Multicarrier Modulation for HF Communications

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***Abstract*—High-frequency (HF) communications can be flexibly realized using multicarrier modulation techniques. This paper compares the performance of three widely utilized MCM techniques, namely, orthogonal frequency-division multiplexing (OFDM), filter bank multicarrier/offset-QAM (FBMC/OQAM), and filtered multitone (FMT) in HF communications. The performance of these systems is simulated using commonly adopted HF-channel models. It is shown that the simulated uncoded bit-error rate of OFDM is slightly better than that of FBMC/OQAM and FMT. However, with pilot based channel estimation FMT outperforms FBMC/OQAM and OFDM systems in achievable coded frame error rate in case of selective channel models.**

I. INTRODUCTION

Reliable communication over high frequency (HF) channels (3- to 30-MHz band) is known to be challenging due to rapidly changing propagation conditions and disturbances. The multicarrier modulation (MCM) techniques offer an efficient way to cope with frequency selective and time-varying communication channels by dividing the data stream into (quasi) orthogonal multiple substreams to be transmitted over the group of subchannels.

Orthogonal frequency-division multiplexing (OFDM) is the most important multicarrier technique and it is extensively utilized in modern broadband radio access systems. This is due to the simple and robust way of channel equalization, high flexibility and efficiency in allocating spectral resources to different users, as well as simplicity of combining multiantenna schemes with the core functionality [1].

The major limitation of OFDM is its poor spectral containment which leads to high sensitivity to interferences from asynchronous spectral components and undesirable out-of-band emission resulting in an adjacent channel leakage. The spectral containment of the basic OFDM can be improved by straightforward filtering. However, narrow transition-band filtering significantly increases both the computational complexity of the implementation [2] and the time-dispersion introduced by the channel [3].

An alternative scheme is offered by the filter bank based methods of waveform processing and channelization filtering [4]–[6]. A relatively widely studied filter bank based waveform is FBMC/OQAM (filter bank multicarrier/offset-QAM, also known as OFDM/OQAM) [5], [6]. FBMC/OQAM has a considerably better time-frequency localization than that of the OFDM resulting to a lower out-of-band emission and making it more robust to synchronization errors. The orthogonality of FBMC/OQAM is reached by utilizing so called offset-QAM modulation, that is, the real and imaginary parts of the symbols are transmitted at twice the Nyquist rate with the half symbol time offset [7]. The offset-QAM modulation introduces various challenges in developing effective pilot schemes and in applying certain multiantenna configurations, like Alamouti coding.

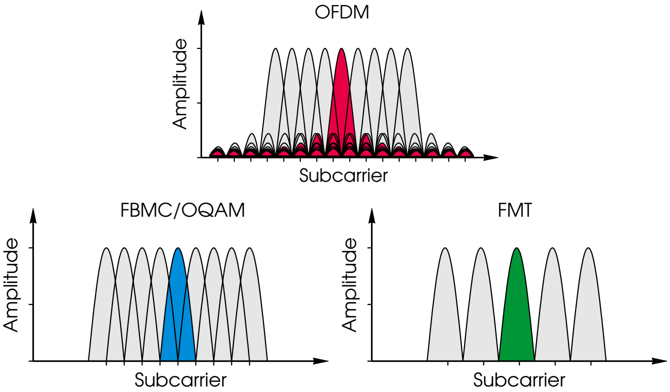


Fig. 1: Examples of different MCM waveforms. Top: OFDM-type multiplex of nine subchannels. Bottom left: FBMC/OQAM-type multiplex of nine subchannels with root-raised-cosine (RRC) type subchannel filtering. Bottom right: FMT-type multiplex of five subchannels with RRC type subchannel filtering.

Another well-known FBMC scheme is filtered multitone (FMT) [8]–[10]. FBMC/OQAM reaches maximal spectral efficiency by using significantly overlapping subcarriers, typically with the roll-off of one, whereas FMT uses non-overlapping subcarriers, and relatively small roll-off is chosen to reach good spectral efficiency. The main benefit of FMT is that basic QAM modulation with Nyquist filtering can be used in subcarriers, which allows more direct application of pilot based synchronization and channel estimation schemes. Also the multi-antenna configurations developed for OFDM can be straightforwardly utilized. Typical spectral characteristics of these multicarrier waveforms are illustrated in Fig. 1.

To support high data rates, it is often desirable to combine multiple non-contiguous spectrum slots in the transmission. In multicarrier systems, this can be achieved by activating only those subcarriers that are within the available frequency slots. In the case of uniform filter banks, the achievable granularity in adjusting the subband bandwidths and the center frequencies is determined by the ratio of the sampling frequency and the number of subchannels. By increasing the number of subchannels the flexibility in utilizing the available spectrum can be improved, however, consequently, the peak-to-average power ratio characteristics of the transmitted signal increase as well, affecting on the requirements of the transmitter power amplifier [11].

In this paper, these MCM techniques are applied to HF-communication by developing three alternative systems and simulating their performance with commonly used HF-channel models. The performance of these systems is simulated in the case on perfect channel knowledge and in the case where channel estimation is carried out using scattered pilots based methods [12]. Both uncoded and coded systems are simulated and it is shown that the inaccuracy of the channel estimates as well as the inter-carrier interference resulting from the imperfect equalization deteriorates the performance in the FBMC/OQAM and OFDM cases more severely than in the FMT case.

The outline of the paper is as follows. First the structures for generating MCM waveforms are shortly discussed in Section II. Then, in Section III, commonly adopted HF channel models are reviewed. The waveform design as well as the frame and pilot structures are discussed in Section IV. Section V presents the simulation results whereas, finally, in Section VI the conclusions are drawn.

II. STRUCTURES FOR GENERATING MCM WAVEFORMS

For filter bank based waveforms, there are several efficient multirate realizations, including lapped transforms, lattice and polyphase structures [14], [15], as well as fast convolution based structures [16]. Common to all these realizations is that they consist of a filter section, the coefficients of which are determined by the prototype filter design, and a transform section implementing the modulation [17].

In the nearly perfect-reconstruction (NPR) transmultiplexer (TMUX), i.e., synthesis-analysis filter bank configuration, the output signals are only approximately delayed versions of the input signals, i.e., certain amount of filter bank structure based distortions can be tolerated as long as they are small in comparison with those induced by the transmission channel [17]. The polyphase structures are especially efficient for implementing NPR filter banks with equally spaced subchannels. Their main advantage is that they can offer drastic simplifications because the filtering operations are performed at the lower sampling rate without unnecessary calculations.

Fig. 2 shows a general model of the efficient polyphase M-channel analysis filter bank. This model consist of delay line, M down-samplers by P, analysis filters $G_\ell(z^L)$ for $\ell = 0,1,\ldots,M-1$, and inverse discrete Fourier transform (IDFT) block. In the case of FBMC/OQAM waveform, $P = M/2$ and $L = 2$, that is, the delay line and the down-samplers form a serial-to-parallel converter with the overlap of $M/2$. The number of subchannels is twice the upsampling and downsampling factors indicating two-times oversampled subband signals if the input and output signals are complex-valued. However, if the input and output signals are purely real/imaginary-valued then the presented TMUX is equivalent to a critically sampled TMUX. This same polyphase filter bank model can be used for realizing FMT waveforms as well. In this case, $P = M$ and $L = 1$ resulting to a critically sampled filter bank [10].

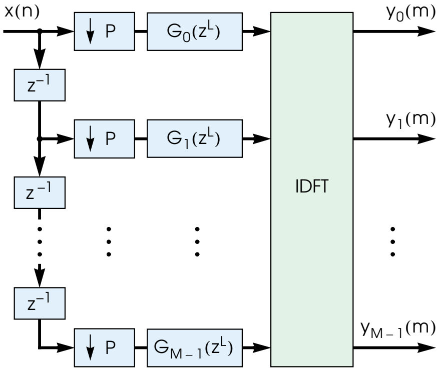


Fig. 2: Efficient polyphase implementation of the analysis filter bank.

In this study, we use the same prototype filter, with the roll-off of one, for FBMC/OQAM and FMT. This means that the uncoded data rate of FMT is 50 percent lower than that of FBMC/OQAM. In this way, we can find out the potential benefit of FMT in robustness against the imperfections of HF channels. Then it remains as a topic for future studies to optimize the roll-off of FMT in terms of throughput, implementation complexity, and other relevant aspects. It is expected that the gain achieved by this optimization depends greatly on the adopted channel model.

The basic OFDM modulation and demodulation can be carried out with the aid of IDFT and DFT pair, typically implemented using a fast Fourier transform (FFT). The increase in the complexity of the above filter bank processing when compared with the OFDM-based MCM is basically determined by the length of the prototype filter. The filter order is usually given in terms of overlapping factor K which is the ratio of the filter impulse response length to the multicarrier symbol period. Here, we have used the overlapping factor of $K = 4$ for both the filter bank based designs.

III. HF CHANNEL MODELS

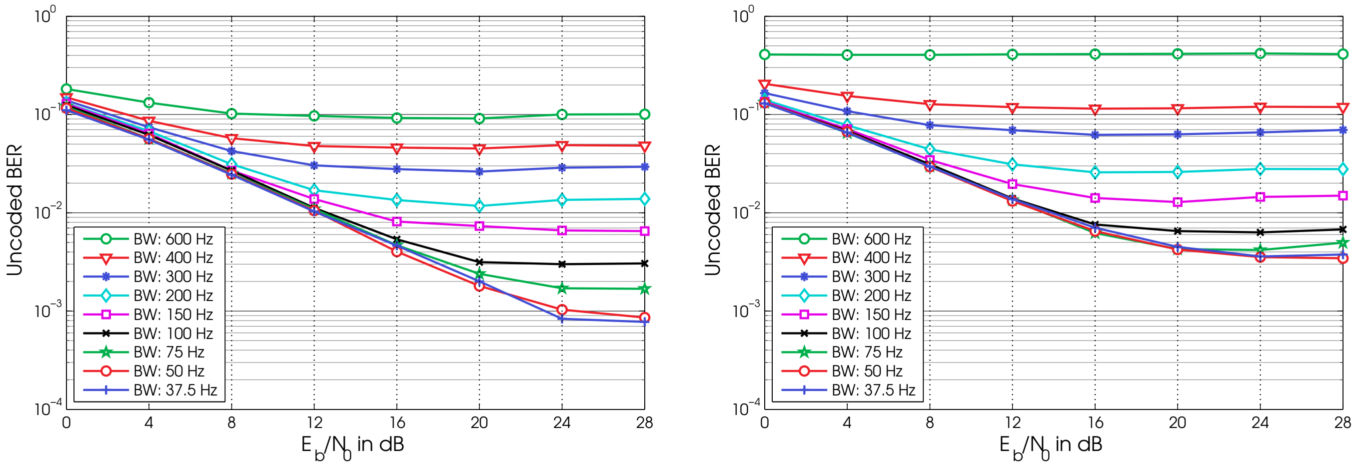
The digital radio mondiale (DRM) standard [13] defines six channel profiles to be considered for the low frequency, medium frequency, and HF broadcast radio transmission. These channel profiles employ the Watterson-type HF channel model [18], [19]. This model is a linear time-variant model assuming that the received signal $s(t)$ is a linear combination of delayed versions of the input signal $e(t)$ as given by

$$s(t) = \sum_{k=1}^{N} \rho_k c_k(t) e(t - \tau_k). \tag{1}$$

Here, ρ_k is the gain of the path k, τ_k is the corresponding relative delay, and the time-variant tap weights $c_k(t)$'s that

TABLE I: Parameters for the HF channel models from [13]

Channel	Delay (τ_k) [ms]	Gain, rms (ρ_k)	Doppler shift (f_D) [Hz]	Doppler spread (B_D) [Hz]
C: US Consortium	[0.0 0.7 1.5 2.2]	[1.0 0.7 0.5 0.25]	[0.1 0.2 0.5 1.0]	[0.1 0.5 1.0 2.0]
D: CCIR poor	[0.0 2.0]	[1.0 1.0]	[0.0 0.0]	[1.0 1.0]
E: Channel no. 5	[0.0 4.0]	[1.0 1.0]	[0.0 0.0]	[2.0 2.0]
F: Channel no. 6	[0.0 2.0 4.0 6.0]	[0.5 1.0 0.25 0.0625]	[0.0 1.2 2.4 3.6]	[0.1 2.4 4.8 7.2]



(a) Unoded BER in HF channel C.

(b) Uncoded BER in HF channel F.

Fig. 3: Uncoded bit-error rate for single-carrier FBMC/OQAM with variable subcarrier spacing. Perfect channel knowledge and QPSK-modulation are used.

are zero-mean complex-valued stationary Gaussian random processes. The magnitudes $|c_k(t)|$ are Rayleigh distributed and the phases $\phi(t)$ are uniformly distributed.

For each weight $c_k(t)$ there is one stochastic process, characterized by its variance and its power spectral density (PSD). The relative gain ρ_k defines the variance of the signal which is received through this path and the PSD determines the average speed of variation in time. The width of the PSD is quantified by the Doppler spread B_D of that path whereas a non-zero center frequency of the PSD is characterized by its Doppler shift f_D. The parameters for the HF channels models C, D, E, and F used in this contribution are collected in Table I.

IV. WAVEFORM PARAMETERIZATION

A. Subcarrier Spacing

The most important factor affecting the performance of the multicarrier system is the subcarrier spacing and, correspondingly, the symbol duration. By reducing the subcarrier spacing the probability that each subcarrier experiences a flat fading increases. On the other hand, this increases the symbol duration and since the HF channel models discussed above are time variable, the probability that channel changes within a symbol duration increases as well. Therefore the coherence time of the channel as well as the delay spread should be taken into account when parametrizing the MCM system.

For the given sampling rate f_s, the subcarrier spacing of the multicarrier system is defined as $\Delta_f = f_s/M$, where M is the number of subcarriers. The effect of the subcarrier spacing to the system performance has been determined by first simulating the uncoded bit-error rate (BER) with only one active subcarrier for the different values of M. In these simulations, the sampling rate was fixed to $f_s = 38.4\,\mathrm{kHz}$ and the number of subcarriers is selected from $M = 64, 96, 128, 192, 256, 384, 512,$ and 768 corresponding to the subcarrier spacing of $\Delta_f = 600, 400, 300, 200, 100, 75, 50,$ and $37.5\,\mathrm{Hz}$, respectively.

Fig. 3 shows the simulation results in the case of FBMC/OQAM waveform with HF channel models C and F. The root-mean-square delay spread of these models is $T_m = 0.75\,\mathrm{ms}$ and $T_m = 1.5\,\mathrm{ms}$, respectively. The QPSK-modulation with perfect channel knowledge is used in the simulations. As can be seen from this figure, 50 Hz and 75 Hz subcarrier spacings result in a nearly identical performance and reducing the subcarrier spacing to 37.5 Hz does not improve the performance any further. Therefore, 50 Hz and 75 Hz subcarrier spacings are selected for further simulations.

In the case of OFDM, a cyclic prefix (CP) is included in the beginning of each symbol to avoid inter-symbol interference. The length of the CP is chosen to be either 7.8125 or 15.625 percent. In the case of 50 Hz subcarrier spacing this corresponds to CP lengths of 1.563 ms or 3.125 ms for the short or long CP, respectively, and in the case of 75 Hz subcarrier spacing, the corresponding values are 1.041 ms and 2.083 ms, respectively.

B. Frame and Pilot Structures

When designing the frame structure, some level of commonality with MIL-STD-188-110C [20] is targeted. The proposed

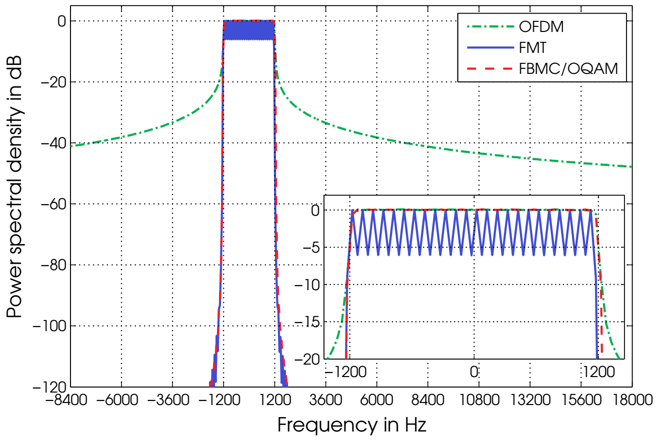
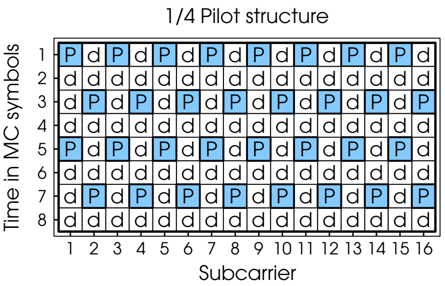


Fig. 4: Power spectral density estimates of OFDM, FBMC/OQAM, and FMT.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	P	d	P	d	P	d	P	d	P	d	P	d	P	d	P	d
2	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
3	d	P	d	P	d	P	d	P	d	P	d	P	d	P	d	P
4	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
5	P	d	P	d	P	d	P	d	P	d	P	d	P	d	P	d
6	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d
7	d	P	d	P	d	P	d	P	d	P	d	P	d	P	d	P
8	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d	d

Fig. 5: Frame structure with the pilot density of 1/4. Here, “P” and “d” denote the pilot and data locations within the transmission frame, respectively.

frame structure utilizes the LTE-like parameterization, where the subcarriers are scheduled into so-called resource blocks (RBs). The size of the RB is 16 subcarriers. The number of active carriers is chosen such that the bandwidth of the signal is around 2400 Hz e.g., for the 50 Hz subcarrier spacing the number of active carriers among the $M = 512$ subcarriers is $M_{\text{act}} = 48$ requiring three RBs and for the 75 Hz subcarrier spacing two RBs are needed. Fig. 4 shows the typical power spectral densities of OFDM, FBMC/OQAM, and FMT and as can be seen from this figure, the spectral containment of conventional OFDM is especially poor when compared with FBMC/OQAM and FMT.

The transmitted burst of data is composed of frames each consisting of four subframes in the case of OFDM and FBMC/OQAM or eight subframes in the case of FMT. The higher value for the FMT is due to the fact that since the subcarriers are non-overlapping, the number of frames has to be doubled for carrying the same information as the FBMC/OQAM or OFDM. One subframe is composed of eight multicarrier symbols and, overall, one frame corresponds to the 1536 or 1024 symbols in the case of 50 Hz or 75 Hz subcarrier spacing, respectively.

The channel estimation is carried out using basic scattered pilot based methods. Several alternative pilot patterns were studied and it has been observed that the pilot density as high as 1/4 is needed for satisfactory performance. For the best pilot pattern, the pilots are included in every subcarrier within each subframe. Specifically, pilots are included in odd subcarriers in the first and fifth multicarrier symbols and in even subcarriers in the third and seventh, as depicted in Fig. 5.

QPSK-modulation is used for the data and pilots. In the case of FBMC/OQAM, the auxiliary pilot model [12] is used for scattered pilots. The combined pilot/auxiliary pilot symbol is boosted on average by 4.5 dB with respect to the data. The OFDM and FMT pilots are boosted by the same value with respect to the data.

In the OFDM case, the equalizer is a conventional single-tap subcarrier-wise equalizer whereas, in the FBMC/OQAM and FMT cases, three-tap frequency-sampling based subcarrier-wise equalizer with MSE criterion is used [21]. The channel estimates are interpolated in the time direction over consecutive processing blocks. In these simulations, the overall channel response is obtained from the scattered channel estimates by triangulation-based two-dimensional (in time and frequency direction) linear interpolation

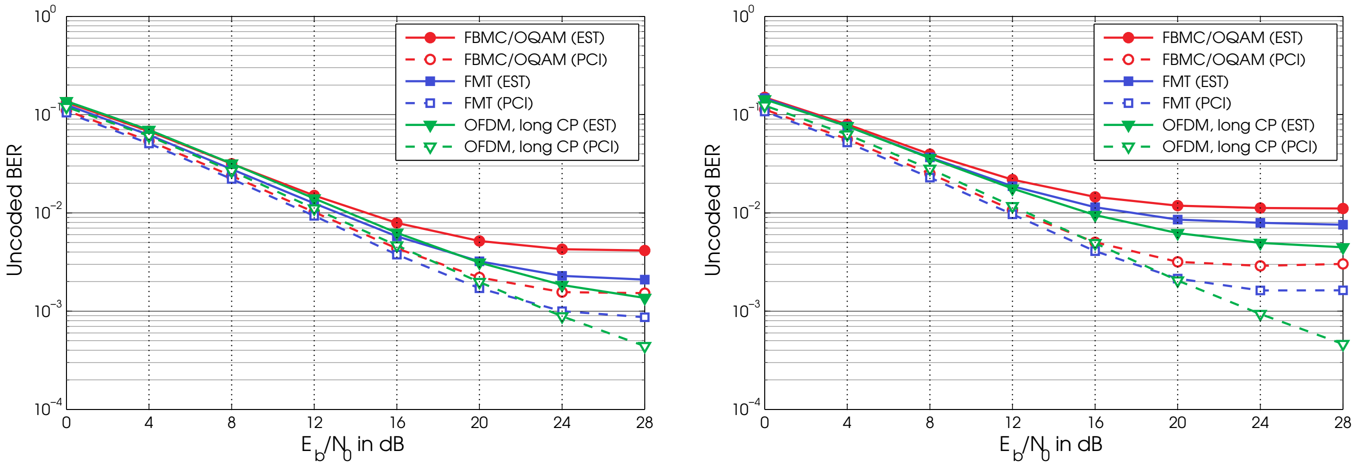
V. NUMERICAL RESULTS

Figs. 6(a)–6(d) show the simulated uncoded bit error rate (BER) of FBMC/OQAM, FMT, and OFDM systems for QPSK modulation in the case of HF channel models C and F, respectively. In these figures, both the perfect channel knowledge and pilot based estimation results are shown. In the case of FBMC/OQAM, the equalizer coefficients are updated for each OQAM half-symbol whereas in the FMT and OFDM cases the coefficients are updated for each symbol. The simulations are carried out for 50 Hz and 75 Hz subcarrier spacing. For each simulation, 4000 burst transmissions with independent channel realizations are performed.

As can be seen from these figures, OFDM clearly outperforms FMT and FBMC/OQAM in the case of channel model C for both subcarrier spacings whereas FMT is slightly better in the case of channel model F. It can also be observed from Fig. 6(d), that the perfect channel knowledge performance of OFDM is inferior to FMT and FBMC/OQAM with HF channel model F and 75Hz subcarrier spacing. This is due to the fact that in this case, the CP length of OFDM is not sufficient to eliminate the inter-symbol interference. When comparing the pilot based estimation with the perfect channel knowledge case, it is observed that the performance of the estimation is still far away from desired, especially, in the case of channel model F. This is obviously due to insufficient resolution in channel estimation.

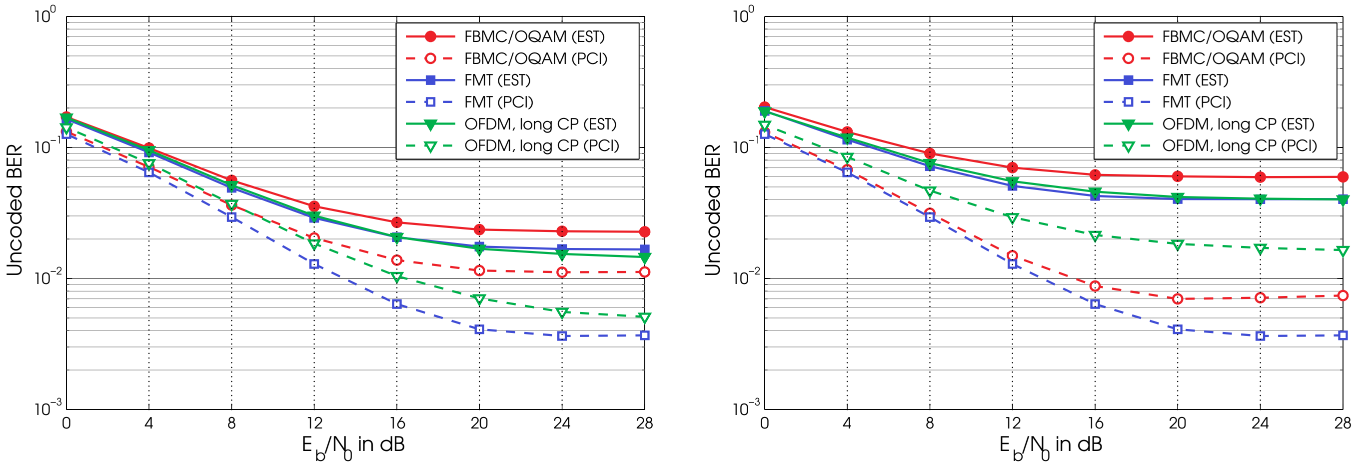
Figs. 7(a)–7(d) show the simulated coded frame-error rates (FER) in the case of HF channel models C, D, E, and F, respectively. The convolutional code with code rate of $R_c = 1/2$ and code length of $L = 9$ with a bit interleaver similar to that in MIL-STD-188-110C [20] is used in all the simulations

As can be seen from Fig. 7(a), in the case of channel model C, the coded FER of all the systems is approximately



(a) Unoded BER in HF channel C with 50 Hz subcarrier spacing.

(b) Uncoded BER in HF channel C with 75 Hz subcarrier spacing.



(c) Uncoded BER in HF channel F with 50 Hz subcarrier spacing.

(d) Uncoded BER in HF channel F with 75 Hz subcarrier spacing.

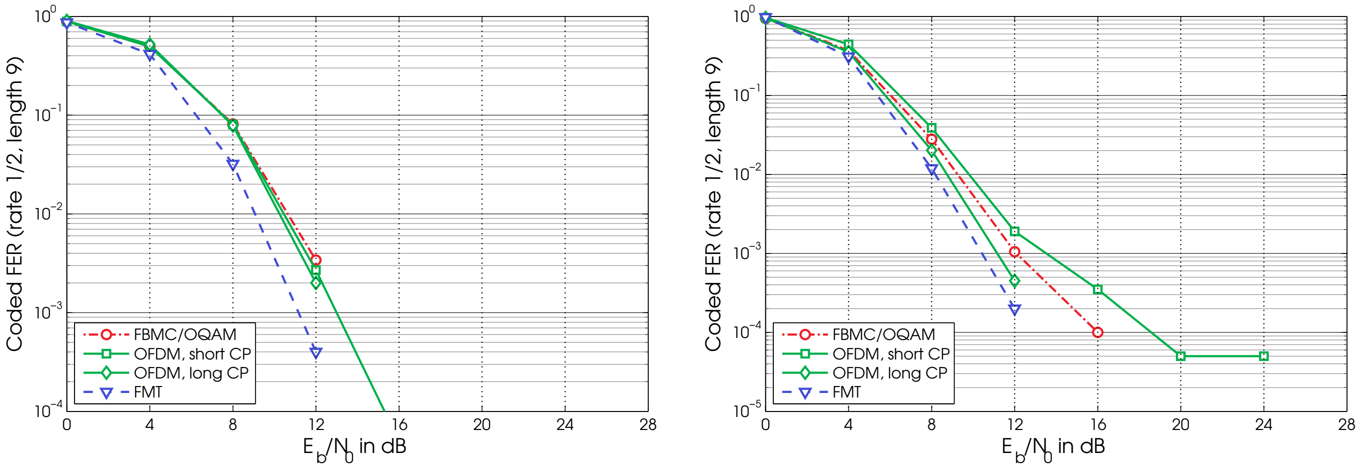
Fig. 6: Uncoded bit-error rate for OFDM, FBMC/OQAM, and FMT in HF channels C and F with 50 Hz and 75 Hz subcarrier spacing. QPSK-modulation with perfect channel knowledge (PCI) or pilot based estimation (EST) is used.

the same. Only the performance of FMT is slightly better than that of FBMC/OQAM and OFDM. In the case of channel model D, again all the systems perform almost equally well as depicted in Fig. 7(b) and the performance of FMT and OFDM with long CP are practically the same. In the case of the channel model E, only the performance of FMT is somehow acceptable. The FER values of FBMC/OQAM and OFDM are all above 60 percent, as illustrated in Fig. 7(c). Finally, the results with channel model F, as depicted in Fig. 7(d), show the similar performance for all the systems, and again FMT and OFDM with long CP are the best.

Overall, it can be assumed that the performance of OFDM can be improved by increasing the CP even further and in that sense OFDM seems to be the best alternative for HF communication. However, taking into consideration the poor spectral containment of OFDM and the fact that the spectral sidelobe suppression techniques based on narrow transition-band filtering increase the time dispersion introduced by the communication channel and, consequently, eventually sacrifice the effect of increased CP [3].

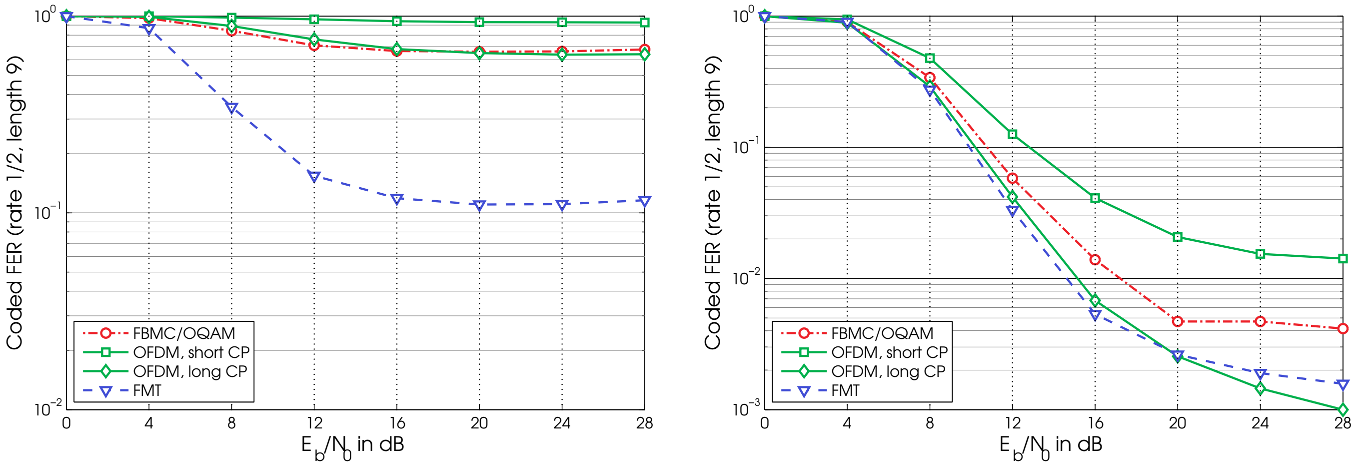
VI. CONCLUDING REMARKS

We have compared the performance of three multicarrier modulation techniques with commonly adopted high-frequency (HF) channel models. It is shown that the simulated bit-error and frame-error rates of these techniques are approximately the same. Only in the case of highly time- and frequency-selective channel model, the filtered multitone (FMT) has clearly the best performance. However, the improved spectral containment of the filter bank based techniques is the main benefit when compared with the orthogonal frequency-division multiplexing. Since FMT was found to be the most robust scheme in case of difficult HF channels, it is important to optimize the roll-off parameter of FMT in terms of throughput, while considering the implementation complexity and latency aspects. Basically, for high spectrum efficiency, small roll-off should be used, but this greatly



(a) Coded FER in HF channel C with 50 Hz subcarrier spacing.

(b) Coded FER in HF channel D with 50 Hz subcarrier spacing.



(c) Coded FER in HF channel E with 50 Hz subcarrier spacing.

(d) Coded FER in HF channel F with 50 Hz subcarrier spacing.

Fig. 7: Coded frame-error rates for OFDM, FBMC/OQAM, and FMT in HF channels C, D, E, and F. QPSK-modulation with pilot based estimation is used.

increases the prototype filter order. The channel estimation for highly selective subchannels remains as an important item for future studies. In addition, the future work is devoted in comparing the performance of the studied multicarrier waveforms with the corresponding single-carrier waveforms.

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