Efficient Implementation of Multicarrier Frequency Hopping Receiver via Polyphase Channelizer

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***Abstract*—The authors present an efficient signal processing algorithm for implementing a full digital multicarrier frequency hopping (MCFH) receiver. FH radios were, at the beginning, developed for military applications because of their characteristic of being highly jamming resistant. The proposed receiver architecture is based on non-maximally decimated filter bank (NMDFB) also known as polyphase channelizer which enables the functionality of simultaneously de-hopping multiple frequency-hopped spread spectrum (FHSS) signals at reduced sample rate. This feature greatly reduces the implementation cost as well as power consumption of a traditional analog based de-hopping circuit. Furthermore, the NMDFB based de-hopping circuit supports fast acquisition by means of conducting parallel search, which gives a much shortened synchronization time. After de-hopping, second tier NMDFBs are used as a bank of band pass filters (BPFs) to perform non coherent demodulation of the underlying M-ary frequency shift keying (MFSK) signal.**

Index Terms: frequency hopping, anti-jamming, multicarrier frequency hopping, non-maximally decimated filter bank.

I. Introduction

Frequency-hopped spread spectrum (FHSS) transmits radio signals by switching their carrier frequencies among many possible frequencies that are determined by a pseudorandom noise (PN) sequence known to both transmitter and receiver. Because of its excellent anti-jamming and anti-interception capabilities [1], [2], FHSS communication systems are commonly found in many military radio applications. Meanwhile, it is also being used widely in a number of civilian applications, i.e. Bluetooth piconet (IEEE 802.15.1) [3], and wireless local area network (IEEE 802.11) [4].

The transmission diversity offers enhanced level of jammer protection as well as resistance to fading channels. In an FHSS system, the frequency diversity can be achieved via fast frequency hopping (FFH), where the chip / hop duration is shorter than the symbol duration [5, 6]. Meanwhile, as stated in Sec 12.7.4 of [5], only the FFH can handle the channels with large delay spread (channel delay spread is more than one chip period) when compared to direct sequence spread spectrum (DSSS) systems. However, the implementation of FFH systems poses great practical challenges due to the following two major issues. The FFH requires building high speed circuit for hopping and de-hopping blocks. This is often limited by the available hardware's maximum on-board clock frequency and its jitter performance. The second issue is the PN sequence synchronization, which becomes more difficult to acquire and track as the hopping frequency increases.

The multicarrier frequency hopping (MCFH) system [7, 8, 9] on the other hand is a capable alternative for FFH system. The idea was first seen in [8], where a MCFH prototype is proposed and probability of error was found in the presence of jammer. Authors in [7] showed that MCFH is superior to FFH when the channel delay spread is large. Also, the diversity gain for MCFH is larger than that of an FFH system. It has also been found that FFH has better performance only when the channel varies rapidly. Authors in [9] have studied the opportunity of using MCFH system for conducting multiple access communication.

Authors in [10] have proposed a full digital frequency hopping system based on polyphase channelizers. It has also been pointed out in [10] that the polyphase channelizer based de-hopping circuit enables parallel search of PN sequence, which is viewed as an optimal solution [5] that significantly reduces the acquisition time. A detailed discussion of non-maximally decimated filter bank (NMDFB) or polyphase channelizers is covered in [11].

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The authors in this paper focus on exploring the efficient signal processing algorithm for implementing a MCFH system. The proposed algorithm is based on NMDFB [11] and polyphase analysis channelizer (PAC) is used throughout our implementation. The novelty of this paper is to provide new receiver architecture for MCFH. The rest of the paper is organized as: Section II reviews FHSS and MCFH; Section III introduces NMDFB based MCFH receiver; Section IV shows the simulation result; Section V compares the workload of the proposed receiver with the legacy receiver; Section VI draws the conclusion.

II. BACKGROUND ON FHSS AND MCFH

The block diagram of the traditional FHSS transmitter (Tx) and receiver (Rx) [5] is shown in Fig .1 and Fig. 2 respectively. The FHSS Tx is a MFSK modulator followed by a frequency hopper whose center frequency is directed by the PN sequence. The FHSS received signal is first de-hopped and then sent to MFSK demodulator. For simplifying the implementation, non-coherent FSK detection in band pass filter (BPF) form [5] is used throughout this paper. The square law envelope detector followed by each BPF is identical with [7]. In order to achieve frequency diversity and combat channel delay spread, FFH mode must be used. This implies added processing cost for the hopping / de-hopping circuit as well as for the PN sequence synchronizer.

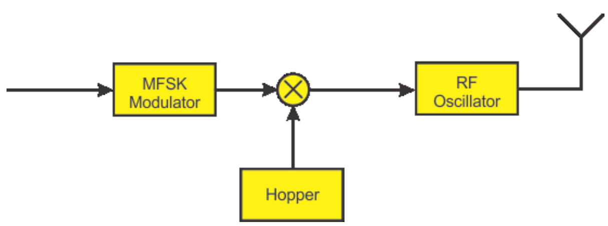

Figure 1. FHSS Transmitter

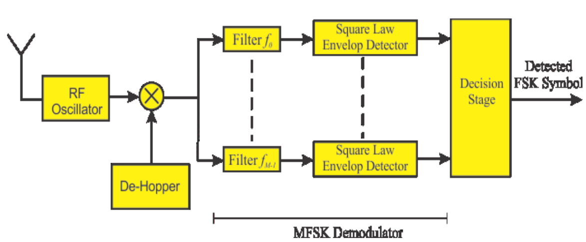

Figure 2. FHSS Receiver

The Tx and Rx block diagrams of an MCFH system [7, 8, 9] are shown in Fig. 3 and Fig. 4 respectively. The MCFH Tx has L-hopping circuits, which translates the same MFSK signal onto different carrier frequency locations. Since multiple hoppers are used for the same MFSK signal, the hopping interval (chip duration) can be set equal to the MFSK symbol duration while still enjoying the frequency diversity. In this paper, the hopping duration is set equal to the MFSK symbol duration. It should be noted that if the selected PN sequences for the L hoppers are mutually orthogonal, then the same MFSK symbol is transmitted L times simultaneously and always appear on different carrier frequencies. Alternatively, if the selected PN sequences are not orthogonal, the symbol "collision" will occur. However, since the L hoppers are hopping the same input signal, the "collision" is permitted. Of course, whenever collision happens, the affected symbol cannot enjoy frequency diversity.

The MCFH Rx, Fig. 4, has L independent de-hopping circuits each synchronized to a set of PN sequences used in the Tx. Followed by each de-hopper, an independent standard MFSK demodulator (as shown in Fig. 2) is needed to demodulate the MFSK signal. The L-branch demodulated MFSK signals are combined based on the optimal combining rule defined in [7] (summation of the MFSK symbol energy across L branches). The decision device then selects the symbol with the largest combined energy across the M BPF outputs and declares the decision based on the BPF's center frequency.

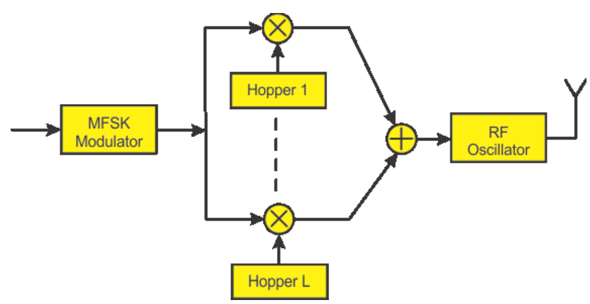

Figure 3. MCFH Transmitter

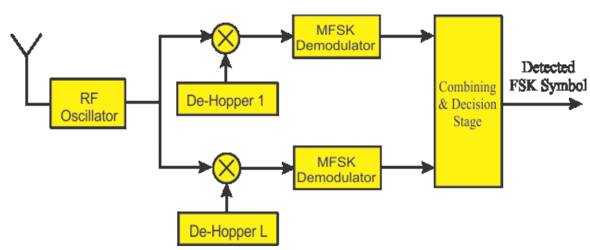

Figure 4. MCFH Receiver

From implementation point of view, the MCFH Tx and Rx do not require building high speed circuits due to the use of multiple hoppers. However, it does require building independent hoppers and de-hoppers and their companion PN synchronizers. In addition, the MFSK demodulator requires building a bank of BPFs running at the input rate, which is a major power consumer. Lastly, the Rx diagram shown in Fig. 4 can only employ serial PN sequence search [5] which yields a long acquisition time.

III. Polyphase Channelizer Based MCFH Receiver

The legacy analog implementation of a FHSS modem as shown in Fig. 1 and 2 requires building PN sequence generator directed analog mixer as hopping / de-hopping circuit. It also requires building a bank of parallel BPFs as an MFSK demodulator. All these operations can be easily converted to digital filters based design. Yet, a direct copy of the analog design may not benefit us much. We next present the NMDFB based MCFH receiver.

The NMDFB based polyphase channelizer [11] is an efficient engine for implementing a bank of BPFs. The block diagram of the M-Path M/2:1 polyphase analysis channelizer is shown in Fig. 5, where $E_i(Z)$, $i = 0, 1, \ldots, M-1$ is the M-path polyphase partition of the low pass prototype filter. The PAC implements M BPFs at the cost of one [11]. Moreover, it avoids building a high speed circuit by running at deeply decimated sample rate, i.e. M/2-to-1 decimation at the input to the PAC.

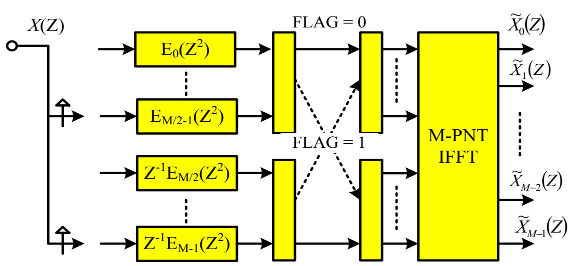

Figure 5. M/2:1 Polyphase Analysis Channelizer

With proper configuration, the PAC can serve as a de-hopping circuit simultaneously de-hopping multiple PN sequences. Authors in [10] demonstrated the de-hopping and synchronization algorithm for one PN sequence via early-late gate. The PAC based de-hopper is simply a PN synchronizer directed commutator that picks the desired signal at the desired moment from the N available output ports of the de-hopping PAC, as shown in Fig. 6. The same algorithm also applies to multiple PN sequences, provided with multiple PN synchronizer directed commutators. The crucial advantages of using one PAC as a de-hopping circuit are: 1) Avoid building analog mixer de-hopper for each diversity branch. This enhances the accuracy for both PN acquisition and tracking. 2) Enabling parallel search, which effectively reduces the acquisition time [5,10].

In addition, the bank of BPFs used in MFSK demodulator can also be implemented via an M-path PAC as shown in Fig. 6. The changes take advantage of the high efficiency of the NMDFB based PAC and avoid running many BPFs at the high sample rate.

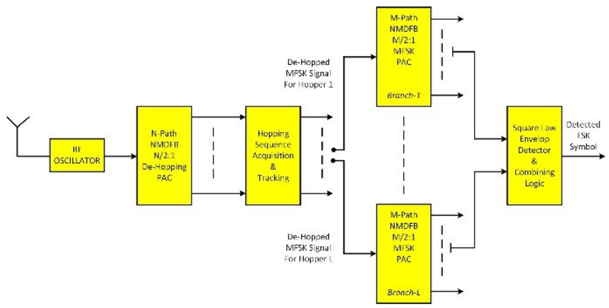

Figure 6. High Level Block Diagram of Proposed NMDFB Based MCFH Receiver

IV. Simulation Results

Simulation results are prepared based on an MCFH system with two diversity branches. There are in total 16 hopping frequencies from -6.0 MHz to +6.0 MHz in steps of 800 kHz. 800 kHz is the bandwidth of the MFSK signal. The 8-FSK is used as the sub-layer modulation with tone frequencies from -280 kHz to +280 kHz in steps of 80 kHz.

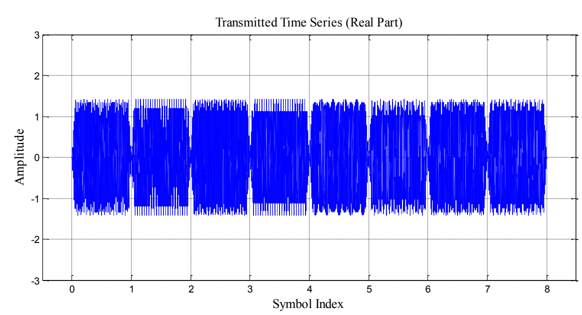

Figure 7. Transmitted Dual Diversity MCFH Signal (Real Part Time Series)

The input signal to the 20-path de-hopping PAC is sampled at 16 MHz, thus the channel spacing is 16 MHz / 20 = 800 kHz. After "20/2:1" PAC processing [11], the de-hopped 8-FSK signal has sample rate at 1.6 MHz, twice the 8-FSK bandwidth. Another 20-path PAC is then used as the 8-FSK demodulation BPF, with channel spacing 1.6 MHz / 20 = 80 kHz (The 8-FSK tone spacing). Figure 7 shows the real part time series of the transmitted MCFH signal. Since dual diversity is adopted, each transmitted symbol is a composite of two hopping frequencies.

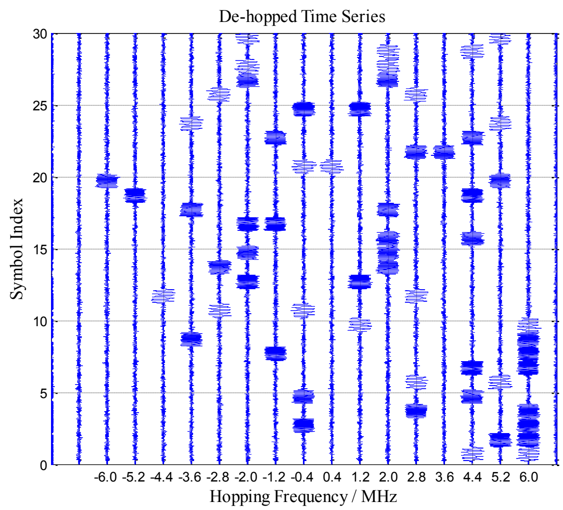

Figure 8. 20-Path PAC De-hopped Time Series (Real Part Time Series) $E_b/N_0 = 15$ dB

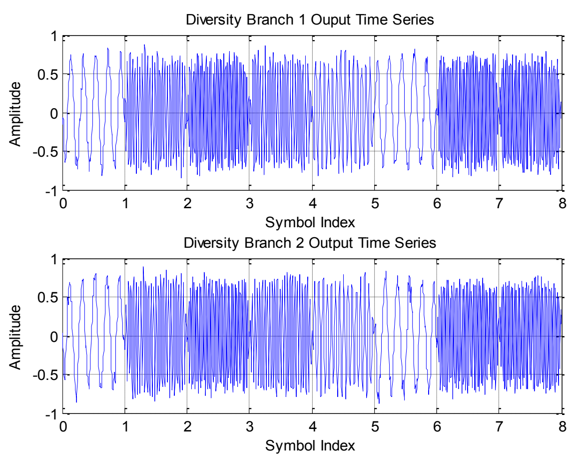

Figure 9. De-hopped and Aligned 8-FSK Output Time Series (Real Part) for Two Diversity Branches, $E_b/N_0 = 15$ dB

Figure 8 shows the real part of the 20-path PAC de-hopped time series for each hopping channel. Since dual diversity is used, one can find at any given symbol duration, two symbols simultaneously occur on different hopping frequencies. Two PN sequence synchronizer [10] directed commutators are used at the output of the de-hopping PAC. They track the hopping patterns across the hopping channels and align the de-hopped 8-FSK time series. Fig. 9 shows the two aligned 8-FSK signals after the de-hopping PAC. We can now see the two de-hopped signals have the same 8-FSK symbols. The last step is to pass the MFSK signal to the square law energy detector; generate the energy combined signal; and make final detection decision [7]. To verify the functionality of the proposed receiver, we performed bit error rate (BER) simulation over Rayleigh fading channel, i.e. each tone is assumed to experience narrow band Rayleigh fading. The channel delay spread is not considered in this verification. Figure 10 below shows the BER of the simulated MCFH system. Based on the narrow band Rayleigh fading setup, the BER should be identical with the traditional MFSK Rayleigh fading result. Shown in Fig. 10 are the theoretical non-coherent detection BER of 8-FSK for $L = 1$ and $L = 2$ diversity branches; and the simulation results obtained for MCFH-8FSK. We find the simulation matches the theoretical results, which further verifies our implementation of the MCFH receiver.

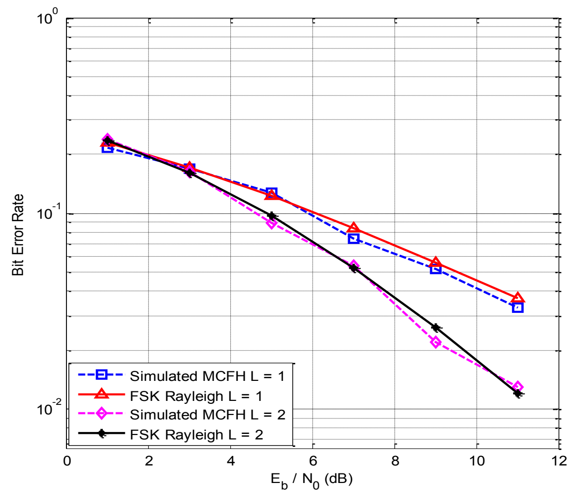

Figure 10. Bit Error Rate of MCFH System under Rayleigh Fading (Single Path vs., Dual Paths)

V. Workload Comparision

The de-hopping block is a 20-path "M/2:1" PAC whose 200-tap FIR low pass prototype filter (LPPF) has pass band from 0 kHz to 300 kHz and stop band from 500 kHz to 8 MHz, with 60 dB stop band attenuation. For every 10 input data samples at 16 MHz, the LPPF and 20-point FFT works once. Therefore, it roughly costs (1/10)*[2*200+4*2*20]=56 real multiplies per input sample (the 20-point FFT computation can be implemented via prime factor algorithm [12]). The existing de-hopper is often realized via analog mixer. We have commented that PAC based de-hopper has improved synchronization performance and enhanced accuracy compared to the analog circuit. For the 8-FSK BPF, we assume the de-hopped signal has sample rate at 1.6 MHz (Decimated from 16 MHz to 1.6 MHz). The conventional 8-FSK receiver requires 16 BPFs operating on 1.6 MHz for two diversity branches. Let the LPPF have pass band from 0 kHz to 20 kHz and stop band from 40 kHz to 800 kHz, with 60 dB stop band attenuation. This filter is 100 taps long. Therefore, it costs $16 \times 100 = 1600$ real multiplies per input sample on de-hopped sample rate. The proposed solution uses two 20-path PACs with the same LPPF and it costs (2*1/10)*[2*100+4*2*20]=72 real multiplies per input de-hopped sample, which is roughly 5% of the conventional BPF solution.

VI. Conclusion

This paper proposed an alternative implementation of MCFH system. The proposed implementation has an NMDFB PAC based unified de-hopping block. This avoids building high speed de-hopping circuits and improves the acquisition time. Further, replacing MFSK receiver BPF with PAC also offers great workload reduction over the conventional approach. The provided simulation results further verified the functionality of the proposed MCFH receiver algorithm.

References

[1] Y. T. Su and L. der Jeng, "Antijam capability analysis of RS-coded slow frequency-hopped system", *IEEE Trans. Commun.,* vol. 48, pp.270 -281 2000

[2] K. C. Teh , A. C. Kot and K. H. Li "Multitone jamming rejection of FFH/BFSK spread-spectrum system over fading channels", *IEEE Trans. Commun*., vol. 46, no. 8, pp.1050 -1057 1998

[3] Bluetooth SIG, Bluetooth Core Specification, Nov. 2003. http://www.bluthtooth.com

[4] IEEE Std 802.11-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Reaffirmed on June 12, 2003.

[5] B. Sklar, "Digital Communications Fundamentals and Applications", Second Edition, Prentice Hall, Upper Saddle River, New Jersey 07458

[6] John G. Proakis, "Digital Communications", Fourth Edition, McGraw-Hill College, Aug 15, 2000

[7] O. S. Shin and K. B. Lee "Performance comparison of FFH and MCFH spread-spectrum systems with optimum diversity combining in frequency-selective Rayleigh fading channels", *IEEE Trans. Commun.*, vol. 49, pp.409 -416 2001

[8] E. Lance and G. K. Kaleh, "A Diversity Scheme for a Phase-Coherent Frequency-Hopping Spread-Spectrum Systems," *IEEE Trans. on Commun.*, Vol. 45, No. 9, pp. 1123-9, Sep. 1997

[9] M. Ebrahimi and M. Nasiri-Kenari "Performance analysis of multicarrier frequency-hopping (MC-FH) code-division multiple-access systems: Uncoded and coded schemes", *IEEE Trans. Veh. Technol.*, vol. 53, no. 4, pp.968 -981 2004

[10] X. Chen, f. harris, E. Venosa, "Polyphase Channelizers for Fully Digital Frequency Hopping Systems", *Analog Integrated Circuits and Signal Processing*, vol. 73, issue 2, pp. 517-530

[11] X. Chen, f. j. harris, E. Venosa, and B. D. Rao, "Non-maximally decimated analysis/synthesis filter banks: Applications in wideband digital filtering," *IEEE Trans. Signal Process*., vol. 62, no. 4, pp. 852–867, 2014

[12] C. S. Burrus, and T. W. Parks. DFT/FFT and convolution algorithms: theory and implementation. New York: Wiley, 1984.