IDFT Based Transmitters for Spectrally Efficient FDM System

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Abstract: Spectrally Efficient FDM systems (SEFDM) promise high bandwidth savings at the expense of increased complexity. In particular, SEFDM signal is generated using a bank of modulators running at the carriers' frequencies. In this paper two new methods to generate SEFDM signal based on utilizing IDFT are proposed. The methods facilitate the migration from conventional OFDM systems to SEFDM systems without the need to change existing infrastructures. The methods will support multi technique systems that combine SEFDM and OFDM for applications that include different QoS and when the available spectrum is not guaranteed.

1 Introduction

The ever growing demand from the wireless communications has always inspired the research for techniques to save the spectrum and combat wireless channel impairments. Spectrally efficient frequency division multiplexing (SEFDM) system promises better utilization of bandwidth by reducing the spacing of sub-channels [1]. However, this enhancement is for the price of increased complexity at receiving end. Maximum likelihood is suggested for detection as the optimum technique in AWGN channels [1]. Kanaras et al in [2] investigated detection using minimum mean square error (MMSE) and zero forcing (ZF). They showed that using sub-optimum detection techniques still provides reliable performance and bandwidth savings. Later sphere decoding (SD) was proposed in [3] as an optimum solution for SEFDM detection. Spectral efficiency could also be achieved by increasing the bandwidth of the individual subcarriers as in the high compaction multi carrier (HC-MC) system proposed in [4].

Although SEFDM system fulfils the objective of saving the spectrum, it has some limiting factors aside from the complex detection. SEFDM transmitter consists of a bank modulators running at the sub-channels frequencies. In [5] the use of Fractional Fourier Transform (FrFT) for signal generations was proposed providing complexity of $O(N\log_2 N)$. In this work we propose the use of Inverse Discrete Fourier Transform (IDFT) to generate SEFDM signal. The use of IDFT for generation of multi carrier signal has been widely known in OFDM applications [6]. The generation of high compaction signal is based on the IDFT to obtain an enlarged sub-channel bandwidth within the same bandwidth of an equivalent OFDM system. IDFT based modulators are also proposed in [7] to generate zero prefix for spectrally efficient signal. The system in [7] employs preparatory stage before the IDFT stage.

The rest of this paper is organized as follows: Spectrally Efficient FDM system is briefly outlined in Section 2. The new methods for designing SEFDM transmitters are presented in Section 3. Section 4 discusses the merits of the proposed methods. The paper is concluded by Section 5.

2 SEFDM System Model

SEFDM signal is constructed by modulating a block of the input data stream on parallel carriers, as shown in Fig 1. The carriers in FDM systems are spaced by a fraction of the inverse of the symbol duration, violating orthogonality condition of OFDM systems where the spacing is inversely proportional to the symbol duration.

$$S(t)=\frac{1}{\sqrt{T}}\sum_{k=-\infty}^{\infty}\sum_{n=0}^{N-1} s_{k,n}\; e^{j2\pi n\Delta f(t-kT)}. \tag{1}$$

Equation (1) gives SEFDM signal denoted by $S(t)$ in baseband representation, where N is number of sub-channels, T is the symbol duration, $s_{k,n}$ denotes the symbol modulated on the nth carrier in the kth SEFDM frame. Δf denotes the frequency distance between the sub-channels in the system and it is related to the symbol duration by α, where $\Delta f=\frac{\alpha}{T}\ Hz$ for $\alpha <=1$.

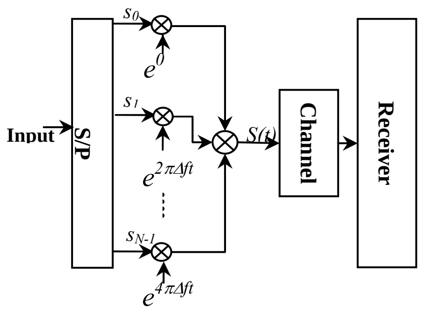

Fig 1 SEFDM System

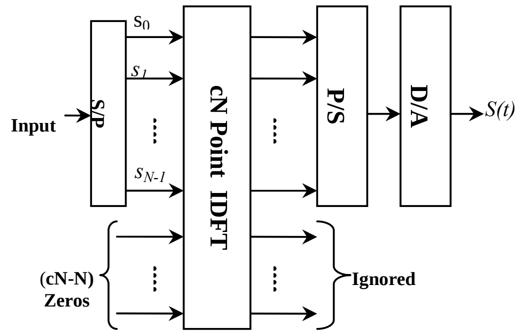

Fig 2 SEFDM IDFT Transmitter for α=1/c

SEFDM signal is generated using a bank of modulators that generates the sub carriers. It requires high frequency precision in order to reduce frequency offset effects. In addition, it will require different equipment for the different possible frequency spacing. This technique of generating the signal could be a serious limiting factor in the deployment of the system. Therefore, suggesting the pursuit of other methods for generating the signal and in the next sections methods that utilize IDFT to generate the signal are presented and evaluated.

3 New SEFDM IDFT Transmitters

Consider the first SEFDM frame from equation (1); sampled at a rate($1/N$) in analogy to OFDM , the frame could be expressed in equation (2) for $k=0, 1, \ldots, N-1$.

$$S[k] = \sum_{n=0}^{N-1} s_n e^{\frac{j2\pi nk\alpha}{N}} . \tag{2}$$

Equation (2) differs from the standard IDFT by the factor α. Sections 3.1 and 3.2 outline how equation (2) could be transformed into IDFT forms depending on the value of α.

3.1 SEFDM Transmitter for $\alpha=1/c$

When $\alpha = \frac{1}{c}$ for $c \in \mathbb{Z}$, equation (2) could be rewritten as

$$S[k] = \sum_{n=0}^{N-1} s_n e^{\frac{j2\pi nk}{cN}} . \tag{3}$$

Now if the sequence s_n is extended with zeros to a length of cN generating the sequence $\hat{s}_n$. The IDFT of $\hat{s}_n$ is given by equation (4) for $g=0, 1, \ldots, cN-1$.

$$\hat{S}[g] = \sum_{n=0}^{cN-1} \hat{s}_n e^{\frac{j2\pi ng}{cN}} . \tag{4}$$

By inspection of equations (3) and (4) it is clear that the sequence $S[k]$ is equivalent to the sequence $\hat{S}[g]$ for $k,g=0, 1, \ldots, N-1$.

Fig 2 illustrates this method applied to generate SEFDM signal. This procedure is effectively similar to the zero padding in IDFT evaluation when a higher frequency resolution is needed; the difference is that only part of the generated IDFT is considered resulting in the compression of spectrum. The transmitter in Fig 2 incorporates a parallel to serial converter and a digital to analogue converter to produce the time domain signal *S(t)*.

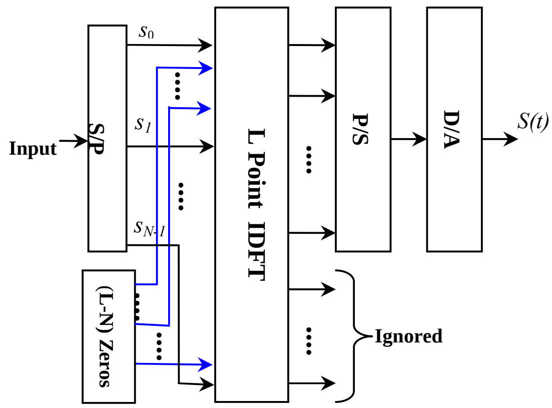

Fig 3 SEFDM IDFT Transmitter for α=b/c

3.2 SEFDM Transmitter for α rational number

Consider the SEFDM signal in equation (2) for $\alpha = b/c$, b & $c \in \mathrm{Z}$ giving:

$$S[k] = \sum_{n=0}^{N-1} s_n e^{\frac{j2\pi nbk}{cN}} . \qquad (5)$$

Substituting by $L = cN$ and $\tilde{n} = bk$ gives

$$S[k] = \sum_{n=0}^{N-1} s_n e^{\frac{j2\pi \tilde{n} n}{L}} . \qquad (6)$$

The system above will be equivalent to an IDFT of a sequence of length L with the original symbols of the sequence s_n inserted at indices of $\tilde{n} = 0, b, 2b, ..., (N-1)b$. A similar concept is presented in [8] to calculate the FrFT of a sequence. When the first N outputs are fed into a parallel to serial converter followed by a digital to analogue converter a signal that is equivalent to an SEFDM signal would be obtained. Figure 4 depicts an SEFDM transmitter using this method, allowing for the generation of SEFDM signal for a more flexible range for frequency separation compared to the structure in section 3.1.

4 Discussion

The methods described in sections 3.1 and 3.2 generate a signal that is equivalent to SEFDM signal generated by a bank of modulators. When $\alpha = 1$, the technique will automatically mimic the well known OFDM IDFT based system [6]. Worth noting that for any arbitrary sampling rate the methods described here will produce the same effect.

The methods eliminate the need for bank of modulators; therefore, preparing the system for digital generation of the signal recalling that IDFT algorithm could be performed economically with the Fast Fourier Transform (FFT) algorithm. The methods will allow for the generation of SEFDM signal for a more flexible range of frequency separation. The structure of the transmitters employ similar building blocks as OFDM systems, hence, facilitate a smooth changeover between existing systems based on OFDM to systems employing SEFDM with a change in the size of the system in terms of the numbers of subcarriers. Moreover, systems that allow for multi-rate communications could benefit from these methods where the operation could be switched between OFDM and SEFDM, though it will require the receiving ends to be employing different technologies. Such feature could be specially useful for applications where the available spectrum changes.

The main limitation of these methods is that it will require a larger IDFT when compared with OFDM. Nevertheless, when compared with generation with bank of modulators, these methods will result in reduced cost of the system and reduced power consumption.

5 Conclusions

In this paper two new methods to generate Spectrally Efficient System signal are presented. The methods are based on using standard IDFT to design SEFDM system in place of using a bank of modulators. They allow for an easy generation of SEFDM signal for a more flexible range of frequency separation. The methods could facilitate the design of multi rate systems or multi technique system as they allow for the switching between SEFDM and conventional OFDM using the same equipment. Therefore, supporting applications that provide different QoS and when the available spectrum is susceptible to changes. The methods will help the use of SEFDM systems for applications where there the space and power are limited. However, the complexity of reception remains an issue and needs to be addressed. Further enhancement could be sought by exploring mechanisms to simplify the IDFT design of SEFDM in order to present SEFDM system as a realistic competitor for next generation communications.

References

[1] M. R. D. Rodrigues and I. Darwazeh, “A spectrally efficient frequency division multiplexing based communications system,” in *Proceedings of the 8th International OFDM Workshop, Hamburg*, 2003.

[2] I. Kanaras, A. Chorti, M. Rodrigues, and I. Darwazeh, “A Combined MMSE-ML Detection for Spectrally Efficient non Orthogonal FDM Signal,” in *Proceedings of IEEE Broadnet conference*, September 2008.

[3] ——, “An Optimum Detection for a Spectrally Efficient non Orthogonal FDM System,” in *Proceedings of the 13th International OFDM Workshop, Hamburg*, August 2008.

[4] M. Hamamura and S. Tachikawa, “Bandwidth efficiency improvement for multi-carrier systems,” in *Proc. 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications PIMRC 2004*, vol. 1, Sep. 5–8, 2004, pp. 48–52.

[5] I. Kanaras, A. Chorti, M. Rodrigues, and I. Darwazeh, “Spectrally Efficient FDM Signals: Bandwidth Gain at the Expense of Receiver Complexity,” in *Proceedings of the International Conference On Communications*, 2009.

[6] S. Weinstein and P. Ebert, “Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform,” *IEEE Transactions on Communication Technology*, vol. 19, no. 5, pp. 628–634, 1971.

[7] W. Jian, Y. Xun, Z. Xi-lin, and D. Li, “The Prefix Design and Performance Analysis of DFT-Based Overlapped Frequency Division Multiplexing (ovFDM-DFT) system,” in *Proc. 3rd International Workshop on Signal Design and Its Applications in Communications IWSDA 2007*, Sep. 23–27, 2007, pp. 361–364.

[8] D. H. Bailey and P. N. Swarztrauber, “The Fractional Fourier Transform and Applications,” *SIAM Review*, vol. 33, pp. 389–404, Sept 1991.