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Cross-frequency coupling: the theoretical framework

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Introduction

Cross-frequency coupling (CFC) generally labels the interactions between two signals at different frequencies [1]. In electrophysiology, empirical evidences revealed the presence of such coupling between low frequency bands, i.e. δ or θ, and higher frequency oscillations, i.e. β or γ, in animals as well as humans, in many different applications [2]. Nevertheless, misinterpretation of CFC results have been highlighted by recent literature. This is possibly due to the lack of a robust theoretical framework to deal with CFC. Rather, the amplitude modulation of one signal by the phase of a second one can be reported to well-known concepts of the signal theory [3]: a parallel amplitude-phase modulation (AM-PM) system can generate the CFC-like signals. This paper provides (i) the theoretical framework to formalize the existence of CFC and (ii) a toolbox to simulate an expected CFC strength, test the effectiveness of an existing CFC quantification method and optimally demodulate a signal to check for CFC.

Amplitude Modulation (AM)

The information signal a(t) is used to modulate the amplitude of a sinusoidal carrier at frequency f_H, that is, formally:

$$x_H(t) = (B + a(t))\sin(2\pi f_H t + \phi_{H0}) \quad \text{with } \varphi_{H0} \text{ and } B \text{ cost}$$

Modulation index: $m = \max(|a(t)|)/B$

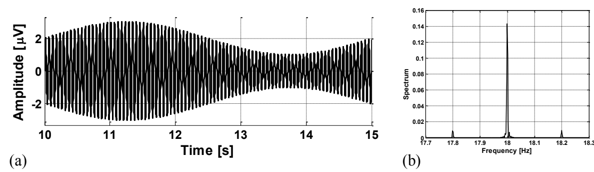


Fig.1. Typical AM signal $x_H(t)$ (a) and its power spectrum (b).

Phase Modulation (PM)

The information signal a(t) is used to modulate the phase of a sinusoidal carrier at frequency f_L, that is, formally:

$$x_L(t) = A\sin(2\pi f_L t + \phi_{L0} + \Delta\phi_L(t)) \quad \text{with } \Delta\phi_L(t) = K_p a(t)$$

Modulation index: $\beta = \max_t |\Delta\phi_L(t)|$ with Kp and φ_{L0} cost

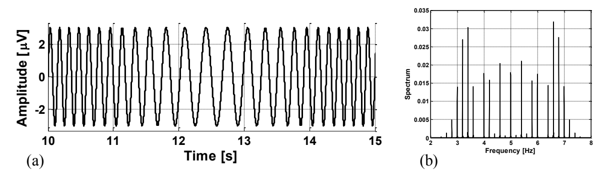


Fig.2. Typical PM signal $x_L(t)$ (a) and its power spectrum (b).

Cross-frequency coupling (CFC) modulator

A parallel AM-PM system can be used to generate CFC-like signals with a common input a(t).

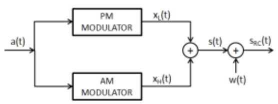


Fig.3. CFC modulator scheme.

Consider to have a sinusoidal information signal a(t):

$$a(t) = a_M \sin(2\pi f_m t)$$

At the output, additive-white-gaussian-noise w(t) with zero-mean and standard deviation σ is added:

$$s_{RC}(t) = s(t) + w(t)$$

CFC demodulator

The aim of the demodulation is:

(1) to extract the closest version $a_o(t)$ to the information signal a(t)
(2) to obtain an estimate of the carriers frequencies, f_L and f_H.

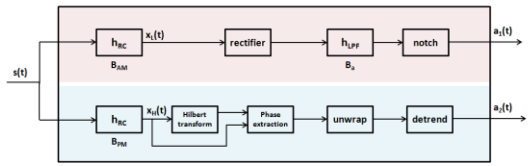


Fig.4. CFC demodulator scheme.

Information about carriers could shed further light to the behaviour of the specific neuronal populations involved in the coupling.

Results I: Demodulation performance

Demodulation performance can be measured by taking the maximum of the normalized cross-correlation between $a_1(t)$ and $a_2(t)$, called ρ. Indeed, in case of perfect demodulation, the condition $a_1(t) = a_2(t) = a(t)$ would be verified and ρ would assume unitary value. In this case, $a_o(t)$ would be identical to exactly a(t).

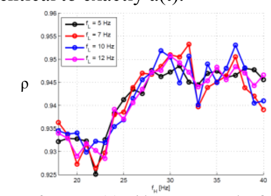


Fig.5. Demodulator performance (ρ) with SNR = 100 dB, β=3 and varying f_L and f_H.

Results II: Reliability of simulated data

Two signals were considered:

(1) s(t), an AM-PM simulated CFC-like signal with f_m = 0.2 Hz, f_L = 5 Hz, f_H = 18 Hz, m = 0.5, β = 5 and SNR = 30 dB.
(2) w(t), a Gaussian white noise signal.

They were tested for the existance of CFC by means of the Mean Vector Length (MVL) method (via toolbox PACT, EEGLab, Matlab).

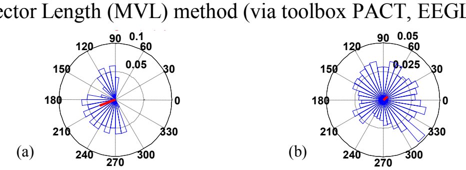
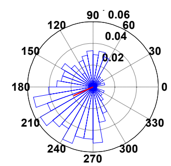


Fig.6. Application of the MVL method to (a) the simulated CFC-like signal s(t) and (b) the Gaussian noise signal w(t).

Results III: Preliminary results on real EEG data

A 10 seconds real EEG signal was tested for CFC by both the MVL method and our demodulation scheme.



In case of MVL, low frequency range was set to 1-12 Hz and high frequency range to 12-40 Hz. CFC was found to be significant (p=0.006).

Fig.7. Application of the MVL method to a real EEG signal.

With the proposed CFC demodulation, CFC was found at f_L = 8.9 Hz and f_H = 17.9 Hz, with ρ = 0.48.

Discussion

This study provided the theoretical framework of CFC, based on the well-established knowledge about modulation theory.

Advantages compared to existing quantification methods:
- rough definition of ranges for f_L and f_H
- contextual identification of f_L and f_H
- lower computational costs

Limitations:
- bursts-like behavior of CFC has not been included, yet
- extensive test on real EEG has to be performed

References
[1] Buszaki G., Cerebral Cortex, 1996.
[2] Canolty R.T. *et al.*, Trends Cogn. Sci., 2012.
[3] Benvenuto N. *et al.*, Communication systems, Wiley, 2007.