Performance Evaluation of Multi-Carrier Modulation Techniques in High Speed Railway Environment with Impulsive Noise

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Abstract—Multi-Carrier Modulation (MCM) techniques are considered as one of the main building blocks for future railway communication systems. This is due to their ability to handle spectrum scarcity and asynchronous communications dilemmas. In this paper, we evaluate the performance of different outstanding MCM techniques while taking the high speed railway environment into consideration. The High Speed Railway (HSR) environment could be represented by the doubly selective nature of the wireless channel in addition to the challenging non-Gaussian nature of the noise. To this end, we integrate in our system several impulsive noise cancellation schemes and we evaluate the performance of the adopted MCM techniques within the overall HSR railway environment. Different observations are made for different channel scenarios and noise parameters. Based on that, we conclude the MCM technique that has a superior performance and that better suits the HSR environment.

Index Terms—Railway, Waveforms, Mobility, Impulsive noise

I. INTRODUCTION

Future railway communication systems are required to handle different imposed challenges such as the scarcity of the available spectrum and the need to support the wide variety of required services ranging from safety and security services to user comfort ones [1]. Many new enabling technologies have been proposed and analyzed recently [2]. Among which, MCM techniques are considered as a major player [3] since they have direct effects on the spectrum scarcity dilemma, the asynchronized communication and the high data rate requirements.

Many MCM techniques have been proposed recently whereas the well known Orthogonal Frequency-Division Multiplexing (OFDM) waveform has been widely adopted in 3GPP standards such as Wi-Fi, Wimax, 4G and recently in 5G as well. The main reason beyond OFDM wide scale adoption is the simplicity of its transceiver system (IFFT/FFT), in addition to its complex orthogonality feature that allows the adoption of the simple one tap equalizer. Furthermore, its Cyclic Prefix (CP) extension makes it immune to multipaths induced interference. However, one of the main disadvantages of the OFDM waveform is its bad frequency localization which causes critical problems to efficient spectrum reuse and asynchronous communications [4]. Hence, many MCM techniques have tried to handle this frequency localization issue. One way is to deal with it from a time domain perspective i.e., windowing [5]. Another way is by using the filtering approach [6]–[8] where MCMs based on subband filterings have been proposed yielding a trade-off between time and frequency localization such as in Filtered-OFDM (F-OFDM) [8]. On the other hand, subcarrier filtering based MCM techniques have offered the best frequency localization at the cost of a new built-in interference, as in the Filter Bank Multi-Carrier (FBMC) waveform [6].

The majority of MCM techniques are designed so that the transmitted symbols can be detected perfectly at the receiver in ideal channel scenario. However, the doubly selective nature of the HSR channel (the time and the frequency selectivity) makes it more challenging due to the induced Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI) [9]. In addition, railway communication systems suffer from the non-Gaussian nature of the noise [10]. The different studies and measurements that have been carried out [11] in this context have revealed that the nature of this noise is heavy-tailed Impulsive Noise (IN) [12]. In order to mitigate the impact of the impulsive noise, multiple techniques have been adopted in the literature such as clipping and blanking where the signal is blanked or truncated, respectively, if it exceeds a predefined threshold [13], [14].

In this paper, the performance of the aforementioned MCM techniques is numerically evaluated in the HSR wireless environment. The doubly selectivity nature of the HSR channel is analyzed while taking the non-Gaussian nature of the additive noise into consideration. In addition, the effects of the non-linear clipping and blanking schemes on the different MCM techniques are investigated. Furthermore, the performance is...
analyzed for different Doppler spread values. Based on that, the FBMC waveform has shown high robustness against high mobility scenarios compared with other MCM schemes. This was noted in both white Gaussian noise and impulsive noise cases. However, in the IN case, we note that the performance gap is decreased between the different MCM schemes and the superiority of the FBMC become negligible. This FBMC superiority could be seen again when applying the IN clipping and blanking schemes. The rest of the paper is organized as follows. Section II presents the MCM technology and the adopted techniques within our study. Section III considers the wireless HSR channel and its accompanied challenges. Section IV conducts the numerical evaluation analysis while section V concludes the work.

II. MULTI-CARRIER MODULATION TECHNIQUES

In multi-carrier modulation techniques, the baseband transmitted signal in the time domain can be written as follows

\[ s(t) = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} g_{m,k}(t) x_{m,k} \]  

(1)

where \( x_{m,k} \) is the mapped symbol e.g. Quadrature Amplitude Modulation (QAM), Pulse Amplitude Modulation (PAM), that is transmitted at the \( mth \) subcarrier and the \( kth \) time symbol with \( K \) denoting the number of time domain symbols and \( M \) the number of sub-carriers of the whole transmission block. \( g_{m,k}(t) \) is the transmitted basis pulse which is given by

\[ g_{m,k}(t) = f(t - kT)e^{j2\pi mF(t-kT)} \]  

(2)

This could be seen as the prototype filter \( f(t) \) after applying a time shift of \( kT \) and a frequency shift of \( mF \), where \( T \) and \( F \) denote to the time and frequency spacing respectively.

After conducting the sampling process, Eq. (1) can be written in a matrix form as follows

\[ s = Gx \]  

(3)

Where

\[ G = [g_{1,1}g_{2,1}...g_{M,1}g_{1,2}...g_{M,2}] \]  

(4)

\[ x = [x_{1,1}x_{2,1}...x_{M,1}x_{1,2}...x_{M,2}]^T \]  

(5)

By sampling \( g_{m,k}(t) \) in Eq. (2), the samples are grouped in one vector \( g_{m,k} \in \mathbb{C}^{N \times 1} \) where \( g_{m,k} = G(:,m,k) \). We denote by \( N \) the number of samples of the whole transmission block.

The design of an MCM technique is subject to the Balian Low Theorem (BLT) [3]. In other words, any MCM technique cannot satisfy the following three properties simultaneously, only two can hold:

1) Complex orthogonality \( QG = I \)

Where \( Q \in \mathbb{C}^{MK \times N} \) is the demodulation matrix at the receiver.

2) Full spectral density \( TF = T_0F_0 = 1 \)

Where \( T_0 = 1/F_0 \) represents the minimal spacing.

3) Time Frequency Localized “TFL” filters. This implies that \( \sigma_f \sigma_f < \infty \) where \( \sigma_t \) and \( \sigma_f \) indicate the prototype filter localization in time and frequency domain, respectively.

Hence, many MCM techniques have been proposed recently while offering different tradeoffs from the BLT perspective, so that they can satisfy the requirements of the application at hand.

A. OFDM

The OFDM waveform has been widely adopted and studied in the last two decades due to guarding the complex orthogonality and the full spectral efficiency properties of the BLT theorem. This features have lead to a low complexity level at the receiver while best exploiting the available time-frequency resource grid. However, on one hand OFDM needs to add a cyclic prefix at to eliminate the ICI coming from multipaths and hence the low complexity receivers. On the other hand, the fact that OFDM utilizes prototype filter with rectangular pulse shape leads to unlocalization in the frequency domain \( \sigma_f = \infty \). This issues have led to major problems in asynchronous communications and efficient spectrum reuse applications [4].

B. Windowed OFDM

One way to handle the degraded frequency localization of OFDM waveform is by using windowing, which results in the so-called OFDM with Weighted Overlap and Add (WOLA) waveform. Windowing is meant to smooth the edges of the rectangular OFDM symbol while guarding the same overhead as that of CP-OFDM waveform. This is possible by allowing the adjacent WOLA symbols to overlap in the edge transition region, as clearly explained in [15]. This windowing principle could be applied at the receiver also since it helps handling ISI problem of asynchronous users. Different kinds of windowing have been studied in the literature as a trade off between the width of the main lobe and the suppression of side lobes.

C. Filtered OFDM

In order to better enhance the frequency localization property, filtering should be included. This can be carried out by filtering each group of subcarriers (subband) on its own that leads to a tradeoff between time and frequency localization. In each subband, a conventional OFDM system is applied and then multiplied by a specific window (e.g., Hann window). In addition to its better frequency localization, F-OFDM offers a high degree of flexibility since it allows each subband to be designed in a specific way that could satisfy the requirements of the application at hand while considering the accompanied channel conditions [8].

D. FBMC-OQAM

In order to provide the best frequency localization characteristics, the FBMC based waveform maintains the frequency localization feature of BLT by sacrificing either the full spectral efficiency as in FBMC-QAM [6], or the complex orthogonality condition as in FBMC-Offset QAM (FBMC-OQAM). In fact,
FBMC-OQAM replaces the complex orthogonality condition with a one in the real domain i.e. $\mathbb{R}(QG) = I$. This becomes possible by adding a phase shift term $\theta_{m,k} = \frac{\pi}{2} (m+k)$ to Eq. (2), which guarantees the real orthogonality in ideal channel scenario.

$$g_{m,k}(t) = f(t - kT)e^{j2\pi mF(t - kT)}e^{j\theta_{m,k}}$$ (6)

Different designs have been proposed for the prototype filter $f(t)$ where we adopt the Hermite filter which is equally localized in time and frequency domains. We consider it with an overlapping factor of $O = 4$.

III. THE HSR RADIO ENVIRONMENT

A. The system transmission matrix

The transmitted signal of Eq. (3) will go through a time varying channel traversing different multi-paths. The time domain received vector $r \in \mathbb{C}^{N \times 1}$ is written as follows:

$$r = HGx + \eta$$ (7)

where $H \in \mathbb{C}^{N \times N}$ represents the time variant channel convolution matrix while the additive noise is represented by the vector $\eta \in \mathbb{C}^{N \times 1}$. Thereafter, the demodulation process is applied and the demodulated signal is written as follows:

$$y = Qr = QHGx + Q\eta$$ (8)

where $D \in \mathbb{C}^{MK \times MK}$ represents the System Transmission Matrix (STM). In doubly flat wireless channels and with MCM techniques that maintain the orthogonality property, the STM becomes diagonal. This diagonality property allows the use of simple equalizers at the receiver, e.g., one tap equalizer.

$$\hat{x} = diag(D)^{-1}y$$ (9)

The doubly selectivity of the HSR environment will spread the power of the diagonal part across the non-diagonal elements of $D$ causing inter-symbol and inter-carrier interference. For the same channel conditions, the robustness against these ISI and ICI depends on the adopted MCM technique. This fact is represented in Fig. 1 where we draw the averaged normalized power distribution $P \propto 10\log(D^*D^H)$ of different MCM techniques while considering the ITU-R Vehicular-A channel model [16] with Jakes Doppler Model for a normalized maximum Doppler spread of $f_D = 0.03$ with terminal speed of 200 km/h.

B. Impulsive Noise

In the railway environment, the noise vector $\eta$ does not follow the widely adopted white Gaussian distribution but it rather has a non-Gaussian one. This fact deteriorates the performance at the receiver and necessitates the need for special treatment.

1) Impulsive Noise Model: Different models have been proposed to simulate the impulsive noise nature, such as the Gaussian mixture and the Middleton class A models [10]. However, the symmetric alpha stable distribution has proven to better model the impulsive noise nature in the railway environment [12]. Hence, we adopt the same assumption.

The characteristic equation of the $S\alpha S$ distribution could be written as follows:

$$\phi(t) = e^{j\mu t - |t|^\alpha}$$ (10)

where $\alpha \in [0, 2]$ is the characteristic exponent that measures the tail heaviness of the distribution i.e. the impulsivity of the noise, while $\gamma > 0$ is the scale parameter (the dispersion). $\mu \in \mathbb{R}$ is the localization parameter. We use the Generalized SNR
(GSNR) definition in our study, defined as the ratio between the average signal power \( P_t \) to the noise dispersion \( \gamma \).

\[
\text{GSNR} = \frac{P_t}{\gamma}
\]  

(11)

C. Impulsive noise pre-processor

The literature of IN cancellation schemes is rich, ranging from many iterative interference cancellation schemes as in [18] to whitening the IN nature by using Myriad [19]. We adopt in our study the simple memoryless nonlinearity pre-processing techniques, such as the blanking and clipping schemes [13], [14]. This choice is made since they do not totally destroy the diagonality property of the STM matrix, as apposite to Myriad case, hence allowing us to maintain low complexity at the receiver side while using the simple one tap equalizer of Eq. (9).

The blanking and clipping schemes are applied on the received signal in time domain, before the demodulation process, on a sample by sample basis.

1) Blanking scheme:

\[
\hat{r}(n) = \begin{cases} 
  r(n), & |r(n)| \leq \lambda \\
  0, & |r(n)| > \lambda 
\end{cases}
\]  

(12)

2) Clipping scheme:

\[
\hat{r}(n) = \begin{cases} 
  r(n), & |r(n)| \leq \lambda \\
  T_e \arg(r(n)), & |r(n)| > \lambda 
\end{cases}
\]  

(13)

where \( \lambda \) is the predefined threshold value.

IV. PERFORMANCE EVALUATION

In this section, we conduct a numerical performance evaluation of the studied MCM techniques in terms of Bit Error Rate (BER) while taking into consideration different aspects of the radio propagation wireless environment. To this end, we consider the one-tap equalizer of Eq. (9) while conducting Monte Carlo simulations with 1000 repetitions. Jakes model is adopted while considering Vehicular-A power delay profile. A subcarrier spacing of 15 kHz and a carrier frequency of 2.5 GHz are considered. In table I, the adopted simulation parameters of the analyzed MCM techniques are illustrated. We consider both the Symmetric \( \alpha \) Stable and the White Gaussian Noise (WGN) cases. The WGN could be considered as a special case of the SoS case by setting \( \alpha = 2 \). Unless stated otherwise, we consider \( \alpha = 1.2 \) and \( \gamma = 0.4 \) where [12] has proven that these settings fit well the high speed railway environment. To handle the impulsive noise induced interference, we study also the performance of the clipping and blanking schemes of Eqs. (12-13). We choose the threshold \( (\lambda) \) to be equal to the maximal value of the noiseless received signal. We consider also a terminal speed of 200 km/h unless stated otherwise.

We start in Fig. 2 by drawing the BER performance of the studied MCM waveforms for different GSNR values and a fixed terminal speed of 200 km/h. Different conclusions could be made from this figure. Starting with the WGN (\( \alpha = 2 \))

\[\text{GSNR} = \frac{P_t}{\gamma} \]  

Figure 2. BER performance versus SNR for different impulsive noise settings and under a terminal speed of 200 km/h.

Figure 3. BER performance versus \( \alpha \) with \( \gamma = 0.4 \) and a speed of 200 km/h where we compare the blanking and clipping schemes with the no IN pre-processing case.

case, we can clearly see the superiority of the FBMC-OQAM waveform, followed by the WOLA and the CP-OFDM waveforms, while ending up with the F-OFDM scheme. Although this order is preserved in all other cases of Fig. 2, we can see that the performance gap of the different MCM schemes is decreasing when treating the IN with clipping and blanking schemes to almost disappear in the non-treatment case. We can also note that adopting clipping and blanking techniques enhances the BER performance of all studied MCM schemes with the blanking scheme giving better accuracy.

Another interesting varying parameter is the terminal speed. In Fig. 4, we fix the GSNR value to 25 dB while evaluating...
the performance for different terminal speeds, ranging from 0 to 500 km/h. We note also that FBMC-OQAM performs the worst in low speed scenarios while CP-OFDM and WOLA has almost the best performance. This could be explained due to the fact that in low speed scenarios, the power spread of the STM matrix in the CP-OFDM and WOLA cases could be seen as almost diagonal. On the other hand, STM is highly non-diagonal in the ideal channel case of FBMC-OQAM waveform, hence explaining its bad performance in low mobility scenarios. In Fig. 3, we consider different settings of the parameter $\gamma$ while fixing the GSNR value to 25 dB and the terminal speed to 200 km/h. We ca note that the same performance order of the different MCM schemes is preserved for all the values of $\gamma$ in the IN clipping, blanking and the non-treatment cases.

V. CONCLUSION

In this paper, we have considered several MCM techniques, CP-OFDM, FBMC-OQAM, WOLA and the filtered OFDM waveforms. These MCM techniques have been numerically evaluated in high speed railway environment. Their performance is evaluated against the doubly selectivity (time and frequency selectivity) nature of the HSR environment where we consider a multipaths channel with different terminal speeds settings. In addition, HSR suffers from a non Gaussian noise which deteriorates the performance of wireless communication systems. Hence, we adopt the Symmetric Alpha Stable distribution to model the IN and we consider the nonlinear blanking and clipping schemes to cope with it. These schemes allow us to maintain to some degree the diagonality property of the system transmission matrix and hence using the simple one tap equalizer. Based on that, we evaluate the overall performance of the different MCM techniques within the HSR environment. The FBMC-OQAM waveform outperforms other MCM techniques and this is due to its well frequency localized filters which makes it more immune to Doppler spread induced interference. In addition, we note that the impulsive noise have equivalent effect on the different MCM techniques and that the adopted nonlinear cancellation schemes well enhance the performance for all studied MCM techniques while guarding the superiority of FBMC-OQAM. Future works include conducting real world measurements in a railway environment while considering practical blanking and clipping schemes. The performance of other impulsive noise filters e.g., the Myriad filter, could be evaluated also for the different MCM schemes.

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