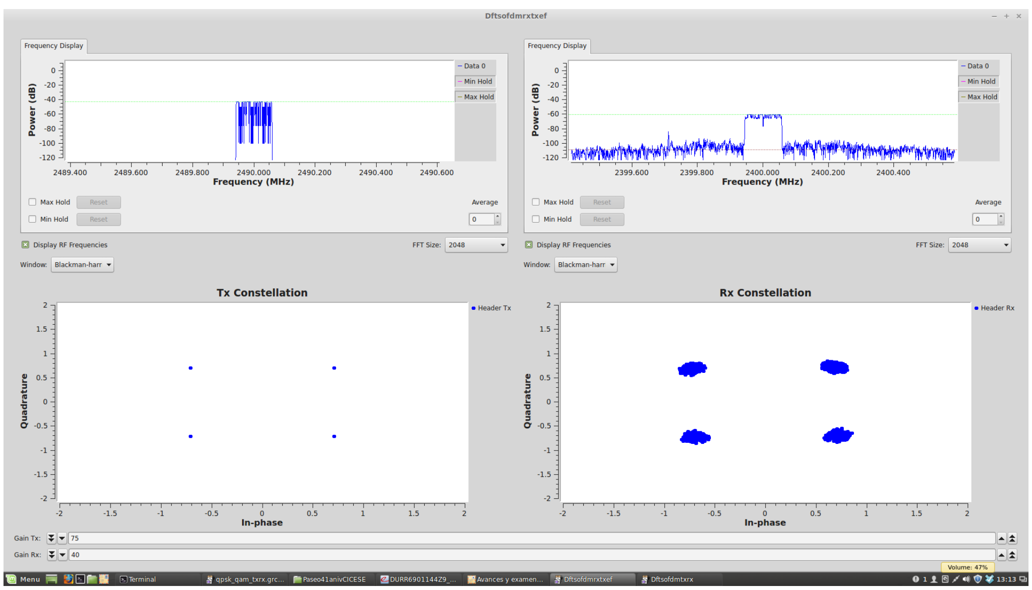


Figure 50: EF node emulation.

All the relay nodes are conformed by the same digital processing blocks, according to the cooperative protocol the stages are disabled to perform the correct operation. The noise presence in the constellation is because the equalizer stage in the digital processing is a basic one, the equalizer developed is a simple division among the received samples and the channel state information estimated through the header packets.

9. Conclusions

9.1 Introduction

The contributions of this dissertation can be listed as follow:

- Implementation of Alamouti coding in phase two of cooperative protocols by dividing the space - time code in every relay node.
- A symbol estimation technique for multiplexed signals over a DFTS-OFDM communication system.
- A reliable point-to-point DFTS-OFDM wireless communication system based on GNU Radio.
- A SNR blind estimation for OFDM at the receiver.
- The integration of IT++ library as a GNU Radio Out-Of-Tree implementation.
- The development AF, DF and EF relay nodes for two hopes in a three SDR hardware array.

The first two consists on simulations for diversity and multiplexing techniques. In the diversity case, one-antenna nodes and devices were utilized; for multiplexing, both, one and two antennas nodes were utilized, while the devices always used two antennas. Points three and four are related with the wireless communication system implementation in GNU Radio, where the DFTS stage was implemented and additionally an algorithm to estimate the SNR of the OFDM symbol at the receiver is required. The fifth contribution corresponds to the Out-Of-Tree implementation protocol for GNU Radio, in this way, external libraries can be included in the communication system. Finally, the last point is related to the relay nodes configuration for the cooperative protocols.

9.2 SFBC with cooperative protocols

Although there is not a specified relay protocol to develop the cooperative communication in any 4G, 5G and WLAN standards, all of them allow a free implementation of the protocol. Considering this, we made a BER-based comparison among the most known cooperative protocols, i.e. AF, DF and EF. We found that the AF protocol performs better than the other two protocols. In order to point out the differences between a direct link and a cooperative communication, we compared the BER performance of MISO 2x1 with SISO direct link. We noticed that the AF protocol outperforms both DF and EF at medium to high SNR.

AF is not a good cooperative protocol in a SISO scenario because there is no channel compensation at phase one and the noise is sent to the destination node, contrary to DF and EF cases where the relay node nullifies the channel effects from the phase one and sends a new symbol to the destination.

When the Alamouti code is implemented in the relay scenario and considering that its BER performance is better than that of a SISO system, the AF protocol has a better performance than DF and EF. This is because in AF the Alamouti receiver mitigates the channel effects from both phases, which is different from the DF and EF protocols, where their respective nodes mitigate the channels effects from phase one leaving to the Alamouti receiver just the channel effects from phase two. In other words, in AF all the relay channels are mitigated by the Alamouti receiver but in DF and EF the Alamouti code efficiency is affected by the relay nodes leaving the second half of the relay channels to the destination node.

More over, in accordance with information theory literature (Gallager, 1968), the average uncertainty about the input of a channel, given the channel output, can never decrease as we advance in a sequence of cascaded channels. As expected, the cooperative protocols cannot perform better than their respective point-to-point version; however, this work objective is to bring an option to single-antenna devices to perform a reliable MIMO communication through virtual MIMO arrays by means of relay nodes.

9.3 MIMO with cooperative protocols

The new technologies consider new networks scenarios where the picocells presence will be the basis of these wireless architectures, the picocells could be provided by users in schemes like user-provided networks or centric-provided networks; the main advantage will be the price reduction and easy installation, at the cost of involving cell-edge management and devices with interference cancellation algorithms, as a result of the presence of network densification.

We made a BER-based comparison among the most known cooperative protocols, i.e. AF, DF and EF protocol. We found that EF protocol performs better than the other two protocols, including AF with one antenna. In order to point out the differences between a direct link and a cooperative communication, we compared the BER performance of MIMO 2x2 with MMSE direct link (SISO array). We noticed that the EF protocol outperforms AF with antenna selection, AF with one antenna and DF at medium to high SNR.

The MIMO simulation presents a very similar result at SISO performance with cooperative protocols, with the difference that EF is a better protocol than DF protocol. Both network scenarios variation presented for AF were considered with single-antennas devices as relay nodes, this is a cheaper relay scenario but not a good option due the BER performance; in the two-antenna relay case, we could consider a waste when disabling an antenna at the phase two, but for a fair comparison with the MIMO 2x2 direct link, a cooperative virtual MIMO 2x2 array was configured in the second phase. However, this goal of this work is to bring an option to single-antenna devices (located close to the edge of a cell) to perform a reliable MIMO communication trough virtual MIMO arrays by means of relay nodes; this would increase the cell coverage.

The symbol estimation technique is a central part in the relay scenario BER performance. Leaving the destination node the task of mitigating all channels effects could be a complex task, mainly due to the channel estimation than to the symbol estimation, the channel estimation in the AF with antenna selection scenarios considers a sum of both channels in phase one which is retransmitted at phase two by the relay node, this way the destination node needs to estimate six channels. For AF with one antenna the complexity is larger due to the mixed symbols received in the relay nodes at phase one, more than to the channel effects; the destination node recovers a mixed symbol from the relay nodes and estimates the original symbol from this signal mixture.

9.4 DFTS-OFDM

The development of a DFTS-OFDM system in GNU Radio involves three main processes: synchronization, channel estimation and transmission. In simulation environments the synchronization and channel estimation is not usually considered, the focus is on bit error rate or channel capacity evaluation. The emulation requires both synchronization and channel estimation to perform a sucessfull transmission allowing the research in many stages and obtaining numerical results in real environments.

GNU Radio includes a good equalizer in the time domain, but a DFTS-OFDM system requires a frequency domain equalizer, this is because the simple DFE equalizer can estimate the digital symbol transmitted. The use of frequency domain equalizers allow to perform a better channel effect cancellation and a more accurate symbol estimation; an alternative would be to customize the simple DFE equalizer, such that includes the DFTS stage in the symbol estimation loop-back, this way the symbol estimation will be performed over digital samples and not over the DFT samples. In the emulation, a simple division of the received signal by the estimated channel was performed; the main problem is that the received symbol does not belong to a known modulation symbol constellation set but a DFT representation of it. The frequency domain equalizers can be included as classes in GNU Radio, this way, the equalizer function can be deployed without a new digital signal processing block and can profit the actual structure of the GNU radio function classes.

9.5 DFTS-OFDM relay

The emulation of a cooperative protocol without diversity or multiplexing is not very helpful for the source node, but it is applicable without many complications and allows to find the weakness in relay channels. As more relay nodes are added to the network scenario, the channel capacity of the system is increased and both error rate and bit rate show improvements, therefore, the development of virtual MIMO scenarios with relay nodes based on GNU Radio could be possible.

At the receiver in diversity mode, the equalizer must be disabled because the Alamouti decoder requires the channel state information to estimate the symbol, at the same time,it is important to note that the header packets will not be encoded by the Alamouti code, because these packets are used in the first stage to estimate the channel and verify that the information is correct.

9.6 Further work

The new generations of wireless communications are actually oriented to DFTS-OFDM, massive MIMO, device-to-device communication and relay nodes for network densification; otherwise it is also considered to work in millimeter waves around 30 and 50 GHz. This platform will allow to work in these research topics with less modifications in the hardware leaving all the customization to the software. Techniques like cognitive radio are highly related with software radio, because the transmitter needs to be tuned to an available frequency.

On the other hand, the development of a DFTS-OFDM testbed via GNU Radio and USRP allows the possibility to deploy and test new techniques in PHY layer, therefore, the research will not give theoretical results in simulated wireless channels but from real wireless channels. Although all the PHY layer processes are performed by a computer and the USRP testbed is only the frontend for the wireless link, to include another layer like MAC or NETWORK will depend on the programmer skills since the USRP testbed does not interfere with those layers.

We have observed that the receiver cannot work at SNRs higher than 14 dB, since even though we increased the TX power, the noise at the RX increased as well, maintaining the SNR at an almost constant value. We propose two possible solutions to this problem; the first one is to modify the Schmidl and Cox block (which detects the signal). The second solution may be to include a digital signal processor block before the Schmidl and Cox, so the noise floor would be kept to a minimum level.

The next step is to develop a block code for achieving diversity or a multiplexing technique with SDR. For the diversity mode, the development of block codes like Alamouti can be performed through mathematical and stream operators signal processing blocks, but this results in a fixed size block code which could not be customized. The development of a signal processing block that performs in any kind of block code like S-T, S-F or S-T-F could make it easy to implement and test in the emulation stage. This signal processing block would generate the data flows required for the specific code and the required number of antennas of the corresponding MIMO array.

In a similar way, the development of a signal processing block for multiplexing could be deployed via software, although for MIMO multiplexing it only requires a data flow splitter to send data to the MIMO array, it will be pertinent to add a signal processing block for the precoding stage. The transmitter is basically simpler than the receiver because a symbol estimation is needed for demultiplexing the received signal, but because there are several techniques that can perform these processes (like ZF, MMSE, SIC-ZF or SIC-MMSE among others), it will be considered a general signal processing block where the symbol estimation technique can be selected and by means of functions or classes will allow the development of new algorithms.

In addition to the frequency domain equalizer class for DFTS-OFDM systems, signal processing block for block codes and precoding for diversity and multiplexing mode respectively, the development of relay scenarios or MIMO array scenarios will require to obtain the channel state information of the MIMO channels. Actually GNU Radio includes the channel state estimation for one-antenna device, so that it will be necessary to include a couple of synchronization words by antenna and specify the way how the header data will be transmitted; either by only one antenna or having each antenna transmitting a different header.

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A. GNU Radio projects

A.1 Cooperative protocols in GNU Radio

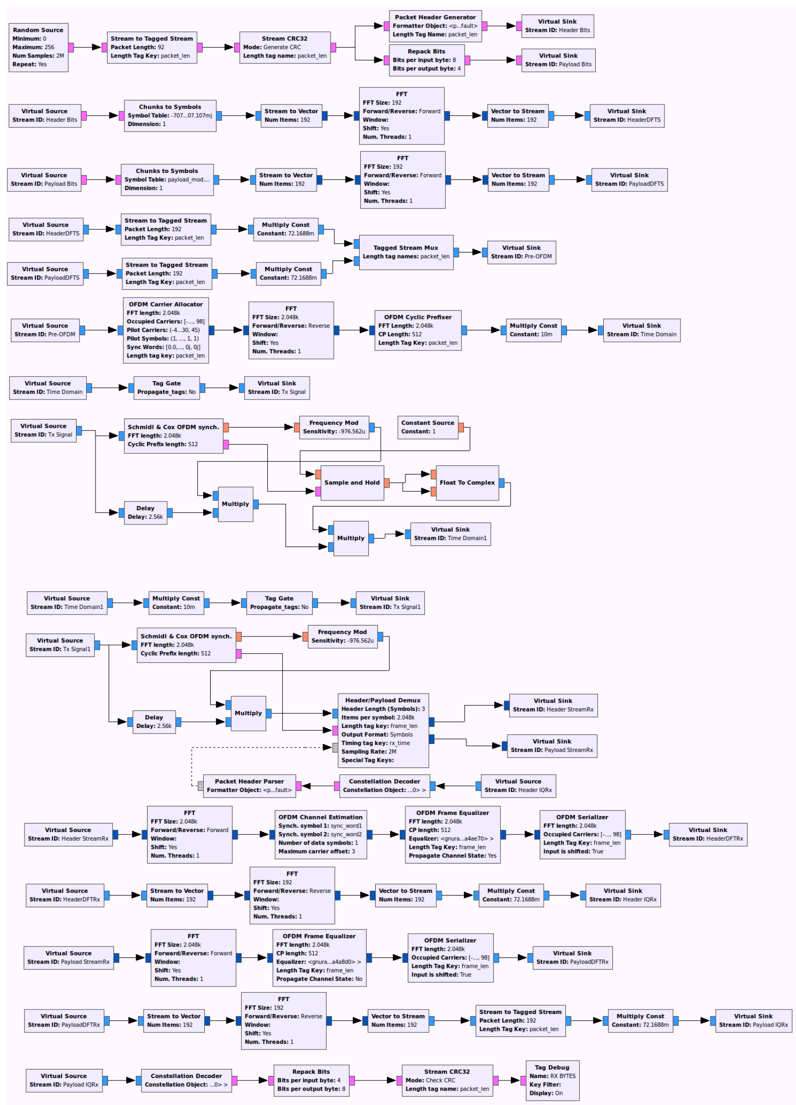

Figure A.1: AF protocol implementation in GNU Radio.

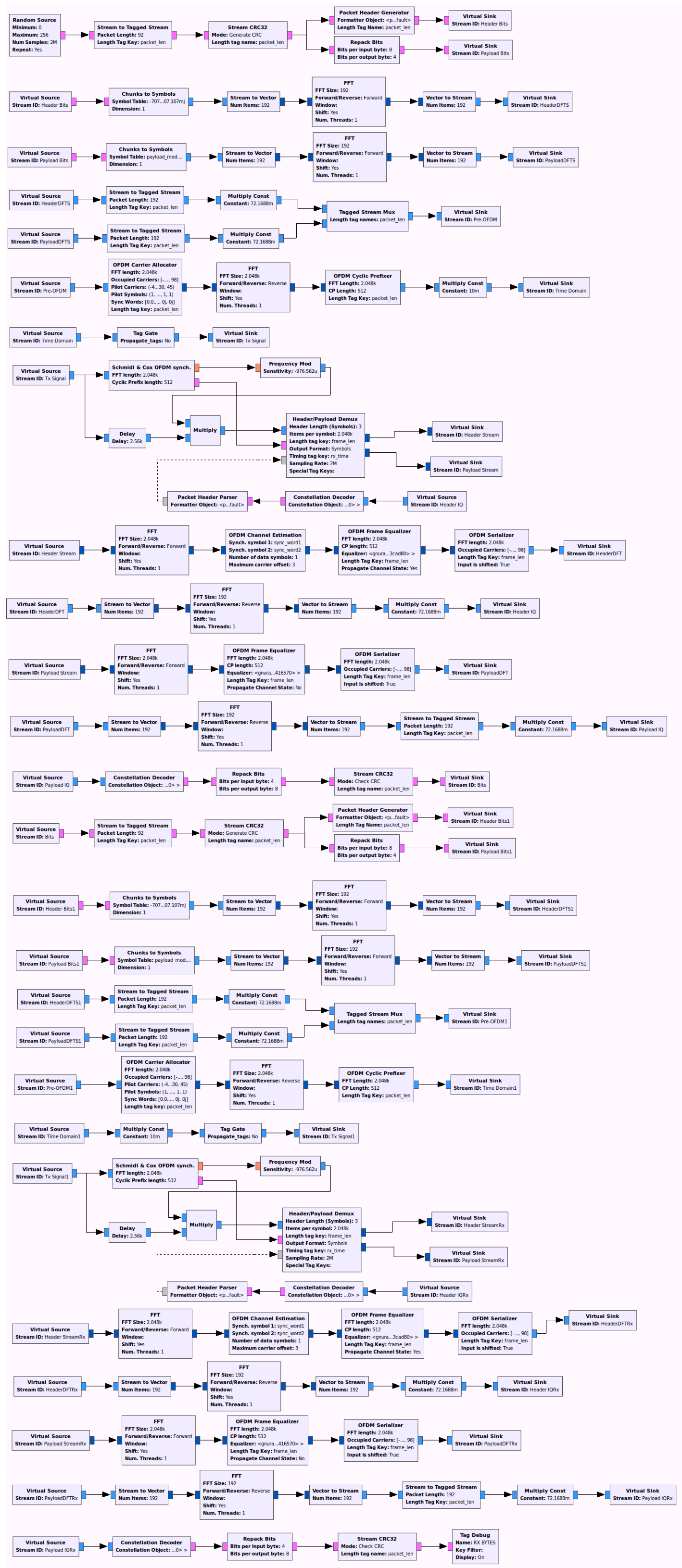

Figure A.2: DF protocol implementation in GNU Radio.

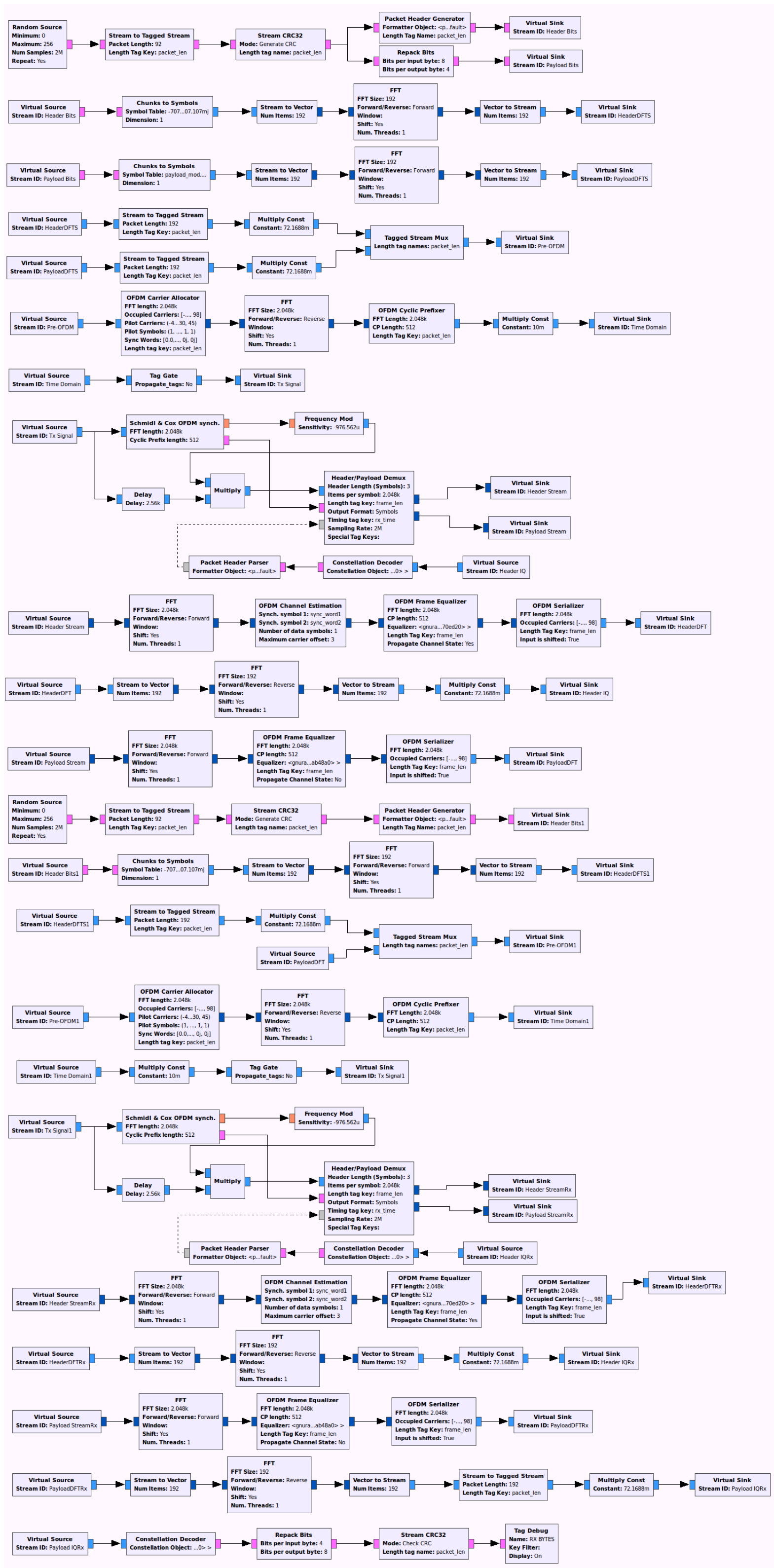

Figure A.3: EF protocol implementation in GNU Radio.