Development of RF Front End Prototype
Compliant with the 802.11a Standard for Wireless Applications

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Nikolaos A. Papageorgiou

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Approved by:

Prof. Joo Laskar, Advisor

Prof. Emmanouil Tenters

Prof. John Papapolymerou

Date Approved
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Dedicated to my family.
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Summary

In recent years, demand for higher data internet access has risen significantly for users of LANs. Customers traditionally would ask only for telephone services or standard internet access. Nowadays, they are interested in multimedia applications, a need that can only be met with broadband communication systems.

This work targets on the development and design of a first transceiver prototype compliant with the IEEE 802.11a standard for wireless applications. Chapter 1 begins with discussion about the need for providing higher date rate mobile communication solutions to the end user. It also includes a presentation of the IEEE802.11a specifications that are related to the physical layer and concludes with a study of the impairments that arise in the case of mixed signal environments. The development phase of this work is presented in Chapter 2. It includes a) the presentation of the co-simulation environment developed in ADS, which provides insight to the mixed signal issues, b) the preliminary budget gain and noise figure graphs, on which the initial transceiver architecture was based and c) the characterization of the devices that were chosen for the prototype implementation. Finally Chapter 3 starts with the summary of the measured performance of the wireless link. It also provides the final architecture of the transceiver as well as I/Os list and directions for the assembly of the prototype. The measurements that verify the performance of the network are presented in the last section of this chapter including, the combined Tx, Rx, PA and Antennas modules test bed.

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Chapter 1: WLAN IEEE802.11a Study

1.1 Introduction

1.1.1 Overview

Traditionally, the demand for high bit rate data transmission has been met with WANs and MANs. Those networks, due to their large scale, had to provide simultaneous connections between thousands of users all over cities or countries. The most popular way to approach such networks is using optical communication systems due to their high capacity, but other solutions are viable now-a-days.

In recent years, demand for higher data internet access has risen significantly for users of LANs. Customers traditionally would ask only for telephone services or standard internet access. Nowadays, users are interested in multimedia applications, a need that can only be met with broadband communication systems.

At the same time a need that seems to be equally important as the data rate, especially after the widespread of cellular technology, is mobility. Users do not only care about data rate, but they also would like to be able to walk while still connected to the network; for example in a library or other university facilities, in a company where employees would like to share or exchange information through their lap tops, or even in coffee shops while they take their break. Not to mention, that from the investor’s point of view, a network that mainly consist of a few PCM-CIA cards that are hooked up in lap tops is very attractive, since the network is fully portable and could be transferred to any place, provided of course that there is a base station to assure connection to the main network.
High data rates are exchanged for mobility as we move from larger scale networks to LANs. Approaching the communications problem from the larger scale networks point of view, it seems that the FTTC (Fiber To The Curb) technology will be able to bring sufficient amount of data to every building to support multimedia for multiple users. Therefore the bottleneck turns out to be on the LAN side. In other words it is critical how each individual user will be connected to the main frame of the wired network with a high data rate connection while maintaining the mobility of the terminal.

Figure 1. WLAN: mobility and high data rate

The emerging solution that can provide both high data rate transmission and mobility is the wireless broadband technology. A few standards for wireless communication have
been proposed that meet different levels of mobility and data rate. Fixed point wireless systems described in IEEE 802.16 would possibly substitute or complement cable connections and support data transfer from building to building, while point to multipoint WLAN networks specified in standard IEEE 802.11a,b,g [1] provide services to mobile users who have installed network cards to their laptops. These users are considered as access points and are served by a base station, which is located in the same room.

Wireless solutions, although very promising, involve issues that had not been addressed for the wired approaches. Although it is more possible to implement the above vision that some call the "global village" incorporating WLAN technology, the wireless environment imposes more stringent specifications for the DSP algorithms and the coding and the modulation schemes, since they have to be robust enough to counter-effect the distortion due to multi-path propagation as well as the alternating nature of the channel. The RF front end, which is responsible for the radio transmission of the signal through the mobile channel, has to be at the same time compact to maintain mobility, as well as low-power to provide greater time life to the system. Different standards have been proposed for such applications that set the specifications to guarantee data rates up to the 54 Mbps range.

Although currently 802.11b seems to dominate the market, the moderate transfer rate of 10Mbps (theoretical maximum) is soon going to be proven insufficient. This limit yields for the evolution of wireless solutions at higher frequency bands as C-band, where standards as 802.11a and 802.11g, which promise bit rates up to 54 Mbps, are going finally to take the larger share of the pie, since as statistics show customers cannot live
with less if they have a better alternative. The trend in the wireless market is definitely towards networks that operate at higher frequency bands where channel capacity is larger and in this context the next generation wireless is going to be the networks at 60 GHz and above.

1.1.2 IEEE 802.11a Standard for wireless applications

The IEEE 802.11a standard [1] provides the specifications that a wireless LAN should meet, if operating in the 5 GHz band. Other standards as the European one, namely HIPERLAN/2, are similar, but it seems that 802.11a is the leading one. Specifications for all the different network layers are provided, but since the scope of this thesis is the development of RF prototype, only issues that refer to the physical layer are going to be addressed here.

The modulation scheme that is adopted for 802.11a is OFDM (Orthogonal Frequency Division Multiplexing). The main idea behind OFDM is to divide the data stream to 52 sub-streams and use each one to modulate a different sub-carrier frequency with one of the following modulations: BPSK / QPSK / 16 QAM / 64 QAM. The main advantages of such a scheme are first that is a compact and real time processing solution due to ASIC implementation of the FFT, second that it achieves optimum spectral management since the modulation of the individual 52 carriers are independent to each other and adaptive to the channel impulse response, and third that the nature of the transfer enables the use of cyclic prefix preceding the OFDM packet as well as frequency domain equalization, features which make the data transmission robust to multi-path fading. The drawbacks
of OFDM are that the modulated signal experiences a high peak to average power ratio (PAP ratio) or alternative high crest factor. At the same time it is very sensitive to frequency offset of the sub-carriers. Both issues arise because of the nature of the Fourier transform (or inverse FFT). The summation of the in phase N modulated carriers (Figure 2) results to a signal that significantly deviates from its rms value at the beginning and the end of each OFDM symbol. High PAP ratio is the main problem of the OFDM signal and although there are some techniques to reduce it, such as clipping, it generally requires a highly linear amplifier in the front end, which in addition will be operated at a back-off of a few dB [2].

Figure 2: PAP ratio of OFDM signal

Before modulation, the data stream is reinforced with interleaving and convolutional coding. Interleaving is used to maintain a random pattern of the data sequence and coding
to assure that after some error detection and correction techniques at the receiver, a low BER is going to be achieved. Coding varies from 1/2 to 3/4 data, where 3/4 means that for every three bits, a fourth is generated and added to the stream as parity bit. This is the “lighter coding” scheme.

An important feature of the OFDM symbol is the guard interval (GI) which is a cyclic extension of the actual modulated symbol and it is added in front of it. The duration of the GI has to be larger than the impulse response of the channel in order to absorb inter-symbol interference. At the same time, it also has to compensate for the delay added due to the transceiver path (especially the passive filters).

The frequency channel plan for 802.11a is shown in figure 3. The transmit and receive operations take place at 5 GHz band, namely the C band, which consists of three main bands. The lower and middle ones which consist of 8 channels of 16.6 MHz of OFDM (N=52) modulated spectrum plus 20 MHz spacing on both sides yield a 200 MHz band (from 5,150 to 5,350 GHz) and the upper one from 5,725 to 5,825 consisting of 4 channels.
Therefore, the DSP processed and modulated signal has now to be I/Q modulated, up converted, and amplified up to 5 GHz. The in phase (I) and quadrature (Q) signals are generated by the Base-band modem with an IFFT (inverse fast Fourier transform). They are base-band signals and the information is encoded on the sinus and cosine coefficients of the individual carriers. The I/Q modulation can either be implemented in the digital domain or integrated in the RF front end, which is either or else responsible for the up conversion and amplification. The transmit spectrum mask specification shown in figure 4 has to be met for all three bands of operation.
The up conversion of the signal is achieved by a mixing operation, which also acts as a source of spurious transmission. The non-linear nature of mixing as well as the nonlinear nature of amplifying have to be well studied in order for the spurious transmission to be suppressed with proper filtering, since stringent national regulations have to be met.

The non-linearity of the transmitter, which is going to be discussed thoroughly later on, distorts also the useful signal. Intermodulation products result in a degradation of the modulation accuracy of the signal and thus, measurement of the relative EVM (error vector magnitude), averaged over sub-carriers is compulsory and it should not exceed specified levels to maintain proper demodulation. The EVM is an average of the error between the signal initially transmitted and received signal. The measurements is performed on the receive side by proper demodulation and comparison of the received
symbols in the constellation diagram and the ones expected in the case of ideal transmission.

Since 802.11a describes a data transmission network, the way to specify proper demodulation is the BER, which in this case is PER (packet error rate) since the network handles the data in packet form. The maximum acceptable value for PER which guarantees QoS of the network is 10%, but for optimum operation, it should be even less than that.

On the receive side of the RF front end, a crucial specification is the dynamic range of the system. Dynamic range is the range between the minimum detectable power that the receiver may distinguish from the existing noise, properly demodulate and provide PER less than 10%, and the maximum power that the front end of the receiver can handle without saturating. The minimum sensitivity is dependent on the modulation scheme and the coding rate, since different signal to noise ratios are expected for proper demodulation at each case, while the maximum power is specified at ~30dBm.

At the same time, the receiver should meet adjacent and alternate adjacent channel rejection specifications. Initially the desired signal’s strength is set 3 dB above the modulation dependent sensitivity and then the power of the interfering signal is raised until 10% PER is caused. At this point the power difference between the interfering and the desired signal is the corresponding adjacent channel rejection and has to be higher than the specified values.

By the above description of the 802.11a standard for the WLAN at 5 GHz band, the critical specifications regarding the physical layer can be clarified and their implications
to the RF section of the transceiver can be implied. Following there is a brief description of the bottlenecks imposed by the RF front end and their relation to the specified parameters is presented, while in the next section extensive analysis and solutions are going to be provided.

1.2. Baseband / RF frontend impairments

The implementation of a RF transceiver, which complies with the IEEE 802.11a standard and at the same time is highly commercial, is still challenging. The impairments of the front end proved to be more important than the designers thought in the beginning, and are mainly related to the architecture selection of the transceiver, the non linearity of the power amplifier, the phase noise of the local oscillators in combination with the non linear mixing, the high PAP ratio of the OFDM signal, the increase of the channel impulse response due to filtering, the electromagnetic coupling between RF devices as the package gets smaller, the maturity of the technology process to be used in order to meet packaging and low power requirements, and finally the adaptive nature of the modem which supports different modulation schemes and different sensitivity levels.

1.2.1 Architecture.

Regarding the architecture of the RF front end, three cases are considered. The following discussion targets to highlight the advantages and drawbacks of each one, and justify the final choice.
The traditional way to build an RF transmitter is through heterodyne architecture. The modulated signal is up converted twice by two subsequent mixing operations. Initially, the OFDM modulated signal after the addition of the GI (guard interval) and a low pass filtering operation to cancel any images generated by the DAC, is mixed with a local oscillator signal of approximately LO1=800 MHz. This first up-conversion creates one up converted version of the OFDM signal centered around LO1 frequency, which before the next up conversion, has to be band pass filtered to suppress any harmonics possibly generated. The second up-conversion occurs due to a mixing with a much higher and also variable LO signal, approximately LO2=(4.3 to 5.1) GHz, that provides an up converted signal at one of the 12 possible carrier frequencies specified in 802.11a. (LO1 + LO2). Then a second Band Pass Filter operation is necessary to cancel the image generated by the mixing operation at LO2-LO1 or reject any LO leakage to the RF output [5].

The main advantages of the super heterodyne approach are that since the components needed are easily realized, it is the fastest to market and more secure implementation. For example, the careful choice of LO signals may relax the specifications for the BPF, yielding moderate Q values.

Disadvantages occur because of the large amount of components. For instance, more mixing operations means additional phase noise which degrades the sensitive OFDM signal, an issue that is going to be addressed in later sections. In addition, it is a more expensive implementation and obviously less compact than others. Not to mention that
because the OFDM signal is as I/Q signal, the first up conversion is vulnerable to I/Q mismatch degrading the OFDM signal.

Direct Conversion is the second architecture to be considered for the implementation of the RF transmitter. In this case, the OFDM modulated signal is directly up converted to the 5 GHz band with the use of only one LO frequency. The simplicity and the use of less components than the heterodyne architecture, makes direct conversion a very attractive solution since it is going to be cheap and compact. Unfortunately, the drawbacks of this method turned out to be more serious challenges than engineers originally anticipated. For instance, the DC offset generated at the receiver due to self-mixing of the LO signal significantly corrupts the baseband signal. On the transmitter side the LO signal leaks through the substrate and since it is located in the center of the transmitted signal it corrupts the OFDM signal while at the same time saturates the PA.

The last architecture considered is the low IF case, as an effort to compromise between DC conversion and heterodyne. The intermediate frequency is now significantly lower than heterodyne, which yields filters that are more reasonable to design and integrate, while not facing the DC offset problems of direct conversion.

The issues involved in Direct Conversion characterize it as the most difficult to realize. The Low IF case was seriously considered but the unavailability of off-the-shelf devices (during the design phase, Oct '02) as well as the stringent specifications imposed on the BPF were the main reasons for abandoning this approach. The Heterodyne system dominated because of its simplicity, relative relaxed specifications regarding the individual building blocks and availability of components. Therefore the Heterodyne
approach was chosen for the implementation of the first RF prototype. Careful selection of LO frequencies will enable for easily realizable filters or use of available in the market devices. At the same time migration of the I/Q modulation to the digital processing unit is going to minimize the I/Q phase mismatch problem. This means that the base-band OFDM I/Q signal is going to digitally modulate an IF carrier at 20 MHz where the I/Q mismatch is only due to the quantization of the samples in the digital modem. Then two consequent up conversions are going to provide the RF signal.

1.2.2 Peak to Average Power Ratio

The time domain OFDM symbols are generated, as a summation of modulated sub-carriers, through an IFFT, and thus, as explained in earlier sections, yields a high PAP ratio for the OFDM signal. Especially OFDM systems with 52 non-zero carriers 64-QAM modulated produce a crest factor of 19. The high PAP ratio apart from unrealizable specs for several RF blocks also affects the word length of the ADC of the receiver. Now, because a crest factor of 19 would cause inefficient implementations in terms of word length in the digital modem and data converters, the signal coming out of the IFFT block are clipped digitally at the optimum level of 4σ where σ (sigma) is the rms amplitude of the time domain signal. Regarding the choice of the word length (6) this is chosen to be 10 digits, which is 2 bits more than the optimum in order to allow for a safety margin of the implementation.
1.2.3 PA Non Linearity

The power amplifier is an essential block of the transmitted path since its operation has to be optimized to give maximum output power in order to achieve maximum cover range for the network, but at the same time to be linear enough so that to maintain maximum modulation accuracy and high efficiency, since especially the later would yield large life of operation for the mobile terminals.

The amplifiers saturate as the signal level is increased. This causes the presence of higher harmonics and a reduction in the incremental gain of the amplifier. The level of saturation of an amplifier is given by its $P_{1dB}$ compression point which is the input power for which the output power is 1 dB below the output power than would be produced if the amplifier was perfectly linear. Saturation occurs if the amplifier is driven over the $P_{1dB}$ compression point.

Especially for sophisticated signals, as the OFDM signal, PA nonlinearity causes serious degradation of the PER of the system. In general, it is wanted that the average power of the input signal to the amplifier to be as close as possible to $P_{1dB}$ so that the maximum efficiency is achieved. However, in the case of a high PAP ratio signal, even after the optimal clipping function, the amplifier has to be operated at a back of at least 5dB to 10dB to take into account the high peaks of the signal, since the PAP effect is not eliminated. Finally simple design configurations such as A class amplifiers promise higher linearity performance.
Figure 5 shows that the non-linearity of the amplifier results in spectral regrowth [7], which means that apart from boosting up the signal level, the PA generates intermodulation products at adjacent and bi-adjacent channels. These products have to be below certain levels to meet the spectral mask specification imposed by the standard.

1.2.4 Phase Noise

It is well known that local oscillators exhibit phase noise around their center frequencies. Phase noise can be interpreted as a parasitic phase modulation in the oscillator's signal which ideally would be a unique carrier with constant amplitude and frequency. Theoretical analysis of the phase noise distinguishes between the common phase error and inter-carrier interference. The common phase error is added to every sub-carrier, is proportional to its (sub-carrier's) value and corresponds to a rotation of the
constellation diagram proportional to the average of the phase noise of the oscillator over the sub-carriers [3]. Since this average is the same for all sub-carriers this common error can be corrected by some kind of phase rotation. On the contrary, inter carrier interference, also known as loss of orthogonality, has a random nature and it cannot be corrected. In fact, the inter-carrier interference on carrier N, corresponds to the summation of the information of the rest N-1 sub carriers each one of them multiplied by a factor proportional to the spectral distance from carrier N. A characteristic of this error is that the center carriers exhibit higher distortion because they have more neighboring carriers.

Phase noise of the local oscillator is going to degrade the PER of the transceiver due to ICI. Since the only way to prevent ICI is to improve the performance of the oscillator itself, it is of great importance to determine how much phase noise a receiver can withstand while maintaining the required performance and provide a phase noise spectrum mask as a specification for the oscillator.

1.2.5 Packaging

Packaging is maybe the most important issue regarding RF front-end implementations, since only compactness can guarantee cheap and highly mobile products. However, at the same time it involves a lot of issues due to electromagnetic coupling between the active devices, consumption of real estate for off chip passive components and thermal management issues.
System on a package approach seems to be the solution for efficient packaging, since system on a chip solutions fail to integrate all the passives and crosstalk causes severe distortion to the signal. Three dimensional SoP approaches have been proposed for integration of the chipset, band select filter and antenna in a multilayer structure, vertically interconnected through via process. LTCC (low temperature co-fired ceramic) technology provides multilayer structures where the chipset may be mounted on one side (bottom) of the package, antenna may be sitting on the top layer and BPF may be embedded inside the multilayer structure [6]. Via walls and arrays may be used to isolate different devices from each other and especially for the PA may act as heat sinks.

Figure 6. SoP front end approach
Chapter 2: RF Front End Development

2.1 ADS Simulations

The complexity of the simulation and testbed phases of the project is increased because of the interaction that has to be established between the RF blocks and the baseband (BB) modem.

Regarding the simulation phase, there was a need for a combined simulation environment that could include the BB modem as well as the RF chain. The 802.11a modem has been implemented with MatLab (The IEEE802.11a Modem was implemented in the Department of Development Programmes, Intracom-Greece). Parameters like the modulating scheme and coding rate may have to be defined at will to produce a sequence of test vectors. With the term test vectors we define, the timed samples can be generated from the digital OFDM modulator.

2.1.1 The OFDM Signal

The OFDM signal is going to be the input of the RF chain in order to test its efficiency and thus has to be the most demanding one. Regarding the modulation and coding schemes, we define the worst case scenario as the one that combines the 64 QAM modulation with 3/4 coding rate scheme. Compared to the other modulation schemes, 64 QAM needs a higher signal to noise ratio at the demodulator input and this is because for the same transmitted power, the density of the points in the constellation diagram is higher and thus less noise can be tolerated. At the same time convolutional coding of 3/4.
as described in previous section is a rather light coding scheme that will not recover too many lost bits of information. Thus, an assumption that if the system works efficiently under this configuration will be able to successfully operate in all other nodes, is fair.

2.1.2 Interface to RF

The modem test vectors comprise a sequence of discrete time samples and thus have to be properly interfaced to stimulate the RF analog components. Sampled at a final rate of 80 MHz, the test vectors represent an OFDM signal up-converted in a low intermediate frequency of 20 MHz. The RF bandwidth of the signal is 16.6 MHz centered at 20 MHz. It is obvious here that the I/Q modulation has been digitally performed by the modem as mentioned earlier.

![Diagram](image)

**Figure 7. Matlab-ADS Interface**

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The digital to analog conversion of the signal has been simulated in Agilent-ADS. The Ptolemy simulator is the environment where the modem would have been implemented. Instead of the actual modem, a Matlab output file is imported as a source to the rest of the simulations. A combination of math and interface components is being used to properly drive the DAC, which finally generates the analog signal to be imported in the RF chain. Timed waveforms and the spectral density of the analog signal may be obtained, to reveal the typical DAC output consisting of the images of the original signal shaped by the sinc(x) function due to the sampling performed by the DAC.

2.1.3 RF Frontend

The RF front end of the system is responsible for the up-conversion of the OFDM signal to C-band, while retaining the constellation accuracy, and for transmission below the maximum power levels. At the receive side low noise reception has to be achieved as well as down-conversion to the low IF of 20 MHz.
Ideal transmitter and receiver chains (ideal by the means that the nonlinearites are only partially included in the behavioral models of the devices) are developed in order to initially establish the simulation platform. All the necessary RF blocks like mixers, LPF, BPF, low noise amplifier, power amplifier, drivers, etc. are incorporated to form the whole path. The components used are RF-Analog components, the models of which include the non-linear characteristics which are the most important degradation factors of the signal.
Instead of Harmonic Balance or Transient, the Envelope controller is used. Proper choice of the controllers’ parameters is going to ensure compatibility between the simulators and enable simulation of the RF blocks with the OFDM modulated signal.

2.1.4 Co-simulation Platform

Co-simulation environment is generated so that the imported Matlab file, the Ptolemy components responsible for the interface, the RF front-end components, as well as the channel model can co-exist on the same platform.
With the addition of a few blocks, the time domain data processed by the Ptolemy controller are transformed to spectrum domain data so that the Envelope controller may further process them. Initially, a simple channel model is placed between transmitter and receiver, equivalent to a flat loss over the spectrum of interest. At the end of the RF path a Read file component is placed to export the down-converted data to the matlab demodulator.

In addition, the co-simulation environment allows us to keep track (figure 10) of the spectral density of the OFDM signal as propagated through the RF path. Multiple outputs are connected between successive components in the envelope controller environment and interfaced to the data flow environment from where they are displayed.

2.1.5 Demodulated Data

The main advantage of the co-simulation technique is appreciated when the actual BER of the entire system is obtained. This is possible since the output file of ADS may be read by the Matlab demodulator. After the removal of the cyclic prefix, the FFT transform, and the error correction algorithms the constellation diagram can be plotted.
In the case described in this example this is a 64 QAM constellation. Parameters like the EVM, the SNR, the I/Q mismatch and of course the BER may be obtained.

![Figure 11. Constellation of received signal 64-QAM.](image)

The system level approach previously discussed is very efficient for wireless systems, since these kind of systems are considered as mixed signal systems, by the means that digital components like CPUs or ASICs coexist with analog and RF components with the proper interface DACs/ADCs. Simulation set-ups may be built to predict the behavior of the different signals environment separately. However the co-simulation environment enables not only to have an integrated view of the system but also to observe how modifications in one part of the system affects the performance of the other. For example, how a smaller clipping level might saturate the amplifier stages, or how the phase noise of the LO degrades the BER due to OFDM demodulator leakage.

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2.2 NF and Budget Gain Calculations

The simulation environment that established a path between the BB modem and the RF chain provided advanced understanding of the mixed signal issues. However, regarding this first implementation of the transceiver the system level performance was finally predicted through NF and budget gain calculations which are presented in the following section.

Figure 12. Initial transceiver architecture

The initial design of the transceiver is presented in figure 12. This architecture is not to be confused with the one finally implemented. Unavailability of components and other
design issues demanded for substitution of some devices, and therefore the final system slightly diverges from the one presented in figure 12. The scope for including the initial architecture is for better understanding of the calculations performed to predict the systems performance and its conformity with the specifications.

2.2.1 NF Calculations

The results of the noise figure NF calculations are shown in tables 1,2 and 3 for the high and low gain scenarios of the receiver path as well as for the high gain scenario of the transmitter path. The receiver chain described in table 1 is able to process a signal of -55 dB and deliver -5 dBm of power to the ADC with a total calculated noise figure of 3.4 dB.

Table 1. Receiver's NF for the minimum received power scenario (-55 dBm)

<table>
<thead>
<tr>
<th>Device P/N</th>
<th>NF (dB)</th>
<th>Gain</th>
<th>NF Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-MA5W350009</td>
<td>1</td>
<td>-1</td>
<td>3.4 dB</td>
</tr>
<tr>
<td>2-MAAM37000</td>
<td>2.2</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>3-TDFM2A-5226-10</td>
<td>2</td>
<td>-2</td>
<td></td>
</tr>
<tr>
<td>4-HMC318MS8G</td>
<td>2.5</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>5-MCA1-60</td>
<td>2</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>6-TDF2A836</td>
<td>2</td>
<td>-2</td>
<td></td>
</tr>
<tr>
<td>7-VNA-25</td>
<td>5.5</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>8-HMC288MS8</td>
<td>1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>9-ADEX 13</td>
<td>7.5</td>
<td>-7.5</td>
<td></td>
</tr>
<tr>
<td>10-LEE-35</td>
<td>4.5</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>11-HMC288MS8</td>
<td>1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>12-SCLF-30</td>
<td>1</td>
<td>-1</td>
<td></td>
</tr>
</tbody>
</table>

This chain receives -55 dB and delivers -5 to the ADC

26
The noise figure of the receiver is a critical specification of the network. The modulation accuracy of the OFDM signal may be significantly degraded if noise is added to the signal and will result in a high EVM level. Different modulation schemes used in OFDM demand different noise figure specifications for the receiver path. However, an overall noise figure of less than 10 dB usually meets the demands even of the worst case scenario of an IEEE 802.11a modulated and coded signal which is a signal of 64 QAM and 3/4 coding rate.

Table 2. Receiver’s NF for the maximum received power scenario (-27.5 dBm)

<table>
<thead>
<tr>
<th>Device p/n</th>
<th>NF(dB)</th>
<th>Chain</th>
<th>NF total</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASWSS0039</td>
<td>1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>2MAAMG37000</td>
<td>2.2</td>
<td>15</td>
<td>3.5 dB</td>
</tr>
<tr>
<td>TDFM2A-5250-10</td>
<td>2</td>
<td>-2</td>
<td></td>
</tr>
<tr>
<td>HMC216MS8G</td>
<td>2.5</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>SCM1-69</td>
<td>7</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>STDF2A836</td>
<td>2</td>
<td>-2</td>
<td></td>
</tr>
<tr>
<td>VNA-25</td>
<td>5.5</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>HMC238MS8</td>
<td>15</td>
<td>-15</td>
<td></td>
</tr>
<tr>
<td>ADEX 10</td>
<td>7.5</td>
<td>-7.5</td>
<td></td>
</tr>
<tr>
<td>LEE-39</td>
<td>4.5</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>HMC238MS8</td>
<td>15</td>
<td>-15</td>
<td></td>
</tr>
<tr>
<td>SCLF-30</td>
<td>1</td>
<td>-1</td>
<td></td>
</tr>
</tbody>
</table>

*This chain receives -27.5 dBm and delivers -5 dB to ADC

The receiver chain described in table 2 is able to process a signal of -27.5 dBm and deliver -5 dBm of power to the ADC with a total calculated noise figure of 3.5 dB. The
digital attenuators provide extra attenuation to prevent the signal from compression while passing through the passive mixers.

The transmitter chain described in table 3 is able to process a signal of -6.5 dBm provided by the DAC and deliver 17 dBm of power to the antenna with a total calculated noise figure of 7.18 dB. The noise figure of the transmitter is not that critical as the receiver's because the S/N ratio of the available signal in the output of the DAC should be high.

Table 3. Transmitter's NF for the maximum transmitted power scenario (17 dBm)

<table>
<thead>
<tr>
<th>device p/n</th>
<th>NF(dB)</th>
<th>Gain</th>
<th>NF total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCLF-30</td>
<td>1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>ERA 5SM</td>
<td>4.3</td>
<td>16</td>
<td>7.18 dB</td>
</tr>
<tr>
<td>ADEX 10</td>
<td>7.5</td>
<td>-2.5</td>
<td></td>
</tr>
<tr>
<td>TDF2A836</td>
<td>2</td>
<td>-2</td>
<td></td>
</tr>
<tr>
<td>SERA 5SM</td>
<td>4.3</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>HMC288MS8</td>
<td>7</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>MCA1-60</td>
<td>7</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>TDFM2A-5250-10</td>
<td>3</td>
<td>-3</td>
<td></td>
</tr>
<tr>
<td>MAAPSM4008</td>
<td>5</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>10MASWSS0039</td>
<td>1</td>
<td>-1</td>
<td></td>
</tr>
</tbody>
</table>

*this chain receives -6.5 dBm from the DAC and transmits 17dBm

2.2.2 Budget Gain Calculations

The following figures present the budget gain calculations. The budget gain calculations apart from demonstrating that the power level that is delivered to the antenna
or the ADC for different gain scenarios is valid and meet the IEEE 802.11a specifications, also provides proof that the components of the RF chain are not driven into compression.

![Transmitter Chain](Image)

**Figure 13. Transmitter Budget Gain Graphs**

Thus by comparing the GP1 values of each component with the power that it delivers to its output, one may monitor the non-linear effects that are present in mixing and amplification stages.

Regarding the previous charts the term “output power level” accounts for the expected power of the signal at the output of the device. In addition, the first device in the graphs (device no 0) accounts for the expected input power level to the RF chain. For example, in the transmitter chain (figure 12) the expected input power is −6.5 dBm and is the power that should be available from the DAC. Similarly the received power on the receiver side should vary from −55 dBm to −27.5 dBm (figure 12).
2.3 Device Characterization

This phase of the project includes measurements of the individual devices that were used in the front end architecture of the WLAN 802.11a transceiver. In addition, it includes design and fabrication of a few evaluation boards that were not provided by vendors.

The S-parameters measurements set up that was used included the HP 8517B S-parameters Test Set and the HP8510C Network Analyzer. For the Power spectrum measurements the following set up was used: Agilent 8565E Spectrum Analyzer, HP 83640L Series Swept CW Generator, an Power Amplifier Module.

2.3.1 Driver VNA-25

The VNA-25 amplifier was used after the first down conversion stage in the receiver chain. It is expected to amplify as low level signals as -40dBm as well as signals up to
-5 dBm. The gain is measured to be 17 dB (between 800 MHz and 900 MHz) and the output P1dB of the VNA-25 is 17.7 dBm.

Figure 15. VNA-25 Input vs Output Power

Figure 16. VNA 25, Gain of 17 dB at 900 MHz

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2.3.2 Driver ERA-5SM

The ERA5SM amplifier was used before and after the first up conversion stage in the transmitter chain.

![Graph showing ERA5SM Gain of 19.4 dB at 900 MHz](image)

Figure 17. ERA-5SM, Gain of 19.4 dB at 900 MHz

It is expected to amplify signals between -10 and 0 dBm. The gain of the amplifier was measured 19 dB in the range 800 to 900 MHz and the output P1dB of the ERA5SM was 19.7 dBm.
2.3.3 MAAPSM0008 Power Amplifier

The MAAPSM0008 MACOM power amplifier was used after the second up-conversion stage in the transmitter chain. It is expected to receive signals of 0 dBm and amplify them to the level of 20 dBm. The gain of the amplifier was measured 21 dB and the $P_{1dB}$ of the PA was 30 dBm.
Figure 19. MAAPSM9008 Input vs Output Power

Figure 20. MACOM PA, Gain of 21dBm at 5.250GHz

The chosen PA is expected to operate in the 5.15 – 5.35 GHz band but it may be used also for the upper band at 5.7 – 5.8 GHz.

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2.3.4 LNA HMC318MS8G

The HMC318MS8G low noise amplifier was used before the first down conversion stage in the receiver path. It is expected to receive signals smaller than -10 dBm. The gain of the amplifier was 9 dB and the output P1dB of the LNA although not critical was -1.5 dBm. Noise measurements are not yet available.

![Graph](image)

**Figure 21.** HMC318MS8G LNA Input vs Output Power
2.3.5 Switch MASWSS0039

The critical specifications for the switch are the insertion loss and the isolation. Therefore the MASWSS0039 switch was tested in two modes of operation. First control input V1 was set to high level and an insertion loss of less than 1 dB was observed for forward transmission between ports 1 and 3 (Figure 22.a). For control inputs V1 low and V2 high the isolation between ports 1 and 3 was measured to be more than 30 dB (Figure 22.b).

![Switch Transmission Port 1 to 3](image1)

![MACOM, Switch Isolation Port 1 to 3](image2)

Figure 22a,b. MASWSS0039 Insertion Loss and Isolation, Port 1 to 3

2.3.6 Filters

The SCLF-30, a Mini Circuits LPF was chosen for the filtering operation of the OFDM signal at the DAC output and the ADC input. This filter is responsible for the image cancellation generated at the DAC output as well as the elimination of unwanted interferers at the receiver side.
For the IF BPF operation the TDF2A836, a Toko B2F, was used. The BPF has a center frequency of 836 MHz, a BW of 20 MHz and provides an attenuation of approximately 10 dB at 20 MHz offset from the center frequency.

For the RF BPF operation the TDFM2A-5250-10, a Toko BPF, was used. The BPF has a center frequency of 5200 MHz, a BW of 300 MHz and provides an attenuation of approximately 30 dB at 1000 MHz offset from the center frequency. The IL of the filter was measured to be less than 3 dB. (Fig. 23)

Figure 23. RF BPF frequency response

2.3.7 Mixer MCA1-60

The MCA1-60 was used for the second up converting stage and the first down converting one. The mixer was initially tested in order to define the optimum LO power level in terms of conversion loss. A sweep of the LO power revealed that the minimum conversion loss was achieved for 8dBm of LO power. Then for constant LO power at 8 dBm the compression of the mixer was investigated. The output P1dB (equivalent
maximum linear power available at mixer output) of the MCA1 is -4 dBm. The mixer is expected to operate close to compression but at this point of operation strong harmonic components are being generated around the wanted signal. This result makes the specifications of the following BPF very demanding. Alternative approaches were investigated (i.e. omitting the ERA5SM and use a driver after the MCA1-60 so that the input signal in the mixer is lower and does not drive the mixer to compression). Figure 24 shows the measurement results for IF=881MHz, LO=4369MHz and RF =5250 MHz.

![MCA1-60_data](image)

**Figure 24. MCA1-60 Input vs Output Power**

2.3.8 Mixer ADEX-10

The ADEX-10 was used for the first up converting stage and the second down converting one.
The mixer was initially tested in order to define the optimum LO power level in terms of conversion loss. A sweep of the LO power revealed that the minimum conversion loss was achieved for 7 dBm of LO power. The LO to RF leakage was measured to be -35dBm. Then for constant LO power at 7 dBm the compression of the mixer was investigated. The output P1dB of the ADEX-10 is -7 dBm.

Figure 25 shows the measurement results for IF=20MHz, LO=861MHz and RF=881 MHz.

2.3.9 Antenna AccuWaveEA5800

The AccuWave EA5800 antenna was used to transmit the 802.11a signal for the lower and middle bands of UNII (5.150 GHz-5.350 GHz).
Figure 26a. AccuWave EA5800 Tri band Antenna

Figure 26b. AccuWave EA5800 Tri band Antenna

The S-parameters measurements (figure 26a,b) in the frequency range of interest showed that the reflection is less than –16dB and –8.5dB respectively. The two graphs refer to the two EA5800 antennas that are currently available on evaluation PCBs.
2.4 PCB Design

2.4.1 4350 HF Rogers Board

The overall transceiver system was implemented on a PC board. Possible materials for such an implementation were the standard FR 4, the Rogers 4350 HF material, the LTCC and the LCP materials. The FR4, although the cheapest solution, has a dielectric constant of 4.5 +/- 1. Such a variance would probably cause matching issues among the different RF components and thus the 4350 Rogers material, with a dielectric constant of 3.48 +/- 0.05, was selected as a superior choice. LTCC and LCP materials, although superior than Rogers material, since they provide features as multilayer design, cavity process and better design rules were not chosen for this first implementation, but will be the most likely candidates for the future implementations of an upgraded module. The PCB was designed using the Agilent ADS layout tools. The interface between the software and the fabrication company (Innovative Circuits) was the gerber file format.

Briefly the material selection was based on:

• High accuracy of dielectric constant
• Low loss
• Small CPW line width to fit micro lead chips
• Matching accuracy
• Fabrication repeatability/accuracy
The characteristics of the material are

- High Frequency Circuit Material: Rogers 4350
- Dielectric Const: 3.48 +/-0.05
- Substrate Thickness: 10 mil
- Tan(d) @ 10 GHz : 0.0037
  
  Fabrication company: Innovative Circuits

The next figure shows the PCB layout generated with ADS. CPW configuration was used for the interconnections of the components in order to achieve better signal ground and to provide easier troubleshooting regarding the off chip matching of the devices as well as the parasitic oscillations that may occur due to loading effects. SMA connectors were used to feed the antennas and for the baseband interface (DAC/ADC).

Figure 27 Transceiver PCB Layout (Rogers 4350 HF Material)
Chapter 3: Transceiver Implementation

3.1. Summary of System Performance

Table 4. Summary of Measured Performance

<table>
<thead>
<tr>
<th>OFDM Signal</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>64QAM</td>
<td></td>
</tr>
<tr>
<td>Data Rate</td>
<td>54</td>
<td>Mbps</td>
</tr>
<tr>
<td>Coding Rate</td>
<td>3/4</td>
<td></td>
</tr>
<tr>
<td>Carriers</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>Modulated Spectrum</td>
<td>16.6</td>
<td>MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spectrum Allocation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Band of Operation</td>
<td>UN-II (5.15-5.35GHz)</td>
<td></td>
</tr>
<tr>
<td>OFDM Channels</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Channel BW</td>
<td>20</td>
<td>MHz</td>
</tr>
<tr>
<td>RF carriers</td>
<td>5180+n*20 [n=0.7]</td>
<td>MHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transmitter</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>58</td>
<td>dB</td>
</tr>
<tr>
<td>OP 1dB</td>
<td>22.5</td>
<td>dBm</td>
</tr>
<tr>
<td>LO 2 leakage suppression</td>
<td>28</td>
<td>dB</td>
</tr>
<tr>
<td>Image Rejection</td>
<td>42</td>
<td>dB</td>
</tr>
<tr>
<td>DC Power Consumption</td>
<td>6.1 (max gain mode)</td>
<td>Watt</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiver</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>High Gain Mode</td>
<td>27</td>
<td>dB</td>
</tr>
<tr>
<td>NF</td>
<td>&lt; 6</td>
<td>dB</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>-65</td>
<td>dBm</td>
</tr>
<tr>
<td>LO leakage Suppression</td>
<td>35</td>
<td>dB</td>
</tr>
<tr>
<td>DC Power Consumption</td>
<td>1.07</td>
<td>Watt</td>
</tr>
</tbody>
</table>
3.2 Transceiver System Architecture

The final heterodyne architecture chosen for the implementation of the RF front end Module is presented in the following schematic (Figure 27).

Figure 28. Transceiver System Architecture
3.3. I/O Interface

The I/Os are labeled on the modules (Appendix I) as described in the following table.

Note that values of the applied signals/voltages are also shown. Before applying any signal check the directions provided in the following paragraphs especially for the PA/driver biasing.

<table>
<thead>
<tr>
<th>Tx I/Os</th>
<th>Signal</th>
<th>Freq</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF.Tx</td>
<td>20 MHz</td>
<td>&lt;-35</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>LO.1</td>
<td>816 MHz</td>
<td>4</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>LO.2</td>
<td>(4344 + n*20) MHz</td>
<td>8</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>RF.Tx</td>
<td>(5180 + n*20) MHz</td>
<td>7</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>PA.in</td>
<td>(5180 + n*20) MHz</td>
<td>7</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>PA.out</td>
<td>(5180 + n*20) MHz</td>
<td>33.5</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>Vcc.ERA</td>
<td>DC</td>
<td>5</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vdd.PA</td>
<td>DC</td>
<td>6</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vgg.PA</td>
<td>DC</td>
<td>-1.8</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vdd.Dr</td>
<td>DC</td>
<td>5.7</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vgg.Dr</td>
<td>DC</td>
<td>-1.8</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rx I/Os</th>
<th>Signal</th>
<th>Freq</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF.Tx</td>
<td>(5180 + n*20) MHz</td>
<td>&gt;-65</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>LO.1</td>
<td>816 MHz</td>
<td>4</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>LO.2</td>
<td>(4344 + n*20) MHz</td>
<td>8</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>IF.Tx</td>
<td>20 MHz</td>
<td>&gt;38</td>
<td>dBm</td>
<td></td>
</tr>
<tr>
<td>Vcc.LNA</td>
<td>DC</td>
<td>3</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vcc.VNA</td>
<td>DC</td>
<td>5</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Cntl.LNA</td>
<td>DC</td>
<td>0-3</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Vcc.ERA</td>
<td>DC</td>
<td>10</td>
<td>V</td>
<td></td>
</tr>
</tbody>
</table>

3.3.1 Assembly and Interface Procedure

Step 1. Assemble the Modules

i. Connect the input ‘PA_in’ of the PA Module directly to the output ‘RF.Tx’ of the Tx Module using the SMA I/Os.
ii. Connect the Antenna to the output 'PA_out' of the PA module using the male to male SMA connector (included).

iii. Connect the Antenna to the output ‘RF_Rx’ of the Rx Module.

Step 2. Connect the Signal Generators.

i. Connect the signal generator (up to 900MHz) to the ‘LO_1’ input for both the Tx and Rx modules. (SMA connection)

ii. Connect the signal generator (up to 4.5GHz) to the ‘LO_2’ input for both the Tx and Rx modules. (SMA connection)

iii. Connect the output of the OFDM Signal Generator (or Modem/DAC outputs/Low IF interface) to the ‘IF_Tx’ input of the Tx Module. (SMA connection)

iv. Connect the output ‘IF_Rx’ of the Rx Module to the power spectrum analyzer. (SMA connection)

Step 3. Biasing and RF I/Os

Tx Module.

The voltage supply ‘Vcc_ERA’ of the ERA amplification stages is 10 volts. The current should not exceed 75 mA.

Caution is needed while biasing the driver and PA stages. Initially the drain to source voltages of both stages, ‘Vdd_PA’ and ‘Vdd_Dr’, has to be set at 0 volts and the gate voltage, ‘Vgg_PA and Vgg_Dr’, has to be set at –1.8 volts. Then gradually the drain to source voltage ‘Vdd_PA and Vdd_Dr’ is increased until it reaches the nominal values of 5.7 and 6 volts. Note that this values maybe tuned for optimum biasing but they should
never exceed the 6.5 volts and the PA or driver stages should draw current that does not exceed 450 mA. Turn off the PA and driver biasing following the opposite sequence, if possible.

Rx Module

Three supply inputs of 3.5 and 10 volts are needed for the LNA (‘Vcc_LNA’), VNA driver (‘Vcc_VNA’*) and ERA driver (‘Vcceresa’), respectively. The gain control input of the LNA (‘Cntl_LNA’*) is initially set to 0 volts providing maximum gain of 9 dB. It may be tuned (0 to 3 volts) to provide less gain or even attenuation in order to protect the receiver from compression in the presence of a extremely strong received signal (greater than -30 dBm).

RF I/Os

The input of the transmitter ‘IF_Tx’ expects an OFDM signal centered at a 20MHz low IF and of maximum power of -35 dBm. The local oscillator signals, ‘LO_1’ and ‘LO_2’, have to be 4 and 8 dBm respectively for the first and second up-conversion. LO_1 should be tuned at 816 MHz and LO_2 should be swept through the values (4344+n*20) MHz.

Similarly the local oscillator signals of the receive side ‘LO_1 and LO_2’ have to be set at 4 and 8 dBm while the RF input (RF_Tx) has to be greater than -65 dBm in order to provide a signal of at least -38 dBm to the ADC (‘IF_Rx’).
3.4. Measurements

3.4.1 Measurements Setup (Appendix I)

Measurement Equipment

- Agilent E4438C ESC Vector Signal Generator
- HP 83640L Series Swept CW Generator (x2)
- Agilent 8565E Power Spectrum Analyzer
- E4432B Series Signal Generator

OFDM Signal Specifications (Agilent Signal Studio IEEE 802.11a)

- Modulation 64QAM
- Data rate 54 Mbps
- Encoder 3/4 rate
- Modulated BW of 16.6 MHz
- 52 Carriers
3.4.2 Transmitter Testing

The input signal in the low IF port of the transmitter module was set at -33 to -35 dBm. The LO1 signal was set to 816 MHz to up-convert the OFDM signal at an IF carrier frequency of 836 MHz, exactly in the pass band of the IF-BPF (low side injection). The LO1 power was set to 4 dBm. The LO2 signal was set to 8 dBm and the oscillating frequency was swept through the values (4344 + n x 20) MHz [where n=0...7], to test the 8 different channels of the lower and middle UN-II band (low side injection). The following figures demonstrate measurement results. The output compression point (OP1dB) of the combined Transmitter and PA modules was measured to be 22.5 dBm. This value was, as expected, approximately 6 dB below the P1dB of the PA (30dBm) due to the PAP ratio of the OFDM signal. The system's overall gain is measured to be 58 dB.

Figure 29. Test-Bed: DUT accounts for Tx and PA or Rx modules

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Figure 30. The 8 OFDM channels of the UN-II
Figure 30 (cont'd).

3.4.3 Spectral Re-growth

The spectral re-growth level was below the one specified by the IEEE 802.11a standard. However, the presence of the unwanted image generated by the $1^\text{st}$ up-conversion mixing operation and the (LO$_1$+LO$_2$) leak were dominating the adjacent channel spurious responses. The spectrum mask of the 802.11a standard is presented in the following figure where the unwanted image is also visible. The 802.11a specifies that the transmitted power level should be below -20dB (dB relative to the spectral density of the signal) at 11 MHz frequency offset from the RF carrier, and below -40dB at a 30 MHz offset. This limitations allow for minimum interference between the OFDM signal as well as prevent out-of-band spurious transmission.
3.4.4 LO₂ Leakage

The LO₂ (4480 MHz) leakage, which is critical on the Tx side because was close to the transmitted OFDM signal (5180 MHz) was −27 dB. The LO₂ leakage component is shown in the following figure at −19.8 dBm. The image generated by the 2nd up-conversion mixing was thus sufficiently suppressed.
3.4.5 Transmitter P1dB Compression Point

The gain of the transmitter was 58 dB. The P1dB compression point, which indicates the level of the output power for which the Tx gain is compressed to 57 dB, was measured to be 22.5 dBm.

The overall compression point was expected to be 6-7 dB lower than the compression point of the PA (PA's P1dB=30dBm) because of the high PAP (Peak to Average Power) ratio of the transmitted OFDM signal. Therefore the transceiver is capable of transmitting up to 22.5 dBm of linear power, which is 5 dB higher than the limitation that IEEE 802.11a imposes for this frequency range of operation.
3.4.6 Receiver Testing

The receiver chain was tested with input signals level as low as -65 dBm. The following figures demonstrate the down-converted OFDM signal for an RF input signal of -60 dBm for different RF carriers (5180MHz, 5200MHz, 5220MHz, 5260MHz, 5280MHz). The Rx gain is measured to be 27 dB. This is the high gain mode of the Rx (i.e. when the LNAs provide the max gain of 9 dB each). The NF of the Rx is calculated to be less than 6 dB, which enables the better sensitivity of the receiver even for the most demanding transmitted signals like the 64 QAM and 3/4 coding rate OFDM modulated signals.
Table 6. OFDM Channels

<table>
<thead>
<tr>
<th>Channel #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF carrier (MHz)</td>
<td>5180</td>
<td>5200</td>
<td>5220</td>
<td>5240</td>
<td>5260</td>
<td>5280</td>
<td>5300</td>
<td>5320</td>
</tr>
</tbody>
</table>

Figure 34. Down-converted OFDM
3.4.7 Receiver Sensitivity

Figure 34 demonstrates the sensitivity of the Receiver Module. Feeding the LNA with input signals as low as \(-65\) dBm the Receiver Module provides \(-34\) dBm of available power to the ADC.

Figure 35. Rx Sensitivity
3.4.8 Combined test of Rx Tx (including antennas)

Finally, a full test bed incorporating both the Transmitter and the Receiver Modules was assembled in order to test the overall performance of the wireless network. Thus, an OFDM modulated signal was fed in the IF input of the Transmitter Module, was up-converted to RF, transmitted through the wireless channel, received by the Receiver Module and down-converted to the low IF of 20 MHz. The measurement results are presented in the following figures.

Figure 36. Transceiver Test-Bed
Figure 37. Down-converted OFDM Signal at 20 MHz
Figure 37 cont'd. Down converted OFDM Signal at 20 MHz
Chapter 4 - Conclusions

4.1 Conclusions

The first RF Front end prototype was designed in order to comply with the IEEE 802.11a specifications. These include the frequency band of operation, the available output power and the spectrum mask. The MIC prototype consists of available off-the-shelf components and was implemented on HF material commercially available. The main criteria for the architecture and implementation was the fast time to market one.

The transceiver and receiver systems were developed and successfully tested. Vector Signal Generator was used to generate the most demanding OFDM signal. Sinus wave generators were used as LO signals and the measurement results were in terms of the received power spectrum.

The summary of the measured performance as described in Table 4 reveals a measured Tx gain of 53. The Tx OP1 of 22.5 dBm enables for linear operation in the full range of the IEEE802.11a standard. The LO_2 leakage as well as the image rejection through the second up-conversion are sufficient and enable for spurious free transmission.

However the poor image rejection and the LO_1 leakage through the first mixing dominate the adjacent and bi-adjacent transmission. The solution to this issue will be the use of a higher performance IF BPF, probably a SAW filter. In addition the power consumption of the transmitter is relatively high.

The receiver sensitivity, which was measured to be −65dBm, is sufficient for this first prototype. Values as low as −85 dBm may be achieved while migrating to the MMIC.
implementation. The receiver gain was measured to be 27 dB and the NF was calculated to be less than 6 dB.

The HF material Rogers 4350 and the process used were reliable and will be strong candidates for future RF prototypes. However LTCC or LCP materials will probably be the future choices for this specific application. In addition, although the thickness of the board does not seem to affect the operation, a thicker board (>10 mils) might provide a more reliable future solution.

Finally, during the troubleshooting stage of the project the major issue was some parasitic oscillations that occurred due to parasitic loading of the active devices. Efficient solutions were provided incorporating off chip components.

4.2 Future Work

This work is meant to be the first stage of the final goal of the implementation of a highly integrated transceiver system including passive devices (antennas, filters) by incorporating state-of-the-art packaging approaches as well as introducing advanced architectural solutions like direct conversion.

In parallel, issues that have to do with system level prototyping have to be addressed like system level characterization through EVM and PER measurements, development of mixed signal testbed (Modem / Transceiver), EMI issues that will be more important as the compactness of the module increases, parasitic oscillations that occur due to loading effect of active devices and optimization of specific RF functions in respect to the overall
system performance (i.e. select better IF BPF to cancel the unwanted image, possibly a SAW filter).

Briefly the future work regarding this project will have to do with

Upgrading current transceiver module focusing on:
- IF_image and LO_1 (816MHz) cancellation incorporating SAW filter
- More Compact Module Implementation
- EM Isolation (supplies at the bottom layer etc.)

While Targeting at:
- Dual band IEEE 802.11a/b. Functionality.
- MMIC implementation
- LTCC/organic materials incorporating multilayer design (interconnects, cavities, 3D passives etc.)

The next figure demonstrates the evolution of the current MIC prototype to a highly integrated solution with increased functionality.

![Figure 38. Future Plan](image)
Appendix 1

Photos of Transmitter, Receiver Modules and Test Setup

Figure 39. Transmitter Test Setup

Figure 40. Receiver Test Setup
References


