The First 15 Years of SEFDM: A Brief Survey

(Invited Paper)

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***Abstract*—Spectrally efficient frequency division multiplexing (SEFDM) is a multi-carrier signal waveform, which achieves higher spectral efficiency, relative to conventional orthogonal frequency division multiplexing (OFDM), by violating the orthogonality of its sub-carriers. This survey provides the history of SEFDM development since its inception in 2003, covering fundamentals and concepts, wireless and optical communications applications, circuit design and experimental testbeds. We focus on work done at UCL and outline work done other universities and research laboratories worldwide. We outline techniques to improve the performance of SEFDM and its practical utility with focus on signal generation, detection and channel estimation.**

I. Introduction

Development of future communication networks, exemplified by 5^{th} generation (5G), where user demand is expected to be significantly in excess of the total network supply and where more devices will be connected to the network, necessitate a fresh look at all aspects of networking, from the physical layer and its basic signals to network architectures and information processing [1], [2], [3] in line with the vision of the internet of things (IoT) paradigm.

A key direction in future wireless standards is improving spectral efficiency; a quest that has been at the forefront of designers minds from the early days of wireless transmission but is acquiring urgency for today's and future systems. This paper looks at work in this area and specifically in the context of multi-carrier systems, that were initially proposed as orthogonal systems in the late 1950s [4] and are used in most of today's mobile and wireless applications. Considering that orthogonality is, at the same time, an advantage and a constraint, a semi-orthogonal signal termed fast-orthogonal frequency division multiplexing (Fast-OFDM) was firstly proposed in 2002 [5], offering twice the spectral efficiency of OFDM by halving the separation between sub-carriers, but only for a limited subset of modulation formats. Fast-OFDM was initially proposed as a wireless technique and is now adopted widely in optical systems [6], [7], [8]. This multiplexing scheme decreases sub-carrier spacing to 50% of that in typical OFDM. Later, based on Fast-OFDM, a spectrally efficient flexible waveform termed spectrally efficient frequency division multiplexing (SEFDM) was developed in 2003 [9]. Furthermore, a technique, termed multistream faster than Nyquist (FTN), redeveloped from a paper published in 1975 [10], was presented both theoretically and experimentally in [11]. FTN is a time domain technique that aims to reduce the transmission time for each FTN symbol, thus improving the overall spectral efficiency. Later, SEFDM and FTN concepts were effectively combined to create a joint spectrally efficient technique termed time frequency packing (TFP) [12]. Aside from the schemes mentioned above, a non-orthogonal waveform termed generalized frequency division multiplexing (GFDM), where each sub-carrier is pulse shaped, was developed in [13], leading to a novel waveform that has very low out-of-band emission (OOBE) leakage. Other related waveforms such as filterbank based multicarrier (FBMC) [14], universal-filtered multi-carrier (UFMC) [15] and Nyquist-SEFDM [16] aim for the same advantage. Recently a new waveform termed Truncated OFDM (TOFDM) was proposed, where the transmission rate is increased by truncating the OFDM symbols in time. This results in shorter transmission time compared to OFDM symbols [17].

In this paper, first, we present a brief survey on SEFDM, deliberately avoiding mathematical developments and system and experimental descriptions, which could be found in two recent book chapters [18], [19], recent summary paper [20] and in the numerous references cited. We provide the development history of SEFDM since 2003, covering wireless and optical communications theory, circuit design and experimental testbed design. Second, we address the main challenges of SEFDM and the developed ongoing work to solve them. Finally, all the studies and experiments on SEFDM are summarized and listed in tables by the end, with a one sentence summary of each to offer guidance to readers.

II. SEFDM Concept

The idea behind SEFDM [9], similar to Fast-OFDM, is based on reducing the spacing between sub-carriers, below the orthogonality limit. In other words, the spacing becomes a fraction of the modulating symbol rate for each sub-carrier. For SEFDM, this is characterized by the bandwidth compression factor (α). This means that when sending the same amount of data, $(1-\alpha)\times 100\%$ bandwidth can be saved in comparison to OFDM, see Fig. 1. Such spectral efficiency improvement and corresponding capacity gain [21] comes at the expense of interference between the sub-carriers, which compromises performance and error rates. Removing such interference was and remains a key challenge for SEFDM systems and leads to complex receivers and systems [22], [23].

III. SEFDM Challenges

Initially, the practicability of SEFDM was hindered by a few obstacles. Firstly, SEFDM signal modulation and demodulation required the use of a bank of analogue waveform generators, both at the transmitter and receiver. Secondly,

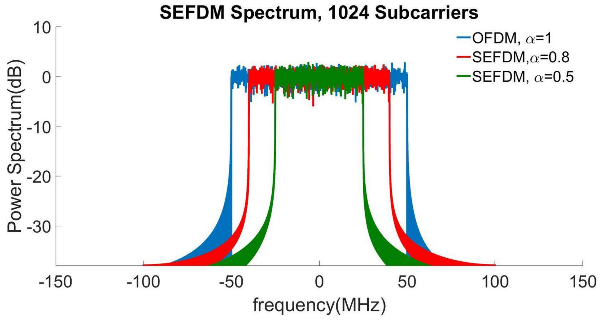

Figure 1. Illustrative spectra of SEFDM and OFDM signals.

SEFDM signal detection was based on maximum likelihood (ML) with exponential algorithmic complexity $O(M^N)$ over the constellation cardinality M and N sub-carriers. The third challenge concerns difficulties in channel estimation due to the non orthogonality of the symbols. Different methods have been developed to overcome these problems to benefit from SEFDM advantages. In the following, each challenge is addressed with a brief summary of the work have been done so far.

A. SEFDM Signal Generation and Transmission

Two simple SEFDM signals generation methods based on inverse discrete Fourier transform IDFT were proposed in [24] to facilitate an easy migration and/or coexistence with OFDM on transmitters. The first approach is operated by taking an IDFT of size (N/α). To output N orthogonal sub-carriers, $((1-\alpha)/\alpha) \times N$ samples from the output of the IDFT are punctured at any position. The idea behind the second method in [24] is based on the mathematical formulations describing correlation (or interference) between the non-orthogonal sub-carriers [25]. For any two arbitrarily chosen sub-carriers (m and n), when the product $\alpha(m-n)$ is an integer, this indicates that the two sub-carriers m^{th} and n^{th} are orthogonal. This method looks at SEFDM signal as a combination of multiple OFDM systems translated in frequency so as to reduce the spacing between sub-carriers. Thus, multiple shorter IDFTs are used in parallel instead of one large IDFT.

To prove the practicability of SEFDM systems, a hardware platform that facilitates the implementation of signals generation in real-time system has been designed in field programmable gate arrays (FPGAs). In [26], [27], [28] the generation of SEFDM signals was implemented based on the multiple IDFTs method [24]. The results of this study confirm the feasibility of SEFDM transmitters and report the challenges for SEFDM systems, which are the chip area and power consumption compared to conventional OFDM.

In addition to signal generation, various methods have been explored to modify signal characteristics at the transmitter for the purposes of reducing spectral out of band emission by signal shaping [16]; optimizing signal shapes for power and spectral efficiencies gain [29]; reducing peak to average power ratio (PAPR) by windowing [30] or by tone reservation and precoding [31].

B. SEFDM Signal Detection

As is the case for most system, optimal performance for SEFDM in AWGN channel, is achievable by maximum likelihood (ML) detection [32]. The complexity of ML increases exponentially with the number of sub-carriers and the constellation cardinality. Therefore, aiming to trade complexity versus terms of optimality, other alternatives were investigated over the years to overcome ICI impairments with lower complexity. It was demonstrated that the application of linear detection techniques such as; zero forcing (ZF) and minimum mean square error (MMSE) perform significantly worse than ML [22]. The detectability of the signals is restricted by the ill-conditioning of the SEFDM correlation matrix turning into an ill posed problem [22].

In [33], truncated singular value decomposition (TSVD) method is proposed to overcome the ill-conditioning problem, outperforming linear detectors (ZF and MMSE) while maintaining a linear system complexity. Approaching the problem from another angle, to reduce the relaxation gap between the sub-optimum solutions and ML detection, a two steps detection method commonly known as boxed ML was investigated. In this method, the ML detection is performed in a neighboring area defined by a less complex detector, such as semi-definite programming (SDP) [34] and MMSE [35]. The boxed detectors of MMSE-ML [35] and SDP-ML [34] show a drastic reduction in detector complexity compared to conventional ML, but with serious limitations to the size of SEFDM system and levels of bandwidth compression.

Inspired by the successful deployment of sphere decoder (SD) in multi-input multi-output (MIMO) systems, SD has been applied to SEFDM, firstly, in [22]. Although SD achieves optimum BER performance, its applicability is limited by two problems. First, SD mainly depends on the invertiblity of the ill-conditioned correlation matrix, thereby limiting its efficacy to SEFDM systems with small number of sub-carriers and ($\alpha \geq 0.8$). Second, the SD practicability is limited due to the dependence of its complexity on the noise level and system condition (i.e. α and N)[22]. Thenceforth, different versions of conventional SD are investigated to overcome its limitations.

In [22], generalized SD (GSD) is used to improve the condition number of the correlation matrix, through regularization based on Cholesky decomposition. Reported results show an enhancement in system performance compared to SD, but still with random complexity and applicability limited to low noise levels and $N \leq 32, \alpha \geq 0.75$. In order to solve the random complexity problem of SD, the utilization of fixed sphere decoder (FSD) was studied in [36]. FSD has a fixed complexity because it fixes the number of nodes visits at each level of the tree. Logically, by increasing the tree width the BER performance improves and the complexity increases [36]. Although SD outperforms FSD in terms of BER, FSD eradicates the problem of random complexity of SD, making it more suitable for hardware implementation [36].

Thereafter, FSD detectors have been used to detect SEFDM signals. For example, a combination of TSVD with FSD is implemented, where TSVD is used instead of ZF in conventional SD to calculate the initial estimate of transmitted symbols which helps in setting the sphere radius. Then an iterative FSD has been applied to detect SEFDM signals over optical fiber in [37].

Detector designs, less complex than ML, such as boxed SDP-SD detector appeared in [38], which achieved a quasi-optimal error performance for limited signal size and compression factor with a fractional computational effort compared to conventional boxed ML with SDP [38]. Also, in [39], a precoding method is implemented based on zero forcing, where the effect of ICI is inverted before transmission. In this work, an ML detector was used but not on all sub-carriers, as it was proved that $(1-\alpha)N$ of the sub-carriers have high Eigenvalue meaning that they can be detected directly by simple method like ZF, while other sub-carriers are detected by ML. Other techniques, based on 'good enough' heuristic were proposed in the early work on SEFDM [9] and in [40]. Little work has been done in this area since, however, emerging techniques of machine learning based detection [41] and optimization may lead to renewed effort in this area.

To sum up, the aforementioned detectors may be considered as the first generation of SEFDM system detectors. The focus here was to reduce the optimum detector complexity (i.e. ML). However, all suggested systems have restrictions on the SEFDM symbol size N, α and the modulation order M is limited to QPSK, because even with SD the complexity becomes impractical for higher M. To make SEFDM a valid competitor and good applicant for the implementation of future communication systems, the above restrictions are to be addressed. For instance, LTE was launched a few years after the invention of SEFDM and its OFDM symbol size is $N = 1200$ with up to 16-QAM signalling and a simple one-tap frequency equalizer. These are the motivations to get a forward step to the second generation of SEFDM.

Channel coding was firstly introduced to SEFDM in 2014 [42]. In this study, recursive systematic convolutional coding (RSCC) of rate $R_c = 1/2$ is used. An iterative turbo equaliser detector is implemented that subtracts the interference gradually at each iteration. The advantage of the turbo equalizer is in the absence of any matrix inversion, thus, avoiding the ill-conditioned SEFDM system problem. Consequently, the restrictions on α and N are relaxed, while maintaining the spectral efficiency improvement over OFDM.

Turbo equalization was proved to be beneficial in different SEFDM scenarios. In [23], an experimental test bed is designed to evaluate the performance of LTE-A like SEFDM with carrier aggregation. radio over fiber test beds were implemented at 2.4 GHz and 60 GHz, respectively in [43] and [44]. It is shown in these experiments that SEFDM outperforms OFDM with the same spectral efficiency in terms of BER performance, however, with a more complex iterative receiver to eliminate the ICI gradually from SEFDM signals [23].

The work of [45], [46] and [47] further investigate the employment of various forward error correction (FEC) techniques, such as convolutional, turbo, Reed-Solomon (RS), serial concatenation codes and low-density parity check (LDPC) codes for different coding rates. A new interference cancellation receiver was studied to improve the overall system performance, which benefits from channel coding to ameliorate the effects of ICI. Results show that the use of turbo coded SEFDM system can drastically increase the spectral efficiency by up to 67% with a power penalty below 3dB. [47], considers the application of SEFDM, in satellite applications, with LDPC channel coding and advanced interference cancellation processing via serial interference cancellation (SIC) turbo equalisation system and proposes a variable coding, compression and modulation (VCCM), showing not only bandwidth saving advantages over OFDM but also better power efficiency with a small loss of error performance.

In addition to this, the current trend for 5G and beyond systems is to employ windowing and pulse shaping [48]. Following this, in [16], Nyquist RRC filtering is introduced to SEFDM, to reduce the OOBE in the same way as GFDM. However, the difference here is the sub-carriers are closer to each other in SEFDM. Results show that even without any filtering, SEFDM has lower OOBE compared to OFDM and these results agree with the previous work of [30], reporting that SEFDM having lower PAPR compared to OFDM. The concern with this design is the rise in the complexity of the transceiver. In 2015, a group [49] proved that the bandwidth compression issue in SEFDM can be alleviated using optimum envelope forms and the out-of-band power leakage is therefore constrained. It should be noted that the interference introduced by waveform shaping can be mitigated using interference cancellation approach [16] since interference is limited to adjacent sub-carriers.

Finally, the last obstacle to underline for SEFDM detectors is its real time implementation. The growth in integrated circuits capability to cope with high complexity demand makes SEFDM implementation more promising. However, until now, only two detectors have been designed using FPGAs. The first one is a simple linear TSVD detector [26]. Although TSVD is not an optimum solution in terms of BER perfromance, this technique has low complexity which allows it to be implemented in real-time system [26]. The second is an FSD for a 16-sub-carrier receiver system and it is combined with TSVD for the special case of $\alpha = 0.8$ [50].

C. Channel Estimation

The non-orthogonality nature of SEFDM signals further complicates the channel estimation problem. Two time domain channel estimation schemes for SEFDM systems were proposed in [55] and another one in [64]. These schemes show acceptable performance, however, their complexity limits their practical utilisation because they require matrix inversions. Frequency domain channel estimation was therefore proposed in [65]. However, this scheme suffers from the disadvantage of interpolation, that increases the estimation complexity and reduces its accuracy, as the frequencies of sub-carriers in OFDM region are not the same as SEFDM region [65]. The recent work of [61] devise a scheme, where an orthogonal pilot symbol is sent before the SEFDM information symbols. Therefore, this simple yet highly effective scheme does not

Table I
SEFDM: WIRELESS AND OPTICAL COMMUNICATIONS THEORETICAL WORK IN UCL

Reference	Descriptions
2002[5]	Fast OFDM: A proposal for doubling the data rate of OFDM
2003[9]	Proposal of the non-orthogonal waveform (SEFDM) concept
Sept. 2008[35]	An ML SEFDM signal detector
Jun. 2009[22]	Complexity analysis of SEFDM receivers
Sept. 2009[34]	Investigation of SDP signal detector
Sept. 2009[51]	An application of SEFDM in physical layer security
Sept. 2009[38]	A pruned SD signal detector
Jul. 2010[52]	An IFFT SEFDM signal generator
Sept. 2010[53]	A joint channel equalization and detection scheme
Sept. 2010[39]	Precoded SEFDM
Nov. 2010[54]	The use of a fast constrained SD for signal detection
Mar. 2011[33]	Proposal of a TSVD detector
May. 2011[30]	PAPR reduction in SEFDM
May. 2011[36]	Evaluation of FSD detector in SEFDM
Mar. 2012[40]	A stripe detector for interference cancellation
Apr. 2012[55]	A robust partial channel estimation (PCE) scheme for SEFDM
Jul. 2014[56]	Soft demapping for different modulation schemes
Jul. 2014[57]	Block signal detection investigation
Oct. 2014[42]	A soft detector using Turbo principle
Nov. 2014[20]	Overview of SEFDM in 5G
2016[18]	5G enabling technologies book chapter summarizes SEFDM
2016[19]	5G signal processing book chapter summarizes SEFDM
Jul. 2016[17]	Truncating OFDM signals to achieve high spectral efficiency
Jul. 2016[45]	Comparison of Turbo decoder and Turbo equalizer for SEFDM
Jul. 2016[16]	Waveform shaping for IoT
Mar. 2017[58]	Precoding for DSL communications
May 2017[46]	Multiple channel coding schemes are studied
Nov. 2017[59]	Multi-Sphere decoding of block segmented SEFDM signals
Jan. 2018[47]	Applications in satellite systems
Mar. 2018[60]	Reach enhancement in optical fiber transmission
Mar. 2018[61]	New robust low-complex frequency-domain channel estimation scheme for SEFDM
Jul. 2018[62]	Statistical distribution and bounds of SEFDM signals and ICI
Aug. 2018[41]	Machine learning detector for interference cancellation
2018[63]	An efficient narrowband IoT scheme

require channel interpolation and results in accurate channel estimation, at the expense of slightly increased pilot duration overhead.

IV. TABULATED SUMMARY OF SEFDM KEY PAPERS

The overview of the theoretical studies on wireless and optical communications are listed in Table I and Table II. Various signal generation approaches and developed signal detection algorithms have been researched and included. In addition to signal generation and detection, many applications are designed based on SEFDM such as physical layer security, satellite communications, power amplifiers, Internet of things, digital subscriber line (DSL) communications, PAPR suppression and multi-antenna systems. The details of these applications are referred to the references in Table I and Table II. Aside from theoretical studies of SEFDM, significant circuit design work, listed in Table III, and experimental testbed design work, listed in Table IV, have been performed for SEFDM.

Table II
SEFDM: WIRELESS AND OPTICAL COMMUNICATIONS THEORETICAL WORK OUTSIDE UCL

Reference	Descriptions
Mar. 2012[66]	Soft cancellation MMSE Turbo equalization for n-OFDM
Sep. 2013[67]	Frequency packing for spectral coexistence in satellite scenario
Oct. 2013[68]	An improved FSD detector using iterative soft decision method
2013[69]	Gabor transform to reduce the receiver side complexity
2014[70]	BER performance improvement using smoothed envelope signals
May 2015[71]	Asymptotically optimal algorithm was studied
Aug. 2015[72]	Nonlinear distortions caused by power amplifiers were studied
Aug. 2015[49]	Optimum envelope forms were studied
Oct. 2015[21]	The achievable capacity of SEFDM was studied
Oct. 2015[73]	Optimization of envelope forms for the duration of the signals
2015[74]	Mitigation of aliasing and inter carrier interference (ICI) using ASK-manipulated signals
Jun. 2016[31]	Reduced complexity PAPR reduction algorithm for SEFDM
Oct. 2016[75]	Comparison study of sinc pulse and RRC pulse
Oct. 2016[76]	fractional Hartley transform for SEFDM
Dec. 2016[77]	Index modulation was applied to SEFDM
Dec. 2016[29]	Improve spectral and energy efficiency employing optimal envelope
May 2017[78]	Peak to average power ratio suppression study
Jun. 2017[79]	A new system architecture for FTN-SEFDM
Jun. 2017[80]	Multi-antenna SEFDM
Jun. 2017[81]	Performance analysis via using optimal spectrum shape
Aug. 2017[82]	Zero head DFT based waveform design
Sep. 2017[83]	Frequency-domain interference cancellation
Nov. 2017[84]	Decision-feedback SEFDM demodulation
Nov. 2017[85]	ICI mitigation using ICI components reconstruction and cancellation at the receiver

V. CONCLUSIONS

In this survey, we summarized the active research work on SEFDM in the past 15 years. This literature quoted comprises a large but incomplete subset of published work in this area and aims to help in addressing upcoming future lines of work.

Table III
SEFDM: CIRCUIT DESIGN

Reference	Descriptions
May. 2011[27]	A real-time FPGA SEFDM signal generator
Sept. 2011[26]	FPGA design of the TSVD detector
May. 2012[28]	52.2 Mbit/s VLSI based SEFDM transmitter was in 32-nm CMOS
Jun. 2012[86]	A hardware verification methodology for SEFDM signal detection
Sept. 2012[87]	A hybrid DSP-FPGA implementation of the TSVD-FSD detector
May. 2013[50]	1.06 Gbit/s real-time FPGA implementation of TSVD-FSD detector
Jun. 2013[88]	A pure DSP implementation of the modified TSVD-FSD detector
Oct. 2017[89]	FPGA modelling verification on a non-orthogonal iterative detector

Table IV
SEFDM: EXPERIMENTAL TESTBEDS

Reference	Descriptions
Feb. 2014[90]	10 Gbit/s direct detection optical testbed demonstration
Jun. 2014[37]	Direct detection optical transmission experiment
Jun. 2015[43]	Beyond 4G SEFDM radio over fiber transmission
Jun. 2015[91]	5G signal transmission experiment
2016[92]	60 GHz millimeter wave signal transmission experiment
Jan. 2016[65]	24 Gbit/s coherent detection optical testbed demonstration
Jun. 2016[93]	Optical experiment using cascaded BPSK iterative detection (CBID)
Jun. 2016[94]	Overview of SEFDM experiments
Jul. 2016[44]	60 GHz millimeter wave signal transmission at 3.75 Gbit/s
Jul. 2016[95]	2.4 Gbit/s WDM visible light communication (VLC) experiment
Sep. 2016[64]	VLC experiment using RLS time-domain channel estimation
May 2017[23]	Transmission experiment for carrier aggregation in a wireless channel
Oct. 2017[96]	Over-the-Air testing using software defined radio USRP RIO devices
Jan. 2018[97]	Experimental implementations of real-time systems in fading channel
Jun. 2018[98]	Pipelined iterative detection experiment
Jun. 2018[99]	Self interference cancellation experiment
Jul. 2018[100]	Coexistence of LTE and SEFDM signals

Significant 15-year achievements of SEFDM are summarized and listed in the tables at the end of this survey, with a one sentence summary of each. We hope for this survey to be a tool for studying the potential challenges of SEFDM and to pave the way for future development SEFDM fundamentals and practical solutions with the hope that this spectrum saving technique and other related non-orthogonal ones, will find their way towards adoption in future communications standards.

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