IQ Impairments and Corrections in Ultra-wideband transmitters

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Outline

1. Motivations
2. Mathematical formulation
3. Image suppression impact on Comm. Systems.
4. Corrective Topologies
5. Adaptive blind estimations methods
6. Experimental data
7. Summary
8. Future work

Motivations

1. Multi-channel Transmitters
2. Ultra-Wideband Transmitters
   a. Beam hopping and time slicing satellite communications
   b. 5G waveforms

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Mathematical formulation and Pictorial depictions

IQ impairments

Modulated Baseband signal

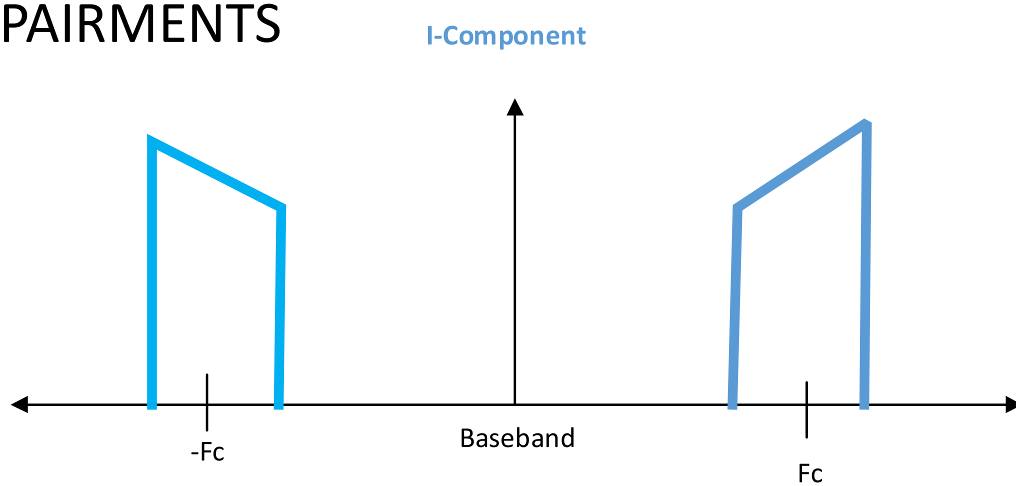
$$y_m(t) = y_i(t) + jy_q(t) \qquad (1)$$

Translated to RF

$$y_{trans}(t) = real\{y_m(t)e^{-jw_{lo}t}\} \qquad (2)$$

I-component

$$y_i(t) = x_i(t)\cos(w_c t) \qquad (3)$$

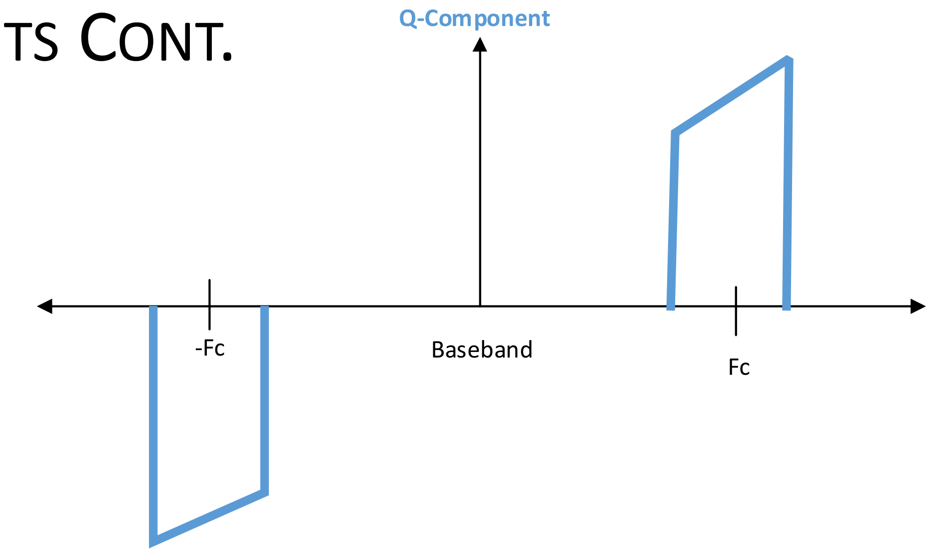


Frequency Domain representation of I-component depicting an even-mode

Substitution and manipulation

$$\begin{aligned} Y_i(w) &= F\{y_i(t)\} = F\{x_i(t)\} * F\{\cos(w_c t)\} \\ &= X_i(\mathrm{w}) \left\{\frac{e^{jw_c t} + e^{-jw_c t}}{2}\right\} Y_i(w) \qquad (4) \\ &= \frac{X_i(\mathrm{w})}{2} * [\delta(\mathrm{w} - w_c) + \delta(\mathrm{w} + w_c)] \end{aligned}$$

Mathematical formulation and Pictorial depictions IQ impairments Cont.



Q-component

$$y_q(t) = -x_q(t)\sin(w_c t) \qquad (5)$$

Substitution and manipulation

$$\begin{aligned} Y_q(w) &= F\{x_q(t)\} * F\{-\sin w_c t\} \\ &= X_q(\mathrm{w}) * F\left\{\frac{e^{-jw_c t} - e^{jw_c t}}{2j}\right\} \qquad (6) \\ &= \frac{X_q(\mathrm{w})}{2j} * [\delta(\mathrm{w} - w_c) - \delta(\mathrm{w} + w_c)] \end{aligned}$$

Frequency Domain representation of Q-component depicting an odd-mode

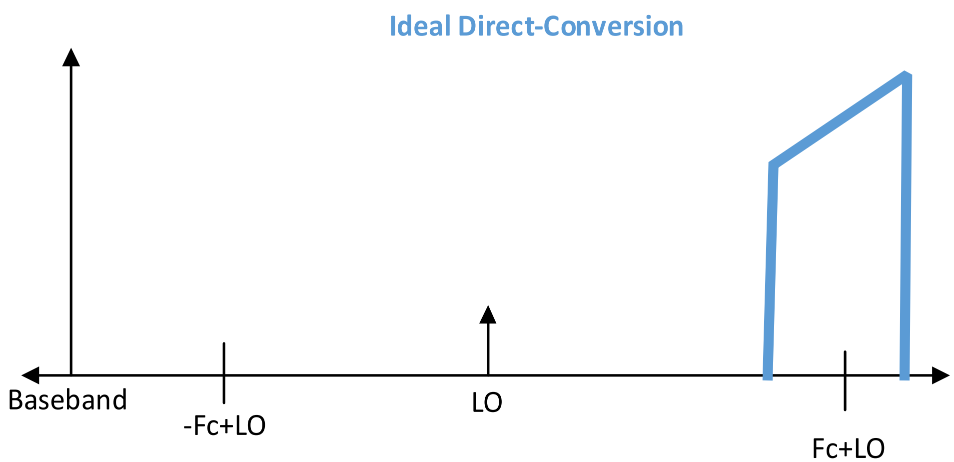
Mathematical formulation and Pictorial depictions IQ impairments Cont.

Rewriting the translation equation

$$y_{trans}(t) = \frac{y_m(t)}{2} e^{-jw_{lo}t} + \frac{y_m^*(t)}{2} e^{jw_{lo}t} \qquad (7)$$

Assuming, $Y_m(w) = Y_m^*(w)$

$$Y_{trans}(w) = \frac{Y_m(w)}{2} * [\delta(\mathrm{w} + w_{lo}) + \delta(\mathrm{w} - w_{lo})] \qquad (8)$$



Ideal direction conversion with baseband offset

Adding I and Q to translation

$$Y_m(w) = \frac{Y_i(w)}{2} * [\delta(\mathrm{w} - w_c) + \delta(\mathrm{w} + w_c)] + \frac{Y_q(w)}{2} * [\delta(\mathrm{w} - w_c) - \delta(\mathrm{w} + w_c)] \qquad (9)$$

Mathematical formulation and Pictorial depictions IQ impairments Cont.

Combining everything

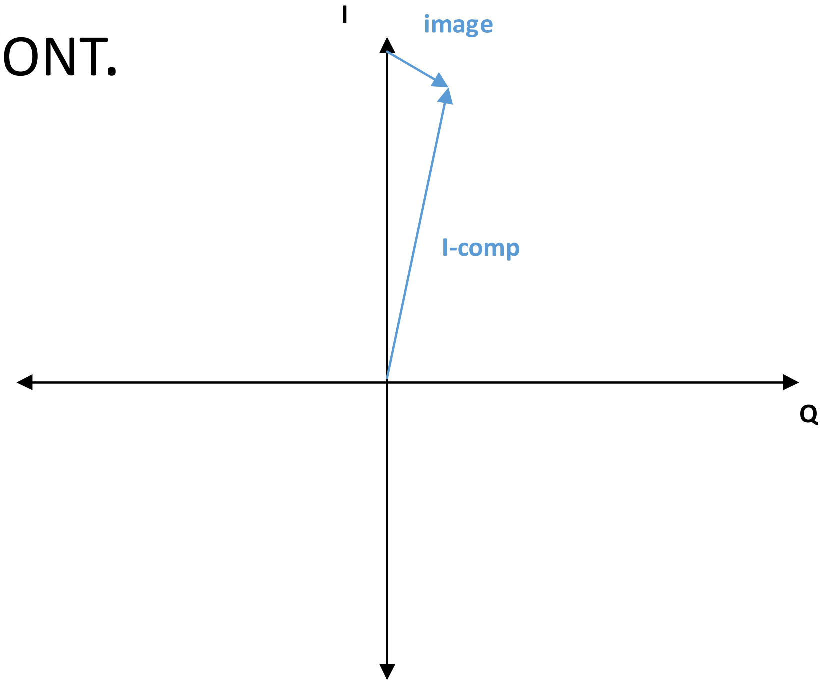
$$Y_{trans}(w) = \{\frac{X_i(\mathrm{w}) + X_q(\mathrm{w})}{4} * \delta(\mathrm{w} - w_c)$$
$$\frac{X_i(\mathrm{w}) - X_q(\mathrm{w})}{4} * \delta(\mathrm{w} + w_c) \qquad (10)$$
$$* \, [\delta(\mathrm{w} + w_{lo}) + \delta(\mathrm{w} - w_{lo})].$$

Wanted Signal

$$\frac{X_i(\mathrm{w}) + X_q(\mathrm{w})}{4} * \delta(\mathrm{w} - w_c) \qquad (11)$$

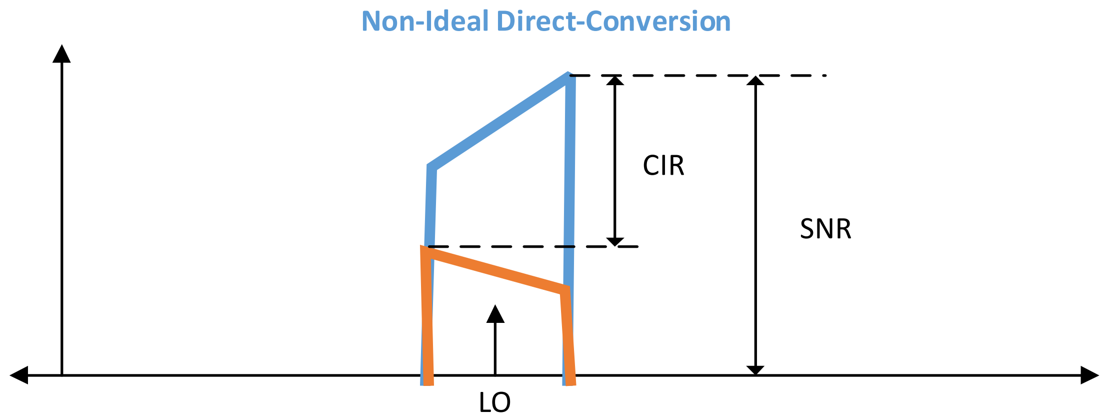
Image Signal

$$\frac{X_i(\mathrm{w}) - X_q(\mathrm{w})}{4} * \delta(\mathrm{w} + w_c) \qquad (12)$$



Vector relationship of I/Q Components

Impact on Image-Suppression on Communication systems



Non-ideal direct conversion

Degradation of signal

$$CNIR = 10log_{10}\left(\left(\frac{1}{10^{\frac{SNR_{input}}{10}}} + \frac{1}{10^{\frac{CNIR_{image}}{10}}}\right)^{-1}\right) \qquad (13)$$

Rule of thumb: Keep CIR 15 dB below target SNR value

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Frequency Impact on IQ imbalances

Frequency Dependent Amplitude Imbalance

$$L_{imb}(w) = L_I(w) \;/ L_Q(w) \qquad (14)$$

Frequency Dependent Phase Imbalance

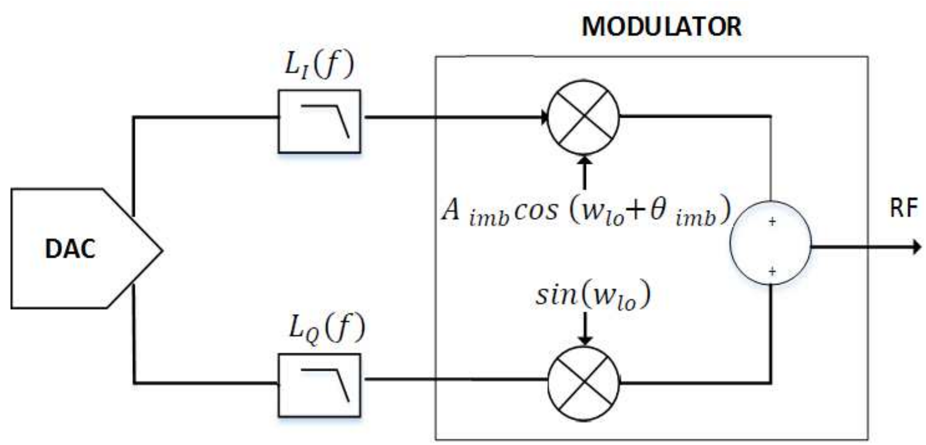
$$\theta_{delay} = w_{baseband} T_{delay} \qquad (15)$$

Total Amplitude Imbalance

$$G_{imb}(w) = L_{imb}(w) * A_{imb} \qquad (16)$$

Total Phase Imbalance

$$\emptyset_{imb}(w) = \angle L_{imb}(w) + \theta_{imb} + \theta_{delay} \qquad (17)$$



Typical direct conversion transmitter implementation with amplitude and phase imbalance.

Corrective Topology Time Domain

Imbalance Compensation

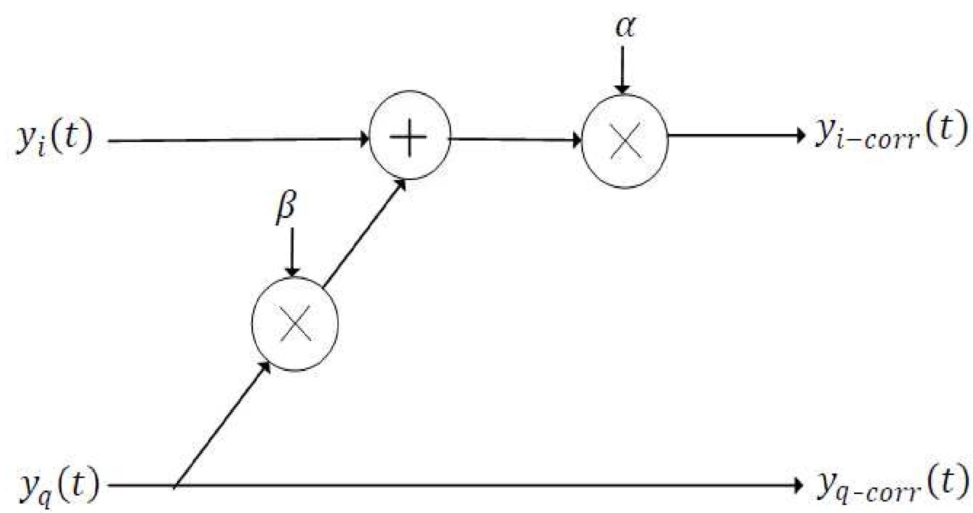
$$y_{i-corr}(t) = \alpha\{y_i(t) + \beta y_q(t)\} \quad (18)$$

Mostly Amplitude Compensation

$$\alpha = (1 + A_{\ imb})\cos(\theta_{\ imb}) \quad (19)$$

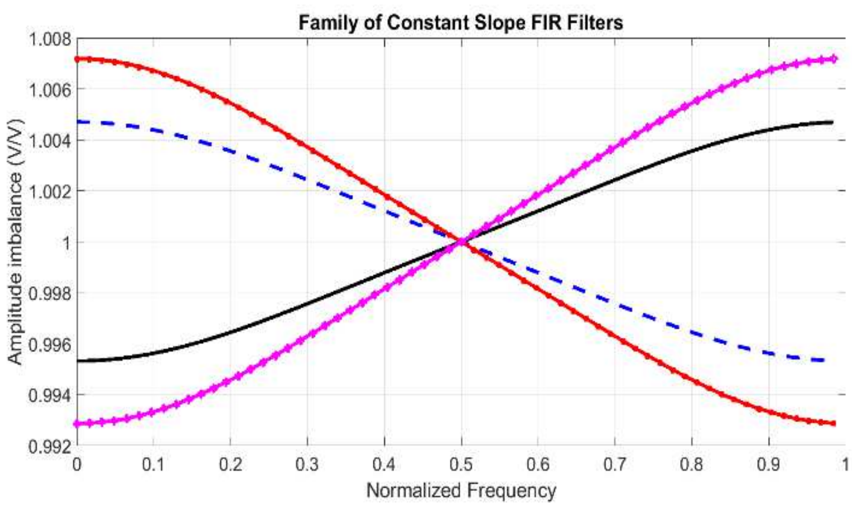
Phase Compensation

$$\beta = sin(\theta_{\ imb}) \quad (20)$$

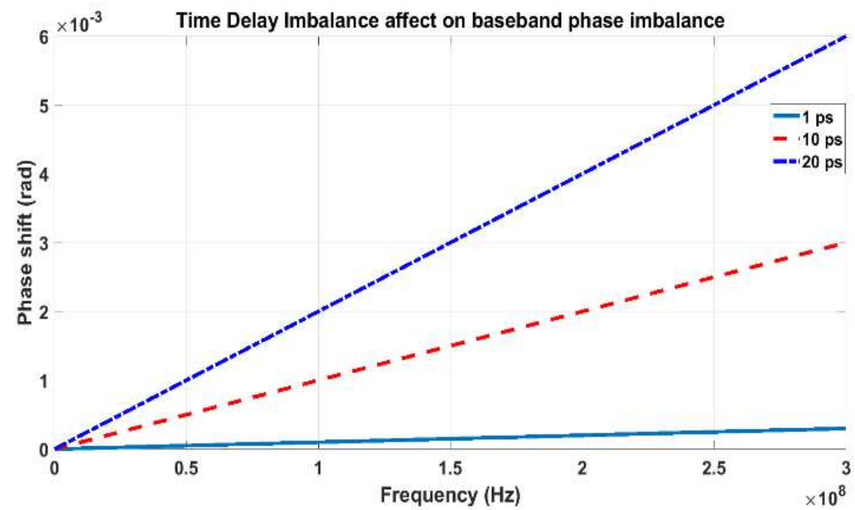


Wideband corrective topology for phase and amplitude imbalances for direct conversion transmitter

Corrective Topology Time Domain

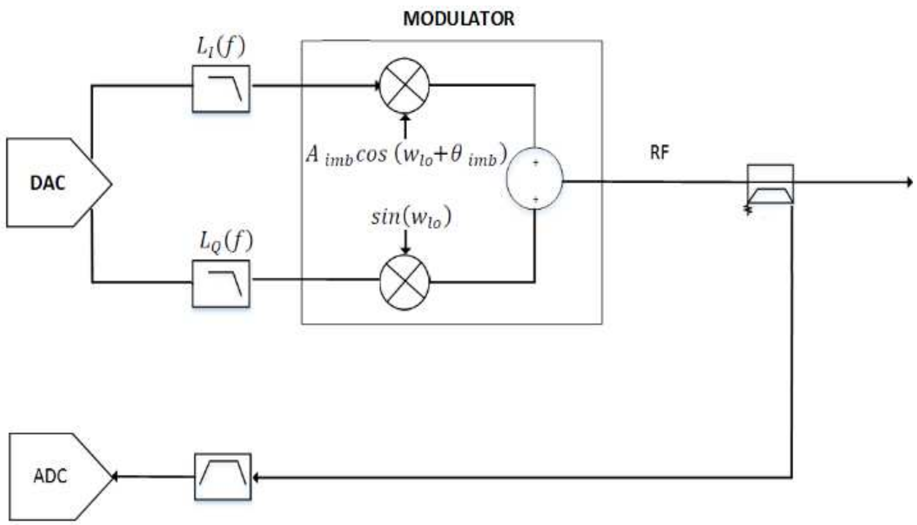


Constant slope FIR filter for frequency dependent imbalance correction.

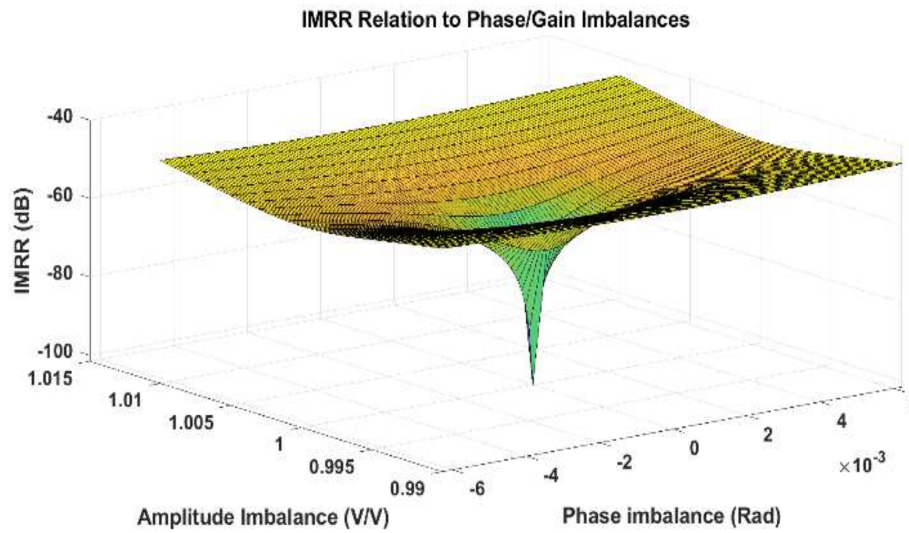


Phase imbalance over baseband frequency as a result of time delay imbalance

Adaptive Blind ESTIMATION IQ IMPAIRMENTS



Direct conversion transmitter with generic feedback path for adaptive correction



IMRR as function of phase and amplitude imbalance

Adaptive Blind ESTIMATION IQ IMPAIRMENTS

Orthogonality

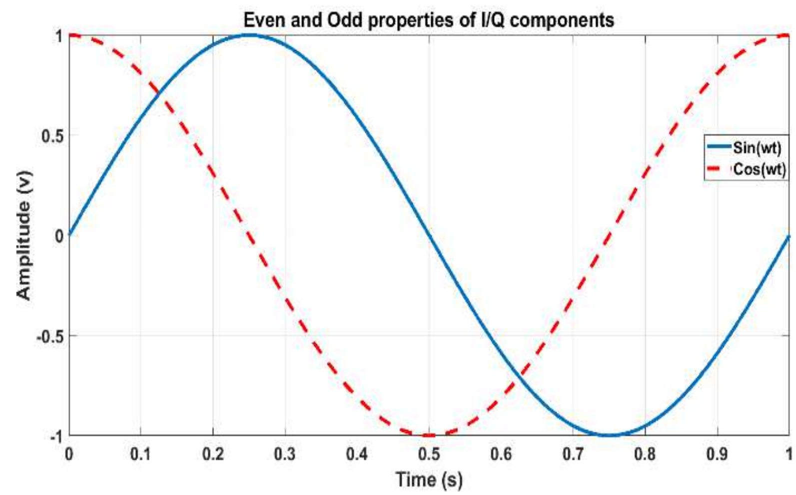
$$Error = \int_{-l}^{l} I(t)Q(t)dt, \quad (21)$$

Orthogonal error accumulation

$$\emptyset_{imb-new} = \emptyset_{imb-old} + \lambda_{phase} I(t) Q_{corr1}(t) \quad (22)$$

Amplitude error accumulation

$$G_{imb-new} = G_{imb-old} + \lambda_{gain}[I(t)^2 - Q_{corr2}(t)^2] \quad (23)$$



Plot of sin and cos function to illustrate even and odd properties.

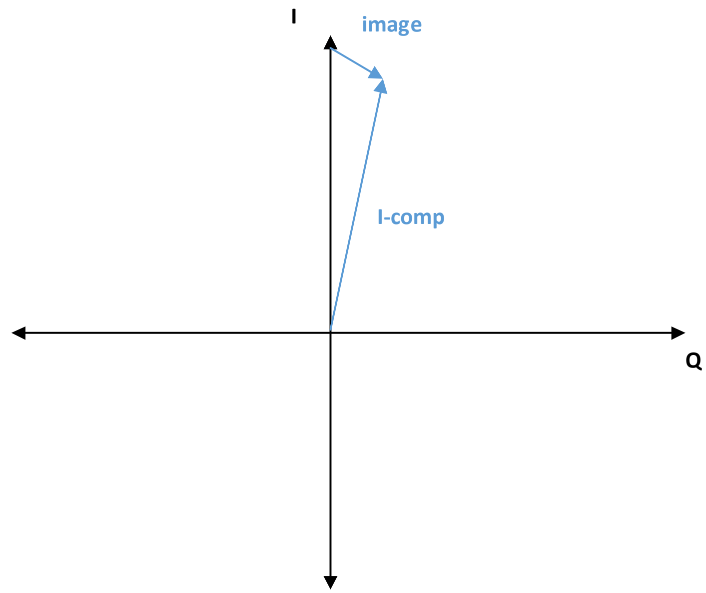
Adaptive Blind ESTIMATION IQ IMPAIRMENTS

Orthogonality correction update

$$Q_{corr1}(t) = Q(t) - \emptyset_{imb-new} I(t) \quad (24)$$

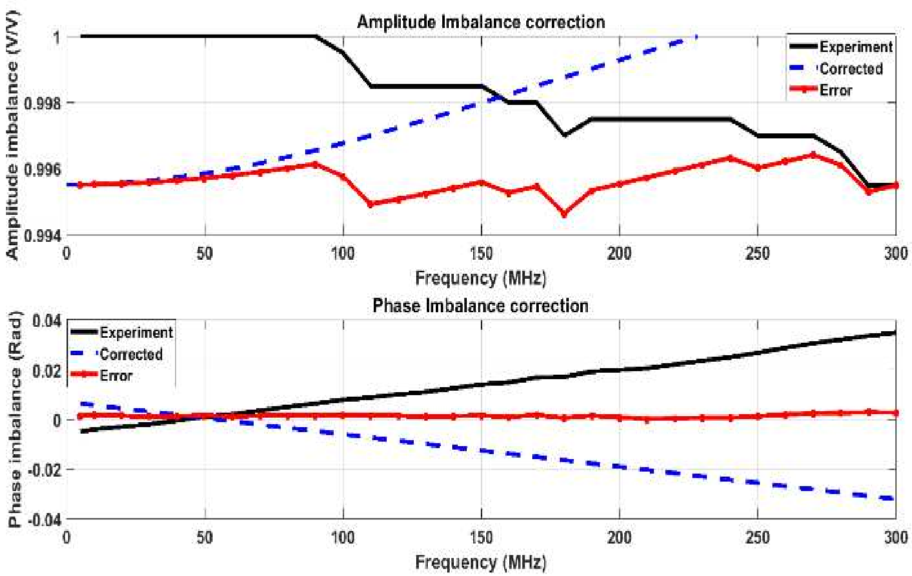
Gain correction update

$$Q_{corr2}(t) = G_{imb-new} Q_{corr1}(t). \quad (25)$$



Vector relationship of I/Q Components

Experimental Results



Amplitude and phase correction of baseband IQ imbalances

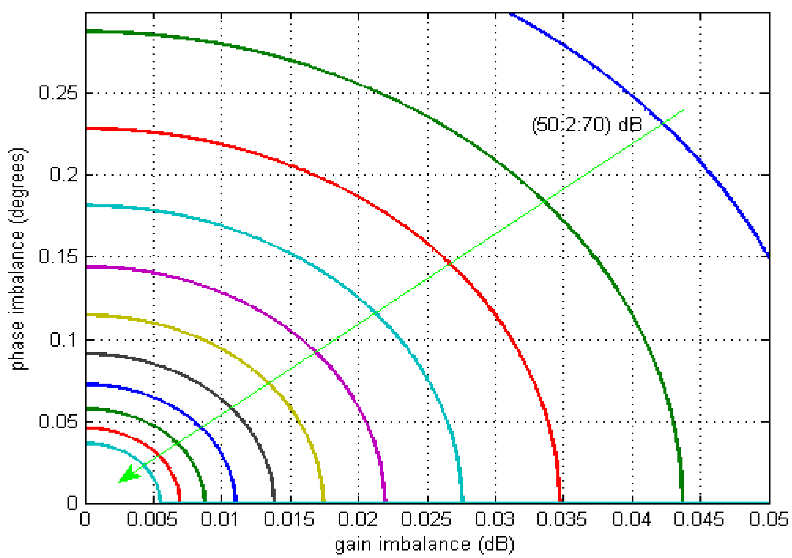
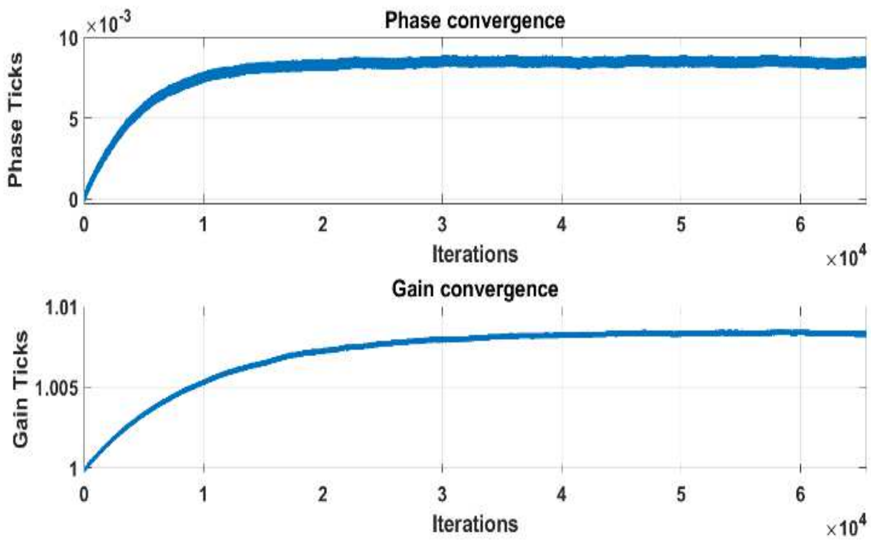
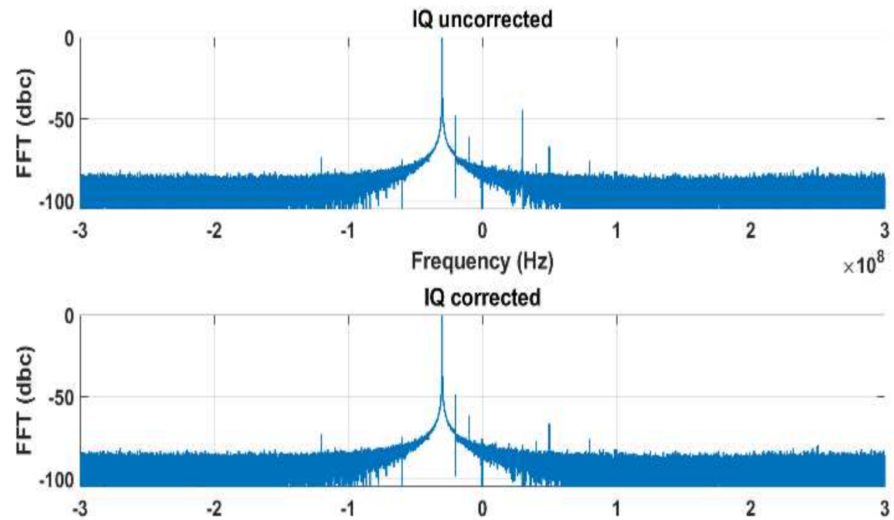


Image error vs gain/phase imbalance error

Experimental Results

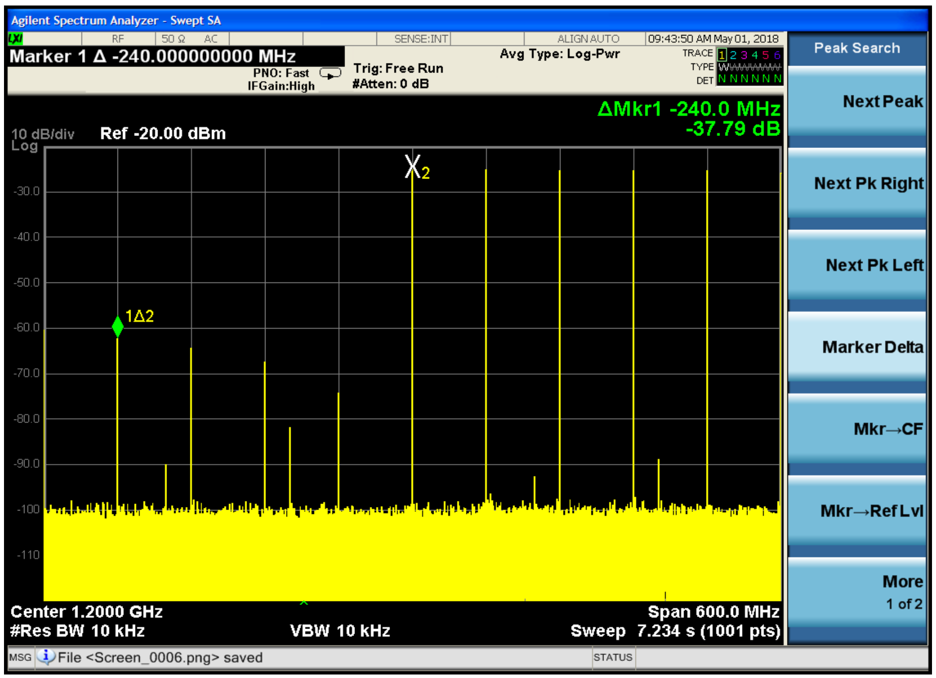


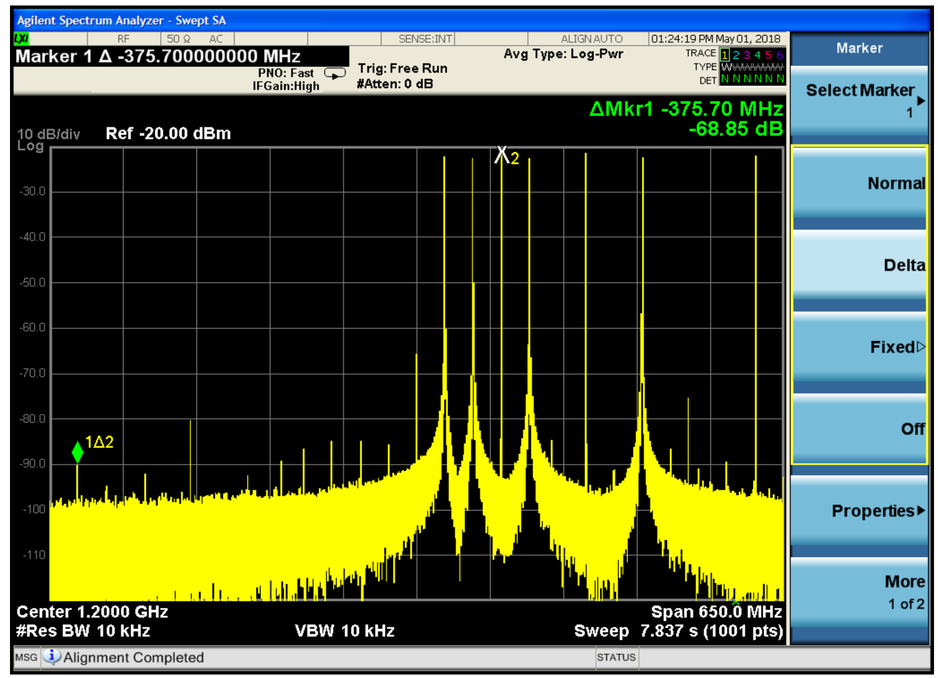
Phase and gain estimates conversion using gradient decent algorithm



Amplitude and phase correction of LO dependent IQ imbalances

Experimental Results





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Summary

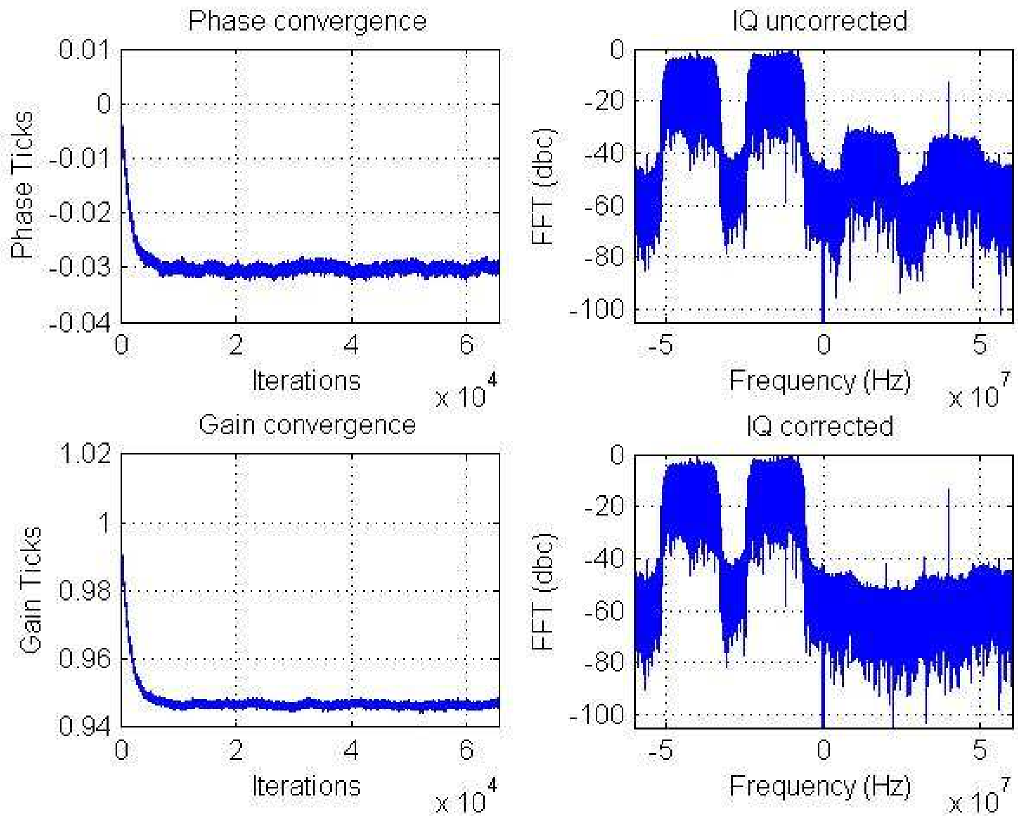
1. Mathematically derived root cause of image
2. Explored implications on image suppression in communications
3. Identified frequency compensation methods for phase/gain imbalance
4. Blind estimation and compensation methods for dynamic systems presented
5. Experimental results for frequency and dynamic compensation methods presented

Future Work

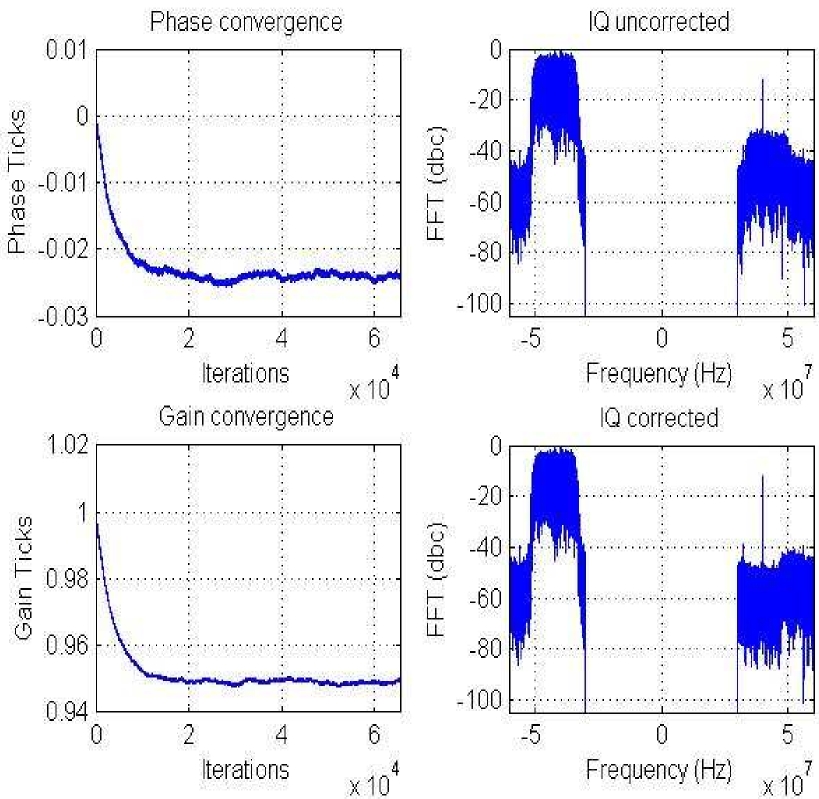
1. Further exploration of different imbalance estimation methods

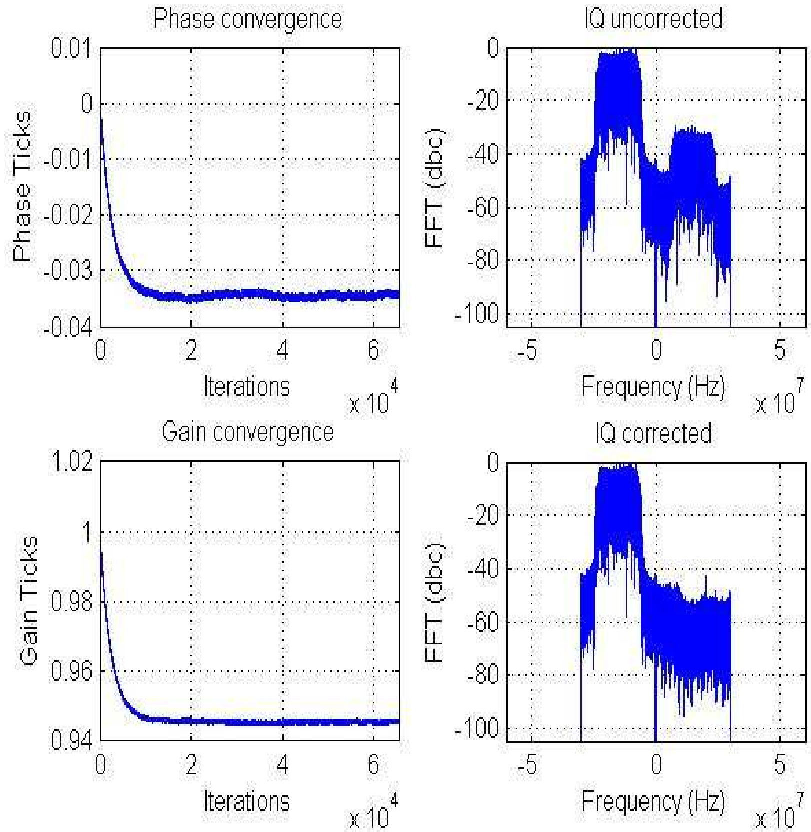
2. Compensation methods in frequency domain

Additional slides
Linearity of estimation methods

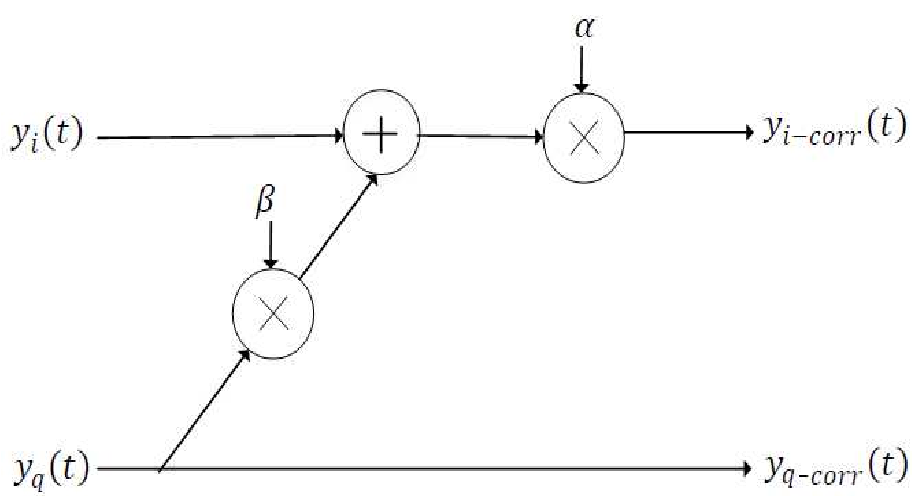


Additional slides
Linearity of estimation methods Cont.





Additional Slides
Corrective Topology Frequency Domain

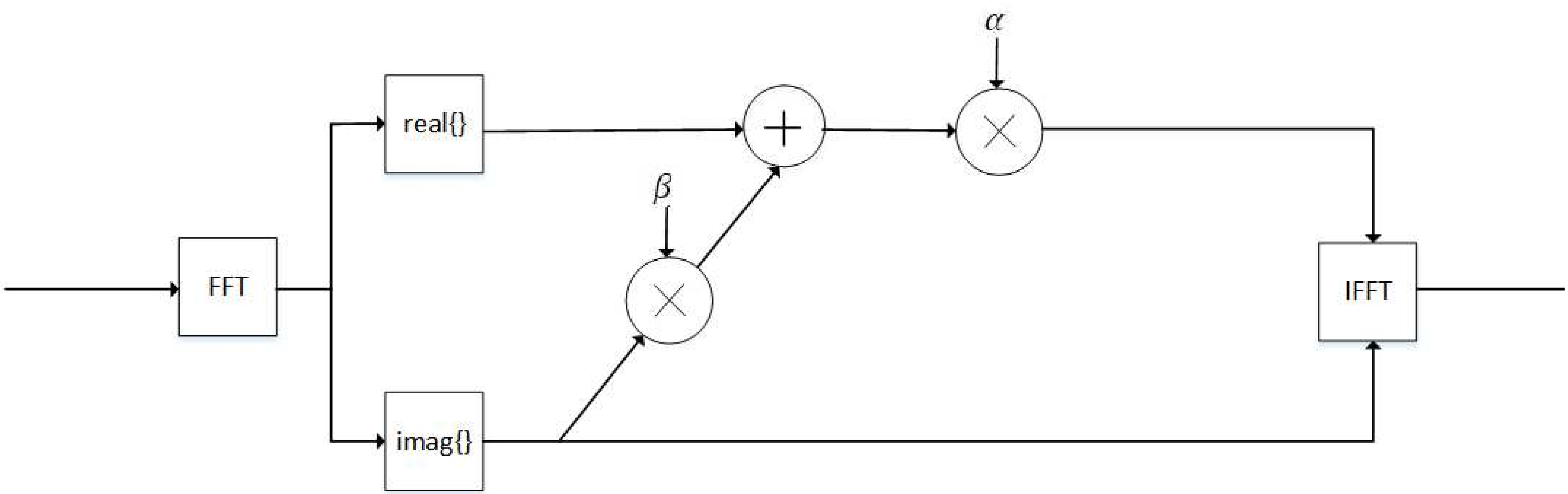


Wideband corrective topology for phase and amplitude imbalances for direct conversion transmitter

Fourier Transform of corrective domain structure

$$Y_{i-corr}(w) = y_{i-corr}(t) = \alpha F\{y_i(t)\} + \alpha\beta F\{y_q(t)\} \qquad (26)$$

Additional Slides
Corrective Topology Frequency Domain Cont.



Frequency selective corrective topology for phase and amplitude imbalances for direct conversion transmitter

References

[1] J.J Witt, ‘Modelling, Estimation, and Compensation of Imbalances in Quadrature Transceivers’, Stellenbosch University, 2011.

[2] L. Hars, “Frequency Response Compensation with DSP”, in Streamlining Digital Signal Processing 2nd Edition. Hoboken, NJ: Wiley, 2011, ch. 39.

[3] V. Valimaki and T. I. Laakso, "Principles of fractional delay filters," 2000 IEEE International Conference on Acoustics, Speech, and Signal Processing. Proceedings (Cat. No.00CH37100), Istanbul, Turkey, 2000, pp. 3870-3873 vol.6.

[4] ‘IQ Correction’, MEP Newsletter 3, 2011. [Online] Available:http://www.delmarnorth.com/microwave/requirements/IQGainPhaseCorrection.pdf, [Accessed: Aug. 6, 2018]