All Digital Baseband Frequency Hopping OFDM System

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Abstract— **In this paper, an all digital baseband frequency-hopping orthogonal frequency division multiplexing (OFDM) system based on sampling rate conversion has been proposed. By changing the ratio of sampling rate conversion, the frequency hopping (FH) gain can be configured easily. Comparing with the conventional fixed carrier frequency OFDM, this system can achieve frequency diversity gain; while comparing with the analog frequency hopping OFDM (FH-OFDM) emerging recently, our proposed system has more flexibility, lower complexity, and better acquisition and synchronization performance for digital receiver. Superimposed sequence has been employed as the training sequence for synchronization and channel estimation, unlike preamble sequence inserted in time domain and pilot subcarriers inserted in frequency domain, this scheme can improve spectrum efficiency at the cost of a little bit SNR loss, moreover, it can perform joint FH pattern acquisition and frame synchronization for the proposed system simultaneously. Simulation results show that the proposed system has better performance than non-FH system, and achieves good SER performance over additive white Gaussian noise (AWGN) channels as well as multipath channels. The power ratio of superimposed signal to information signal provides a way of trade-off between SNR loss and synchronization performance. Changing the power ratio also affects the system performance.**

Keywords-OFDM ; frequency hopping; synchronization; superimposed training

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is one of promising techniques for high-data rate transmission over frequency selective fading channels, and has been adopted for various standards, such as ADSL, WLAN, DAB, DVB-T. OFDM can easily overcome inter-symbol-interference (ISI) in severe delay spread environments [1].

Frequency Hopping (FH) is one of two basic spread spectrum techniques. It can obtain frequency diversity gain in frequency selective fading channels, and has low probability of interception (LPI) [2]. It has been widely used in military communication for its anti-jam performance, and also been employed in some wireless standards such as GSM, Bluetooth for its interference resistance.

Recently, the combination of OFDM and frequency hopping, called FH-OFDM, has attracted significant attention due to their excellent spectral efficiency and robustness to multipath effect as well as the benefits of frequency diversity and frequency hopping gain. There are two types of combinations typically. One is RF carrier frequency hopping OFDM, which has been used in one of Ultra-Wideband (UWB) standard called multi-band OFDM (MB-OFDM) [3], the other is subcarrier frequency hopping, such as Flash-OFDM [4], and has been employed in orthogonal frequency division multiple access, called FH-OFDMA [5].

When investigating the RF carrier frequency OFDM as shown in Fig. 1, the following shortcomings can be observed. First, RF carrier frequency hopping is hard to be implemented with digital integrated circuit, while the system complexity and cost will be increased for analog circuit to meet stringent synchronization demand, especially for high speed frequency synthesizer. Second, the acquisition of frequency hopping pattern is not fast enough and difficult to track once lost for the RF analog processing. Last but not least, it is difficult to maintain phase coherence in the synthesis of the carrier frequencies used in the hopping pattern, so FSK modulation with non-coherent detection is usually employed [2], which limits the use of other high efficiency modulation techniques such as PSK, QAM, and the system throughput stays at very low level.

In this paper, we propose an all digital baseband frequency hopping OFDM system called baseband FH-OFDM (BB-FH-OFDM), while the RF carrier frequency hopping OFDM system is called RF-FH-OFDM. Sampling rate conversion and digital direct conversion is employed to achieve flexible baseband frequency hopping. BB-FH-OFDM has three main features compared with RF-FH-OFDM. Firstly, all digital baseband processing reduces the complexity that appears in RF-FH-OFDM system; Secondly, baseband processing makes it easier to reconfigure the frequency hopping gain by changing the sampling rate conversion ratio; Finally, it can support rapid and joint frame synchronization and frequency hopping pattern acquisition and achieve high throughput when high efficiency modulation techniques, such as QPSK or QAM, are adopted.

The remainder of this paper is organized as follows. Section II presents the system model for the proposed baseband

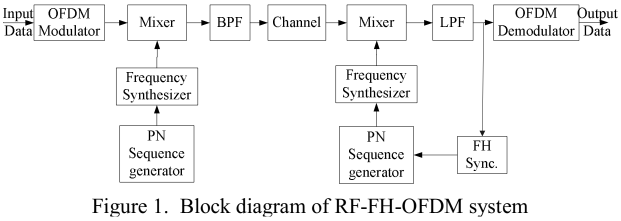


Figure 1. Block diagram of RF-FH-OFDM system

frequency hopping OFDM system. In section III, simulation results are given. Conclusions are made in section IV.

II. SYSTEM MODEL FOR BB-FH-OFDM

A. *BB-FH-OFDM Transmitter*

Fig. 2 shows the block diagram of BB-FH-OFDM transmitter. The input data after coding and mapping are sent into OFDM modulator and formed the data block containing relevant system information. Then they are fed into baseband frequency hopping modulator, which is described in detail later. The baseband frequency hopping signal will be combined with the superimposed training sequence arithmetically (to be explained in subsection B) before it comes to the Digital-to-Analog Converter (DAC). After DAC, the signal will be modulated with the fixed RF carrier frequency at the mixer (here the RF carrier frequency can also be slow frequency hopping in the case of combined system to achieve additional processing gain and higher frequency-hopping bandwidth). The frequency-hopped RF signal will be transmitted after band-pass filtering (BPF) via RF frontend.

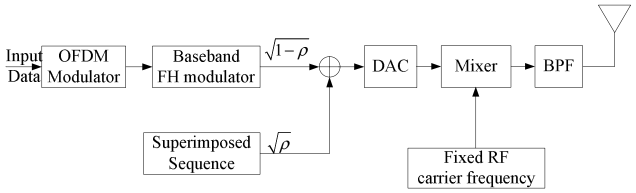


Figure 2. Block diagram of BB-FH-OFDM transmitter

The key part of the transmitter is the baseband frequency hopping modulator, which is illustrated in Fig. 3. The baseband modulated signal $x[n]$ is sent into low sampling rate SRRC block for pulse shaping, and the low sampling clock is configurable for different frequency-hopping gain. Then the signal is upsampled by factor *M* and filtered by a well-designed fixed bandwidth anti-image lowpass filter (LPF), such as Nyquist filter [6]. After upsampling and filtering, the signal $x_u[n]$ then comes to a complex multiplier, and multiplies with a baseband FH complex sinusoid signal $e^{j\omega_i n}$ generated by baseband FH carrier synthesizer according to frequency hopping pattern. Finally a baseband FH signal $x_i[n]$ is obtained. By changing the upsampling factor *M*, the baseband frequency hopping gain can be changed easily.

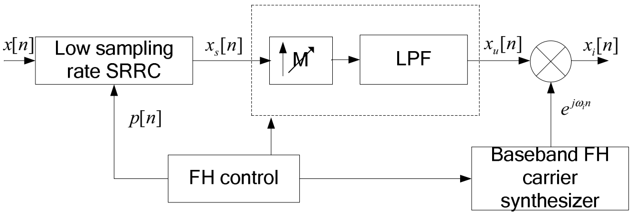


Figure 3. Baseband frequency hopping modulator

Fig. 4 gives the representation of the baseband frequency hopping signal. Let $x[n]$ denotes the input modulated signal, after oversampled by a low sampling rate and filtered by a squared root raised cosine (SRRC) filter, the output $x_s[n]$ can be expressed as

$$x_s[n] = \sum_{k=-\infty}^{\infty} x[k]p[n-Lk] \qquad (1)$$

where $p[n]$ is the *L*-times SRRC sampling pulse, L is the upsampling factor for low sampling rate. Then the signal is further upsampled with a configurable factor *M.* The high sampling rate digital baseband modulated signal $x_u[n]$ turns into

$$x_u[n] = \sum_{k=-\infty}^{\infty} x[k]p[n-LMk] \qquad (2)$$

The baseband carrier synthesizer generates carrier frequencies according to the frequency hopping pattern which is controlled by the FH controller. Let ω_i represent the *i* th baseband frequency hopping carrier frequency, then the *i* th baseband frequency hopping modulated signal can be expressed as:

$$x_i[n] = x_u[n]e^{j\omega_i n} \qquad (3)$$

B. *Frame structure*

We employ superimposed sequence as the training sequence to perform synchronization and channel estimation for BB-FH-OFDM system [7].

The transmitting signal sequences are calculated as follow:

$$s[n] = \sqrt{1-\rho}\cdot d[n] + \sqrt{\rho}\cdot c[n] \qquad (4)$$

where $d[n]$ represents the transmitted data which can be

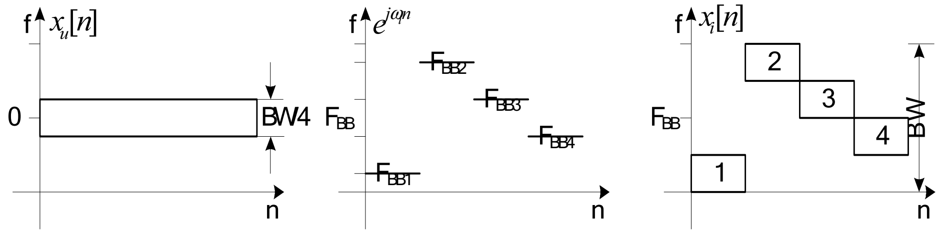


Figure 4. Representation of baseband frequency hopping signal

expressed as

$$d[n] = \sum_{i=-\infty}^{\infty} x_i[n] \qquad (5)$$

$c[n]$ represents the superimposed training sequence, $s[n]$ represents the combined sequence. While ρ is the training sequence power factor which represents the ratio of training sequence power to the combined sequence power and is given by

$$\rho = \frac{\sigma_c^2}{\sigma_c^2 + \sigma_d^2} = \frac{\sigma_c^2}{\sigma_s^2} \qquad (6)$$

where σ_c^2 , σ_d^2 , and σ_s^2 denote the variance of training sequence, data, and the combined signal, respectively. ρ is called as training sequence power factor. So the signal to noise ratio (SNR) has become into

$$SNR_{data} = \frac{\sigma_d^2}{\sigma_n^2} = \frac{(1-\rho)\cdot\sigma_s^2}{\sigma_n^2} = (1-\rho)\cdot SNR \qquad (7)$$

where σ_n^2 denotes the variance of noise, SNR_{data} and SNR represent the signal to noise ratio of combined signal and data only signal, respectively.

Fig. 5 shows the combination of data and training sequence. Superimposed sequences are added arithmetically with the data block to form the data frame without occupying extra time slot or frequency resource unlike the time-division or frequency-division training sequence, so it gains higher spectrum efficiency at the cost of extra power consumption and a little bit SNR loss.

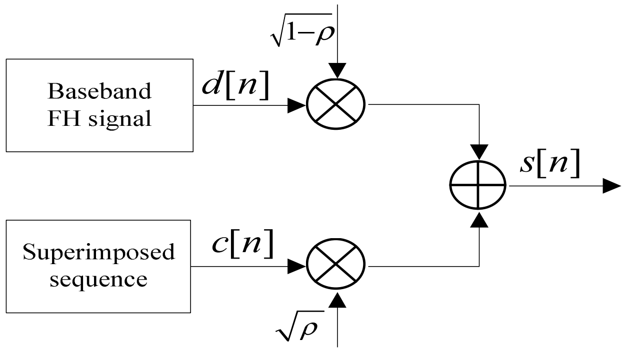


Figure 5. Superimposed sequence combined with baseband FH signal

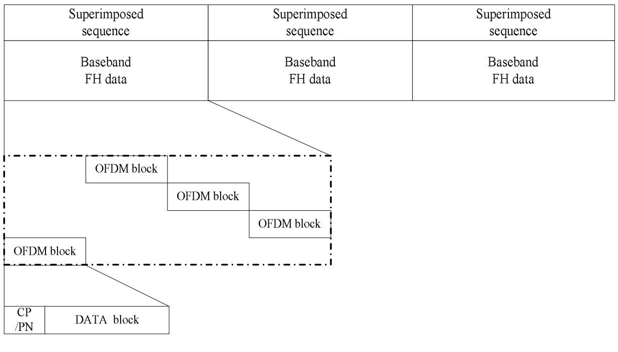


Figure 6. Frame structure of BB-FH-OFDM

Fig. 6 illustrates the frame structure of BB-FH-OFDM system. Each superimposed sequence relates to one frequency hopping pattern, which contains integral OFDM blocks. Each OFDM block consists of one data block and one guard interval (GI). Cyclic prefix (CP) or PN sequence can be used as GI padding.

C. *Multipath channel*

In this paper, we take the American ATSC measurement channel as the multipath channel, whose static channel impulse response can be expressed as

$$\begin{aligned} h[n] = {} & 0.1\delta[n+16] + \delta[n] + 0.1\delta[n-2] \\ & + 0.3162\delta[n-16] + 0.1995\delta[n-52] + 0.1295\delta[n-168] \end{aligned} \qquad (8)$$

where $\delta[n]$ is Dirac function that indicates the impulse response at sampling time n . The channel is distributed equidistantly in the symbol cycle.

D. *BB-FH-OFDM Receiver*

Fig. 7 presents the block diagram of BB-FH-OFDM receiver. The down-converted signal mixed with a fixed local oscillator frequency passes the LPF firstly, then after ADC, it is split by a data/superimposed sequence splitter unit (usually by correlation methods). Superimposed sequence is employed to perform joint frame synchronization and FH pattern synchronization. This can support the baseband dehopping through the FH control unit. Superimposed sequence can also acts as the training sequence for channel estimation. With the equalization the dehopped signal can be demodulated by OFDM demodulator. Unlike preamble sequence inserted in time domain and pilot subcarriers inserted in frequency domain, superimposed sequence method improves spectrum efficiency at the cost of slight SNR loss, moreover, it can support high hopping rate according to [8]. Due to baseband processing, we can perform joint synchronization of frequency hopping pattern and OFDM block to realize faster acquisition and synchronization. The detailed techniques will be investigated in succeeding papers.

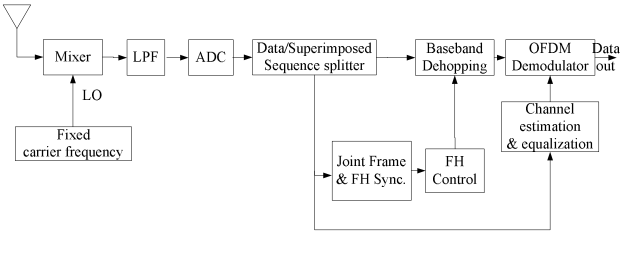
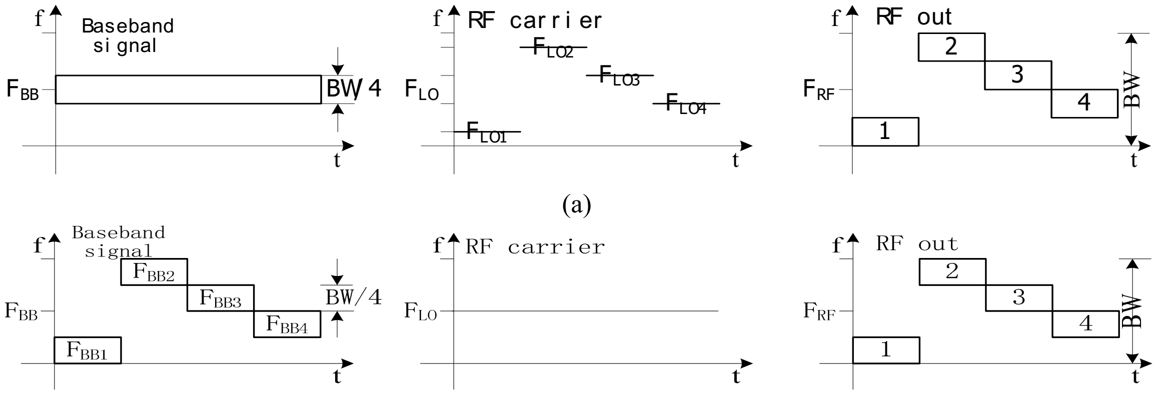


Figure 7. Block diagram of BB-FH-OFDM receiver



(a)

(b)

Figure 8. Representation of RF-FH-OFDM (a) and BB-FH-OFDM (b) signal

E. Comparison with RF-FH-OFDM system

Compared with RF-FH-OFDM system, BB-FH-OFDM has some advantages, such as flexible and easy to implement, fast synchronization, high FH rate, and reconfigurable. It can be accomplished through all digital baseband processing. Fig. 8(a) shows the frequency spectrum representation of conventional RF-FH-OFDM signal, it has fixed baseband signal and hopping RF carrier, then obtains the hopping RF out signal; Fig. 8(b) shows the frequency spectrum representation of proposed baseband frequency hopping OFDM signal, it has hopping baseband signal and fixed (also can be slow-hopping) RF carrier, then obtains the equivalent hopping RF out signal as that in RF-FH-OFDM. However, the two systems have significant differences indeed at least in the following three aspects: Firstly, all digital baseband processing in the BB-FH-OFDM system reduces the hardware complexity comparing with RF-FH-OFDM; Secondly, baseband processing makes it easier to reconfigure the frequency hopping gain by changing the sampling rate conversion ratio; Finally, BB-FH-OFDM can support rapid and joint synchronization of frequency hopping pattern and data frame, while RF-FH-OFDM needs much long time for acquisition and synchronization. With these features, BB-FH-OFDM will be extended to wide potential applications such as cognitive radio, 4G, and WiMAX for flexible multiple-access. If operating with the RF carrier slow frequency hopping (SFH) simultaneously, it can also play an important role for wireless systems under interference channels.

III. SIMULATION RESULTS

In this section, simulations are presented to verify the performance of the proposed BB-FH-OFDM. The main simulation parameters are shown in Table I. The channel has been described in Part II, subsection C. Assumed that the system is uncoded, and the receiver has perfect synchronization but without channel estimation and equalization.

TABLE I. SIMULATION PARAMETERS

Number of hopping frequencies M	8
Symbol rate Rs	0.9Msymbol/s
Sampling rate Fs	28.8MHz
Hopping rate	11.25khops/s
Modulation	QPSK
Number of subcarriers N	64
Length of GI L	16
Training sequence power factor ρ	0,0.05,0.1,0.2

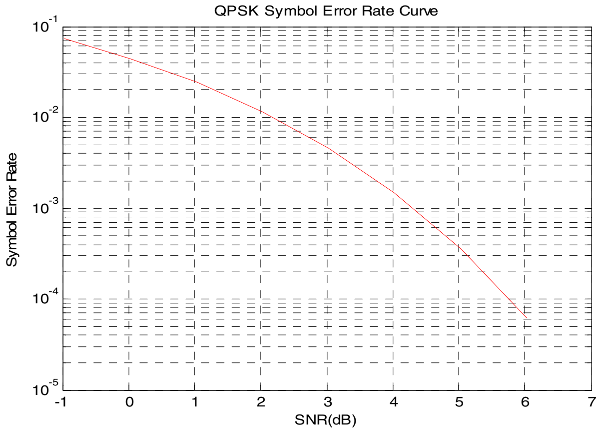


Figure 9. Non-FH single carrier system SER vs SNR

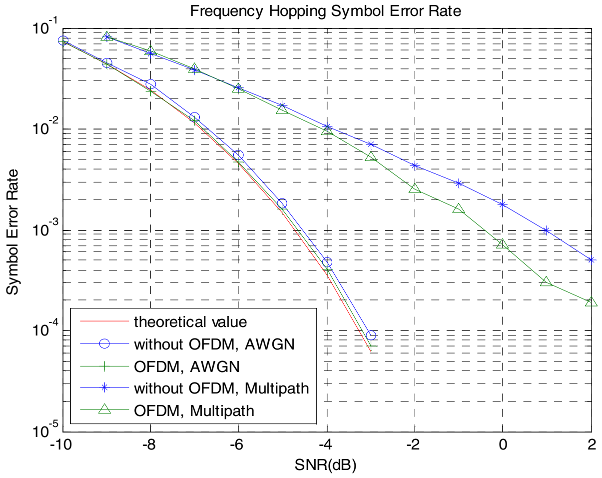


Figure 10. BB-FH with and without OFDM SER vs SNR under AWGN channels and multipath channels

Fig. 9 gives the theoretical SER performance of a non-FH standard single carrier QPSK system as a reference. Fig. 10 illustrates the average SER of BB-FH-OFDM under AWGN and multipath channels. Both are under the condition of $\rho = 0$ (without the superimposed sequence). Compared with Fig. 9 we can find that the theoretical value of Fig. 10 has about 9dB SNR gain, this is approximately equal to the FH gain whose theoretical value is $10\lg M = 9.0309$ dB.

Fig. 10 illustrates the SER performance FH system over AWGN channels and multipath channels as expressed in (8). Under AWGN channels, the performance of BB-FH-OFDM is very close to that of theoretical value and without OFDM the performance has a slight degradation. While under multipath channels, for both FH systems, no matter with or without OFDM, cause severe deterioration, about 5~6dB under 10^{-3} SER. This is mainly due to the multipath effect and no channel estimation and equalization for the receiver. However, with OFDM, the FH system performance still has 1~2dB gain improvement than that of system without OFDM when SER is lower than 10^{-3}, that is to say, BB-FH-OFDM has better performance than conventional FH systems under multipath environment.

Fig. 11 shows the SER performance of BB-FH-OFDM with different power ratio ρ of superimposed sequence. As ρ increasing from 0.05 to 0.20 under SER of 6×10^{-4}, the SNR loss is about 1dB. This value conforms to (7).

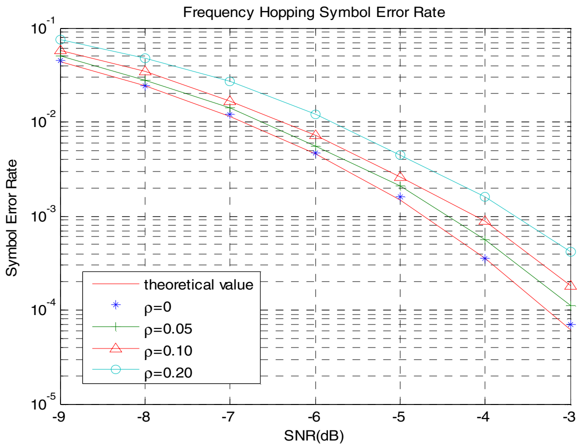


Figure 11. SER performance with different training sequence power ratio

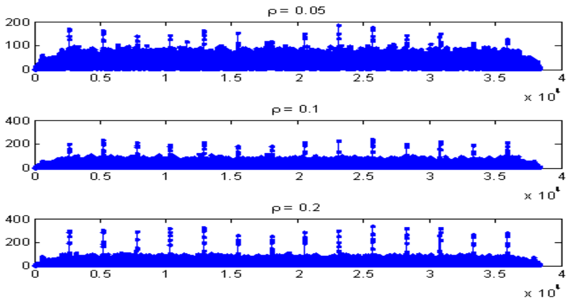


Figure 12. Correlation peak between local PN sequence and received PN sequence with different power ratio

Fig. 12 presents the synchronization performance performed by superimposed PN sequence under different power ratio. As ρ increasing from 0.05 to 0.2, the correlation peaks against noise are becoming more clear, so the synchronization performance of the receiver will get better.

From Fig. 11 to Fig. 12 we can find that the power ratio of superimposed signal to information signal provides a way of trade-off between SNR loss and synchronization performance. While the synchronization algorithm will be investigated in succeeding papers later.

IV. CONCLUSIONS

In this paper, we present a novel all digital baseband frequency hopping OFDM system, whose potential application may be expanded to cognitive radio, 4G, and WiMAX for multiple access or combating frequency selective fading. It has the features of low complexity, high flexibility and good SER performance over multipath channels. Simulation results demonstrate that BB-FH-OFDM has better SER performance than conventional non-FH single carrier as well as FH single carrier systems under both AWGN channels and multipath channels. Superimposed sequence with different power ratio over signal provides a trade-off between the loss of SNR and synchronization performance.

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