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Hybrid Equalization and Interference Suppression for Orthogonal Chirp Division Multiplexing Systems

Tarak Arbi

Department U2IS, ENSTA Paris
Institut Polytechnique de Paris, France
tarak.arbi@ensta-paris.fr

Bruno Monsuez

Department U2IS, ENSTA Paris
Institut Polytechnique de Paris, France
bruno.monsuez@ensta-paris.fr

Benoît Geller

Department U2IS, ENSTA Paris
Institut Polytechnique de Paris, France
benoit.geller@ensta-paris.fr

Abstract—Orthogonal Chirp-Division Multiplexing (OCDM) has emerged as a promising modulation scheme for high-speed communication: it uses orthogonal linear chirps to spread data symbols across both time and frequency domains. OCDM offers better Bit Error Rate (BER) performance than Orthogonal Frequency Division Multiplexing (OFDM) over frequency-selective channels, since multiple low-complexity OCDM receivers designed to leverage channel diversity have already been proposed in the literature. However, the performance of OCDM state-of-the-art receivers becomes significantly poor under jamming or in interference contexts. In this paper, we propose a novel receiver design to mitigate the impact of interference on the OCDM system performance. The receiver first estimates and suppresses interference in the frequency domain before proceeding with channel estimation and equalization. Residual Inter-Symbol Interference (ISI) and interference may persist in the Fresnel domain. Therefore we propose to use an adaptive linear filter in the Fresnel domain to enhance the system performance. Furthermore, in heavily jammed environments, we propose to reduce the system spectral efficiency and by utilizing underloaded OCDM and optimizing filter coefficients across all known symbols, including the added zero symbols. Simulations demonstrate that our proposed receiver design significantly improves OCDM system robustness against interference.

Index Terms—Orthogonal Chirp Division Multiplexing (OCDM), channel estimation, channel equalization, interference suppression,

I. INTRODUCTION

Orthogonal Chirp-Division Multiplexing (OCDM) has considerably gained attention, in particular for high-speed communication, due to several advantages [1], [2]. First, OCDM employs a set of orthogonal chirps that share the same time and spectral resources without causing interference, resulting in high spectral efficiency. Additionally, various low-complexity OCDM receivers have been proposed, enabling effective utilization of channel multipath diversity. As a result, OCDM outperforms Orthogonal Frequency-Division Multiplexing (OFDM) over frequency-selective channels. Furthermore, OCDM has been shown to be robust against several impairments, including insufficient guard intervals, Doppler shifts, and time or frequency-limited interference [1], [3], making it an attractive modulation scheme for many wireless communication protocols.

At the receiver end, OCDM signals can be equalized using multiple approaches, such as Time Domain Equalizers (TDEs), Frequency Domain Equalizers (FDEs), or other

advanced detection techniques [1]. FDEs are particularly favored in the literature [4] due to their low complexity and strong Bit Error Rate (BER) performance. However, the effectiveness of FDEs is highly dependent on the quality of the channel estimation, which can be challenging in OCDM because the symbols are interdependent in both time and frequency domains. Channel estimation becomes particularly unreliable in time-varying channels and in the presence of interference [5], [6].

Wireless communication systems also operate over an open channel which make them vulnerable to interference from other systems and intentional jamming [7]–[10]. To deal with this issue, spread spectrum technique, such as Direct Sequence Spread Spectrum (DSSS) or Frequency Hopping (FH), are typically used [11]–[13]. In addition, the use of interference cancellation methods, at the receiver side, could lead to a considerable system performance enhancement. In the literature, several interference excision methods have been proposed for spread spectrum techniques. For instance, Finite Impulse Response (FIR) filter for interference suppression in DSSS systems were studied in [14]–[18]. Frequency domain excision methods have been also proposed in the literature [19] and lead to similar performance to those obtained with time domain algorithms based on least squares methods for estimating the jamming signal. Other nonlinear jamming excision methods were proposed in the literature [20].

This paper proposes a novel hybrid domain equalization and interference suppression in OCDM systems. We propose to first use a frequency domain jamming excision algorithm to reduce the impact of jamming on channel estimation. The receiver then uses the Least Square (LS) method to estimate the channel and performs channel equalization in the frequency domain. As the obtained observations may still suffer from jamming and InterSymbol Interferences (ISI) in the Fresnel domain, we propose to use an adaptive Finite Impulse Response (FIR) filter to both reduce the impact of both the residual ISI and interference in the Fresnel domain. Finally, in heavy jamming environments, we propose to lower down the system spectral efficiency by employing an underloaded OCDM scheme. In this scenario, we use all known symbols including the added zeros symbols to update the FIR filter

coefficients. Simulation results show that our approach offers greater resistance to jamming compared to receiver architectures proposed in the literature. The remainder of this paper is organized as follows. Section II reminds the principle of the OCDM transmission schemes and provides the two jammer models that we used in our simulations. Section III details our proposed hybrid equalization and interference suppression method. Section IV presents some numerical results, and Section V concludes the paper.

II. THE SYSTEM MODEL

A. The transmitter side

The information bits b undergo channel encoding as the initial step [21]. The resulting coded bits are subsequently interleaved and mapped to potentially complex modulation symbols. These symbols are organized into blocks, with each block containing N_s symbols. Within a block, $\frac{N_s}{N_u}$ coded symbols are included, where N_u is an integer divisor of N_s for ease of implementation. The parameter N_u represents the number of chirps modulated by the coded symbols. For an underloaded Orthogonal Chirp Division Multiplexing (OCDM) scheme, characterized by $N_u > 1$, the symbols in the i -th block, denoted as $\mathbf{d}^{(i)}$, are arranged as follows [22]:

$$\mathbf{d}^{(i)} = [d_0^{(i)} \quad 0_{1 \times N_s/N_u-1} d_1^{(i)} \cdots d_{N_u-1}^{(i)} \quad 0_{1 \times N_s/N_u-1}]^T. \quad (1)$$

Pilot symbols are inserted so that the i -th transmitted symbol block can be represented as:

$$\mathbf{x}^{(i)} = [\mathbf{p}_0^T \quad \mathbf{d}^{(i)} \quad \mathbf{p}_1^T]^T,$$

where the pilot design in our simulations is given by:

$$\mathbf{p}_0 = \begin{bmatrix} b \\ \mathbf{0}_{K-1} \end{bmatrix}, \quad \mathbf{p}_1 = \mathbf{0}_{K-1},$$

with $\|b\|^2 = \mathcal{P}_b$, where \mathcal{P}_b denotes the power allocated to the pilot symbols. This pilot structure has been shown to effectively minimize the mean square error in channel estimation, as demonstrated in [5].

The time-domain OCDM symbol block, denoted as $\mathbf{s}^{(i)}$, has a length $N = N_s + 2K - 1$ and can be expressed as:

$$\mathbf{s}^{(i)} = \Phi^H \mathbf{x}^{(i)}, \quad (2)$$

where Φ is an $N \times N$ discrete Fresnel transform (DFnT) matrix whose (m, n) th entry is defined as:

$$[\Phi]_{m,n} = \frac{e^{-j\frac{\pi}{4}}}{\sqrt{N}} \begin{cases} e^{j\frac{\pi}{N}(m-n)^2} & N \equiv 0(\text{mod}2) \\ e^{j\frac{\pi}{N}(m+\frac{1}{2}-n)^2} & N \equiv 1(\text{mod}2). \end{cases} \quad (3)$$

Finally, a cyclic prefix, larger than the maximum delay spread of the channel L_h , is added at the beginning of the frame. In the sequel, the block index i is dropped for simplicity reasons.

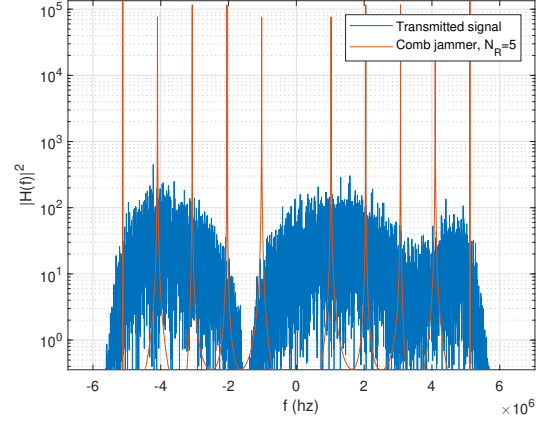


Fig. 1. PSD of the received signal in presence of a comb jammer with $N_R = 5$

B. The received signal

The received signal is the superposition of three components: the transmitted signal, a Gaussian noise and an interference signal. In order to recover the information bits, the receiver first uses several synchronization algorithms such as frame synchronization and Doppler compensation. Assuming the channel to be constant within one block and perfect time and frame synchronization [23]–[26], the received observations for a given symbol block can be expressed as:

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{w} = \mathbf{H}\Phi^H \mathbf{x} + \mathbf{j} + \mathbf{w}, \quad (4)$$

where \mathbf{H} is the Channel Impulse Response (CIR) matrix, \mathbf{j} is the potential jamming signal, and \mathbf{w} is an additive Gaussian noise. The CIR matrix \mathbf{H} is circulant: its first column is $\mathbf{h} = [h^0, h^1, \dots, h^{L_h-1}, 0, \dots, 0]^T$, where h^l are the CIR taps.

In our simulations, we consider two types of interference: the Narrowband Gaussian noise interference and the comb jammer.

1) *Narrowband Gaussian noise interference*: The interference signal can be written as:

$$j_G(t) = \sqrt{2J} p_G(t) \cos(2\pi f_0 t), \quad (5)$$

where J is the interference power, f_0 is the central frequency and $p_G(t)$ is a power normalized narrowband Gaussian noise.

2) *Comb jammer*: The comb jammer can be written as:

$$j_C(t) = \sqrt{\frac{J}{N_R}} \sum_{i=-N_R}^{N_R} \cos(2\pi(f_0 + i\delta_f)t), \quad (6)$$

where N_R represents the number of comb lines within the one-sided Power Spectral Density (PSD) of the interference signal's complex envelope and δ_f is chosen in our simulation so that the jamming signal covers the entire bandwidth of the legitimate signal. Fig.1 illustrate the impact of the comb jammer on the received signal's PSD with $N_R = 5$.

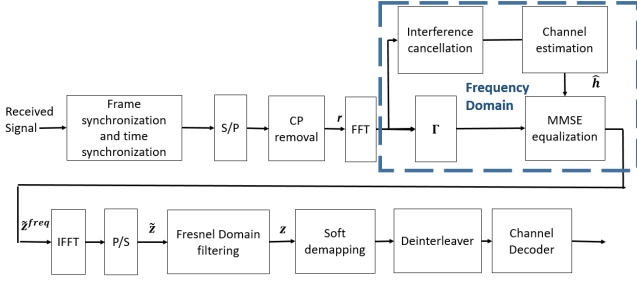


Fig. 2. The proposed receiver design.

III. THE PROPOSED HYBRID DOMAIN EQUALIZATION AND INTERFERENCE MITIGATION

Figure 2 illustrates the design of the proposed receiver. Initially, the receiver conducts frame and time synchronization. The sampled received observations are modeled as described in Eq. (4). Subsequently, we introduce a hybrid equalization and interference suppression algorithm, detailed in the next two subsections. Finally, the receiver calculates the Log-Likelihood Ratio (LLR) for each received bit and performs Bit-Interleaved Coded Modulation (BICM) decoding to retrieve the transmitted information bits.

A. Our proposed equalization and interference suppression algorithm in the Frequency domain

With our proposed algorithm, the receiver first applies a Fast Fourier Transform (FFT):

$$\mathbf{r}_1 = \mathbf{F}\mathbf{H}\Phi^H \mathbf{x} + \mathbf{F}\mathbf{j} + \mathbf{F}\mathbf{w} = \mathbf{\Gamma}^H \mathbf{\Lambda} \mathbf{F}\mathbf{x} + \mathbf{j}_1 + \mathbf{w}_1; \quad (7)$$

where \mathbf{F} is the Fourier matrix of size N , $\mathbf{\Lambda} = \mathbf{F}\mathbf{H}\mathbf{F}^H$, and $\mathbf{\Gamma}$ is a diagonal matrix with $\{\mathbf{\Gamma}\}_{n,n} = e^{-j\frac{\pi}{N}n^2}$. Thereafter, the receivers clips the Fourier components whose energy values exceed the value of a predefined threshold, to the value of the threshold. In our simulation, the threshold is fixed to twice the mean energy. After initial interference suppression, the receiver estimates the Channel Frequency Response (CFR). In our simulations, the channel $\hat{\mathbf{h}}_{LS}$ is estimated using the Least Square (LS) criterion.

Then the receiver performs channel equalization in the Frequency domain as:

$$\tilde{\mathbf{z}}^{Freq} = \mathbf{G}\mathbf{\Gamma}\tilde{\mathbf{r}}_1, \quad (8)$$

where $\tilde{\mathbf{r}}_1$ is the obtained observation after interference suppression in the frequency domain, and \mathbf{G} is a diagonal equalization matrix.

Under the Minimum Mean Square Error (MMSE) criterion $\mathbf{G}(k)$ is given by:

$$\mathbf{G}(k) = \frac{\tilde{\Lambda}^*(k)}{|\tilde{\Lambda}(k)|^2 + \rho^{-1}}, \quad (9)$$

where $\mathbf{\Lambda}$ is the estimated channel frequency response and ρ is the Signal-to-Noise Ratio.

B. Our proposed equalization and interference suppression in the Fresnel domain

In the Fresnel domain, the obtained observations can be written as :

$$\tilde{\mathbf{z}} = \mathbf{F}^H \tilde{\mathbf{z}}^{Freq}. \quad (10)$$

In practice, perfect channel estimation is usually out of reach. Furthermore, the jamming signal can not be completely eliminated in the frequency domain. Thus, the symbols after frequency domain equalization can be expressed in the Fresnel domain as:

$$\tilde{z}_n = \tilde{h}_0 x_n + \sum_{l \neq 1} \tilde{h}_l x_{n-l} + j_2 + w_2, \quad (11)$$

where the second (resp. the third) term in (12) represents the residual ISI (resp. residual interference) in the Fresnel domain. Thus, we propose to use a FIR filter to reduce the impact of both these terms. The output of the FIR filter can be written as:

$$z_n = P_n^T \tilde{Z}_n, \quad (12)$$

where $f_n = [f_{-L}(n), \dots, f_0(n), \dots, f_L(n)]^T$ is a transversal FIR filter of length $2L+1$ and $\tilde{Z}_n = [\tilde{z}_{n+L}, \dots, \tilde{z}_n, \dots, \tilde{z}_{n-L}]^T$.

The filter coefficients P_n is updated over the known symbols so as to minimize the Mean-Square-Error (MSE) criterion defined as [27]–[29]:

$$MSE = \mathbb{E}(|z_n - x_n|^2), \quad (13)$$

The filter coefficients P_n are updated as:

$$P_{n+1} = P_n - \mu \nabla_{P_n} (|z_n - x_n|^2), \quad (14)$$

The filter coefficients P_n are updated over information symbols in a Decision-Directed (DD) mode.

The step size μ is updated using all known symbols, including zero symbols in the case of underloaded OCDM transmissions, as:

$$\mu_{k+1} = \mu_k - \beta \nabla_{\mu} (|z_n - x_n|^2), \quad (15)$$

with β is the second-order step-size.

Finally, in terms of implementation, the computational complexity is an important factor for real-time systems. The frequency-domain jamming excision can be efficiently implemented using FFT-based techniques, while the Fresnel-domain filtering benefits from adaptive methods, making the overall process viable for DSP or FPGA platforms.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed method in terms of Bit Error Rate (BER) across various scenarios.

In the simulations, the information bits are encoded using a 1/2-rate convolutional code with generator polynomials (37, 33). The length of the pilot symbols p_0 is set to 15, while

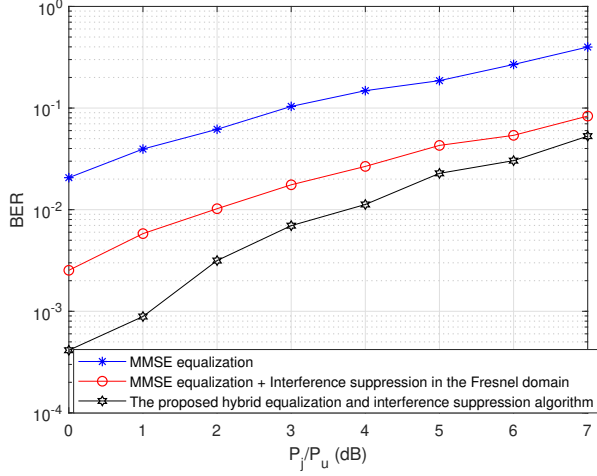


Fig. 3. BER comparison with fully loaded OCDM under narrowband Gaussian interference.

the FIR filter length L is chosen as 10. We consider $N = 1024$ and employ a QPSK constellation.

In our simulations, we also considered a synthetic channel model where each tap is defined as in [27]:

$$h_l(k) = \sqrt{\frac{P_l}{I}} \sum_{i=1}^I e^{j(k\epsilon\pi \cos \psi_{l,i} + \zeta_{l,i})}, \quad (16)$$

where ϵ represents the Doppler shift, P_l is the mean power of the l -th channel path, and $\psi_{l,i}$ and $\zeta_{l,i}$ are uniformly distributed random variables over $[0, 2\pi[$.

For the simulations, we considered three channel paths, each with identical mean power. The parameters were set as $I = 10$ and $\epsilon = 1 \times 10^{-4}$. Similar performance results were observed under different parameter settings.

Finally, we considered three algorithms in our simulations: our proposed hybrid Frequency-Fresnel algorithm, the conventional MMSE equalization in the frequency domain [1], and the conventional MMSE equalization followed by a FIR filter in the Fresnel domain (i.e. no interference suppression in the frequency domain). The last algorithm is referred to in the sequel as "FresOnly".

Figure 3 presents the BER performance obtained with a fully loaded OCDM under a Gaussian noise interference occupying 10% of the transmitted signal bandwidth. It can first be observed that the use of a FIR filter in the Fresnel domain after equalization in the frequency domain offers a considerable gain of roughly 3 dB compared to the conventional MMSE equalization technique. Moreover, our proposed hybrid Frequency-Fresnel equalization and interference suppression outperforms the conventional MMSE by about 5.5 dB and the algorithm "FresOnly" by roughly 1.5 dB.

Moreover, figures 4 and 5 compare the BER performance of the considered algorithms. It is obtained with $N_s/N_u = 2$ and $N_s/N_u = 4$ respectively under the narrowband Gaussian

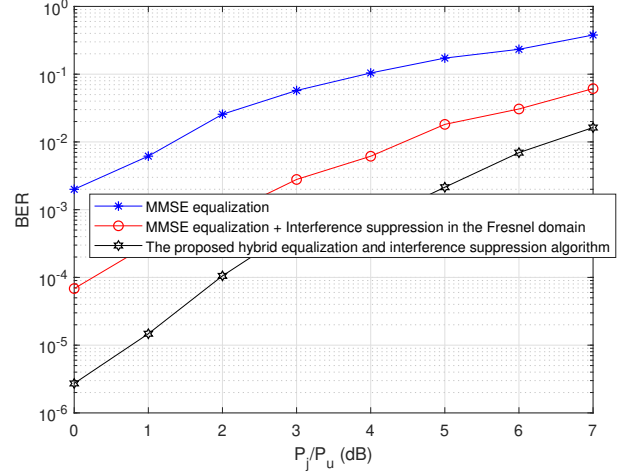


Fig. 4. BER comparison with $N_s/N_u = 2$ under narrowband Gaussian interference.

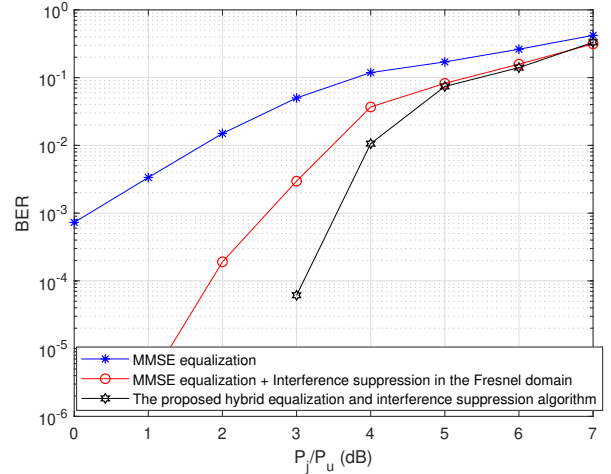


Fig. 5. BER comparison with $N_s/N_u = 4$ under narrowband Gaussian interference.

noise interference. It can be observed again that our proposal outperforms the conventional MMSE equalization by roughly 4.7 dB (resp. 3.5 dB) with $N_s/N_u = 2$ (resp. $N_s/N_u = 4$). It also outperforms the algorithm "FresOnly" by 2 dB (resp. 1.5 dB) with $N_s/N_u = 2$ (resp. $N_s/N_u = 4$). It can finally be observed from figures 3, 4 and 5 that reducing the spectral efficiency, by using an underloaded OCDM system, lead to a higher resistance to interference independently of the receiver architecture. With our proposed receiver architecture, $N_s/N_u = 2$ (resp. $N_s/N_u = 4$) lead to a BER gain of roughly 3.5 dB (resp. 4.5 dB) compared to the fully loaded OCDM.

Finally, figures 6, 7 and 8 compare the BER performance of the 3 considered algorithms under comb jamming with $N_R = 10$, for $N_s/N_u = 1$, $N_s/N_u = 2$, and $N_s/N_u = 4$ respectively. We can observe again that our proposed

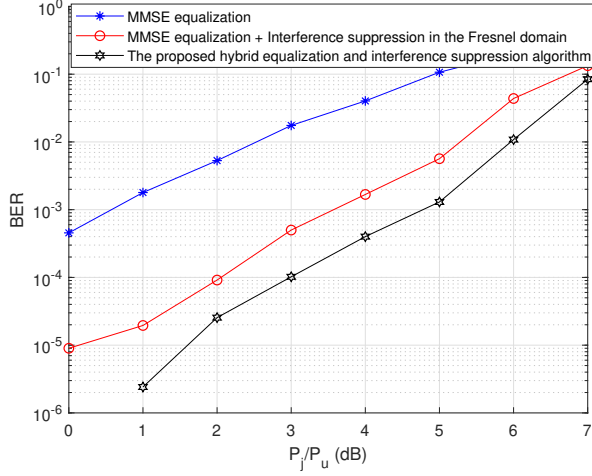


Fig. 8. BER comparison with $N_s/N_u = 4$ under comb jamming.

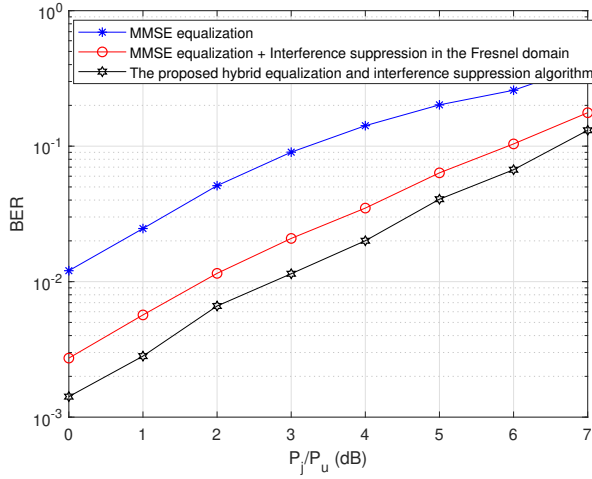


Fig. 6. BER comparison with fully loaded OCDM under comb jamming.

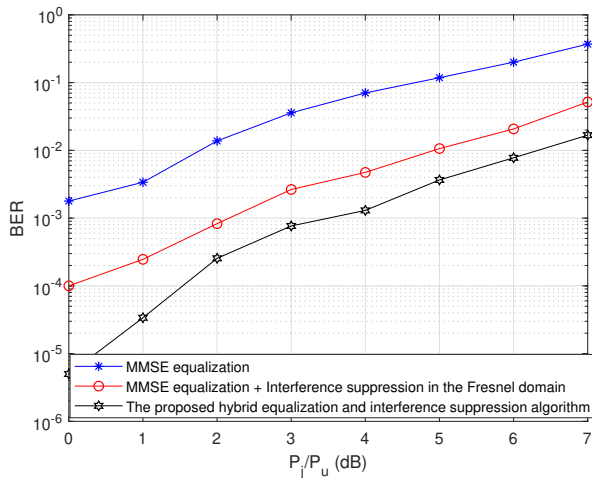


Fig. 7. BER comparison with $N_s/N_u = 2$ under comb jamming.

algorithm provides a gain of between 3 and 4.5 dB depending on N_s/N_u compared to the conventional MMSE equalization and a gain of approximately 1 dB compared to the algorithm "FresOnly". We can also observe that the resistance to the comb jamming increases with N_s/N_u : with the proposed algorithm, a gain of 4 dB (resp. 5 dB) is observed with $N_s/N_u = 2$ (resp. $N_s/N_u = 4$) compared to $N_s/N_u = 1$.

V. CONCLUSION

In this paper, we proposed a novel hybrid domain equalization and interference suppression technique for Orthogonal Chirp-Division Multiplexing (OCDM) systems. First, in the Frequency domain, we propose to use a jamming suppression method prior to channel estimation and equalization. Then, we propose to deal with the residual ISI and interference by using a FIR filter.

Additionally, in heavily jammed environments, we propose to lower the system's spectral efficiency by employing an underloaded OCDM. In this case, we optimize the FIR filter coefficients over all known zero symbols. Simulation results confirmed that our proposal leads to a significant performance gain compared to conventional OCDM receiver architectures, demonstrating its potential for robust high-speed communication in challenging wireless environments. In the future, we would like to further enhance the resistance of OCDM system to jamming by exploring a cross-layer design [30] and studying OCDM systems using rotated constellations [31]–[34]

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