Abstract—The new level of connectivity among machines and people promised by the forthcoming 5G mobile communication system will shape diverse application areas from healthcare and education to smart factories and autonomous driving. These applications have a variety of different sets of requirements on data rates, latency, and reliability which are expected to be supported by an enhanced version of the OFDM modulation used today in the physical layer of 4G LTE systems. Thus, a new waveform design that allows multiplex flexibly different communication services within a common framework is an ongoing research topic. On the other hand, software defined radio is an appealing concept to introduce such flexibility since the functionality of the system relies on the software implemented on a programmable device. In order to investigate the performance of new OFDM-based systems, this work presents a preliminary prototype of an OFDM communication link for video transmission using the open-source tool GNU radio and the RF hardware interface NI USRP and proves the feasibility of employing SDR for real-time signal processing of configurable radios.

I. INTRODUCTION

Over the past years, the development of wireless communication systems has been largely influenced by the increasing of the traffic demand. Emerging new 5G applications of lower latency, higher connection density and ubiquitous gigabit connectivity, require, however, modem and information processing algorithms more flexible, scalable and efficient than those in 4G LTE systems to cope with that high degree of service heterogeneity [1], [2]. Thus, motivating intense research and development work, in industry and university research labs, on the building blocks for 5G communication systems. Several innovations are also being proposed for the physical (PHY) and medium access control (MAC) layers because they can expand, and also constraint, the overall system capability and performance in terms of energy efficiency, spectral efficiency, achievable data rates and quality of service (QoS). In this regard, platforms for rapid prototyping are of high interest for performance evaluation and proof-of-concept of ongoing development modem algorithms [3], [4].

On the other hand, software defined radio (SDR) is a flexible approach for prototyping of communication systems, where the functionality of the systems relies on the software implemented on a programmable chip, e.g. system on chip (SOC) - field programmable gate array (FPGA), digital signal processor (DSP) or general purpose processor (GPP). Thus, the reconfiguration of the system is possible, even during the execution time, by reloading a firmware or modifying the software and recompiling it. With SDR techniques, it seems logical that the design of new baseband algorithms can be flexibly tailored to different requirements, e.g. vehicle-to-vehicle (V2V) communications can require not only short frames to achieve low latency but also enlarged subcarrier spacing to cope with high mobility propagation conditions, internet of things (IoT) can require the use of single carrier waveforms to achieve sufficient coverage with low power, and variable cyclic prefix (CP) may be needed for service covering in different application cell sizes [5].

Aiming to assess preliminary the feasibility of using SDR in the study of enhanced OFDM waveforms, this work presents the implementation of an SDR-based orthogonal frequency division multiplexing (OFDM) communication link for video transmission using the universal software radio peripheral (USRP) for the RF processing and GNU Radio for the digital baseband processing. GNU radio is a open-source set of libraries of signal processing functions written in C++ and uses Python to generate flow-graphs of the system [6]. OFDM modulation was chosen as an example case since it is used in several current communication systems such as long LTE and 802.11 standards, and very probably will be also part of the 5G new radio (NR) air interface because of its advantages: spectrum efficiency, resistance to frequency selective fading, easy support of multiple-input multiple-output (MIMO) and adaptive modulation and coding schemes, among others.

The remainder of this work is structured as follows: a basic model of a OFDM communication system is presented in section II. Section III presents an SDR implementation of this model and presents some performance results. Section IV presents our conclusions.

II. SYSTEM MODEL

OFDM is a multicarrier modulation scheme based on the division of a serial data stream in a group of parallel data streams which are transmitted on orthogonal subcarriers. With proper parameterization, when an OFDM signal is sent through a frequency selective fading channel, each individual subcarrier can experience only flat fading. These channels can also distort the received signal with intersymbol interference (ISI), a crosstalk between signals arrived with different delays. This is solved by OFDM by extending each symbol with a cyclic prefix (CP), which is a copy of the last part of the symbol, to absorb channel delay spreads. The CP is also used in the
source-coded
bit stream
Mapper
subcarrier
allocator
IFFT
CP
insertion
packet
formation
MUX
pilots
guard
subcarriers
preamble
generator

Fig. 1: Block diagram of an OFDM transmitter

![Block diagram of an OFDM transmitter](image)

Fig. 2: Effect of RC pulse shaping on the reduction of the OOBES of a OFDM signal. \( \beta \) is the roll-off length of the RC filter. The conventional OFDM case (\( \beta = 0 \)) is included for comparison.

![Effect of RC pulse shaping on the reduction of the OOBES of a OFDM signal](image)

Synchronization process, helps to preserve the subcarrier orthogonality, and also introduces a cyclic convolution between the transmitted signal and the channel impulse response, which enables the use a one-tap frequency domain equalizers and therefore reduce the receiver complexity. A CP-OFDM signal of \( N \) subcarriers can be expressed in the time domain as

\[
x[n] = \sum_{l=-\infty}^{\infty} \sum_{k=0}^{N-1} S_{k,l}[n - lN_T]e^{j2\pi k(\tau-1N_T)/N},
\]

where \( N \), \( N_{CP} \) and \( N_T \) are the number of samples of the payload, CP and entire OFDM symbol, respectively, and \( N_T = N_{CP} + N \).

A block diagram of a transmitter is shown in Fig.1, where a stream of bits is converted into complex data symbols by the constellation mapper and then placed on determined positions of a \( N \)-order inverse fast Fourier transform (FFT) by the subcarrier allocation block. The subcarrier allocator also places the pilots for channel estimation purposes and leaves unused some subcarrier positions (guard subcarriers) to contain the out-of-band emission (OOBE) produced by active subcarriers. Then, groups of \( N \) frequency-domain samples are converted to the time domain by an inverse FFT and a CP is appended at the beginning of each symbol. Optionally, CP-OFDM symbols can be shaped in the time-domain by an inverse FFT and a CP is appended at the beginning of each symbol. Optionally, CP-OFDM symbols can be inserted in the front of every frame for detection, time and frequency synchronization or initial channel state estimation. For simplification, it is illustrated as a separate block in Fig. 1. At this point, the OFDM signal is ready for conversion to RF and further amplification, including other processes, for instance, digital up-conversion (DUC) and digital pre-correction of a possible IQ imbalance.

At the receiver side, two procedures are needed before data demodulation, namely, synchronization, which detects the beginning of the OFDM symbols and estimates the frequency offset, and channel estimation to compensate the distortions introduced by the channel. Then, the CP is discarded, the time-domain samples are converted to the frequency domain, and the payload data symbols are extracted and then equalized using the estimated channel response. These symbols are demodulated into bit streams and then corrected by a forward error correcting block.

### A. Synchronization and channel estimation

Synchronization aims to correct the time and frequency errors of the received signal. The receiver determines the time instants at which the incoming signal has to be sampled, i.e., aligns the sampling interval of the FFT with the OFDM symbol boundaries (timing synchronization). Also, it adapts the frequency and phase of the local oscillator to those of the received signal (carrier synchronization) to ensure that subcarrier orthogonality is maintained. The carrier frequency error (CFO) must be reduced to a fraction of the frequency subcarrier spacing to avoid severe performance degradation. Synchronization errors are sources of intercarrier interference (ICI), so accurate synchronization is essential in an OFDM receiver. A block diagram of this process is illustrated in Fig.3. By assuming that the transmit carrier frequency is \( f_c \) and the received signal \( y(t) \) is down-converted by a non-matched local oscillator of frequency \( f_{LO} \), the initial CFO is \( f_o = f_c - f_{LO} \), which causes distortion (rotation and spreading) of the constellation [8]. Then, the sampled received signal can be expressed as

\[
r[n] = y[n - \Delta m]e^{j2\pi f_o n T_s},
\]

where \( T_s \) is the sampling frequency and \( \Delta m \) is a timing error of the position of the FFT window. \( \Delta m \) and \( f_{LO} \) are estimated in the timing and frequency estimation blocks, respectively. Then, a numerically controlled oscillator (NCO) rotates the signal by \( \exp(j2\pi f_o n T_s) \), where \( f_o \) is the estimated frequency offset. For online tracking and compensation of the errors as soon as possible, the synchronizers need to respond immediately [9], which requires fast signal processing algorithms. They can be classified as either blind or data-aided. Blind techniques exploit the redundancy of the symbol

Fig. 3: Block diagram of the time and frequency OFDM synchronization stages
structure, for instance, the CP and the end of the symbol. Data-aided methods consider insert special data for synchronization into the transmitted signal, for instance, a time-domain preamble (training symbol) of identical halves with good autocorrelation properties [8] or pilot subcarriers. In this case, the time-frequency overhead for synchronization must keep to a minimum for good spectral efficiency. Additionally, the distortions produced by the channel can be removed by a frequency domain equalizer, thus the estimation of the channel response becomes necessary. Techniques for this purpose can also be classified as blind or data-aided schemes, e.g. reference pilot subcarriers can be inserted in the resource allocation map structure of the waveform to estimate the channel response in the rest of subcarriers. The estimation and compensation processes using this approach are depicted in Fig. 4.

III. SDR PROTOTYPING

An OFDM communication link is implemented using the software tool GNU Radio and the NI USRP B210 radio card. Each card is connected via USB to a PC running either a OFDM transmitter or receiver. The USRP is a platform for implementation of SDRs and is equipped with DACs, ADCs, MIMO antennas, reference clocks and RF chip transceivers.

Implementation

The transmitter and receiver blocks are shown in Fig. 5 and 6, respectively, and the general transmission parameters are defined as variables. The source information is an MPEG-2 transport stream (TS) with video and audio packets, indicated in the block file source. Then, it is passed to the block stream to tagged stream which adds tags to the data as a mechanism to pass information to following blocks. The information goes through the block stream CRC32 which appends cyclic redundancy check (CRC) codes for error checking. Synchronization header bits are generated in parallel and mapped to BPSK symbols. Payload bits are mapped to QPSK symbols. Then, the block OFDM carrier allocator places the pilots and useful data symbols/preambles at determined subcarrier positions of the IFFT input vector. After the conversion to the time domain, a CP can be appended in front of every OFDM symbol. Finally, the symbol is ready to be transmitted by the block USRP sink, which configures several parameters of the USRP card, for instance, sampling rate, bandwidth, carrier frequency, channel gain, etc. The system has been configured with carrier frequency of 2 GHz, transmission bandwidth of 1 MHz and sampling rate of 2 MHz. The preamble-based synchronizer block Schmidl & Cox OFDM is used in the receiver. The payload and header streams are extracted in the block Header/Payload Demux block and then channel estimation is performed to compensate the channel distortions. The decoded information is saved in a file and then reproduced as is shown in Fig. 7.

IV. CONCLUSION

The aim of this paper was to implement an OFDM communication link that can be used as a basis to research enhanced OFDM waveforms and modem algorithms. Preliminary results of experimental work show that SDR provides a great flexibility in the design and test of a communication system in a very practical way taking into account the real conditions of the channel and front-end imperfections.

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Fig. 5: Transmitter block diagram.

Fig. 6: Receiver block diagram.