# *OFDM Simulation Using Matlab®*

# Smart Antenna Research Laboratory

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# FIGURES AND TABLES

## Abstract

Orthogonal frequency division multiplexing (OFDM) is becoming the chosen modulation technique for wireless communications. OFDM can provide large data rates with sufficient robustness to radio channel impairments. Many research centers in the world have specialized teams working in the optimization of OFDM for countless applications. Here, at the Georgia Institute of Technology, one of such teams is in Dr. M. A. Ingram's Smart Antenna Research Laboratory (SARL), a part of the Georgia Center for Advanced Telecommunications Technology (GCATT). The purpose of this report is to provide Matlab® code to simulate the basic processing involved in the generation and reception of an OFDM signal in a physical channel and to provide a description of each of the steps involved. For this purpose, we shall use, as an example, one of the proposed OFDM signals of the Digital Video Broadcasting (DVB) standard for the European terrestrial digital television (DTV) service.

## 1 Introduction

In an OFDM scheme, a large number of orthogonal, overlapping, narrow band sub-channels or subcarriers, transmitted in parallel, divide the available transmission bandwidth. The separation of the subcarriers is theoretically minimal such that there is a very compact spectral utilization. The attraction of OFDM is mainly due to how the system handles the multipath interference at the receiver. Multipath generates two effects: frequency selective fading and intersymbol interference (ISI). The "flatness" perceived by a narrow-band channel overcomes the former, and modulating at a very low symbol rate, which makes the symbols much longer than the channel impulse response, diminishes the latter. Using powerful error correcting codes together with time and frequency interleaving yields even more robustness against frequency selective fading, and the insertion of an extra guard interval between consecutive OFDM symbols can reduce the effects of ISI even more. Thus, an equalizer in the receiver is not necessary.

There are two main drawbacks with OFDM, the large dynamic range of the signal (also referred as peak-to average [PAR] ratio) and its sensitivity to frequency errors. These in turn are the main research topics of OFDM in many research centers around the world, including the SARL.

A block diagram of the European DVB-T standard is shown in Figure 1.1. Most of the processes described in this diagram are performed within a digital signal processor (DSP), but the aforementioned drawbacks occur in the physical channel; i.e., the output signal of this system. Therefore, it is the purpose of this project to provide a description of each of the steps involved in the generation of this signal and the Matlab® code for their simulation. We expect that the results obtained can provide a useful reference material for future projects of the SARL's team. In other words, this project will concentrate only in the blocks labeled OFDM, D/A, and Front End of Figure 1.1.

We only have transmission regulations in the DVB-T standard since the reception system should be open to promote competition among receivers' manufacturers. We shall try to portray a general receiver system to have a complete system description.

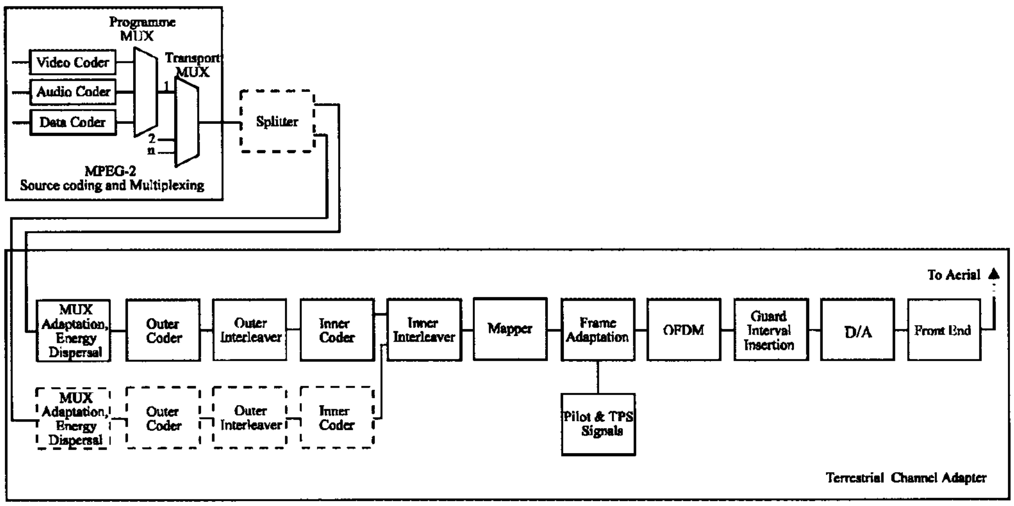


Figure 1.1: DVB-T transmitter [1]

# 2 OFDM Transmission

## 2.1 DVB-T Example

A detailed description of OFDM can be found in [2] where we can find the expression for one OFDM symbol starting at $t = t_s$ as follows:

$$s(t) = \mathrm{Re}\left\{ \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \exp\left( j2\pi \left( f_c - \frac{i+0.5}{T} \right)(t-t_s) \right) \right\},\ t_s \le t \le t_s + T \qquad (2.1.1)$$

$$s(t) = 0,\ t < t_s \quad \wedge \quad t > t_s + T$$

where $d_i$ are complex modulation symbols, $N_s$ is the number of subcarriers, $T$ the symbol duration, and $f_c$ the carrier frequency. A particular version of (2.1.1) is given in the DVB-T standard as the emitted signal. The expression is

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{m=0}^{\infty} \sum_{l=0}^{67} \sum_{k=K_{min}}^{K_{max}} c_{m,l,k} \cdot \psi_{m,l,k}(t) \right\} \quad (2.1.2)$$

where

$$\psi_{m,l,k}(t) = \begin{cases} e^{j2\pi \frac{k'}{T_U}(t-\Delta-l\cdot T_S-68\cdot m\cdot T_S)} & (l+68\cdot m)\cdot T_S \le t \le (l+68\cdot m+1)\cdot T_S \\ 0 & \text{else} \end{cases} \quad (2.1.3)$$

where:

| | |
|---|---|
| k | denotes the carrier number; |
| l | denotes the OFDM symbol number; |
| m | denotes the transmission frame number; |
| K | is the number of transmitted carriers; |
| $T_S$ | is the symbol duration; |
| $T_U$ | is the inverse of the carrier spacing; |
| $\Delta$ | is the duration of the guard interval; |
| $f_c$ | is the central frequency of the radio frequency (RF) signal; |
| $k'$ | is the carrier index relative to the center frequency, $k' = k - (K_{max} + K_{min})/2$; |
| $c_{m,0,k}$ | complex symbol for carrier k of the Data symbol no.1 in frame number m; |
| $c_{m,1,k}$ | complex symbol for carrier k of the Data symbol no.2 in frame number m; |
| ... | |
| $c_{m,67,k}$ | complex symbol for carrier k of the Data symbol no.68 in frame number m; |

It is important to realize that (2.1.2) describes a working system, i.e., a system that has been used and tested since March 1997. Our simulations will focus in the 2k mode of the DVB-T standard. This particular mode is intended for mobile reception of standard definition DTV. The transmitted OFDM signal is organized in frames. Each frame has a duration of $T_F$, and consists of 68 OFDM symbols. Four frames constitute one super-frame. Each symbol is constituted by a set of K=1,705 carriers in the 2k mode and transmitted with a duration $T_S$. A useful part with duration $T_U$ and a guard interval with a duration $\Delta$ compose $T_S$. The specific numerical values for the OFDM parameters for the 2k mode are given in Table 1.

The next issue at hand is the practical implementation of (2.1.2). OFDM practical implementation became a reality in the 1990's due to the availability of DSP's that made the Fast Fourier Transform (FFT) affordable [3]. Therefore, we shall focus the rest of the report to this implementation using the values and references of the DVB-T example. If we consider (2.1.2) for the period from t=0 to t=$T_S$ we obtain:

Table 1: Numerical values for the OFDM parameters for the 2k mode

| **Parameter** | **2k mode** | | | |
|---|---|---|---|---|
| Elementary period T | 7/64 μs | | | |
| Number of carriers K | 1,705 | | | |
| Value of carrier number $K_{min}$ | 0 | | | |
| Value of carrier number $K_{max}$ | 1,704 | | | |
| Duration $T_U$ | 224 μs | | | |
| Carrier spacing $1/T_U$ | 4,464 Hz | | | |
| Spacing between carriers $K_{min}$ and $K_{max}(K-1)/T_U$ | 7.61 MHz | | | |
| Allowed guard interval $\Delta/T_U$ | 1/4 | 1/8 | 1/16 | 1/32 |
| Duration of symbol part $T_U$ | 2,048xT<br>224 μs | | | |
| Duration of guard interval $\Delta$ | 512xT<br>56 μs | 256xT<br>28 μs | 128xT<br>14 μs | 64xT<br>7 μs |
| Symbol duration $T_S=\Delta+T_U$ | 2,560xT<br>280 μs | 2,304xT<br>252 μs | 2,176xT<br>238 μs | 2,112xT<br>231 μs |

$$s(t) = \mathrm{Re}\left\{ e^{j2\pi f_c t} \sum_{k=K_{min}}^{K_{max}} c_{0,0,k} e^{j2\pi k'(t-\Delta)/T_U} \right\} \quad (2.1.4)$$

with $k' = k - (K_{max} + K_{min})/2.$

There is a clear resemblance between (2.1.4) and the Inverse Discrete Fourier Transform (IDFT):

$$x_n = \frac{1}{N}\sum_{q=0}^{N-1} X_q e^{j2\pi\frac{nq}{N}} \quad (2.1.5)$$

Since various efficient FFT algorithms exist to perform the DFT and its inverse, it is a convenient form of implementation to generate N samples $x_n$ corresponding to the useful part, $T_U$ long, of each symbol. The guard interval is added by taking copies of the last $N\Delta/T_U$ of these samples and appending them in front. A subsequent up-conversion then gives the real signal s(t) centered on the frequency $f_c$.

## *2.2 FFT Implementation*

The first task to consider is that the OFDM spectrum is centered on $f_c$; i.e., subcarrier 1 is $\frac{7.61}{2}$ MHz to the left of the carrier and subcarrier 1,705 is $\frac{7.61}{2}$ MHz to the right. One simple way to achieve the centering is to use a 2N-IFFT [2] and T/2 as the elementary period. As we can see in Table **1**, the OFDM symbol duration, $T_{U,}$ is specified considering a 2,048-IFFT (N=2,048); therefore, we shall use a

4,096-IFFT. A block diagram of the generation of one OFDM symbol is shown in Figure 2.1 where we have indicated the variables used in the Matlab® code. The next task to consider is the appropriate simulation period. T is defined as the elementary period for a baseband signal, but since we are simulating a passband signal, we have to relate it to a time-period, 1/Rs, that considers at least twice the carrier frequency. For simplicity, we use an integer relation, Rs=40/T. This relation gives a carrier frequency close to 90 MHz, which is in the range of a VHF channel five, a common TV channel in any city. We can now proceed to describe each of the steps specified by the encircled letters in Figure 2.1.

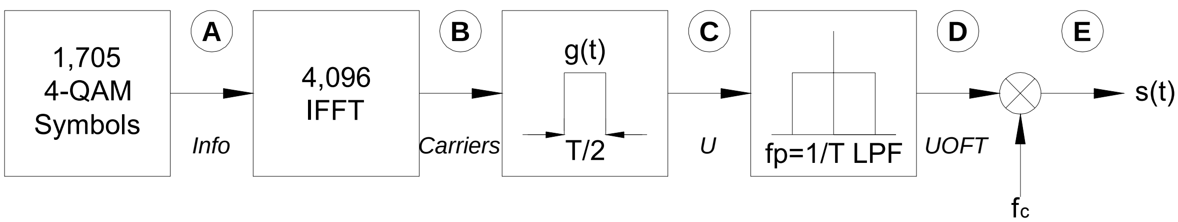


Figure 2.1**:** OFDM symbol generation simulation.

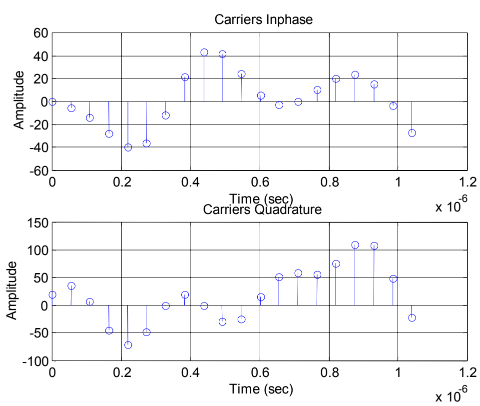


Figure 2.2: Time response of signal *carriers* at (B).

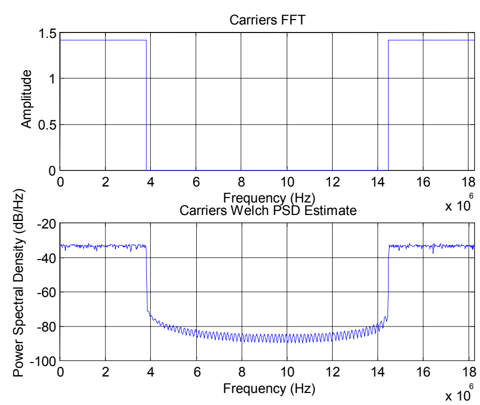


Figure 2.3: Frequency response of signal *carriers* at (B).

As suggested in [2], we add 4,096-1,705=2,391 zeros to the signal *info* at (A) to achieve over-sampling, 2X, and to center the spectrum. In Figure 2.2 and Figure 2.3, we can observe the result of this operation and that the signal *carriers* uses T/2 as its time period. We can also notice that *carriers* is the discrete time baseband signal. We could use this signal in baseband discrete-time domain simulations, but we must recall that the main OFDM drawbacks occur in the continuous-time domain; therefore, we must provide a simulation tool for the latter. The first step to produce a continuous-time signal is to apply a transmit filter, g(t), to the complex signal *carriers*. The impulse response, or pulse shape, of g(t) is shown in Figure 2.4.

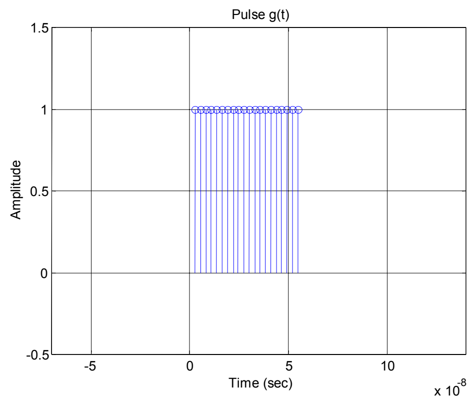


Figure 2.4: Pulse shape g(t).

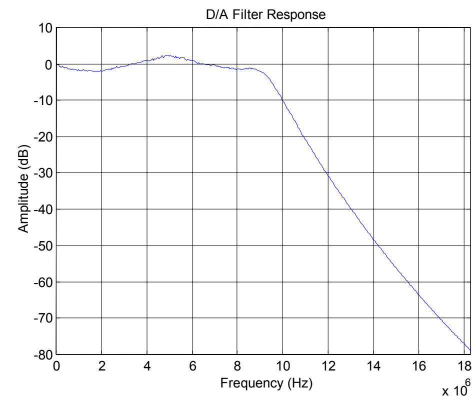


Figure 2.5: D/A filter response.

The output of this transmit filter is shown in Figure 2.6 in the time-domain and in Figure 2.7 in the frequency-domain. The frequency response of Figure 2.7 is periodic as required of the frequency response of a discrete-time system [4], and the bandwidth of the spectrum shown in this figure is given by Rs. U(t)'s period is 2/T, and we have (2/T=18.286)-7.61=10.675 MHz of transition bandwidth for the reconstruction filter. If we were to use an N-IFFT, we would only have (1/T=9.143)-7.61=1.533 MHz of transition bandwidth; therefore, we would require a very sharp roll-off, hence high complexity, in the reconstruction filter to avoid aliasing.

The proposed reconstruction or D/A filter response is shown in Figure 2.5. It is a Butterworth filter of order 13 and cut-off frequency of approximately 1/T. The filter's output is shown in Figure 2.8 and Figure 2.9. The first thing to notice is the delay of approximately $2x10^{-7}$ produced by the filtering process. Aside of this delay, the filtering performs as expected since we are left with only the baseband spectrum. We must recall that subcarriers 853 to 1,705 are located at the right of 0 Hz, and subcarriers 1 to 852 are to the left of $4f_c$ Hz.

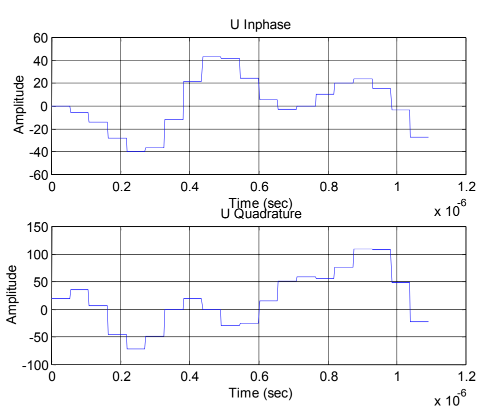


Figure 2.6: Time response of signal *U* at (C).

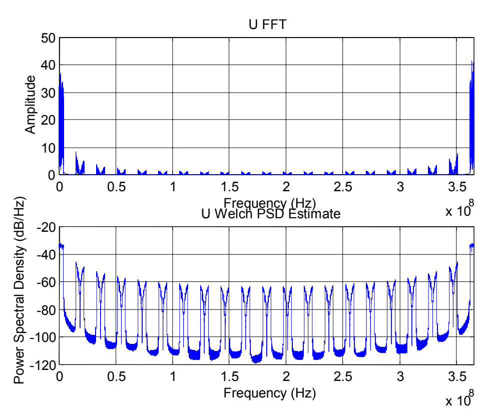


Figure 2.7: Frequency response of signal *U* at (C)

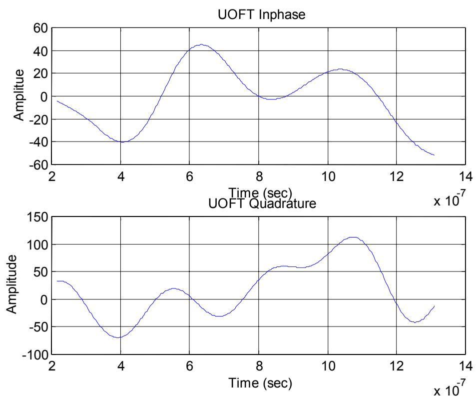


Figure 2.8: Time response of signal *UOFT* at (D).

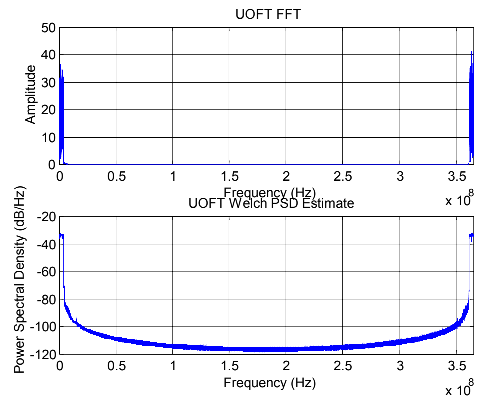


Figure 2.9: Frequency response of signal *UOFT* at (D).

The next step is to perform the quadrature multiplex double-sideband amplitude modulation of *uoft(t)*. In this modulation, an in-phase signal $m_I(t)$ and a quadrature signal $m_Q(t)$ are modulated using the formula

$$s(t) = m_I(t)\cos(2\pi f_c t) + m_Q(t)\sin(2\pi f_c t) \tag{2.2.1}$$

Equation (2.1.4) can be expanded as follows:

$$\begin{aligned} s(t) = &\sum_{k=\mathrm{K_{min}}}^{\mathrm{K_{max}}} \mathrm{Re}\left(\mathrm{c}_{0,0,k}\right)\cos\left[2\pi\left(\left(\frac{\left(k-\frac{\mathrm{K_{max}}+\mathrm{K_{min}}}{2}\right)}{\mathrm{T_U}}+f_c\right)t-\frac{\Delta}{\mathrm{T_U}}\right)\right] \\ &-\sum_{k=\mathrm{K_{min}}}^{\mathrm{K_{max}}} \mathrm{Im}\left(\mathrm{c}_{0,0,k}\right)\sin\left[2\pi\left(\left(\frac{\left(k-\frac{\mathrm{K_{max}}+\mathrm{K_{min}}}{2}\right)}{\mathrm{T_U}}+f_c\right)t-\frac{\Delta}{\mathrm{T_U}}\right)\right] \end{aligned} \tag{2.2.2}$$

where we can define the in-phase and quadrature signals as the real and imaginary parts of $\mathrm{c}_{\mathrm{m,l,k}}$, the 4-QAM symbols, respectively.

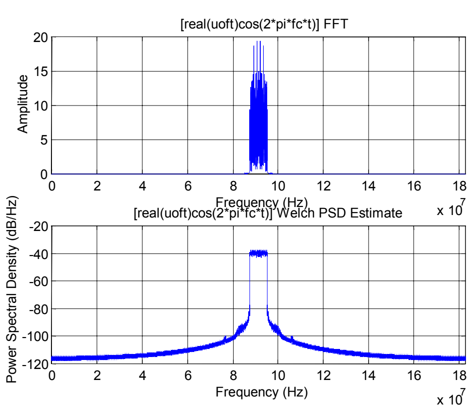


Figure 2.10: $uoft_I(t)\cos(2\pi f_c t)$ frequency response.

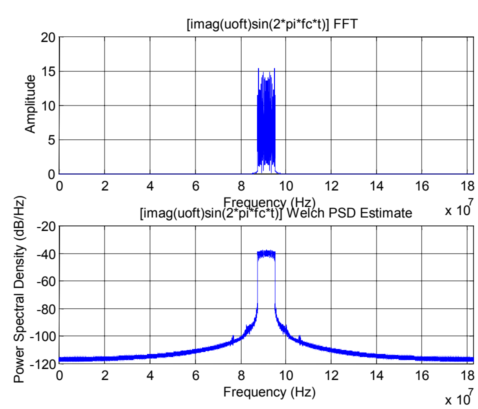


Figure 2.11: $uoft_Q(t)\sin(2\pi f_c t)$ frequency response.

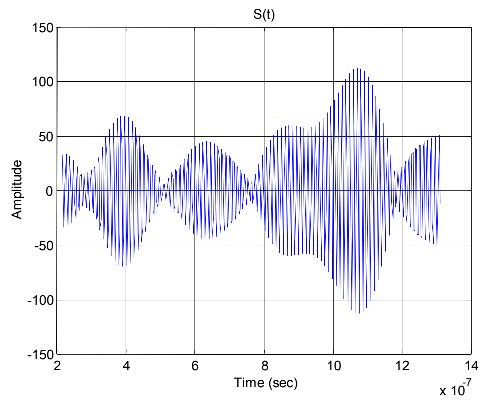


Figure 2.12: Time response of signal *s(t)* at (E).

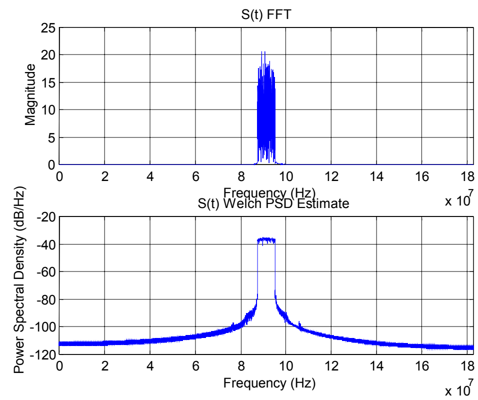


Figure 2.13: Frequency response of signal *s(t)* at (E).

The corresponding operation for the IFFT process is

$$s(t) = uoft_I(t)\cos(2\pi f_c t) - uoft_Q(t)\sin(2\pi f_c t). \tag{2.2.3}$$

The frequency responses of each part of (2.2.3) are shown in Figure 2.10 and Figure 2.11 respectively. The time and frequency responses for the complete signal, s(t), are shown in Figure 2.12 and in Figure 2.13. We can observe the large value of the aforementioned PAR in the time response of Figure 2.12.

Finally, the time response using a direct simulation of (2.1.4) is shown in Figure 2.14, and the frequency responses of the direct simulation and 2N-IFFT implementation are shown in Figure 2.15. The direct simulation requires a considerable time (about 10 minutes in a Sun Ultra 5, 333 MHz); therefore, a practical application must use the IFFT/FFT approach. A direct comparison of Figure 2.12 and Figure 2.14 shows differences in time alignment and amplitude, and a study of the frequency responses shown in Figure 2.15 reveals amplitude variations but closely related spectra. We could not expect an identical signal since we obtain different results from a 1,705-IFFT vs. a 4,096-IFFT using the same input data.

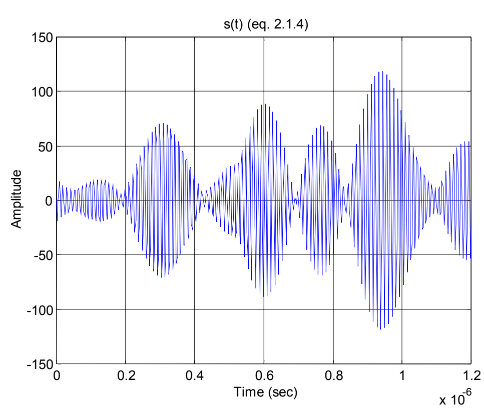


Figure 2.14: Time response of direct simulation of (2.1.4).

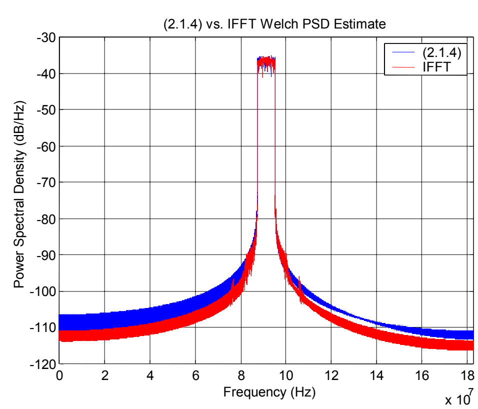


Figure 2.15: Frequency response of direct simulation of (2.1.4) and IFFT.

# 3 OFDM Reception

As we mentioned before, the design of an OFDM receiver is open; i.e., there are only transmission standards. With an open receiver design, most of the research and innovations are done in the receiver. For example, the frequency sensitivity drawback is mainly a transmission channel prediction issue, something that is done at the receiver; therefore, we shall only present a basic receiver structure in this report. A basic receiver that just follows the inverse of the transmission process is shown in Figure 3.1.

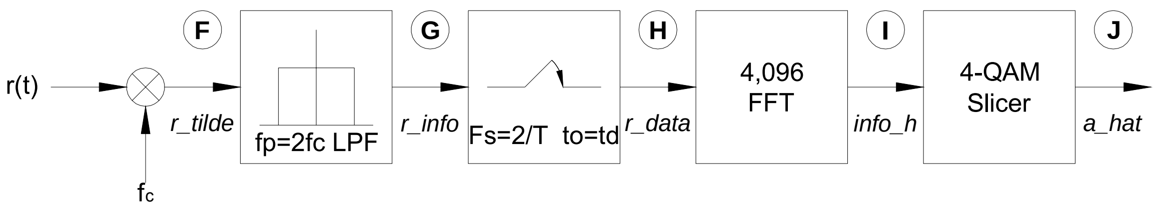


Figure 3.1: OFDM reception simulation.

OFDM is very sensitive to timing and frequency offsets [2]. Even in this ideal simulation environment, we have to consider the delay produced by the filtering operation. For our simulation, the delay produced by the reconstruction and demodulation filters is about $t_d$=64/Rs. This delay is enough to impede the reception, and it is the cause of the slight differences we can see between the transmitted and received signals (Figure 2.3 vs. Figure 3.7 for example). With the delay taken care of, the rest of the reception process is straightforward. As in the transmission case, we specified the names of the simulation variables and the output processes in the reception description of Figure 3.1. The results of this simulation are shown in Figures 3.2 to 3.9.

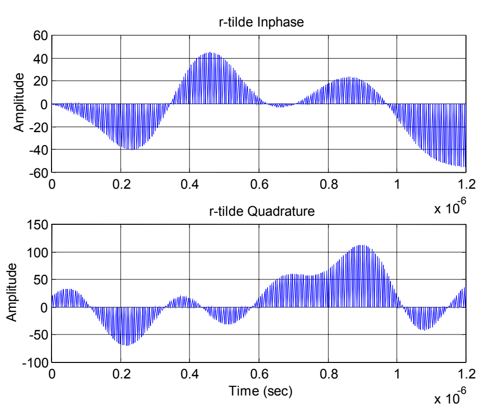


Figure 3.2: Time response of signal *r_tilde* at (F).

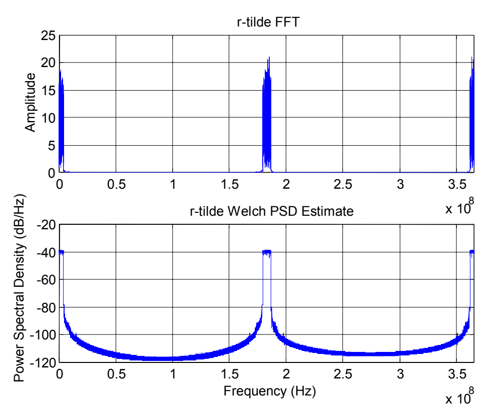


Figure 3.3: Frequency response of signal *r_tilde* at (F).

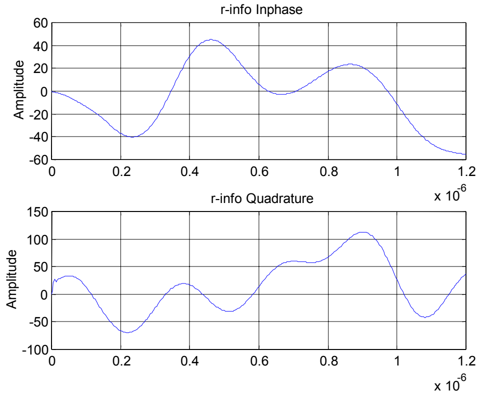


Figure 3.4: Time response of signal *r_info* at (G).

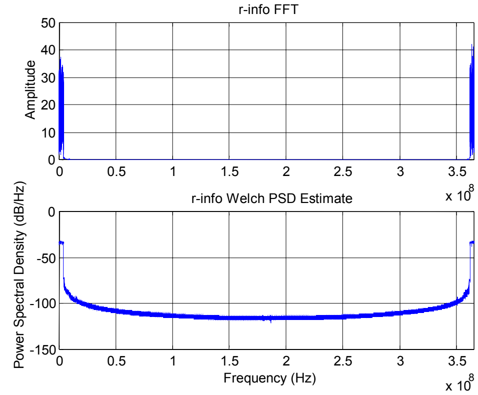


Figure 3.5: Frequency response of signal *r_info* at (G).

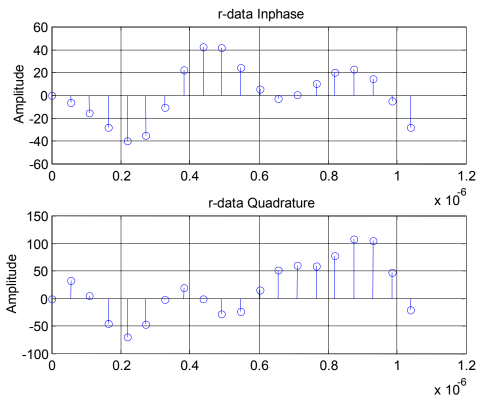


Figure 3.6: Time response of signal *r_data* at (H).

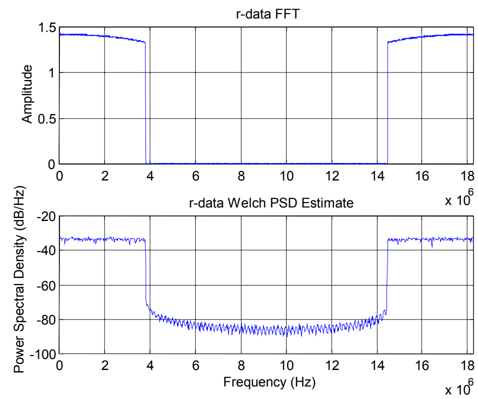


Figure 3.7: Frequency response of signal *r_data* at (H).

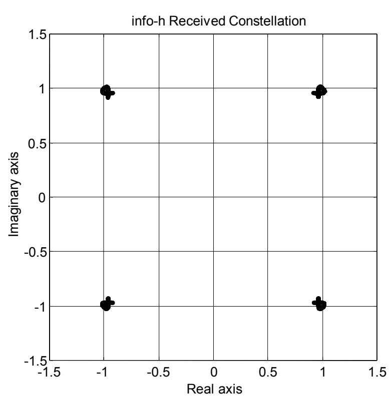


Figure 3.8: *info_h* constellation.

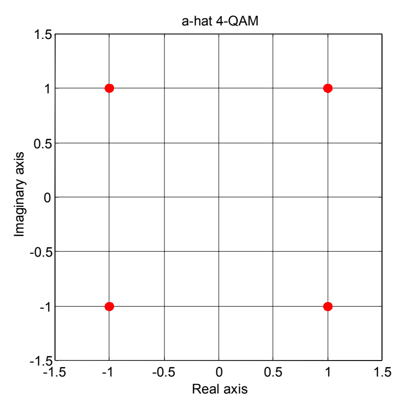


Figure 3.9: *a_hat* constellation.

# 4 Conclusion

We can find many advantages in OFDM, but there are still many complex problems to solve, and the people of the research team at the SARL are working in some of these problems. It is the purpose of this project to provide a basic simulation tool for them to use as a starting point in their projects. We hope that by using the specifications of a working system, the DBV-T, as an example, we are able to provide a much better explanation of the fundamentals of OFDM.

# 5 Appendix

## 5.1 OFDM Transmission

```
%DVB-T 2K Transmission
%The available bandwidth is 8 MHz
%2K is intended for mobile services
clear all;
close all;

%DVB-T Parameters

Tu=224e-6;            %useful OFDM symbol period
T=Tu/2048;            %baseband elementary period
G=0;                  %choice of 1/4, 1/8, 1/16, and 1/32
delta=G*Tu;           %guard band duration
Ts=delta+Tu;          %total OFDM symbol period
Kmax=1705;            %number of subcarriers
Kmin=0;
FS=4096;              %IFFT/FFT length
q=10;                 %carrier period to elementary period ratio
fc=q*1/T;             %carrier frequency
Rs=4*fc;              %simulation period
t=0:1/Rs:Tu;


%Data generator (A)

M=Kmax+1;
rand('state',0);
a=-1+2*round(rand(M,1)).'+i*(-1+2*round(rand(M,1))).';
A=length(a);
info=zeros(FS,1);
info(1:(A/2)) = [ a(1:(A/2)).']; %Zero padding
info((FS-((A/2)-1)):FS) = [ a(((A/2)+1):A).'];

%Subcarriers generation (B)

carriers=FS.*ifft(info,FS);
tt=0:T/2:Tu;
figure(1);
subplot(211);
stem(tt(1:20),real(carriers(1:20)));
```

```
subplot(212);
stem(tt(1:20),imag(carriers(1:20)));
figure(2);
f=(2/T)*(1:(FS))/(FS);
subplot(211);
plot(f,abs(fft(carriers,FS))/FS);
subplot(212);
pwelch(carriers,[],[],[],2/T);

% D/A simulation

L = length(carriers);
chips = [ carriers.';zeros((2*q)-1,L)];
p=1/Rs:1/Rs:T/2;
g=ones(length(p),1); %pulse shape
figure(3);
stem(p,g);
dummy=conv(g,chips(:));
u=[dummy(1:length(t))]; % (C)
figure(4);
subplot(211);
plot(t(1:400),real(u(1:400)));
subplot(212);
plot(t(1:400),imag(u(1:400)));
figure(5);
ff=(Rs)*(1:(q*FS))/(q*FS);
subplot(211);
plot(ff,abs(fft(u,q*FS))/FS);
subplot(212);
pwelch(u,[],[],[],Rs);
[b,a] = butter(13,1/20); %reconstruction filter
[H,F] = FREQZ(b,a,FS,Rs);
figure(6);
plot(F,20*log10(abs(H)));
uoft = filter(b,a,u);    %baseband signal (D)
figure(7);
subplot(211);
plot(t(80:480),real(uoft(80:480)));
subplot(212);
plot(t(80:480),imag(uoft(80:480)));
figure(8);
subplot(211);
plot(ff,abs(fft(uoft,q*FS))/FS);
subplot(212);
pwelch(uoft,[],[],[],Rs);



%Upconverter

s_tilde=(uoft.').*exp(1i*2*pi*fc*t);
s=real(s_tilde);      %passband signal (E)

figure(9);
plot(t(80:480),s(80:480));
figure(10);
subplot(211);
```

```
%plot(ff,abs(fft(((real(uoft).').*cos(2*pi*fc*t)),q*FS))/FS);
%plot(ff,abs(fft(((imag(uoft).').*sin(2*pi*fc*t)),q*FS))/FS);
plot(ff,abs(fft(s,q*FS))/FS);
subplot(212);
%pwelch(((real(uoft).').*cos(2*pi*fc*t)),[],[],[],Rs);
%pwelch(((imag(uoft).').*sin(2*pi*fc*t)),[],[],[],Rs);
pwelch(s,[],[],[],Rs);
```

## 5.2 OFDM Reception

```
%DVB-T 2K Reception

clear all;
close all;

Tu=224e-6;          %useful OFDM symbol period
T=Tu/2048;          %baseband elementary period
G=0;                %choice of 1/4, 1/8, 1/16, and 1/32
delta=G*Tu;         %guard band duration
Ts=delta+Tu;        %total OFDM symbol period
Kmax=1705;          %number of subcarriers
Kmin=0;
FS=4096;            %IFFT/FFT length
q=10;               %carrier period to elementary period ratio
fc=q*1/T;           %carrier frequency
Rs=4*fc;            %simulation period
t=0:1/Rs:Tu;
tt=0:T/2:Tu;


%Data generator
sM = 2;
[x,y] = meshgrid((-sM+1):2:(sM-1),(-sM+1):2:(sM-1));
alphabet = x(:) + 1i*y(:);
N=Kmax+1;
rand('state',0);
a=-1+2*round(rand(N,1)).'+i*(-1+2*round(rand(N,1))).';
A=length(a);
info=zeros(FS,1);
info(1:(A/2)) = [ a(1:(A/2)).'];
info((FS-((A/2)-1)):FS) = [ a(((A/2)+1):A).'];
carriers=FS.*ifft(info,FS);

%Upconverter
L = length(carriers);
chips = [ carriers.';zeros((2*q)-1,L)];
p=1/Rs:1/Rs:T/2;
g=ones(length(p),1);
dummy=conv(g,chips(:));
u=[dummy; zeros(46,1)];
[b,aa] = butter(13,1/20);
uoft = filter(b,aa,u);
delay=64;                                  %Reconstruction filter delay
s_tilde=(uoft(delay+(1:length(t))).').*exp(1i*2*pi*fc*t);
```

```
s=real(s_tilde);

%OFDM RECEPTION

%Downconversion
r_tilde=exp(-1i*2*pi*fc*t).*s; %(F)
figure(1);
subplot(211);
plot(t,real(r_tilde));
axis([0e-7 12e-7 -60 60]);
grid on;
figure(1);
subplot(212);
plot(t,imag(r_tilde));
axis([0e-7 12e-7 -100 150]);
grid on;
figure(2);
ff=(Rs)*(1:(q*FS))/(q*FS);
subplot(211);
plot(ff,abs(fft(r_tilde,q*FS))/FS);
grid on;
figure(2);
subplot(212);
pwelch(r_tilde,[],[],[],Rs);

%Carrier suppression

[B,AA] = butter(3,1/2);
r_info=2*filter(B,AA,r_tilde); %Baseband signal continuous-time (G)
figure(3);
subplot(211);
plot(t,real(r_info));
axis([0 12e-7 -60 60]);
grid on;
figure(3);
subplot(212);
plot(t,imag(r_info));
axis([0 12e-7 -100 150]);
grid on;
figure(4);
f=(2/T)*(1:(FS))/(FS);
subplot(211);
plot(ff,abs(fft(r_info,q*FS))/FS);
grid on;
subplot(212);
pwelch(r_info,[],[],[],Rs);

%Sampling

r_data=real(r_info(1:(2*q):length(t)))...    %Baseband signal, discrete-
time
   +1i*imag(r_info(1:(2*q):length(t)));      % (H)
figure(5);
subplot(211);
stem(tt(1:20),(real(r_data(1:20))));
axis([0 12e-7 -60 60]);
grid on;
```

```
figure(5);
subplot(212);
stem(tt(1:20),(imag(r_data(1:20))));
axis([0 12e-7 -100 150]);
grid on;
figure(6);
f=(2/T)*(1:(FS))/(FS);
subplot(211);
plot(f,abs(fft(r_data,FS))/FS);
grid on;
subplot(212);
pwelch(r_data,[],[],[],2/T);

%FFT

info_2N=(1/FS).*fft(r_data,FS);                     % (I)
info_h=[info_2N(1:A/2) info_2N((FS-((A/2)-1)):FS)];

%Slicing

for k=1:N,
   a_hat(k)=alphabet((info_h(k)-alphabet)==min(info_h(k)-alphabet)); %
(J)
end;

figure(7)
plot(info_h((1:A)),'.k');
title('info-h Received Constellation')
axis square;
axis equal;
figure(8)
plot(a_hat((1:A)),'or');
title('a_hat 4-QAM')
axis square;
axis equal;
grid on;
axis([-1.5 1.5 -1.5 1.5]);
```

### 5.3 Eq. (2.1.4) vs. IFFT

```
%DVB-T 2K signal generation Eq. (2.1.4) vs. 2N-IFFT

clear all;
close all;

Tu=224e-6;           %useful OFDM symbol period
T=Tu/2048;           %baseband elementary period
G=0;                 %choice of 1/4, 1/8, 1/16, and 1/32
delta=G*Tu;          %guard band duration
Ts=delta+Tu;         %total OFDM symbol period
Kmax=1705;           %number of subcarriers
Kmin=0;
FS=4096;             %IFFT/FFT length
q=10;                %carrier period to elementary period ratio
fc=q*1/T;            %carrier frequency
Rs=4*fc;             %simulation period

a=-1+2*round(rand(M,1)).'+i*(-1+2*round(rand(M,1))).';
A=length(a);
info = [ a.'];
tt=0:1/Rs:Ts;
TT=length(tt);
k=Kmin:Kmax;
for t=0:(TT-1);                      % Eq. (2.1.4)
   phi=a(k+1).*exp((1j*2*(((t*(1/Rs))-delta))*pi/Tu).*((k-(Kmax-
Kmin)/2)));
   s(t+1)=real(exp(1j*2*pi*fc*(t*(1/Rs))).*sum(phi));
end

infof=zeros(FS,1);
infof(1:(A/2)) = [ a(1:(A/2)).'];
infof((FS-((A/2)-1)):FS) = [ a(((A/2)+1):A).'];
carriers=FS.*ifft(infof,FS);     % IFFT

%Upconverter
L = length(carriers);
chips = [ carriers.';zeros((2*q)-1,L)];
p=1/Rs:1/Rs:T/2;
g=ones(length(p),1);
dummy=conv(g,chips(:));
u=[dummy(1:TT)];
[b,a] = butter(13,1/20);
uoft = filter(b,a,u);
s_tilde=(uoft.').*exp(1i*2*pi*fc*tt);
sf=real(s_tilde);
figure(1);
plot(tt,s,'b',tt,sf,'g');
figure(2);
pwelch(s,[],[],[],Rs);
hold on;
pwelch(sf,[],[],[],Rs);
hold off;
```

# 6 References


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[4] A. V. Oppenheim and R. W. Schafer, *Discrete-Time Signal Processing*, Englewood Cliffs, NJ: Prentice Hall, 1989