Optimized Amplitude Modulated Multi-Band RF pulses
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Introduction

Multi-Band RF pulses require more peak RF power to produce a given flip angle than single band equivalents. This can severely limit the achievable multi-band factor (MBF; number of simultaneously excited slices). If all slices are excited with the same phase the peak pulse amplitude scales with MBF:

\[ i.e. \ b_{\text{max}} = \text{MBF} \]

Where \( b_{\text{max}} \) is the maximum amplitude relative to a single-band pulse of the same flip angle.

Wong showed that optimizing the phase of each slice can result in much lower \( b_{\text{max}} \), approaching theoretical minimum \( b_{\text{max}} = \sqrt{\text{MBF}} \). This approach has been combined with time-shifting to further reduce the peak amplitude.\(^3\)

The resulting MB-RF pulses have rapid modulation in both amplitude and phase. Accurate reproduction of this modulation can be problematic. Faithful reproduction of rapid phase modulation can be more error prone than amplitude modulation, especially on systems requiring frequency rather than phase modulation to be defined by the pulse designer.

Goal

To compute optimal phase offsets to produce amplitude modulated MB-RF pulses that minimize \( b_{\text{max}} \).

Methods

The modulation function \( b(t) \) required to produce slices at locations \( \chi \) with gradient \( G \) is given by:

\[ b(t) = \sum_{j=1}^{\text{MBF}} \exp \left\{i\left(\gamma Gx_j t + \phi_j\right)\right\} \]

Phase offsets \( \phi_j \) are to be optimized so as to minimize \( b_{\text{max}} = \text{max}(b(t)) \).

AM only pulses are achieved if we obtain real valued \( b(t) \). This can be achieved if \( \phi \) have conjugate symmetry.

Design:

- Form pairs of slices at equal distance \( x \) from centre \( x=0 \).
- Assign phase offset \( \phi \) for each pair such that \( \phi_l = -\phi_r \). For odd MBF, slice at \( x=0 \) is treated independently.
- Find \( \phi \) to minimize \( \text{max}(b(t)) \) using MATLAB’s fincon with 50 random initializations for each MBF.

Results

Optimized phase offsets are given in Table 1. The table also quantifies the percentage reduction compared with all slices in phase (\%MBF) and the relative amplitude reduction from AM only pulses compared with AM and FM together (expressed as percentage, \%AMFM). Figure 2 shows performance compared with AM and FM pulses, Figure 2 shows a specific example for MBF=6.

Discussion

With amplitude modulation only, no improvement is possible for MBF4. Therefore, the AM solutions reduce \( b_{\text{max}} \) by an increasing proportion as MBF increases, with reductions over 50% for MBF>8. Relatively performance compared with complex waveforms is variable, but \%AMFM averages to 80% across all MBFs.

Some factors perform better, for example MBF=6 results in \%AMFM=87%, meaning that an AM pulse achieves 87% of the reduction possible using AM/FM.

The rapid frequency modulation required to realize complex multi-band pulses is sensitive to errors in interpolation and to poor stability. Although not as effective as full complex modulation, AM only pulses can achieve about 80% of the gains, while avoiding issues associated with rapid frequency modulation. As a result these have been found to have more robust performance.

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References


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