New Waveform Candidates for 5G: Options and Opportunities

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Impact of timing and frequency offsets on multicarrier waveform candidates for 5G
Waveform Candidates for 5G

Waveform Candidates

Linear pulse shaping
- Universal filtered multicarrier (UFMC)
- Filter bank multicarrier (FBMC)

Circular pulse shaping
- Generalized frequency division multiplexing (GFDM)
- Circular filter bank multicarrier (C-FBMC)
Linear Pulse Shaping

- Universal filtered multicarrier (UFMC)

Fig. 1. UFMC system model in the uplink [1].

Linear Pulse Shaping

- UFMC signal in frequency domain

Fig. 2. UFMC signal representation in frequency domain and its comparison with OFDM [1].
Linear Pulse Shaping

- Filter bank multicarrier (FBMC)

Fig. 3. Filter bank multicarrier (FBMC) system model.
Circular Pulse Shaping

Fig. 4. Filter bank multicarrier with circular pulse shaping.
Circular Pulse Shaping

Fig. 5. Time-frequency overlapping.
Circular Pulse Shaping

• OFDM vs. GFDM or C-FBMC data packet

![Diagram of OFDM and GFDM/C-FBMC data packets]

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Linear vs. Circular Pulse Shaping

Fig. 6. Linear FBMC transmit signal.

Fig. 7. Circular FBMC transmit signal.
Impact of Synchronization Errors on Waveform Candidates for 5G

Fig. 8. Timing misalignment between different users.

Fig. 9. Frequency misalignment between different users.
Timing and Frequency Misalignment

\[ x_{\ell}(t) = \sum_{m=-\infty}^{+\infty} \sum_{k=0}^{N-1} X_{m_k}^{(\ell)} g_{m_k}(t) \]  
Transmit signal of user \( \ell \)

\[ y(t) = \sum_{\ell} y_{\ell}(t - \tau_{\ell}) e^{j2\pi f_{\ell} t / T} + n(t) \]  
Received signal at the base station

\[ y_{\ell}(t) = \int_{\tau} c_{\ell}(\tau, t) x_{\ell}(t - \tau) d\tau \]  
Signal of user \( \ell \) after going through the channel

\[ \hat{X}_{m_k}^{(\ell)} = \langle y(t), h_{m_k}(t) \rangle = X_{m_k}^{(\ell)} + I_{\text{MAI}} + \eta \]  
Transmitted symbols estimated at the base station
Sensitivity to Timing Offset

Fig. 10. Multiple access interference (MAI) as a function of timing offset for different waveforms.
Sensitivity to Frequency Offset

Fig. 11. Multiple access interference (MAI) as a function of frequency offset for different waveforms.
Sensitivity to Frequency Offset

Fig. 12. Amplitude spectrum of the receiver matched filter (MF) in C-FBMC and zero-forcing (ZF) detector in GFDM.
Sensitivity to Timing and Frequency Offset

Fig. 13. Bit error rate (BER) performance of different waveforms. The normalized TOs and CFOs are selected randomly between -0.5 and +0.5.
Sensitivity to Timing and Frequency Offset

Fig. 14. BER performance of different waveforms. The users are quasi-synchronous in time and the CFO errors are selected randomly between -0.5 and +0.5.
Conclusions

• To reduce sensitivity to timing and frequency offsets, windows with smooth edges should be applied to both transmitter and receiver.

• Among all the waveforms, FBMC and UFMC partially satisfy this condition.

• OFDM, GFDM, and C-FBMC fail our tests as they lack windowing in their conventional form. However, improvements are possible in these waveforms.
Frequency Spreading Equalization in Multicarrier Massive MIMO
New Waveforms and Massive MIMO for 5G

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New Waveforms and Massive MIMO for 5G

- Massive MIMO: a multiuser system similar to code division multiplexing (CDMA) systems
Cosine Modulated Multitone (CMT)

- CMT modulation

(a) Spectra of baseband data streams (black) and vestigial side band (VSB) portion of each (other colors). (b) CMT spectrum consisting of modulated versions of the VSB spectra of the baseband data streams. VSB signals are modulated to the subcarrier frequencies \( f_0, f_1, \ldots, f_{N-1} \).

Frequency Spreading implementation of CMT
Frequency Spreading implementation of CMT
Filter Bank Multicarrier for Massive MIMO

- Self-equalization property of FBMC, [2], makes it a viable candidate for MIMO application.

- CMT offers the following advantages over OFDM:
  - Higher bandwidth efficiency
  - Lower sensitivity to CFO
  - Lower PAPR
  - More flexible carrier aggregation
  - Blind channel equalization capability enabling pilot decontamination, [3]


Minimum Mean Square Error
Frequency Spreading Equalization

\[ \tilde{r}_i = \sum_{\ell=0}^{M-1} \tilde{r}_i^\ell + v_i = H_i r_i + v_i \]

Number of users
Number of receive antennas

\[ N_r \times 1 \]

\[ r_i^\ell = r_i h_i(\ell) \quad , \quad H_i = [h_i(0), \ldots, h_i(M-1)] \]

\[ r_i = [r_i^0, \ldots, r_i^{M-1}]^T \]
Minimum Mean Square Error
Frequency Spreading Equalization

\[ \hat{r}_i = W_i^H \tilde{r}_i \]

MMSE estimates of \( r_i \)'s

\[ W_i = H_i (H_i^H H_i + \sigma_v^2 I_M)^{-1} \]

MMSE filter tap weights

\[ \hat{S} = \Re\{ \Phi^{-1} A^T \hat{R} \} \]

Phase adjustment matrix

\[ \hat{R} = [\hat{r}_0, \ldots, \hat{r}_{N-1}]^T \]

Spreading matrix
Numerical Results

• Single user case

(a) and (b) compare the signal to interference ratio (SIR) performance of the MF linear combining technique for the cases of 8 and 16 subcarriers, respectively, for different number of receive antennas, $N_r$. 
Numerical Results

SIR performance comparison between polyphase implementation (PPN) and frequency spreading FBMC systems having 16 subcarriers for different number of receive antennas.
Numerical Results

- Multiuser case

Signal to noise plus interference (SINR) performance of MMSE linear combining for the case of having 16 subcarriers and 6 users where the receiver input signal to noise ratio is -1dB.
Conclusions

• An effective MMSE equalization scheme for FBMC-based massive MIMO systems was derived.

• Frequency spreading equalization enables us to widen the subcarrier bands further than what was proposed in [2].

• Further widening the subcarrier bands in frequency brings improvements in terms of bandwidth efficiency, robustness to carrier frequency offset, peak-to-average power ratio and latency compared with polyphase based FBMC systems.

Thank you

Any comments or questions?