DIFFERENT ALGORITHMS FOR VLSI IMPLEMENTATION OF OFDM

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ABSTRACT: *OFDM is a multi-carrier system where data bits are encoded to multiple sub-carriers, while being sent simultaneously. This results in the optimal usage of bandwidth. A set of orthogonal sub-carriers together forms an OFDM symbol. To avoid ISI due to multi-path, successive OFDM symbols are separated by guard band. This makes the OFDM system resistant to multi-path effects. Although OFDM in theory has been in existence for a long time, recent developments in DSP and VLSI technologies have made it a feasible option. Many wired and wireless standards like DVBT, DAB, xDSL and 802.11a have adopted OFDM. This paper first lists various approaches to implement an OFDM system. It then describes the VLSI implementation of OFDM in details. Specifically the 802.11a OFDM system has been considered in this paper. However, the same considerations would be helpful in implementing any OFDM system in VLSI.*

I. INTRODUCTION

In older multi-channel systems using FDM, the total available bandwidth is divided into N non-overlapping frequency sub-channels Each sub-channel is modulated with a separate symbol stream and the N sub-channels are frequency multiplexed. Even though the prevention of spectral overlapping of sub-carriers reduces (or eliminates) Interchannel Interference, this leads to an inefficient use of spectrum. The guard bands on either side of each sub-channel is a waste of precious bandwidth. To overcome the problem of bandwidth wastage, we can instead use N overlapping (but orthogonal) subcarriers, each carrying a baud rate of 1/T and spaced 1/T apart. Because of the frequency spacing selected, the sub-carriers are all mathematically orthogonal to each other. This permits the proper demodulation of the symbol streams without the requirement of non overlapping spectra.

Another way of specifying the sub-carrier orthogonality condition is to require that each sub-carrier have exactly integer number of cycles in the interval T. It can be shown that the modulation of these orthogonal sub-carriers can be represented as an Inverse Fourier Transform. Alternatively, one may use a DFT operation followed by low-pass filtering to generate the OFDM signal. The details of this method are explained in the next section. It must be noted that OFDM can be used either as a modulation or a multiplexing technique. Multi-Carrier Modulation is a technique for data-transmission by dividing a high-bit rate stream is several parallel low bit-rate data streams and using these low bit-rate data streams to modulate several carriers. Multi-Carrier Transmission has a lot of useful properties such as delay-spread tolerance and spectrum efficiency that encourage their use in unmetered broadband communications. The frequencies used in OFDM system are orthogonal. Neighbouring frequencies with overlapping spectrum can therefore be used. This property is shown in the figure where f1, f2 and f3 orthogonal. This results inefficient usage of BW. The OFDM is therefore able to provide higher data rate for the same BW.

A. OFDM with transceiver

OFDM is a multi-carrier system where data bits are encoded to multiple sub-carriers. Unlike single carrier systems, all the frequencies are sent simultaneously in time. OFDM offers several advantages over single carrier system like better multi-path effect immunity, simpler channel equalization and relaxed timing acquisition constraints. But it is more susceptible to local frequency offset and radio front-end non-linearity. The frequencies used in OFDM system are orthogonal. Neighboring frequencies with overlapping spectrum can therefore be used. This property is shown in the figure where f1, f2 and f3 orthogonal. This results in efficient usage of BW. The OFDM is therefore able to provide higher data rate for the same BW.

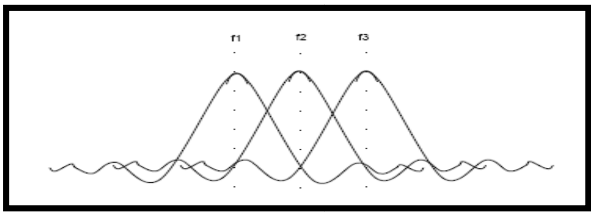

Fig. 1. Frequencies used in OFDM

Each sub-carrier in an OFDM system is modulated in amplitude and phase by the data bits. Depending on the kind of modulation technique that is being used, one or more bits are used to modulate each sub-carrier. Modulation techniques typically used are BPSK, QPSK, 16QAM, 64QAM etc. The process of combining different sub-carriers to form a composite time-domain signal is achieved using Fast Fourier transform. Different coding schemes like block coding, convolution coding or both are used to achieve better performance in low SNR conditions. Interleaving is done which involves assigning adjacent data bits to non-adjacent bits to avoid burst errors under highly selective fading.

B. Types of OFDM

1. C-OFDM- Coded OFDM Digital Audio Broadcasting (DAB) Digital Video Broadcasting (DVB-T) COFDM offers real benefit in the presence of isolated narrow band interfering signals
2. Multiple Input, Multiple Output OFDM (MIMO-OFDM)- Developed by Io span Wireless Uses multiple antennas to transmit and receive radio signals S patial multiplexing.
3. V-OFDM- Vector OFDM Developed by CISCO Increases subscriber coverage Lowers the cost of provisioning and deploying infrastructure Employs both frequency and spatial diversity Creates a robust processing technique for multi-path fading and narrow band interference.
4. W-OFDM- Wideband OFDM Invented by Wi-LAN Large spacing between carriers. It has advantages of optimal performance against Multi-path - Less sensitive to carrier offset -Optimal power efficiency of the transmitter amplifier - More immune against fading.
5. Flash-OFDM- Fast-hopped OFDM Wide-bandspread-spectrum technology Avoids the compromises inherent in other mobile data systems Capability to work around interfering signals

C. OFDM Implementation Techniques

Following choices are available for implementing an OFDM system-

1. DSP based implementation.
2. DSP based implementation with hardware accelerators.
3. VLSI implementation

VLSI implementation –

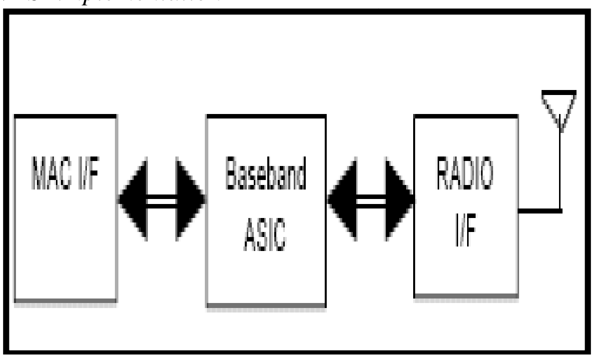

Fig. 5. VLSI Implementation

In the approach shown in Figure 4 the entire functionality is implemented in hardware. Following are the advantages of this approach-

a) Lower gate count compared to DSP+RAM+ROM, hence lower cost

b) Low power consumption

Due to the advantages mentioned above a VLSI based approach was considered for implementation of an 802.11a Baseband. Following sections describe the VLSI based implementation in details.

Design Methodology - The design approach for the OFDM modem is slightly different than a typical ASIC flow. Early in the development cycle, different communication and signal processing algorithms are evaluated for their performance under different conditions like noise, multipath channel and radio non-linearity. Since most of these algorithms are coded in "C" or tools like Matlab, it is important to have a verification mechanism which ensures that the hardware implementation (RTL) is same as the "C" implementation of the algorithm. The flow is shown in the Figure 5.

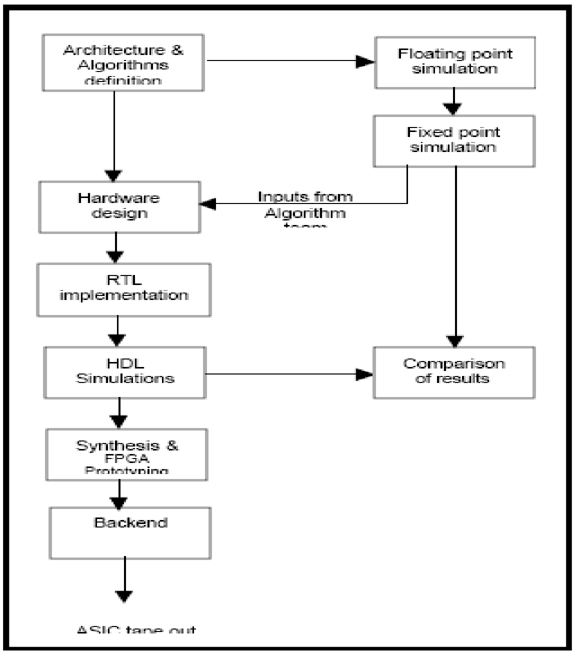

Fig. 5. Design flow for Baseband development

Architecture definition - Following points need to be considered in the architecture definition phase-

a). Specifications of the OFDM transceiver-

- Data rates to be supported
- Range and multipath tolerance
- Indoor/Outdoor applications
- Multi-mode: 802.11a only or 802.11a+HiperLAN/2

b). Design trade-offs –

- Area – Smaller the die size lesser the chip cost
- Power – Low power crucial for battery operated mobile devices
- Ease of implementation – Easy to debug and maintain.

- Customizability – Should be customizable to future standards with variations in OFDM parameters.

D.Algorithm survey & simulation - The simulation at algorithmic level is to determine performance of algorithms for various non-linearities and imperfections. The algorithms are tweaked and fine tuned to get the required performance. The following algorithms/parameters are verified.

a. Channel estimation and compensation for different channel models (Rayleigh, Rician, JTC, Two ray) for different delay spreads.
b. Correlator performance for different delay spreads and different SNR (AWGN model).
c. Frequency estimation algorithm for different SNR and frequency offsets.
d. Compensation for Phase noise and error in Frequency offset estimation.
e. System tolerance for I/Q phase and amplitude imbalance
f. FFT simulation to determine the optimum fixed-point widths
g. Wave shaping filter to get the desired spectrum mask
h. Viterbi BER performance for different SNR and trace back length
i. Determine clipping levels for efficient PA use.
j. Effect of ADC/DAC width on the EVM and optimum ADC/DAC width
k. Receive AGC

Fixed point simulation - One of the decisions needs to be taken early in the design cycle is the format or representation of data. Floating point implementation results in higher hardware costs and additional circuits related with normalizing of numbers. Floating point representation is useful when dealing with data of different ranges. a fixed-point representation will be more efficient. Further in fixed point a choice can be made between signed and 2's complement representation.

Module	Width	Gate count
Complex	12	6K

Simulation setup - The algorithms could be simulated in a variety of tools/languages like SPW, MATLAB, “C” or a mix of these.

SPW has an exhaustive floating point and fixed-point library. SPW also provides feature to plug-in RTL modules and do a co-simulation of SPW system and Verilog. This helps in verifying the RTL implementation of algorithms against the SPW/C implementation

Interface definition- Baseband interfaces with two external modules: MAC and Radio

1) Interface to MAC

a. Baseband should support the following for MAC
b. Should support transfer of data at different rates
c. Transmit and receive control
d. RSSI/CCA indication
e. Register programming for power and frequency control
f. Following options are available for MAC interface:
g. Serial data interface – Clock provided along with data. Clock speed changes for different data rates
h. Varying data width, single speed clock – The number of data lines vary accord ing to the data rate. The clock remains same for all rates.
i. Single clock, Parallel data with ready indication – Clock speed and data width is same for all data rates. Ready signal used to indicate valid data
j. Interfaces like SPI/Micro-wire/JTAG could be used for register programming.

2) Radio

i. I/Q interface

On the transmit side, the complex Baseband signal is sent to the radio unit that first does a Quadrature modulation followed by up-conversion at 5 GHz. On the receive side, following the down-conversion to IF, Quadrature demodulation is done and complex I/Q signal is sent to Baseband. Shown below is the interface

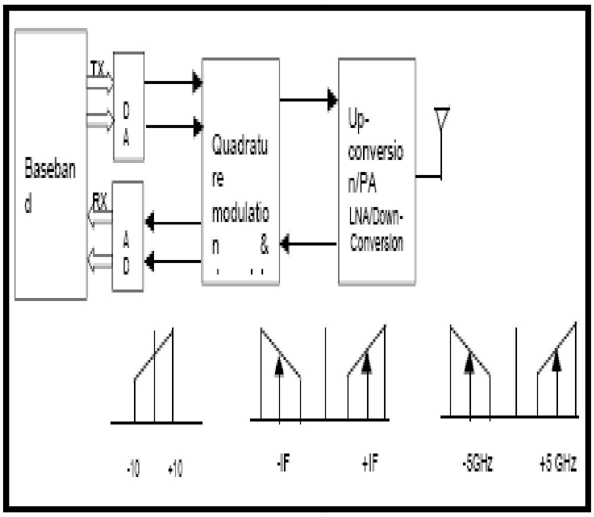

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Fig. 6. I/Q interface to Baseband

ii. IF interface

The Baseband does the Quadrature modulation and demodulation digitally.

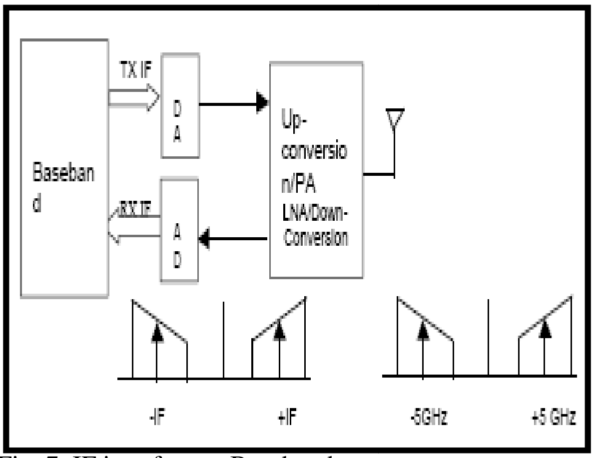


Fig. 7. IF interface to Baseband

Following table gives the Difference between IQ and IF Interface

I/Q interface	IF interface
I/Q Phase/Amplitude imbalance is an issue as the modulation/demodulation is done in analog	No phase imbalance as Quadrature components are produced digitally
Two ADC/DAC channels required for I/Q	Single ADC/DAC channel required
Sampling frequency is lower (>BW)	Higher sampling frequency needed (>2BW)
DC-offset introduced by I/Q ADC has to be compensated	DC-offset introduced at the receiver ADC is not a problem as there is a mixing stage inside

D. Viterbi

The ½ , length 7, convolutionally encoded stream is decoded using a Viterbi decoder.

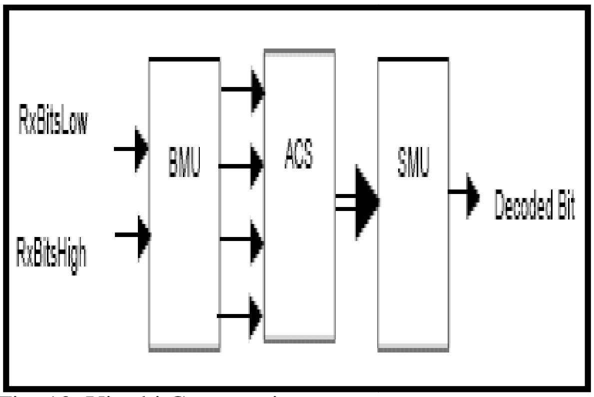


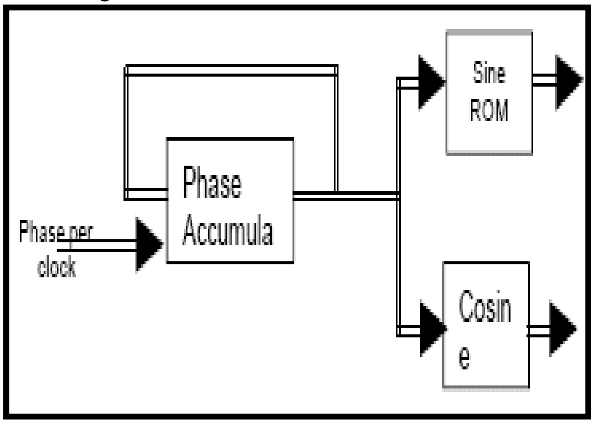
Fig. 10. Viterbi Construction

BMU - Branch metrics computation unit calculates the hamming distances for the incoming pair of codes from four possible codes.

ACS - Add, compare and select unit is used to update the path metric for all the 64 states and to select the predecessor. For each of the 64 states, it adds current path metric and branch metric for both the predecessor states and selects the lower of the two as the new path metric and the predecessor information is passed on to the SMU unitThe width of the Path metric register and the ACS adders and subtractor will change based on whether a soft-decision or a hard-decision viterbi is ued. It also depends on the maximum metrics accumulated by metrics registers before a normalization is done.

SMU - Survivor metrics unit can be implemented by register-exchange or trace back memory method

NCO - NCO (Numerically controlled oscillator) is used for frequency offset correction. NCO generates sine and cosine waves that are mixed with the incoming Baseband signal to correct the frequency error. Various design parameters to be decided in NCO are given below.



Width of phase-accumulator. Will decide on the accuracy or "ppm" of generated waveform .Width of Sine and cosine outputs. Decides Quantization error. But this also decides the size of ROM used to keep the sine and cosine tables. By using the fact the cos (q) = sin (90 - q), a single LUT can be used to generate both sine and cosine values The need for Sine/Cosine ROM can be eliminated by using a CORDIC rotator (if the pipeline delay that the CORDIC introduces can be tolerated)

RTL Simulations - RTL simulations are conducted to achieve the following objectives:

a. Functional verification for all transmit and receive Baseband functions for different data rates is done

b. Necessary models are written to introduce noise and channel effects. Verilog PLI interface can be used to plug-in "C" models if they are available

c. It is verified that different algorithmic blocks are implemented correctly in RTL, the same set of vectors used in algorithm simulations are applied to the RTL system and the outputs are compared. If simulations for algorithms are done in a tool like SPW, then this can be easily be done by importing the RTL blocks in SPW system.

V.CONCLUSIONS

OFDM has several interesting properties that suit its use over Wireless channels and hence many Wireless standards have started to use OFDM for modulation and multiple access. The various methods of generation and demodulation of OFDM and specific issues such as linearity and synchronization were analyzed. Application of OFDM such MC-CDMA, DAB, DVB , WLAN etc, were also discussed in detail.

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