

Theoretical Design and FPGA Implementation of the Baseband Transceiver for the HD Radio FM System

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Abstract— The advance of wireless communications brings in various schemes of wireless digital communication technology. In the field of digital radio broadcasting, several specifications have been proposed, such as Eureka-147 and DRM (Digital Radio Mondiale). These systems require new spectrum assignment, which is a huge cost due to depletion of the available spectrum. Therefore, the IBOC (In-Band On-Channel) system has been developed to work in the same band with the conventional analog radio and broadcasting digital signal simultaneously.

In this paper, the function and algorithm of the HD Radio FM digital radio broadcasting system are discussed. Content includes data format allocation, constellation mapping, and OFDM modulation of the transmitter; timing synchronization, OFDM demodulation, integer and fraction carrier frequency (ICFO & FCFO) estimation, and channel estimation of the receiver. When implementing the system on the FPGA based hardware platform, both the theoretical and the practical aspects have been considered to reach the available hardware resource.

Keywords— HD Radio FM, OFDM, FPGA, IBOC

I. INTRODUCTION

With the advance of wireless communication era, there have been many schemes developed and available nowadays. In the digital radio broadcasting area, several specifications are currently in use, for example, the Eureka-147 in Europe [1]. It is known as DAB (Digital Audio Broadcasting) [2], and has been adopted by many European countries; one of its commercial pioneer adopters is BBC, UK, who went into digital broadcasting in 1995. This system utilizes the OFDM (Orthogonal Frequency Division Multiplexing) technology. Another digital radio broadcasting proposition is called DRM (Digital Radio Mondiale), which is developed in France and operates at the frequencies below 30 MHz [3]. Both of the above two digital radio broadcasting technologies require new spectrum assignment for their proprietary use, which is costly due to the scarce of spectrum availability. Therefore, an IBOC (In-Band On-Channel) system has been developed, which allows the conventional radio and the digital signal to broadcast simultaneously in the same channel allocation.

IBOC has been adopted by U.S. as its digital radio broadcasting standard, which offers two sets of specifications: the HD Radio FM and the HD Radio AM. Their working

frequencies are the same as the conventional FM and AM spectrums, respectively. The HD Radio FM system is a digital radio broadcasting system developed by the iBiquity Digital Corporation, which can simultaneously broadcast analog and digital audio signals in the same FM spectrum. The benefit of adopting this system is that the listeners having digital receivers can receive programs of CD-like quality, and those with the conventional receivers can still receive the same analog programs.

This system specifies two broadcasting modes: the Hybrid mode and the All Digital mode. A station occupies 400 kHz bandwidth to simultaneously transmit its analog and digital signals in the Hybrid mode; while it can utilize the whole 400 kHz bandwidth to transmit the pure digital signal in the All Digital mode [4]. Since this system is restrained by itself from the analog FM station spectrum allocation, it has less bandwidth to transmit the digital signal in the Hybrid mode, which is 140~200 kHz. In the future when the broadcasting transfers to full digital, the All Digital mode will be applied instead. In this mode the HD Radio FM system utilizes the whole 400 kHz bandwidth in digital transmission; it still occupies lesser bandwidth than other digital radio broadcasting standards. Since the located spectrum is the same as that of the conventional analog FM, the broadcast station does not need to drastically change its equipment, and the listeners does not need to memorize the new station allocation frequency. Due to the spectrum attribution, this system is very suitable in the scarce spectrum environment.

The structure of this paper is as follows: Section II describes the transmitter design based on the system specifications. Section III specifies the receiver design and discusses the algorithms of each receiver module, including its specific function and the simulation results. Section IV presents the implementation of the system on the FPGA hardware platform. Finally, the conclusion is given in Section V.

II. TRANSMITTER DESIGN

A. HD Radio FM System Parameters

The technical document released by iBiquity details the specification of the HD Radio FM. The subcarrier spacing is

363.4 Hz, the cyclic prefix width is 7/128, and the FFT size is 4096, which results in the OFDM symbol duration of 2.764 ms. Among the 400 kHz bandwidth assigned to each station, the central 200 kHz is for analog use only, and the two remaining sidebands of totally 200 kHz are for digital use. The spectrum allocation is shown in Figure 1. The digital signal occupies up to 534 subcarriers. In this paper the spectrum distribution is complied with the Hybrid Mode 1 described by the Spec. There are 10 frequency partitions on each side of the analog FM; each partition consists of 19 OFDM subcarriers, with the combination of 1 reference subcarrier for control/synchronization and 18 subcarriers for digital audio data. Each frame lasts for 1.486 seconds, which consists of 16 blocks and 32 OFDM symbols per block. In addition, the OFDM symbol duration and the cyclic prefix length are also specified in the Spec. as 2.902 milliseconds and 7/128, respectively.

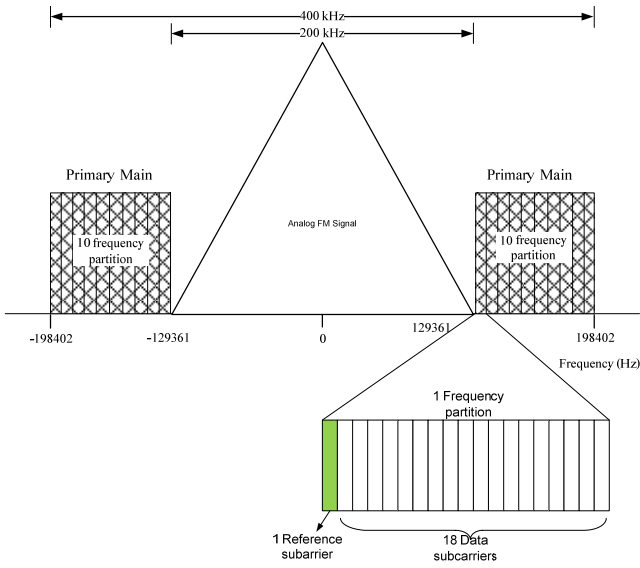


Figure 1. HD Radio FM spectrum

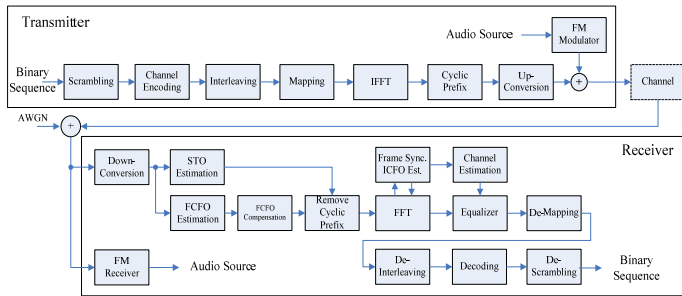


Figure 2. HD Radio FM Transceiver block diagram

B. Transmitter Design

The physical layer architecture of the HD Radio FM system is shown in Figure 2. In this subsection the transmitted block structure defined in the Spec. will be introduced. The data stream first enters the scrambling block, which randomizes the digital data in each logical channel. Afterward, the scrambled

data is encoded by using the convolutional code to add redundancy to the digital data in each logical channel. Later, the channel encoded bits are interleaved in the time and frequency domains to mitigate the effects of burst errors.

The HD Radio FM system utilizes QPSK mapping in data subcarriers and BPSK mapping in reference subcarriers. OFDM subcarrier mapping converts the interleaved data to the frequency domain. Pairs of adjacent columns within an interleaver partition are mapped to the individual complex, QPSK-modulated data subcarriers in the frequency partition.

The Transmission subsystem formats the baseband IBOC FM waveform for transmission through the VHF (Very High Frequency) channel. Functions include the symbol concatenation and the frequency up-conversion. When transmitting the Hybrid or Extended Hybrid waveforms, this function modulates the baseband analog signal before combining it with the digital waveforms. Figure 3 shows the Hybrid transmission subsystem block diagram. The input to this module is a complex, baseband, time-domain OFDM signals, $y(t)$. After implementing the diversity delay T_{dd} , the baseband analog signal $m(t)$ comes out from an analog source. T_{dd} is adjustable to account for the processing delays between the analog and the digital chains. In the IBOC system the analog and digital signals carry the same audio program.

The analog signal $m(t)$ is transmitted by the conventional FM modulation, i.e.,

$$a(t) = \cos(2\pi f_c t + 2\pi f_d \int_{-\infty}^t m(\tau) d\tau) \quad (1)$$

where f_c denotes the FM carrier frequency, $\max_t |m(t)| = 1$, and $f_d = 75$ kHz is the maximum frequency deviation. The FM RF signal is then combined with the digitally-modulated RF OFDM signal, which is passed through the up-conversion, to produce the IBOC FM Hybrid waveform, $s(t)$.

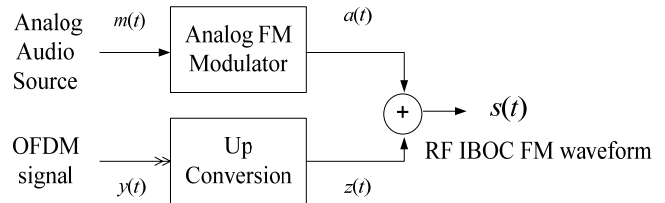


Figure 3. Hybrid Transmission Subsystem Functional Block Diagram

III. RECEIVER DESIGN

A. Signal Synchronization

The CP delay correlation is designed in this system to detect the symbolic timing offset (STO) and the FCFO [7]. The ICFO can be solved by using the control data placed in the reference subcarrier. Since the HD radio FM system adopts the OFDM modulation technique, the cyclic prefix of the OFDM symbol allows the receiver to utilize the periodic feature of signals to estimate the starting point of one symbol. The algorithm is shown in Eq. (2).

$$\begin{aligned}
\Lambda(n) &= \sum_{k=0}^{N_g-m-1} r(n-k) \times r(n-k-N)^* \\
\Lambda'(n) &= 2|\Lambda(n)| - \rho E(n) \\
\rho &\equiv \frac{\sigma_s^2}{\sigma_s^2 + \sigma_n^2} \\
E(n) &\equiv \sum_{k=n}^{n+L-1} |\Lambda(k)|^2 + |\Lambda(k+n)|^2
\end{aligned} \tag{2}$$

where

$r(n)$: Received complex signal	$(.)^*$: Complex conjugate
N : FFT points	N_g : Cyclic prefix length
m : Summation correction	$\rho E(.)$: Energy correction
σ_s^2 : Signal energy	σ_n^2 : Noise energy

The peak value in the autocorrelation indicates the starting point of an OFDM symbol by the high autocorrelation feature in one symbol. Correction functions must be added to compensate for the influence induced by the multipath channel. Nevertheless, it is still difficult to distinguish the peak value from the surrounding noises. Thus, averaging the cumulative autocorrelation values of one symbol length is applied to increase the decision reliability.

There are two main sources of the carrier frequency offset (CFO). First, the relative speed between the transmitter and the receiver results in the Doppler shift. The second source is the mismatch between the oscillator of the transmitter and that of the receiver. The working carrier frequency of the HD Radio FM can reach as high as 108 MHz. The channel model defined in [6] specifies that the receiver is moving at the speed of 141km/h, resulting in 13Hz of Doppler shift. This value is still less than half of the subcarrier spacing. According to the System Transmission Spec. [5], the mismatch of broadcasting station, i.e., the local oscillator (LO) mismatch, is limited to under 1 ppm. Thus, the LO mismatch of the receiver is the main concern of the CFO issue. The following discussion focuses on the local oscillator mismatch. Assume that the LO mismatch is 20 ppm and the carrier frequency is 108MHz, the CFO can reach to 2160 Hz. As a result, the ICFO can cover up to 6 subcarrier spacings.

As discussed above, the carrier frequency offset which affects this system can be divided into the FCFO and the ICFO. The FCFO can be estimated via the CP delay correlation method mentioned above, as shown in Eq. (3).

$$\Delta f_f = \frac{-1}{2\pi} \angle \Lambda \left(\arg \max_n (\Lambda'(n)) \right) \tag{3}$$

As for the ICFO part, it can be resolved by using the evenly spacing reference subcarriers in the frequency domain. According to the Spec., the length of the System Control Data Sequence is 32 bits and one bit is transmitted in one OFDM symbol at a time. In this sequence there exists an 11-bit synchronization pattern which is designed for the purpose of frame synchronization.

Based on this property, the receiver is able to cross-correlate the received subcarriers to the 11-bit synchronized pattern upon receiving the OFDM signal. If a highly correlated subcarrier combination in each 19 subcarriers apart is found, then the position of the reference subcarrier is reached and the ICFO is acquired. The frame and synchronization methodology is shown in Figure 4.

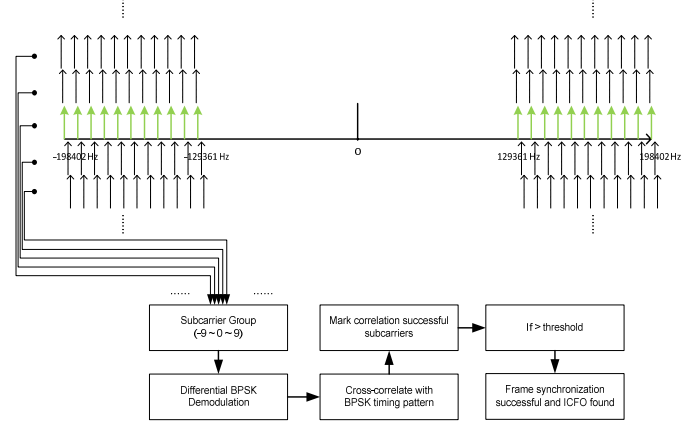


Figure 4. HD Radio FM frame and ICFO synchronization

B. Channel Estimation

In designing of the receiver, attention should be paid to the timing/frequency synchronization as well as the channel effects. In the receiver these harmful effects should be estimated and compensated. The pilot signals, which are located in the reference subcarriers, can be used in the channel estimation.

In each transmission all subcarriers but bit 20 and bit 21 are transmitted the same data in one OFDM symbol. These two bits are transmitted in a predefined order. Upon receiving these two signals, the system control data sequence can be decoded correctly by using the signals' redundancy feature. The decoded signal is then used as the known pilot signal to assist the channel estimation. The channel response of each reference subcarriers is estimated by using the Least Squares (LS) channel estimation method. Then, the channel response of each data subcarrier is estimated by using linear interpolation.

$$H_e(k) = \frac{Y_p(k)}{X_p(k)} \quad k = 0, 1, \dots, N_p - 1 \tag{4}$$

where $Y_p(k)$: Received pilot signal at the k th pilot subcarrier

$X_p(k)$: Transmitted pilot signal at the k th pilot subcarrier

N_p : Number of pilot subcarriers

$$\begin{aligned}
H_e(k) &= H_e(mL + l), \quad 0 \leq l < L \\
&= (H_p(m+1) - H_p(m)) \frac{l}{L} + H_p(m)
\end{aligned} \tag{5}$$

where $\{H_p(k), k = 0, 1, \dots, N_p\}$: The frequency response of the channel at pilot subcarriers L : Number of carriers/ N_p .

TABLE 1. FM BAND CHANNEL MODELS

Ray	CM1* ($f_d = 0.1744$ Hz), CM2** ($f_d = 5.2314$ Hz)		CM3*** ($f_d = 13.0785$ Hz)		CM4**** ($f_d = 5.2314$ Hz)	
	Delay (ms)	Attenu. (dB)	Delay	Attenu.	Delay	Attenu.
1	0.0	2.0	0.0	4.0	0.0	10.0
2	0.2	0.0	0.3	8.0	1.0	4.0
3	0.5	3.0	0.5	0.0	2.5	2.0
4	0.9	4.0	0.9	5.0	3.5	3.0
5	1.2	2.0	1.2	16.0	5.0	4.0
6	1.4	0.0	1.9	18.0	8.0	5.0
7	2.0	3.0	2.1	14.0	12.0	2.0
8	2.4	5.0	2.5	20.0	14.0	8.0
9	3.0	10.0	3.0	25.0	16.0	5.0

*CM1: Channel Model 1, represents the Urban Slow Rayleigh Multipath Profile.

**CM2: Channel Model 2, represents the Urban Fast Rayleigh Multipath Profile.

***CM3: Channel Model 3, represents the Rural Flow Rayleigh Multipath Profile.

****CM4: Channel Model 4, represents the Terrain-Obstructed Fast Rayleigh Multipath Profile.

+ f_d represents the Doppler frequency.

The FM Band Channel Model proposed by EIA (Electronics Industries Association) in 1993[6] is used to the simulations of the proposed channel estimation method. This method can achieve 10^{-4} bit error rate when the convolution code and the interleaver are applied, as shown in the simulation charts below. The response characteristics of all the four channel models are listed in Table 1. The robustness of different coding schemes under these channel models are shown in Figure 5.

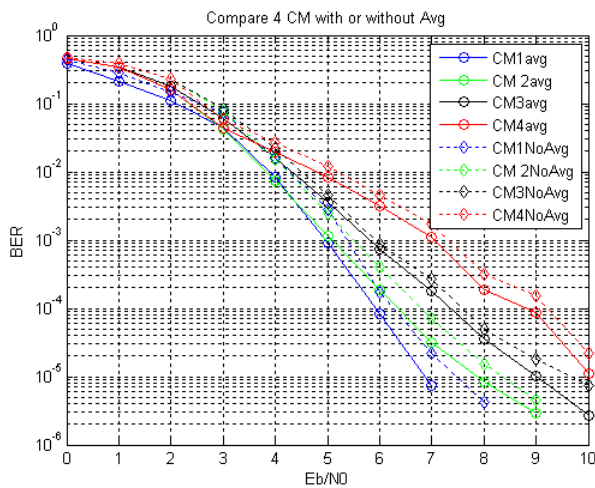


Figure 5. BER performance under FM Band Channel Models

Note that a convolutional code with code rate 2/5 is been implemented in this system. Besides, a three-element sliding window is applied to execute the averaging operation in Figure 5. That is, the final outcome of each symbol in each subcarrier is the weighted sum of the current symbol and the two most adjacent ones, as shown in Figure 5. When

averaging is incorporated with the channel estimation, system performance improves again. The main reason for this benefit is that more pilot data are be used to estimate the corresponding channel response. The averaging process used in this paper is shown in Figure 6.

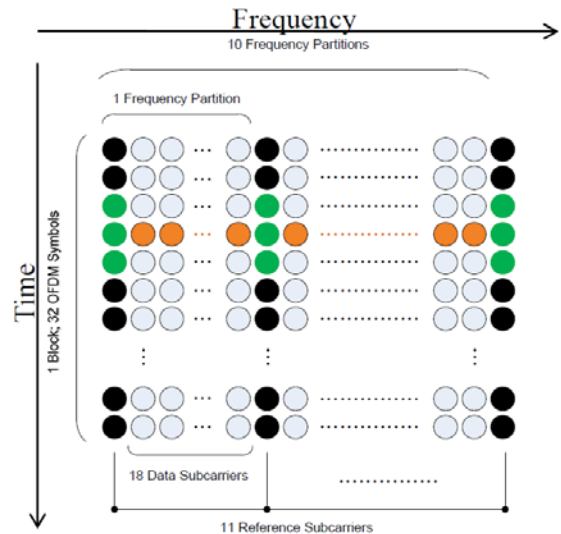


Figure 6. Time domain averaging by using a 3-element sliding window

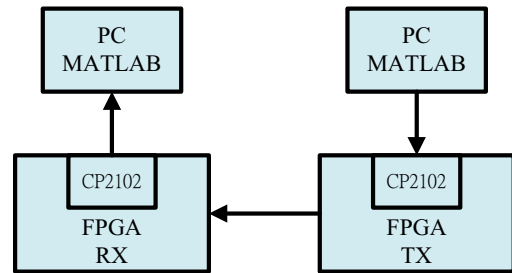


Figure 7. Diagram of the communication interface between the computer and the FPGA

IV. IMPLEMENTATION ON THE FPGA HARDWARE PLATFORM

After careful examination of the parameters defined in the Spec. and the available hardware resources, the following parameters are chosen in the hardware implementation.

FFT size: 2048
CP length: 112
Sampling rate: 781.25 kHz
Subcarrier spacing: 381.5 Hz
Symbol rate: 361.9 Hz
Transmission rate: 104.2 kbps (code rate 2/5)

The built-in CP2102 USB-UART bridging chip on the FPGA board is used as the communication interface between the Board and the computer.

A. Constellation Mapping

The Agilent 89600 Vector Signal Analyzer is used to monitor the QPSK constellation map generated by the transmitter, as shown in Figure 8. It can be seen that all the constellation points are mapped into the four corresponding clusters of QPSK.

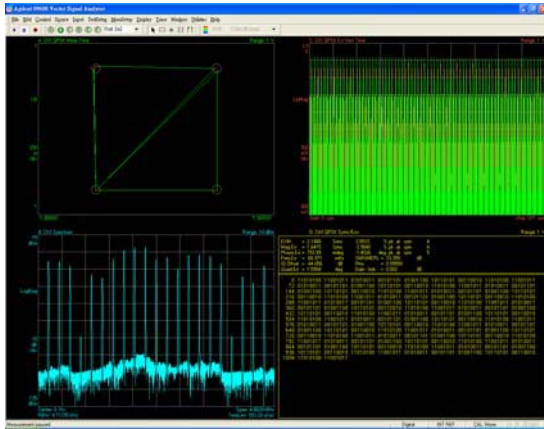


Figure 8. Using the Agilent 89600 Vector Signal Analyzer to monitor the constellation points of the transmitter

B. The Transmitter Spectrum Diagram

The OFDM waveforms generated by the transmitter are fed into the Agilent 89600 Vector Signal Analyzer to analyze its spectrum map. The result is shown in Figure 9. The simulation frequency map generated by MATLAB is shown in Figure 10. It is found these two spectrum distributions are basically similar.

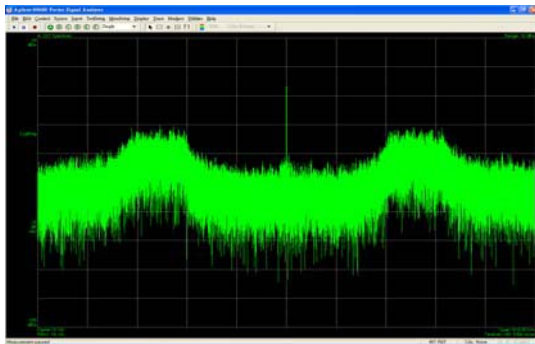


Figure 9. Real transmitting spectrum of the HD Radio FM implementation

This FPGA implementation provides a prototype baseband system which is complied with the HD Radio FM specifications. The synthesis software ISE 9.1.03i is being used to synthesize the transmitter and the receiver. The synthesized gate count of the transmitter is about 1,938,975, while the highest operation clock is 96.375MHz; the synthesized gate count of the receiver is about 1,788,016, while the highest operation clock is 81.264MHz.

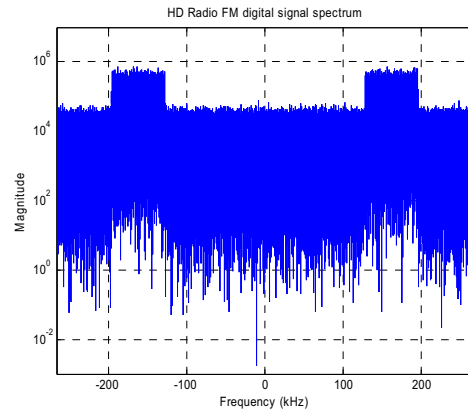


Figure 10. Simulated transmitting spectrum of the HD Radio FM implementation

V. CONCLUSION

In this paper, the HD Radio FM structure and algorithms of its transmitter and receiver are presented. The transmitter design is fully complied with the of HD Radio FM specification. In the receiver algorithms, the timing and frequency synchronization issues are studied and discussed. As for the channel impairments, a channel estimation and compensation algorithm is presented and performed in different channel models. From the simulation results, it can be clearly seen that the system performance can maintain in a descent range under various channel environments. A hardware prototype system is realized on FPGA and a PC platform. The system is capable of processing signals at a fast pace due to the nature of FPGA and also adding flexibility for the future algorithm configuration.

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