Signal Properties of Hybrid LFSK Modulated MQAM (HQFM) OFDM Transceiver

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Summary

Orthogonal Frequency Division Multiplexing (OFDM) is a promising candidate supporting high data rates with reasonable complexity in wireless fading channels. However, a major disadvantage of OFDM is its large peak-to-average power ratio (PAPR), which significantly decreases the transmitter high power amplifier's efficiency.

There are several techniques to reduce this PAPR. Almost, all of them, are either suited for specific application or works with small number of subcarriers. If these problems are overcome, then they, like PTS, usually need side-information to be transmitted along with the modified signal. A simple and efficient Hybrid OFDM Transceiver is suggested that effectively reduces PAPR. Also, system's BER is improved. Unlike PTS, no side-information for transmission is needed. Two modified algorithms for the proposed modulator are presented for which the PAPR reduction capability is either comparable or better as compared PTS.

Key words:
OFDM; PAPR; PTS.

1. Introduction

Multicarrier Modulation (MCM) especially Orthogonal Frequency Division Multiplexing (OFDM) systems are used in high data-rate digital transmissions and found optimum on frequency selective channels. It transports a single-input data stream on large number of subcarriers within the usable frequency band of the channel. DSP implementation of both transmitter and receiver using FFT techniques simplifies the realization of MCM systems [1].

Many problems arise in the practical implementation of these systems. One of them is large Peak-to-Average Power Ratio (PAPR), which calls for High Power Amplifier (HPA) of large linear range, to avoid inter-modulation products (IMD) and out-of-band radiations. Research is being carried out to discover its root cause, methods and modifications to reduce PAPR [2]. One such method described in literature is Partial Transmit Sequences (PTS) [3], which divides the OFDM symbol into V (V being power of 2) non-overlapping blocks, where each block is rotated so that low PAPR is achieved. These rotation vectors are sent as side-information (SI) along with modified PTS-OFDM.

Although MPSK or MQAM can be employed in OFDM, but OFDM employing M-ary Quadrature Amplitude Modulation (MQAM) is considered only (for comparison). The key advantage of QAM is that it is highly spectral efficient supporting high data-rates, but is not power efficient. The required E_b/N_o increases with the increase in the amplitude levels of QAM. On the other side, L-ary Frequency Shift Keying (LFSK) is a power efficient, constant envelope modulation scheme. In order to keep the constant envelope, phases of the FSK modulated carriers are varied continuously, while keeping the amplitude constant [4]. Therefore LFSK has very low PAPR as compared to QAM and can be amplified using a non-linear amplifier without degrading the BER performance. If LFSK is applied in conjunction with OFDM, PAPR can be reduced by exploiting the freedom of arbitrary phase choice using non-coherent detection [5].

In this paper an OFDM transceiver is proposed which, makes use of Hybrid MQAM and LFSK Modulation (HQFM) scheme, supporting same data-rates as for QAM-OFDM. There is a tradeoff between power and bandwidth efficiencies of both MQAM and LFSK. Due to the significance of FSK described above, the PAPR of such OFDM signal, employing FSK hybrid with smaller QAM, is reduced as compared to pure MQAM-OFDM. Also, the BER performance is improved, but at the expense of transmitter's complexity and bandwidth efficiency [6]. Like PTS, this works with arbitrary number of subcarriers but needs no side-information. Two modified algorithms, termed here as HQFM-I and HQFM-II, are proposed which further reduces the PAPR.

This paper is organized as follows: In section 2, the description of a typical OFDM system model and its PAPR statistics is presented. A hybrid modulation system is proposed which can be used with MCM whose signal properties, bandwidth efficiency, PSD and FOBP analysis are discussed in section 3. The paper is concluded by discussing the BER performance in a frequency selective channel and PAPR reduction capability.

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2. Classical OFDM System

In a typical OFDM system, the incoming serial data is first converted into parallel groups (subcarriers), each with n bits to form N_{active} complex numbers of the form $c_{i,q} = c_{ic,q}+jc_{is,q}$, typically drawn from 2^nQAM. These subcarriers are zero-padded and modulated in a baseband fashion by the N-point IFFT and converted back to serial data for transmission. Mathematically an OFDM symbol is expressed as:

$$s(t) = \frac{1}{\sqrt{N}} \sum_{i=0}^{\infty} \sum_{q=0}^{N-1} c_{i,q} e^{j2\pi q\Delta f(t-iT)}; \quad 0 \le t \le T \tag{1}$$

where $\Delta f = 1/T$ is the frequency separation between each subcarrier, $T = NT_s$ is the OFDM symbol period, T_s is the data symbol period. To combat multipath distortions introduced by frequency selective channel, guard interval is cyclically inserted. These discrete symbols are converted to analog and lowpass filtered for RF upconversion. The receiver performs the inverse process of the transmitter.

2.1 PAPR Statistics

Peak-to-Average Power Ratio (PAPR), ξ, [2,3] of the OFDM symbol is defined as

$$\xi = \frac{\max\limits_{t\in[0,T)} |s_i(t)|^2}{E\{|s_i(t)|^2\}}; i = 0,1,2,... \tag{2}$$

where $E\{.\}$ denotes the expectation. It is well known that as number of subcarriers increases, the occurrence of OFDM with large ξ against given threshold, ξ_0 becomes rare. Computer simulation shows that increase in PAPR is linear to the increase in N, but this PAPR is not equal to the number of subcarriers, N [2, 3]. Also, PAPR of any signal can be controlled by decreasing the number of subcarriers (N) or subcarrier's phase properties.

3. Signal Properties of Hybrid MQAM/LFSK (HQFM)

3.1 General HQFM Signals

In HQFM (pre-IFFT), instead of modulating n random bits per subcarrier, n-k random bits are used to select the frequency f_c' from LFSK according to $f_c' = lf_\Delta$; $l = 0,1,2,\ldots,L-1$, where f_Δ is the frequency difference between two adjacent tones. The choice of choosing $\log_2 L$ bits is arbitrary. During the same symbol period, T_s, the remaining $k = \log_2 M$ bits are then mapped using ordinary MQAM.

The complex form of HQFM signal, prior to IFFT, can be expressed as:

$$s_{HQFM}(t) = C_{m,l} e^{j\vartheta_{m,l}} u_l(t) \tag{3}$$

where $C_{m,l} = \sqrt{C_{mc,l}^2 + C_{ms,l}^2}$; $\theta_{m,l} = \tan^{-1}(C_{ms,l}/C_{mc,l})$; $u_l(t) = \mathbf{exp}(2\pi l f_\Delta t)$, $m\in\{0,1,2,\ldots,M-1\}$ (from QAM), $l\in\{0,1,2,\ldots,L-1\}$ (from FSK), $0 \le t \le T_s$, $T_s = T_b\log_2 ML$, T_b being bit duration in seconds. C_{mc}'s and C_{ms}'s can takes up to values from $(2m-1-\sqrt{M})$, defining the I- and Q-axis of the signal space diagram.

From (4) it can be observed that L/M HQFM constitute of L sets, each with MQAM modulated symbols, where in each set, the cross correlation coefficient $|\rho| = 0$ implies that the frequency difference, f_Δ, is at least $1/T_s$ (non-coherent detection), or in other words, the modulation index $h = f_\Delta T_s = 1$. Also, since non coherent FSK require atleast twice bandwidth than coherent, so in HQFM, the sampling rate of QAM is also increased accordingly. To avoid the confusion of frequency separation between OFDM subcarriers and FSK tones, the term of modulation index, h, is used for FSK, onwards, otherwise mentioned.

It is worth mentioning that, QAM uses 2D, while, HQFM uses 2^{L+1} dimensional signaling. Also, for ordinary MQAM, $L = 1$. For $L = 2$, $M = 4$, HQFM reduces to special modulation format known as Q^2PSK [7] which is a member of general class of modulation format known as JPFM [8]. However, JPFM generally phase shifts the carriers, while HQFM utilizes amplitude/phase shift (QAM). One advantage of QAM over PSK is that QAM is more power efficient and supports high data rates for the same required SNR [4].

Relationship between OFDM subcarrier separation, Δf and FSK tone separation, f_Δ, is $f_\Delta = N\Delta f \Leftrightarrow N = f_\Delta/\Delta f$. Also, increase in PAPR (ξ), is linear function of N or $f_\Delta/\Delta f$. Therefore, for fixed N, PAPR can be reduced either by increasing Δf or decreasing f_Δ. Bringing FSK tones closer to each other while maintaining their orthogonality, means that more frequencies can be adjusted in a given frequency band. Therefore PAPR decreases by decreasing f_Δ or increasing L. For HQFM-OFDM, PAPR therefore, decreases by increasing the number of FSK tones as compared to 2^nQAM-OFDM ($L = 1$).

As mentioned earlier, HQFM signal set consists of L set of MQAM signals where the signal in each set is orthogonal to signals in other sets. Therefore, a two stage demodulation process (after FFT application) is carried out to extract the information bits. In stage I, the correct frequency estimate is using bank of L matched filters followed by an envelope detector. In stage II, when correct frequency estimate is made, QAM symbols are detected by computing the distance between the received symbol $\hat{s}$, and M possible transmitted symbols. Decision is made in favor of the point closest to $\hat{s}$. The whole HQFM modulation (pre IFFT) and demodulation (post FFT) process is shown in figure 1.

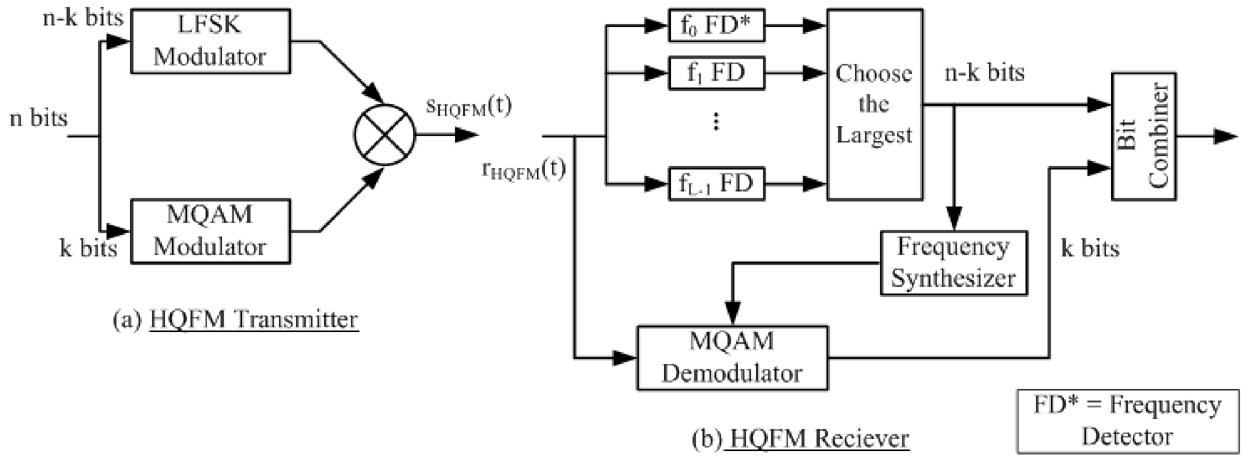

Fig 1. HQFM (Hybrid Quadrature Frequency Modulation) (a) Transmitter (b) Receiver

3.2 Bandwidth Efficiency

In many design problems, the signal's bandwidth efficiency μ_B can be calculated in terms of Fractional Out-of Band Power (FOBP) containment:

$$\mu_B = 1 - \frac{1}{P_T}\int_{-B/2}^{B/2} S(f)df \qquad (4)$$

where $P_T = \int_{-\infty}^{\infty} S(f)df$ is the total power confined in a Bandwidth, B and $S(f)$ is PSD of the modulation format under consideration. Using the same techniques developed to evaluate the PSD of JPFM in [4], the PSD of HQFM can be approximated as:

$$S_{HQFM}(f) = \frac{\sigma^2 T_s}{L}\sum_{i=1}^{L}\left(\frac{\sin \pi(fT_s - \lambda_i)h/2}{\pi(fT_s - \lambda_i)h/2}\right)^2 \qquad (5)$$

where $\lambda_i = 2i\text{-}1\text{-}L$, σ^2 is variance of QAM and $T_s = T_b \log_2 ML$. Equation (5) shows that PSD of HQFM can be approximated as similar to PSD of FSK [4]. The PSD for LFSK with continuous phase falls off as the inverse fourth power of the frequency offset from the carrier frequency f_c [4], whereas, for HQFM, it falls off with the same rate as MQAM i.e. as the inverse square of the frequency offset from f_c. Also, main lobe of HQFM becomes wider if number of LFSK tones increases. For instance, consider 4/16 HQFM. Its PSD is plotted and compared with 4FSK along with power spectra of 2^n (64) and 2^k (16) QAM in figure 2. Note that at -10dB, the main lobe of 4/16 HQFM is 50% wider than 64QAM.From equations, (4), (5) and (6), it is obvious that for $L = 1$, the overall system reduces to ordinary MQAM.

If the spectral occupancy of different HQFM formats, viewed in terms of FOBP using equations (4) and (5), which contains 90% of the total power (-10dB), then it can be shown that FOBP increases with the increase in number of keying frequencies, e.g. $B_{90\%} \approx 0.5/T_b$ for 4/16HQFM. Evaluating 4 using equation 5, FOBP values are plotted for 4/16 HQFM in figure 3. Also for calculating $B_{99\%}$, it can be proved that HQFM is more spectral efficient than FSK. $W_{99\%} \approx 3.5/T_b$ for 4/16HQFM, that is double the value for 4FSK and is almost as spectrally efficient as 64QAM. So 4/16 HQFM can be replaced with 64QAM to support same data rate.

For OFDM, PSD of each orthogonal subcarrier, modulated by rectangular pulse is of the form of sinx/x pulses, thus the overall PSD for the complex envelope can be evaluated as:

$$S_{OFDM}(f) = \sum_{q=0}^{N-1}\left(\frac{\sin \pi(f - f_q)T}{\pi(f - f_q)T}\right)^2 \qquad (6)$$

where T is OFDM symbol duration and $f_q = (2q\text{-}1\text{-}N)/NT_s$; $T_s = nT_b$; n being number of bits per subcarrier. Equation (6) clearly states that PSD of OFDM depends on frequency separation of each subcarrier ($1/T = 1/NT_s$), irrespective of the modulation format used, so bandwidth occupancy in of HQFM-OFDM, terms of PSD/ FOBP remains unchanged

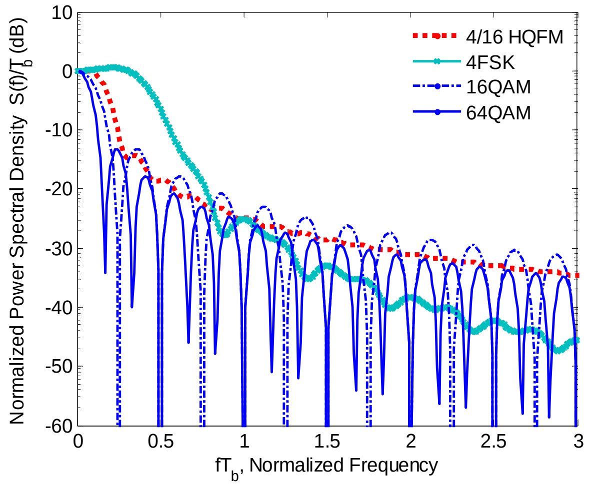

Fig 2. Power Spectral density of HQFM compared with QA and FSK

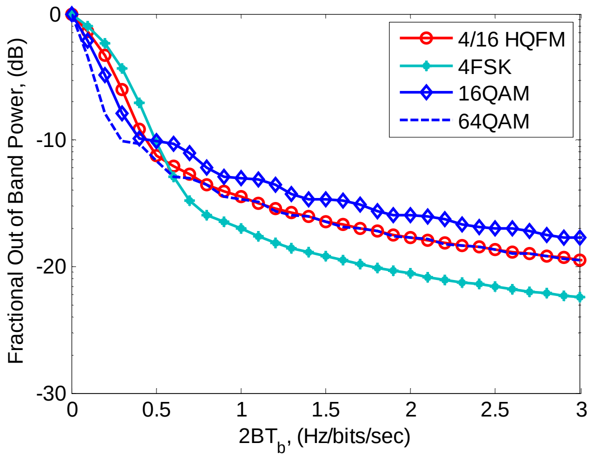

Fig 3. Fractional Out of Band Power (FOBP) of HQFM compared with QAM and FSK

4. Results and Discussion

The OFDM system parameters, used in simulation, for this paper are listed in table I. The side-information for PTS-OFDM $\in [0, \pi/2, \pi, 3\pi/2]$ is transmitted along with each OFDM symbol. The modulation index, $h = 1$. According to table I, τ_{max} = 360nsec, therefore a guard interval of 128 carriers (>360*2nsec) is sufficient to combat the frequency selectivity of such a channel induced. The maximum mobile speed of 240km/hr is assumed at carrier frequency of 900MHz.

Table I: OFDM Parameters defined for Simulation

Modulation Type	64QAM, 4/16 HQFM
Number of Subcarrier, N	512
Guard Interval, N_{cp}	¼ , Cyclic Extension
Number of Active Carriers, N_{used}	208
Data bits per subcarrier	6
OFDM symbol duration ,T	3.9µsec
Guard Interval T_{cp}	780nsec
Symbol Rate = 1/T	256.41kSym/sec
Δf = Subcarrier Spacing	320.5kHz
Data Rate, R	320Mbps
Channel Bandwidth, W	164.1MHz
Channel Delay Profiles	[0, 60, 120] x 3nsec
Channel Gain	[0,-3,-6]dB
Doppler Frequency	200Hz

Figure 4 plots the probabilities $\mathbf{Pr}\{\xi_0\}$ against a specified threshold ξ_0. It is obvious that HQFM-OFDM make the probabilities to decay faster, yielding a more desirable statistical behavior, i.e., ξ_{HQFM} does not exceed ~13dB. While this value can take up a value of ~16dB for a conventional one at $\mathbf{Pr}\{\xi_0\} = 10^{-7}$.

HQFM-OFDM shows poor behavior as compared to PTS-OFDM. Therefore, a modification is proposed, termed as HQFM-I. This modification is made on the fact that PAPR is highly dependent on number of keying frequencies (L) in HQFM-OFDM [6]. In HQFM-I, a multi-stage modulator is designed which uses variable FSK modulator to generate frequencies. In first stage, n-k = $\log_2 L$ bits are used to generate L frequencies and remaining $k = \log_2 M$ bits are used for QAM Modulation. Other stages generate $2L$, $4L$, …, frequencies which are used for $M/2$, $M/4$,…, QAM Modulation respectively. The overall number of bits, n, for HQFM signal remains constant. After applying IFFT, HQFM signal with least PAPR is chosen. The receiver first demodulates the OFDM symbols using FFT, then determine the number of bits used by QAM by observing the maximum amplitude C_{max}. The demodulation process is carried out to detect the correct HQFM symbol as per figure 1b. Only two-stage HQFM modulator is sufficient to achieve the desirable results. Monte Carlo simulations show that PAPR reduction capability is comparable to PTS-OFDM.

To further reduce the PAPR, HQFM-II is proposed. A PTS algorithm is used where the whole HQFM signal set is divided into V subblocks, V being power of 2 with number of carriers $N_v \geq 64$ in each subblock. Phase vector of $\{0, \pi\}$ is sufficient to obtain the results, which can be detected, in one or two iterations, without transmitting it.

Figure 5 shows the BER comparison of different HQFM-OFDM combination described above, after

PAPR reduction, both in AWGN and fading channel with parameters given in Table I. The figure shows that HQFM-I performs better than ordinary HQFM and HQFM-II. This is because of the use of multi-FSK utilization in HQFM II. Comparing it with QAM-OFDM, its performance improves with an increase in number of FSK tones and is more robust to channel impairments. The poor performance of HQFM-II can be stated as an extra overhead paid to decode the iterative phase vector before the conventional HQFM demodulation. Also, any combination of HQFM is better than QAM-OFDM.

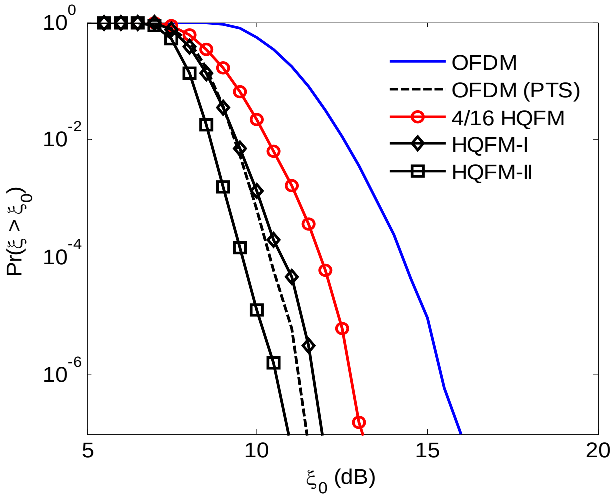

Fig. 4: CCDF Comparison of HQFM-OFDM and its modifications with PTS-OFDM (For HQFM-II, $V = 4$, hence $N_v = 128$)

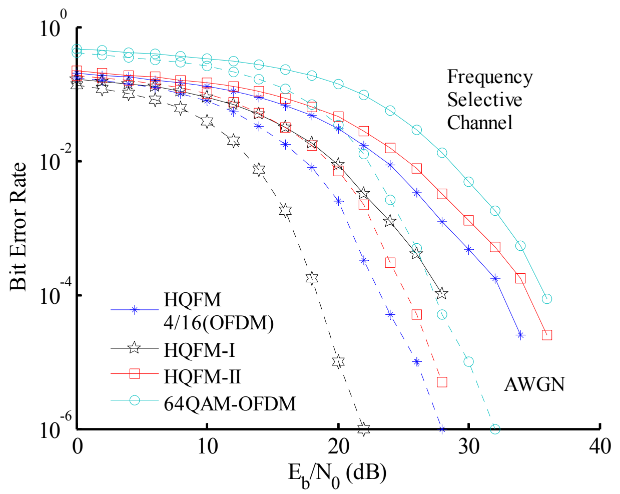

Fig. 5: BER of 4/16 HQFM, OFDM in Rayleigh Fading Channel, compared with HQFM-I and HQFM-II

Conclusion

In this paper, a novel modulation scheme is proposed. The BER performance, PSD analysis shows a trade off between power efficiency of FSK and spectral efficiency of QAM. Comparing 99% of Power containment, HQFM is as spectral efficient as MQAM. Thus, HQFM is proved to be replaced by higher order QAM to support high data rates. Also the frequency selective channel simulation shows that it is best suitable for high speed wireless applications like OFDM.

When applied in conjunction with OFDM, it shows low PAPR and better BER performance against conventional system as well as PTS. These results are discussed and compared based upon different simulations. This also works with arbitrary number of subcarriers. In contrast to PTS, it requires no or little side-information to be transmitted with the signal. It is capable of improving the statistical behavior of OFDM's PAPR. Therefore this OFDM transceiver is more useful than conventional systems.

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