Experimental Implementation of Real-Time Non-Orthogonal Multi-Carrier Systems in a Realistic Fading Channel

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***Abstract*—Spectrally efficient frequency division multiplexing (SEFDM) has the potential to improve spectrum utilisation through bandwidth compression at the cost of self-induced inter-carrier interference. In this paper, an experimental test-bed is designed and implemented to evaluate the performance of SEFDM systems in real-time using frequency-domain channel estimation/equalisation and iterative signal detection. Our innovation lies in the development and experimental, real-time implementation of baseband generation, signal assembly, signal decoding and a novel frequency-domain channel estimation and equalisation method for the SEFDM transceiver. Our system compresses the transmitted signal bandwidth up to 60%, 30% and 20% for BPSK, QPSK and 8PSK respectively, offering significant bandwidth savings, and moving towards satisfying one of the key 5G challenges.**

I. INTRODUCTION

In future (5G) networks, user demand is expected to be significantly in excess of the total current network supply. Although future 5G standards are still not fixed, one of the most important requirements is higher spectrum efficiency. To achieve this, either the frequency distance between subcarriers is scaled down to save bandwidth, breaking the orthogonality limit, or the data is sent faster. Generally, both techniques result in non-orthogonal signals, that could either save bandwidth or time.

During the last decade, spectrally efficient frequency division multiplexing (SEFDM) signals and systems have been proposed to reduce the spacing between the subcarriers and pack more subcarriers into the available bandwidth [1], whilst avoiding the degradation of the bit error rate (BER), relative to orthogonal frequency division multiplexing (OFDM). Similarly, multi-stream faster-than-Nyquist (MFTN) systems have been suggested to improve the spectral efficiency beyond the Nyquist limit [2] [3]. Recently, a new waveform termed truncated OFDM (TOFDM) is proposed [4], where the transmission rate is increased without sacrificing bandwidth by partial time transmission of OFDM symbols, resulting in a shorter transmission time for OFDM symbols and frames to improve the data rate.

One of the major disadvantages of SEFDM is its high computationally complex receivers. The two main suggestions to reduce computational complexity are, (*i*) employing channel estimation and equalisation in the frequency-domain, and (*ii*) applying a low complexity coded iterative detector [5] [6], which employs convolutional coding and the turbo principle.

This paper is organised as follows, Section II describes the experimental setup for the SEFDM system under test. The measured BER results are used to evaluate the system performance and are shown in Section III. Finally, Section IV concludes the paper.

II. EXPERIMENTAL SETUP

This section presents the software and hardware setup of the real time experiment for evaluation of SEFDM systems in the Long Term Evolution (LTE) EPA5 channel. In general, the test-bed of this experiment consists of universal software radio peripheral (USRP) transceivers (NI USRP RIO N2395R) programmed using LabVIEW, plus, a Spirent VR5 channel emulator to generate realistic LTE channels. Both software and hardware specifications are detailed below.

A. Design and Setup System Transmitter

At the transmitter, a stream of pseudorandom bits $U1$ is generated before coding. This experiment employs a recursive systematic convolutional coder with code rate $R_c = 1/2$, followed by a block interleaver before being mapped onto the appropriate constellation (shown in blue in Fig. 2). In this work, we test binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) and 8-phase shift keying (8-PSK).

Next, the complex data is divided into parallel streams by a serial-to-parallel converter. The parallel streams are fed to

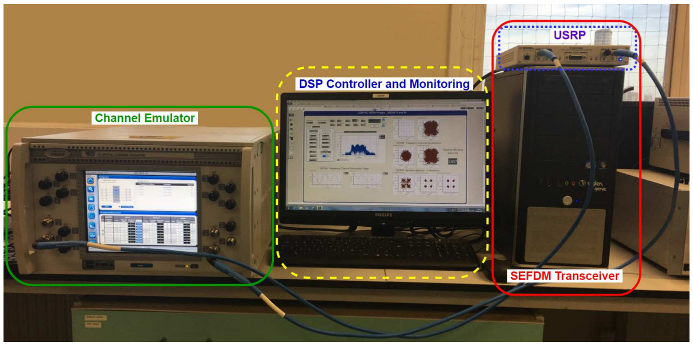

Fig. 1. SEFDM transceiver test-bed setup

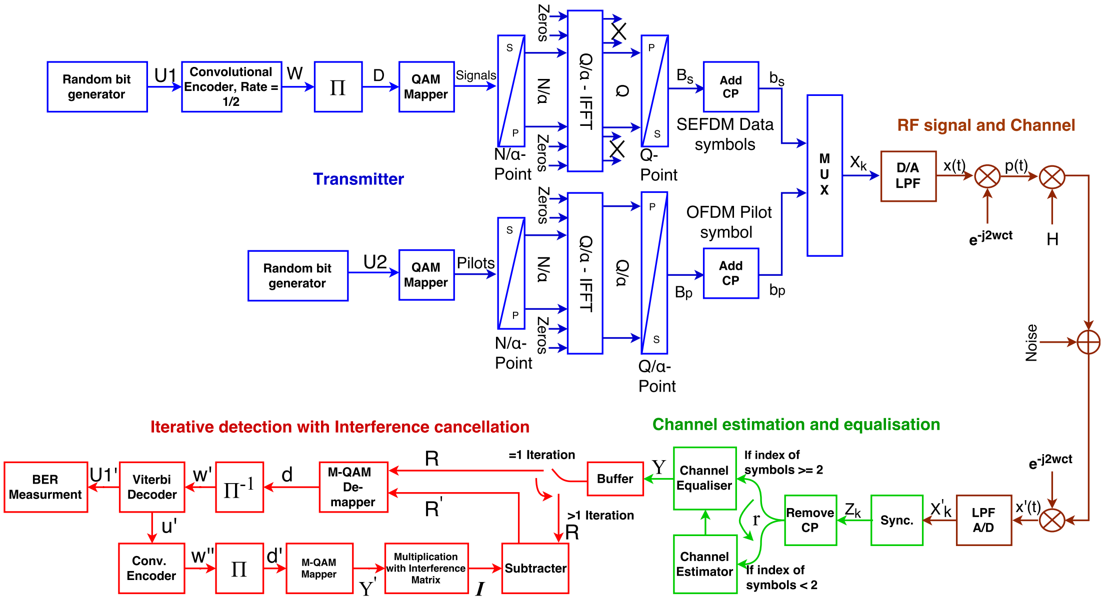

Fig. 2. Schematic block diagram of SEFDM system

an inverse fast Fourier transform (IFFT) of length (the upper one in the blue part in Fig. 2). After that, a cyclic prefix (CP) is added at the beginning of every transmitted symbol. In this work, the symbols are transmitted in frames, where each frame consists of a pilot symbol followed by 24 data symbols.

In the final stage of the transmitter, the complex baseband signal, X_k, is fed to an FPGA contained within the aforementioned USRP to perform digital-to-analogue (D/A) conversion and up-conversion to the 2 GHz band. Table I depicts the system parameters of this experiment.

TABLE I
EXPERIMENTAL SYSTEM SPECIFICATIONS

Parameters	**Values**
Central carrier frequency	2 GHz
Sampling frequency	30.72 MHz
Signal bandwidth	18 MHz
Values of α	1 (OFDM); 0.9; ...; 0.4
Subcarrier baseband bandwidth	60 KHz
Subcarrier spacing	$\alpha \times 60$ KHz
IFFT/FFT size	512
Cyclic prefix	128 time samples
Modulation scheme	BPSK; QPSK; 8-PSK

B. LTE Fading Channel Model and Channel Estimation and Equalisation

The RF signal is transmitted through a VR5 channel emulator that has LTE EPA5 wireless channel model [9]. The signal output of the VR5 is fed to the USRP receiver to deliver the baseband digital domain signal. A Schmidl and Cox [10] synchronization is applied in this experiment, where two identical timing sequences are added at the start of each frame to estimate the first sample of the data symbols.

Following this, the CP is removed from the received symbols and the first symbol of r, the OFDM pilot symbol is fed to a single tap channel estimator. Consequently, the channel estimator output with the data symbols are fed to the channel equaliser to mitigate the phase and amplitude distortion from the signal.

C. Iterative Detector with Interference Canceller

At the detection stage, an iterative detector with an interference canceller are utilised to retrieve the data. The equalised signal, Y is de-mapped and de-interleaved before viterbi decoding. Next, the recovered, decoded data, in combination with the knowledge of the correlation matrix, are used to estimate the interference, I generated in SEFDM due to the compression of the subcarriers spacing. The correlation matrix contains information about the contribution of the interference from all the subcarriers to to each subcarrier [11]. After subtracting the estimated interference, the signal, R' is sent to the next iteration to get an enhanced version of the estimated signal; repetition of this process leads to a better signal estimates. A buffer stores the equalised symbols, Y until a specified number of iterations have been performed.

III. EXPERIMENTAL RESULTS

The measured BER of BPSK, QPSK and 8PSK-SEFDM are shown in Fig. 3, Fig. 4 and Fig. 5, respectively.

It is evident that SEFDM systems are compatible with varying degrees of modulation cardinality. For instance, in Fig. 3, a BPSK-SEFDM system can achieve sufficiently low BERs at $\alpha \longrightarrow 0.4$, where a power penalty of approximately 2 dB is observed. In terms of trade-off for the improved spectral efficiency obtained using this particular system, such a power penalty may be tolerable.

From Fig. 4, it should be noted that at a compression factor of 20%, i.e. $\alpha = 0.8$, QPSK-SEFDM shows pseudo-equivalent performance in comparison to conventional OFDM, where less than 1 dB power penalty is observed. Furthermore, the 8-PSK-SEFDM system works for $\alpha = 0.8$, with a power penalty $<$3 dB. The results from Fig. 4 and Fig. 5 also show that subcarriers can be compressed to a limit where an error floor appears at low values of α, such as $\alpha \sim 0.6$ for QPSK-SEFDM and $\alpha \sim 0.7$ for 8PSK-SEFDM.

IV. CONCLUSION

In SEFDM systems, which demonstrate significant spectral efficiency gains, real-time system implementation is a challenge due to the combined impact of inter-carrier interference and multi-path effects. The paper introduces a world-first, experimental real-time implementation of baseband generation, signal assembly, signal decoding and a novel frequency-domain channel estimation and equalisation method, where OFDM pilot symbol precedes the SEFDM information signal to facilitate accurate frequency-domain channel estimation. Such experimental results were obtained by testing signals over the LTE EPA5 fading channel generated by a VR5-channel emulator operating at a frequency of 2 GHz.

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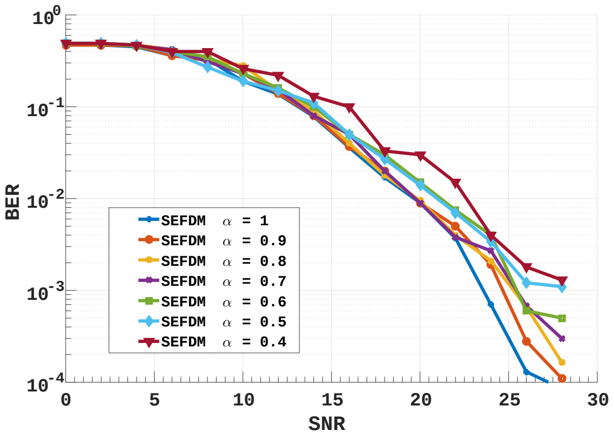

Fig. 3. BER of BPSK-SEFDM using OFDM pilots

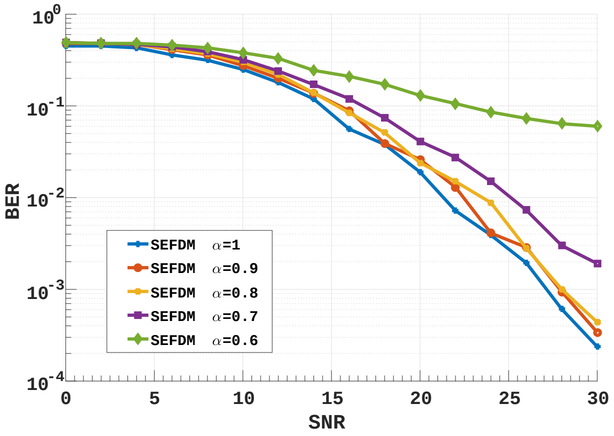

Fig. 4. BER of QPSK-SEFDM using OFDM pilots

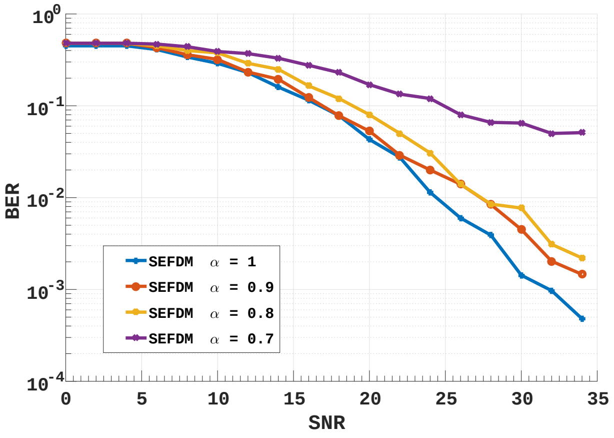

Fig. 5. BER of 8-PSK-SEFDM using OFDM pilots

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