Throughput-Based Performance Evaluation of 5G-Candidate Waveforms in High Speed Scenarios

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***Abstract*—The radio access technology for railway communications is expected to migrate from GSM for Railways (GSM-R) to a more suitable generation of communication systems for the services offered nowadays, like the fourth generation (4G) or the fifth generation (5G). Recently, considerable attention has been devoted to high-speed trains since this particular environment poses challenging problems in terms of performance simulation and measurement. In order to considerably decrease the cost and complexity of high-speed measurement campaigns, we proposed in the past a technique to induce effects caused by highly-time varying channels on multicarrier signals while conducting measurements at low speeds. This technique has been proved to be accurate for Orthogonal Frequency-Division Multiplexing (OFDM) signals, as well as for the waveforms proposed for 5G systems, such as Filter Bank Multicarrier (FBMC). In this work, we employ the technique to estimate experimentally the throughput of modulation schemes proposed for 5G (Cyclic Prefix Orthogonal Frequency-Division Multiplexing (CP-OFDM) and FBMC) at high speeds.**

I. Introduction

Broadband communications in high-speed scenarios is a hot research topic. Particularly, the so-called High-Speed Train (HST) scenario became attractive because the obsolete GSM for Railways (GSM-R) has to be replaced with a much better technology supporting advanced broadband railway services. Long Term Evolution (LTE) is the best candidate to replace GSM-R in near future. In the long term, however, the so-called fifth generation (5G) systems are well positioned to become the fundamental communications technology for railways.

Among the novelties to be introduced by 5G systems, Filter Bank Multicarrier (FBMC) has been proposed as a candidate waveform to replace the widespread Cyclic Prefix Orthogonal Frequency-Division Multiplexing (CP-OFDM) [1]. In theory, FBMC offers important benefits like for example a higher bandwidth efficiency or a better optimization for channels exhibiting both time and frequency selectivity [1], [2]. Therefore, although it is expected that FBMC outperforms CP-OFDM in HST doubly selective scenarios [2]–[6], measurement-based analyses are required to validate the theoretical predictions, which is the main objective of this paper.

Unfortunately, performing measurements in railway scenarios at high speeds is extremely expensive and takes too much time in advance for their preparation. To mitigate this problem, we have previously proposed and validated a technique to emulate high speeds by means of inducing their effects in multicarrier signals (CP-OFDM and FBMC) whereas the measurements are performed at much more affordable velocities [7]–[10]. Particularly, in [11] we employed such a technique to assess the performance of FBMC and CP-OFDM signals –in terms of uncoded Bit Error Ratio (BER) versus Signal-to-Noise Ratio (SNR)– in a high speed scenario.

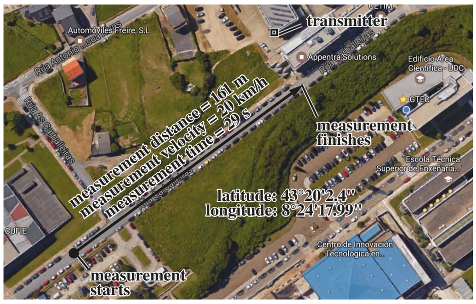

Fig. 1. Scenario considered for the measurements.

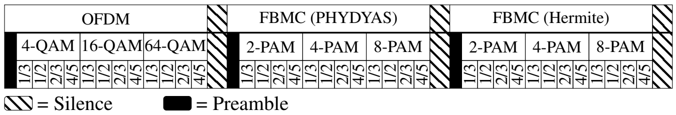

Fig. 2. Frame structure considered for the measurements.

Based on the same scenario and measurement setup as those described in [11], we carried out a new measurement campaign after incorporating channel coding to both CP-OFDM and FBMC signals, hence allowing for a measurement-based throughput analysis considering different modulation and coding schemes. Furthermore, the relative contribution per constellation type and code rate to the total throughput is also presented considering receiver speeds up to 500 km/h.

II. Description of the Experiments

We considered the same scenario (see Fig. 1), setup, measurement hardware and software[1] as in [11]. The main parameters used in the experiments are summarized in Table I.

The throughput is estimated at the receiver by making use of the frame structure shown in Fig. 2. This frame contains three subframes: CP-OFDM, FBMC with the so-called PHYDYAS prototype filter, and FBMC with the Hermite filter. Each subframe is divided into blocks having different constellation sizes and coding rates as shown in Table I.

[1]Hardware and software used in the measurements are part of the "GTEC 5G Simulator" [12], which is publicly available under the GPLv3 license [13].

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TABLE I
FUNDAMENTAL PARAMETERS OF THE EXPERIMENTS.

parameter	value
used subcarriers	600 (excluding DC)
subcarrier spacing	15 kHz
CP length (CP-OFDM)	72 samples
constellations	2-PAM, 4-PAM, 8-PAM (FBMC) 4-QAM, 16-QAM, 64-QAM (CP-OFDM)
pilot spacing	frequency: 8 subcarriers time: 8 symbols (FBMC), 4 (CP-OFDM)
symbols per block	8 (FBMC), 4 (CP-OFDM)
carrier frequency	2.6 GHz
transmit power	+18.5 dBm (at antenna input)
measurement velocity	fixed at 20 km/h
emulated velocities	200, 300, 420, 500 km/h
coding rates	1/3, 1/2, 2/3, 4/5

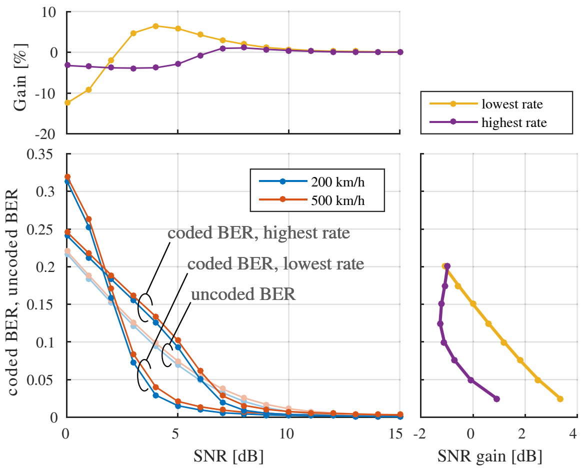

Fig. 3. Coded and uncoded BER versus SNR for the minimum and maximum emulated speeds for FBMC (Hermite case) and 2-PAM constellation. The coding gain for the case of the maximum speed is also provided, both in terms of BER and effective SNR.

To calculate the throughput for a given set of constellation type, interpolation factor, and SNR value, we first add the necessary Additive White Gaussian Noise (AWGN) to obtain the target SNR (if possible, i.e., the SNR of the received signal should be higher than the desired SNR, otherwise the frame is discarded). Next, we demodulate each frame and we find out the block with the highest number of bits among those received without errors. To obtain the throughput for each frame we simply divide the total number of bits in that block by the block duration (calculated as the number of multicarrier symbols times the symbol period). Finally, we average out the obtained throughput values for all the frames.

III. RESULTS

Depending on the considered communication system, it could be desirable to minimize the latency (e.g., critical communications related with train control and safety) or to maximize the throughput (e.g., provisioning of non-critical services to train passengers). In the first case, the goal is to reduce the BER to the minimum achievable level, hence minimizing the number of retransmissions. For the second case, by considering a less conservative coding rate, we can transmit more data bits per frame, possibly increasing the latency since more retransmissions will be required. In this section we evaluate the performance of the system both in terms of (coded and uncoded) BER as well as throughput.

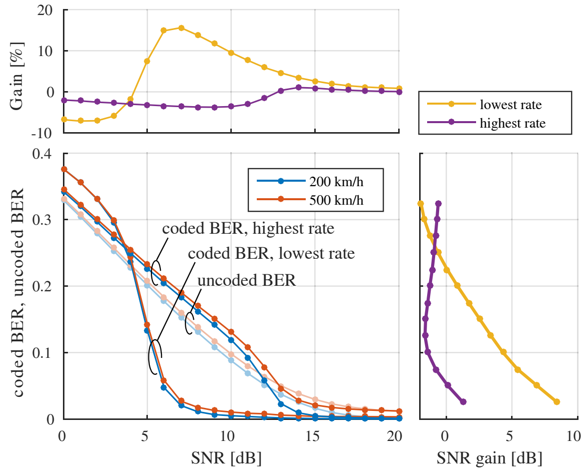

Fig. 4. Coded and uncoded BER versus SNR for the minimum and maximum emulated speeds for FBMC (Hermite case) and 4-PAM constellation. The coding gain for the case of the maximum speed is also provided, both in terms of BER and effective SNR.

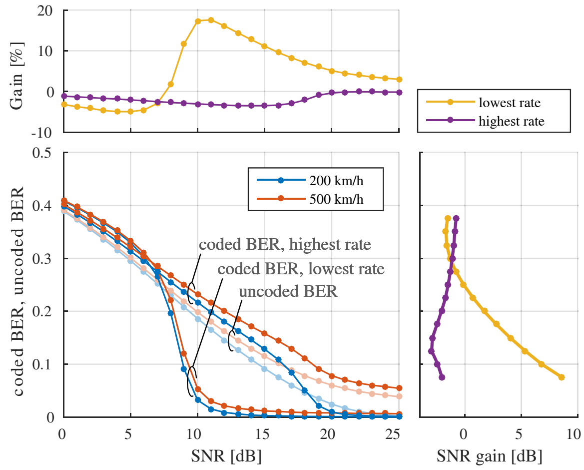

Fig. 5. Coded and uncoded BER versus SNR for the minimum and maximum emulated speeds for FBMC (Hermite case) and 8-PAM constellation. The coding gain for the case of the maximum speed is also provided, both in terms of BER and effective SNR.

Fig. 3 shows the coded BER versus SNR for the case of an FBMC modulation (Hermite pulse) when considering a 2-PAM constellation. The uncoded BER results previously obtained in [11] are also shown for comparison. We show the coded BER for the highest and the lowest coding rates, as well as the maximum and minimum emulated speeds (see Table I). It can be seen that, for very low SNR values, the channel coding is not able to outperform the case where the coding is not considered. Thus, when the coding rate is not low

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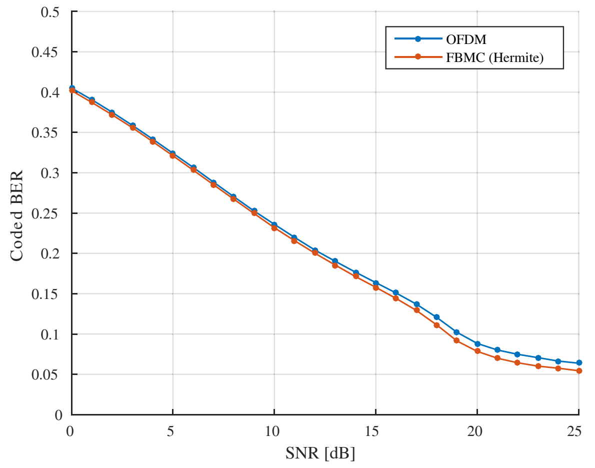

Fig. 6. Coded BER versus SNR for FBMC (8-PAM) and OFDM (64-QAM), the maximum emlated speed, and the highest coding rate.

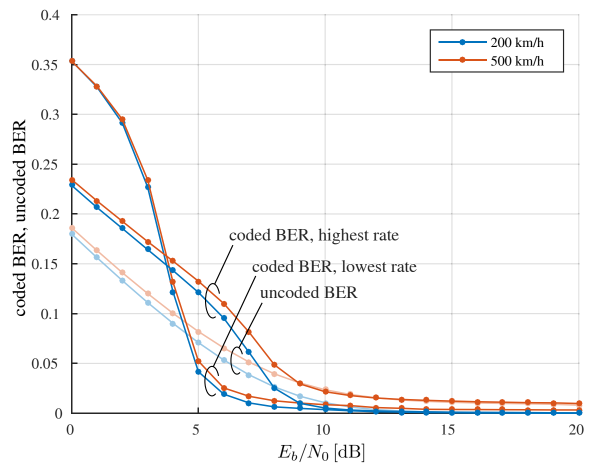

Fig. 7. Coded and uncoded BER versus E_b/N_0 for the minimum and maximum emulated speeds for FBMC (Hermite case) and 4-PAM constellation.

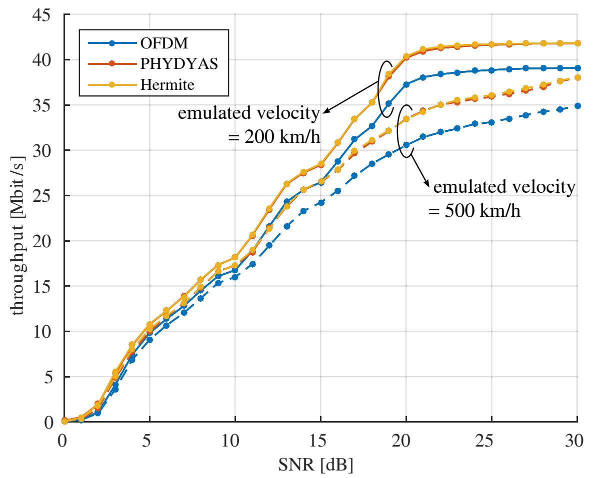

Fig. 8. Throughput versus SNR for the minimum and maximum emulated speeds. All the modulation schemes are shown.

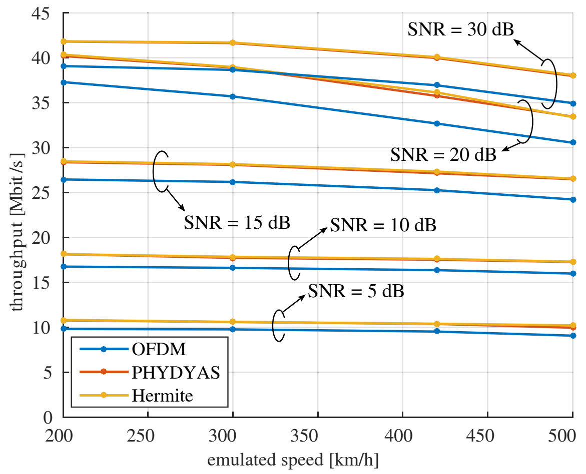

Fig. 9. Throughput versus emulated speed for different SNR values.

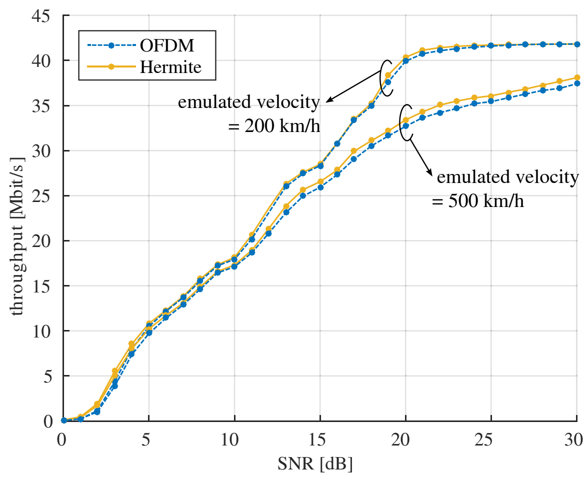

Fig. 10. Throughput versus SNR for the minimum and maximum emulated speeds. The OFDM results are scaled to compensate for the spectral efficiency loss due to the CP.

enough to correct the errors introduced by the channel, then the effective energy devoted to transmit the data bits decreases with respect to the uncoded case since the transmit power is constant and part of the energy is lost by the redundancy bits. Consequently, coding can increase the BER for low SNR values. For SNR values higher than a certain level, the coded BER values are lower than their corresponding uncoded counterparts. This effect can be also appreciated by means of the coding gain shown at the top of Fig. 4, calculated as the difference between the ratio of correctly received bits for the coded and uncoded cases. If we consider the coding rate $r \in \mathcal{R} = \{1/3, 1/2, 2/3, 4/5\}$ and the constellation $c \in \mathcal{C} = \{\text{2-PAM}, \text{4-PAM}, \text{8-PAM}, \text{4-QAM}, \text{16-QAM}, \text{64-QAM}\}$ (where PAM constellations correspond to the FBMC case and QAM constellations to CP-OFDM), the coding gain for the l-th frame is calculated as:

$$G_{\text{cod}}^{(r,c,l)} = 100 \times \left(\frac{C_{\text{cod}}^{(r,c,l)}}{D_{\text{cod}}^{(r,c)}} - \frac{C_{\text{uncod}}^{(r,c,l)}}{D_{\text{uncod}}^{(r,c)}} \right), \qquad (1)$$

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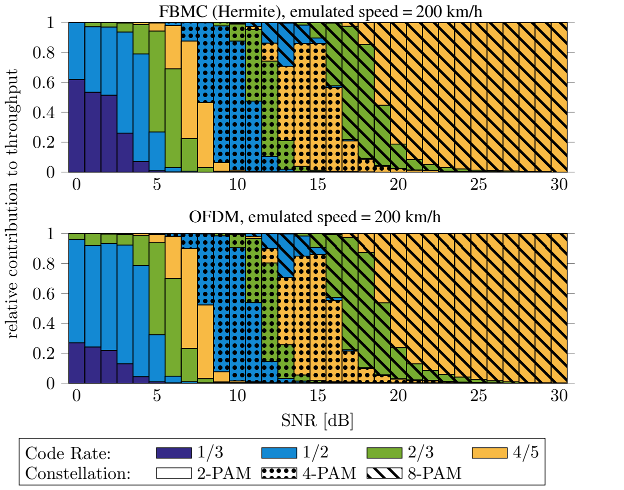

Fig. 11. Relative contribution per constellation and code rate to the total throughput for all the considered SNR values for OFDM and FBMC (Hermite case) and the minimum speed considered.

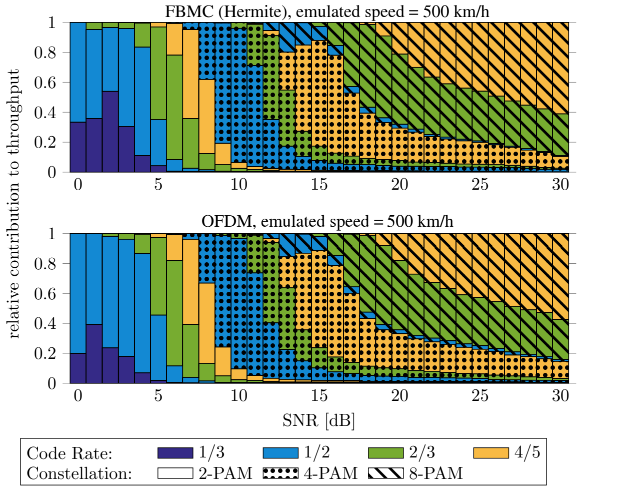

Fig. 12. Relative contribution per constellation and code rate to the total throughput for all the considered SNR values for OFDM and FBMC (Hermite case) and the maximum speed considered.

where $C_{\text{cod}}^{(r,c,l)}$ and $C_{\text{uncod}}^{(r,c,l)}$ are the number of correctly received bits for the coded and the uncoded case, respectively, and $D_{\text{cod}}^{(r,c)}$ and $D_{\text{uncod}}^{(r,c)}$ the number of data bits transmitted for each case. Note that, for the sake of brevity, only the emulated velocity of $500\,\text{km/h}$ was considered for the gain curves.

An alternative way to evaluate the coding gain is to check the difference in terms of SNR for each BER value when coding is considered with respect to the uncoded case. The results for the highest and the lowest considered coding rates are shown at the rightmost part of Fig. 3. Coherently with the previous results, it can be seen that the gain is negative for higher BER values, which corresponds to the cases with lower SNR values.

Figs. 4 and 5 show similar results when 4-PAM and 8-PAM constellations are considered, respectively. It can be seen that the larger the constellation, the higher the SNR required in order to ensure a specific BER value. Furthermore, the achieved coding gains are slightly increased with the constellation order when the lowest coding rate is used. It is worth noting that when the constellation order is increased, more SNR is required to achieve positive coding gain values. In fact, for extreme cases (e.g., 8-PAM and the highest coding rate) the obtained gain was negative for the whole SNR range considered.

Note that only the results for FBMC (Hermite case) were shown. This is because the results for other modulation schemes are very similar. In fact, the results for FBMC with the Hermite and the PHYDYAS prototype filters show no significant difference. The largest difference occurs when comparing the coded BER for OFDM and FBMC (e.g., with Hermite pulse) for a receiver moving at $500\,\text{km/h}$ and using the largest constellation and the highest coding rate. Fig. 6 shows the BER curves corresponding to the aforementioned case. It can be seen that the differences are almost negligible except for the higher SNR values.

Other way of analyzing the BER results is to represent them with respect to the transmitted energy per data bit, namely E_b, instead of the SNR. Fig. 7 shows the coded BER versus E_b/N_0 for an FBMC modulation (Hermite pulse) and when considering a 4-PAM constellation, whereas also the uncoded BER results previously obtained in [11] are included. We show the coded BER for the highest and the lowest coding rates, as well as the maximum and minimum emulated speeds (see Table I). In other words, the same results shown in Fig. 4 are plotted with respect to E_b/N_0. While the SNR accounts for the transmit energy both for the data and the redundancy, the E_b/N_0 considers exclusively the energy used to transmit the data bits. Hence, if we compare Figs. 4 and 7 we can see that coded BER curves are shifted horizontally to the left in the second case when the coding rate is increased.

Fig. 8 shows the throughput versus SNR for the minimum and the maximum emulated speeds and all the modulation schemes. We can see that the performance for the two FBMC prototype filters considered is very similar. Both of them exhibit a significant improvement in the throughput with respect to OFDM, which can be explained because of the better spectral efficiency of FBMC due to the absence of a cyclic prefix[2] and the better performance of FBMC for doubly dispersive channels. As stated before, BER results for OFDM and FBMC are very similar, hence we can expect that the main factor for the difference in terms of throughput is the absence of a cyclic prefix in FBMC. The performance for all the speed values is shown in Fig. 9.

Fig. 10 compares the throughput for the Hermite and the OFDM cases, but compensating the latter for the spectral efficiency loss due to the cyclic prefix (multiplying by $(T_s + T_{cp})/T_s$, as shown in Footnote 2). We can see that the

[2]Considering a bit rate b in FBMC, the corresponding bit rate of OFDM would be $bT_s/(T_s + T_{cp})$, being T_s the OFDM symbol period and T_{cp} the cyclic prefix duration.

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FBMC and OFDM curves overlap for the minimum speed. For the maximum speed, when the SNR value is high and thus the ICI is the dominant effect, FBMC slightly outperforms OFDM. In view of Fig. 10, although FBMC with the Hermite pulse is spectrally more efficient than OFDM, once the loss due to the cyclic prefix is removed, their throughput performance is very similar in a scenario with a high time selectivity (200 and 500 km/h for a carrier frequency of 2.6 GHz). Therefore, the theoretical gains expected from the utilization of the Hermite pulse [2] are not meaningful in the considered practical scenario.

Finally, Figs. 11 and 12 show the relative contribution per constellation size and code rate to the total throughput for the OFDM and FBMC (Hermite pulse) cases, when the receiver speed is 200 km/h and 500 km/h, respectively. The results for FBMC with the PHYDYAS pulse are similar to those with the Hermite pulse. It can be seen that the 4-QAM (OFDM case) and the 2-PAM (FBMC case) constellations contribute the most to the total throughput for SNR values lower than 8 dB, regardless of the receiver speed. For the minimum speed, the 16-QAM (OFDM case) and the 4-PAM (FBMC case) constellations contribute the most to the total throughput for SNR values between 9 and 16 dB, whereas for higher SNR values the 64-QAM (OFDM case) and the 8-PAM (FBMC case) constellations are the best choice. For the maximum speed, higher SNR values are required for the 64-QAM (OFDM case) and the 8-PAM (FBMC case) constellations to be the main contributors to the throughput. However, unlike in the minimum speed case, the 16-QAM (OFDM case) and the 4-PAM (FBMC case) constellations significantly contribute to the throughput regardless of the SNR. According to the results shown, the differences between the OFDM and the FBMC cases are negligible.

IV. Conclusions

The performance of a vehicle-to-infrastructure link using 5G-candidate technologies in very high speed conditions was assessed by measurements. The setup emulated the typical scenario found in high speed railways (vehicles passing by a static base station). More specifically, we measured at low speeds and used a previously proposed technique to emulate the results for the high speed case. This way we evaluated the BER (coded and uncoded) and the throughput obtained by using modulation techniques proposed for future 5G systems (FBMC with Hermite and PHYDYAS prototype pulses), as well as CP-OFDM for typical high-speed train velocities between 200 and 500 km/h.

Thanks to an improved bandwidth efficiency, FBMC schemes ease the co-existence between the current GSM-R-based systems and the new 5G-based candidate ones for the railway environment, while they avoid multiple-access interference in the uplink. The results show that the throughput of FBMC is higher due to the improved spectral efficiency, although its theoretically better suitability than CP-OFDM for doubly dispersive channels was not appreciated, neither in terms of BER nor throughput. While for low speeds ($\lesssim$ 200 km/h) and high SNR values ($\gtrsim$ 20 dB) it is possible to achieve the maximum throughput by using 8-PAM (FBMC case) or 64-QAM (CP-OFDM case), lower-ordered constellations may be required to decrease the coded BER, hence reducing the number of retransmissions, which results in lower delays, as required by train control systems.

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