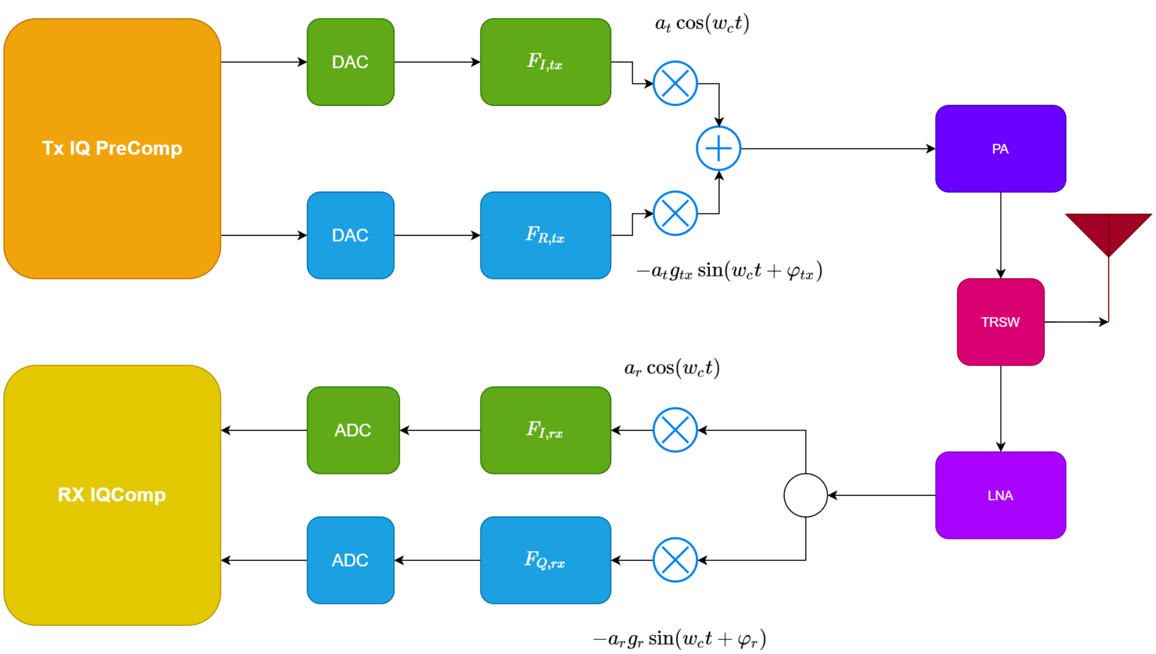
TX IQImbalance, RX IQImbalance Calibration for Direct Conversion Architecture

- A summary and proposal
- KC Hung

The Impairment Modeling

- IQ Impairment Sources
  - DAC/ADC IQ latency skew(especially for very high speed AD/DC)
    - different latency causes **linear phase variation** with frequency
  - TRX IQ ALPF response mismatch (wider bandwidth, or A/D Die)
    - different variation causes **magnitude response variation** with frequency
  - Mixer phase/gain: cause constant **iq coupling** due to phase mismatch and const magnitude response mismatch.
  - In WiFi application, typically LPF response response and mixer iq
- Blockdiagram



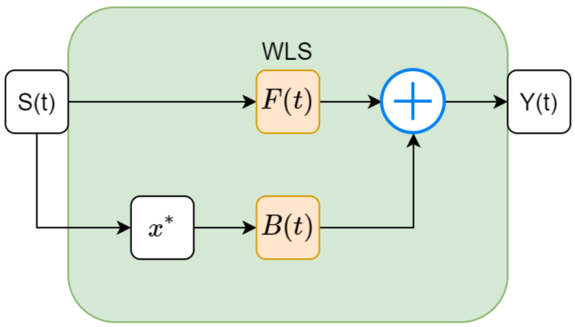
- IQ-path View
  - TX Side modeling:

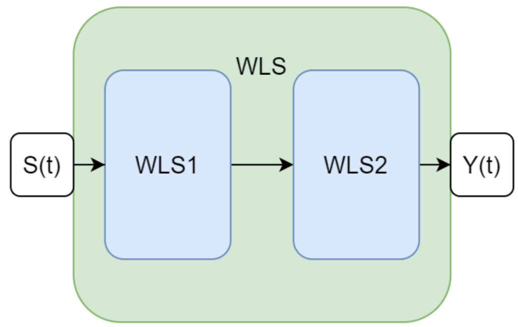
$$\begin{bmatrix} x_I(n) \\ x_Q(n) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & g_t \end{bmatrix} \begin{bmatrix} \cos(\theta/2) & -\sin(\theta/2) \\ -\sin(\theta/2) & \cos(\theta/2) \end{bmatrix} \begin{bmatrix} F_{It}(n) & \\ & F_{Qt}(n) \end{bmatrix} \otimes \begin{bmatrix} s_I(n) \\ s_Q(n) \end{bmatrix}$$

  - RX Side modeling:

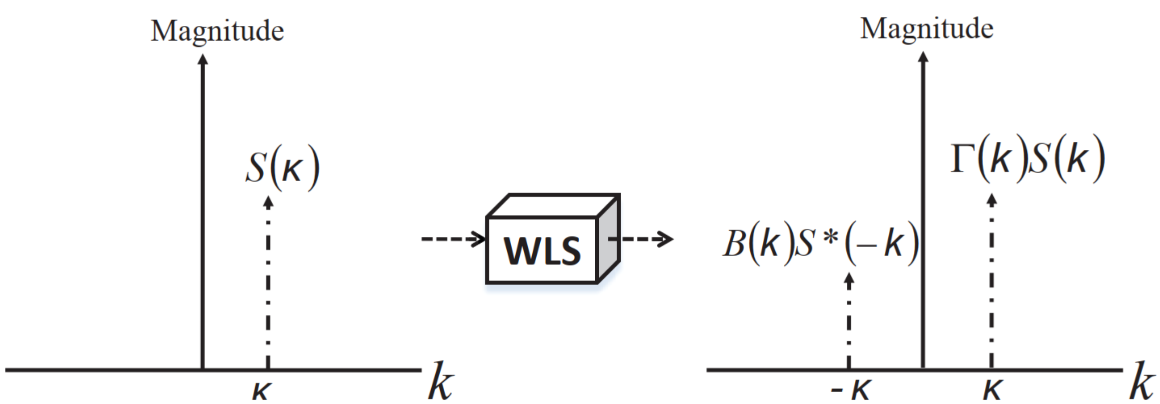
$$\begin{bmatrix} y_I(n) \\ y_Q(n) \end{bmatrix} = \begin{bmatrix} F_{Ir}(n) & \\ & F_{Qr}(n) \end{bmatrix} \otimes \begin{bmatrix} 1 & 0 \\ 0 & g_r \end{bmatrix} \begin{bmatrix} \cos(\theta_r/2) & \sin(\theta_r/2) \\ \sin(\theta_r/2) & \cos(\theta_r/2) \end{bmatrix} \begin{bmatrix} r_I(n) \\ r_Q(n) \end{bmatrix}$$

- Wide-sense Linear System (WLS) View:
  - WLS model:
    - $x(t) = F(t) \otimes s(t) + B(t) \otimes s^*(t)$
    - Closure property: cascade of WLS is still WLS
      - $x = F_1 s + B_1 s^*, y = F_2 x + B_2 x$
      - $y = F_2(F_1 s + B_1 s^*) + B_2(F_1^* s^* + B_1^* s) = (F_1 F_2 + B_1^* B_2)s + (F_2 B_1 + F_1^* B_2)s^* = Fs + Bs^*$
    - Linear system is a **WLS**



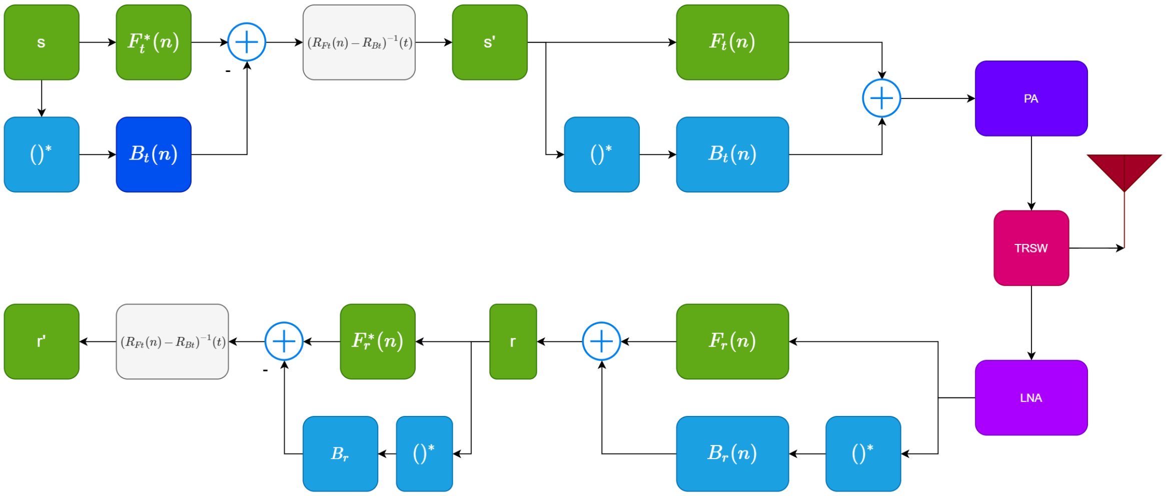


  - IQ mismatch is a **WLS**
    - $\boldsymbol{x}(n) = F_{\mathrm{t}}(n) \otimes \boldsymbol{s} + B_{\mathrm{t}}(n) \otimes \boldsymbol{s}^*$
      - $F_t(n) = \left(F_{it}(n) + g_t e^{j\theta_t} F_{qt}(t)\right)/2)$
      - $B_t(n) = \left(F_{it}(n) - g_t e^{j\theta_t} F_{qt}(t)\right)/2 << Ft(n)$
      - $F_r(n) = \left(F_{ir}(n) + g_r e^{-j\theta_r} F_{qr}(t)\right)/2$
      - $B_r(n) = \left(F_{ir}(n) - g_r e^{j\theta_r} F_{qr}(t)\right)/2 << Ft(n)$
    - $\boldsymbol{y}(n) = \gamma_{\mathrm{r}}(n) \otimes \boldsymbol{r} + \beta_{\mathrm{r}}(n) \otimes \boldsymbol{r}^*$
  - frequency response view of IQ
    - $S_r(k) = \Gamma(k)S(k) + \mathrm{B}(k)S^*(-k)$

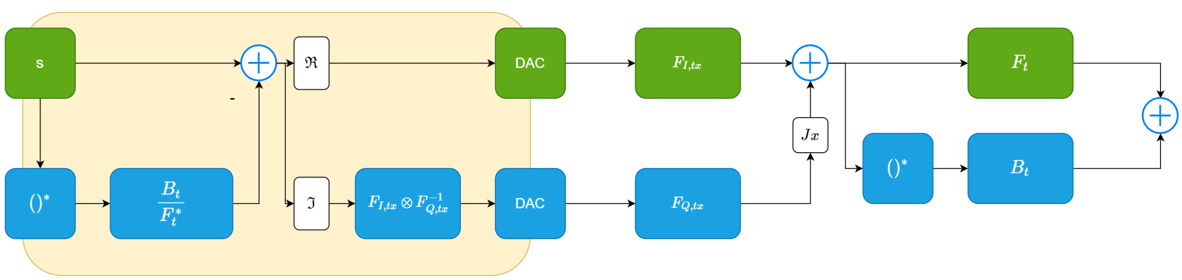


The Compensation approach

- IQ compensation $\equiv$ equalization of WLS system
- General Formula



- Time domain compensator
  - TX precomp: $\boldsymbol{s}'(n) = (R_{Ft} - R_{Bt})^{-1} \otimes (F_t^* \otimes \boldsymbol{s} - B_t \otimes \boldsymbol{s}^*)$
  - Rx comp: $\boldsymbol{r}'(n) = (R_{Fr} - R_{Br})^{-1} \otimes (F_t^* \otimes \boldsymbol{s} - B_t \otimes \boldsymbol{s}^*)$
  - Simplification : $\boldsymbol{x}' = \boldsymbol{x} - (F^{-*} \otimes B) \otimes \boldsymbol{x}^* = \boldsymbol{x} - W \otimes \boldsymbol{x}^*$
- Frequency domain compensator
  - $S(k) = \frac{1}{|F(k)|^2 - |B(k)|^2} (F^*(k) S_t(k) - B(k) S_t^*(-k))$
  - Simplified: $S(k) = S_t(k) - \frac{B(k)}{F^*(k)} S_t^*(-k)$
- Separate FI and FD compensation
  - $s' = s - \frac{B}{F^*} s^*$
  - $s'' = \Re(s) + (F_Q \otimes F_I^{-1}) \otimes \Im(s)$



Calibration Schemes

- Typical Approaches:
  - TX self calibration:
    - Approach:
      - precisely-defined two-tone training sequence
      - square-circuit(self-mixing or diode)
      - LPF + tone-detection after ADC.
    - Algorithm:
      - Search-based: tone-detector output power as cost-function, adaptive adjust/search compensator coefficient
      - Estimation-based: precisely design training pattern, using tone responses at different frequency to estimate parameter directly

- Typically handling the FI part. More complicated for handing FD part.
- RX Self calibration
  - Generate training signal in RF domain
    - single tone or
    - band-limited white gaussian signal
  - Estimation Algorithm:
    - Search-based : adjust compensator such that image is minimum
    - Adaptive filtering: minimize imaginary part or iq-cross-talk

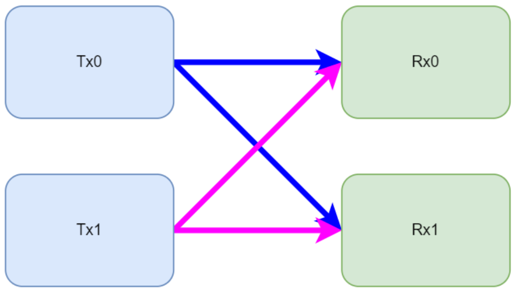
Joint TX RX Calibration

- OTA Joint TX IQ and RX IQ, compensate TX IQ/RX IQ Jointly
  - Key idea: TXIQ/CH/RXIQ as WLS system, equalize whole system after estimate equivalent response.
  - Time-domain(SCM): adaptive training of the WLS equalizer
  - Fequency-domain(OFDM,SC-FDE): channel estimation and then compensated-EQ.
  - Requirement: **No CFO** in-between TX and RX
    - CFO will cause the whole system not a WLS
- Reduce Channel estimation complexity by Golay Complementary Sequence
  - Golay Sequence Properties:
    - $S_{aL}(r) + S_{aL}(L-r-1) + S_{bL}(r) + S_{bL}(L-r-1) = 1$, for $r = 0 \dots \frac{L}{2} - 1$
    - $S_{aL}(n) \odot S'_{aL}(n) + S_{bL}(n) \odot S'_{bL}(n) = 0_L$
    - $S_{aL}(n) \odot S''_{bL}(n) + S_{bL}(n) \odot S'_{aL}(n) = 0_L$
    - $S_{aL}(n) \odot S_{aL}(n) + S_{bL}(n) \odot S_{bL}(n) = 2_L$
    - $S_{xL}\prime(r) = S_{xL}(L-r-1)$
  - Received Signal (in FD) due to TX FS IQ:
    - $S_{ra}(k) = \Gamma(k) S_a(k) + B(k) S'_a(k)$
    - $S_{rb}(k) = \Gamma(k) S_b(k) + B(k) S'_b(k)$
  - Estimation:
    - $C_a(k) = S_{ra}(k) \odot S_a(k)$, $C_b(k) = S_{rb}(k) \odot S_b(k)$
    - $D_a(k) = S_{ra}(k) \odot S'_a(k)$, $D_b(k) = S_{rb}(k) \odot S_{b'}(k)$
    - $\Gamma(k) = \frac{1}{2}\left\{S_{ra}(k) \odot S_a(k) + S_{rb}(k) \odot S_b(k)\right\}$
      $B(k) = \frac{1}{2}\left\{S_{ra}(k) \odot S'_a(k) + S_{rb}(k) \odot S'_b(k)\right\}$
- Issue: Separation of TX and RX IQ parameters.
  - Only get jointly response typically.
  - If involve channel response, can use affine projection iteratively separate TXIQ/CH/RXIQ
    - estimate CH by given TXIQ/RXIQ using subspace projection estimation
    - estimate TXIQ/RXIQ by given CH with sub-space projection of TXIQ/RXIQ
    - iteratively estimate the parameters.
  - If channel is “White”: no **middle-ware**, TXIQ and RXIQ becomes a single response=> hard to separate it!

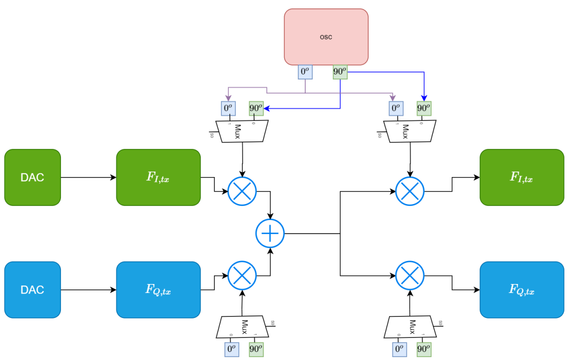
Separation of TXIQ/RXIQ with Jointly Estimation

- Approach 1: TXIQ self-cal or rxIQ self-cal
- Approach 2: Introduce more estimation equations

- Comments: fail due to existence of multiple roots for m unknown 2nd-order polynomial equations
- In MIMO system (ex 2x2):
  - TX0 to RX0 and RX1 to get F_{00},B_{00},F_{01},B_{01}
  - TX1 to RX0 and RX1 to get F_{10},B_{10},F_{11},B_{11}
  - Use F_{00},B_{00},F_{01},B_{01}, F_{10},B_{10},F_{11},B_{11} to derive F_{T0},B_{T0},F_{T1},B_{T1},F_{R0},B_{R0},F_{R1},B_{R1}

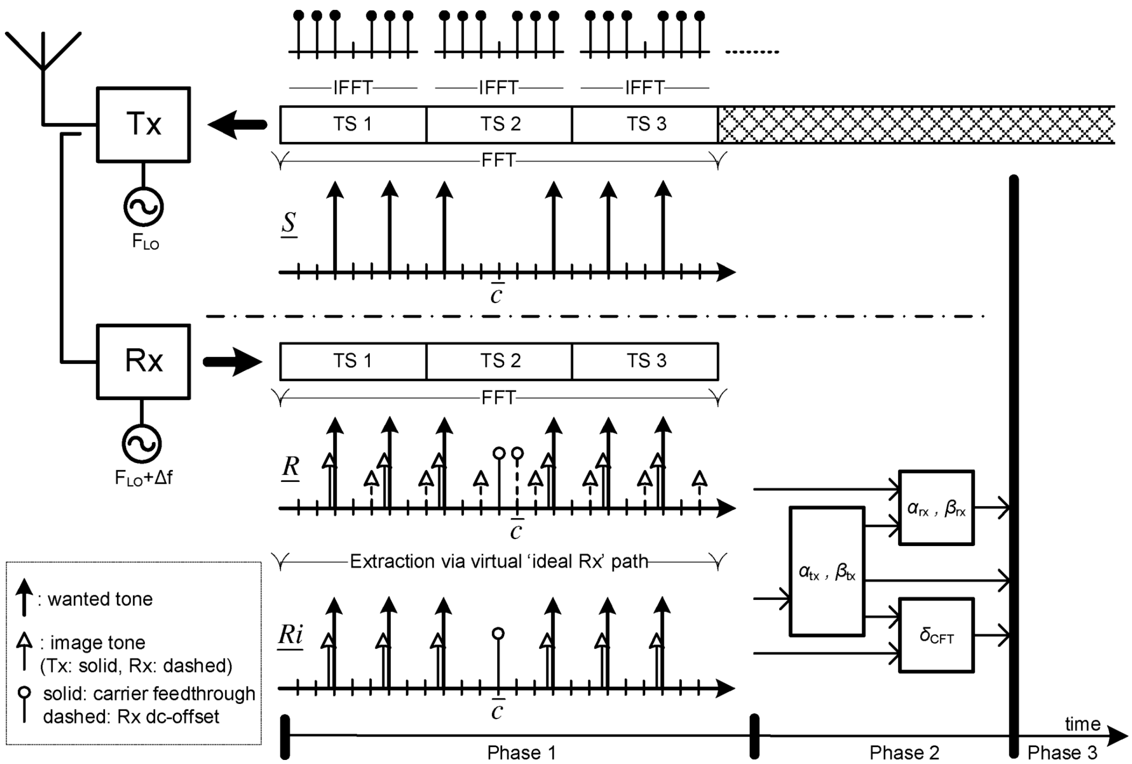


- In SISO:
  - Modify Mixer architecture to introduce MixerTx/MixerTxSwap, MixerRx/MixerRxSwap
  - like 2x2 case, estimate 4 set of the parameter and select the one for MixerTx/MixerRx



- Approach 3: Introduce middle-ware, change response of the loopback path.
  - Ex. Add controllable phase shift/rotation(ex 90deg shifter) in the path
    - accuracy of shifter affects the performance.

  - Ex. Add extra FO between TX/RX



- Proposal:
  - insert different calibration loopback path: ex. phase shift of the path.
  - separate the tx and rx parameters according to two channel condition.
  - requires the estimation of the "middleware", the gain and the phase estimation.
  - Separate algorithm:
  - The TRX model:
  - path1(original): $w_1 = F_r\left(F_t s + B_t s^*\right) + B_r\left(F_t^* s^* + B_t^* s\right) = \left(F_r F_r + B_r B_t^*\right) s + \left(F_r B_t + B_r F_t^*\right) s^*$
  - path2(phase-rotate): $w_2 = W_r(\alpha W_t(s)) = F_r\left(\alpha F_t s + \alpha B_t s^*\right) + B_r\left(\alpha^* F_t^* s^* + \alpha^* B_t^* s\right) = \left(\alpha F_r F_t + \alpha^* B_r B_t^*\right) s + \left(\alpha F_r B_t + \alpha^* B_r F_t^*\right) s^*$
  - $$\begin{aligned} F_1 &= F_r F_t + B_r B_t^*, \\ B_1 &= F_r B_t + B_r B_t^*, \\ F_2 &= \alpha F_r F_t + \alpha^* B_r B_t^*, \\ B_2 &= \alpha F_r B_t + \alpha^* B_r B_t^* \end{aligned}$$
  - We have that:
    - $$\begin{aligned} F_r F_t &= \left(\alpha^* F_1 - F_2\right) / \left(\alpha^* - \alpha\right) = A \\ F_r B_t &= \left(\alpha^* B_1 - B_2\right) / \left(\alpha^* - \alpha\right) = C \\ B_r^* F_t &= \left(\alpha^* B_1^* - B_2^*\right) / \left(\alpha^* - \alpha\right) = D^* \end{aligned}$$
  - And the TX/RX iq mismatch is performed by:
    - $$\begin{aligned} B_t / F_t &= C / A = \left(\alpha^* B_1 - B_2\right) / \left(\alpha^* F_1 - F_2\right) \\ B_r^* / F_r &= D^* / A = \left(\alpha^* B_1^* - B_2^*\right) / \left(\alpha^* F_1 - F_2\right) \end{aligned}$$

Training System Design And Procedure

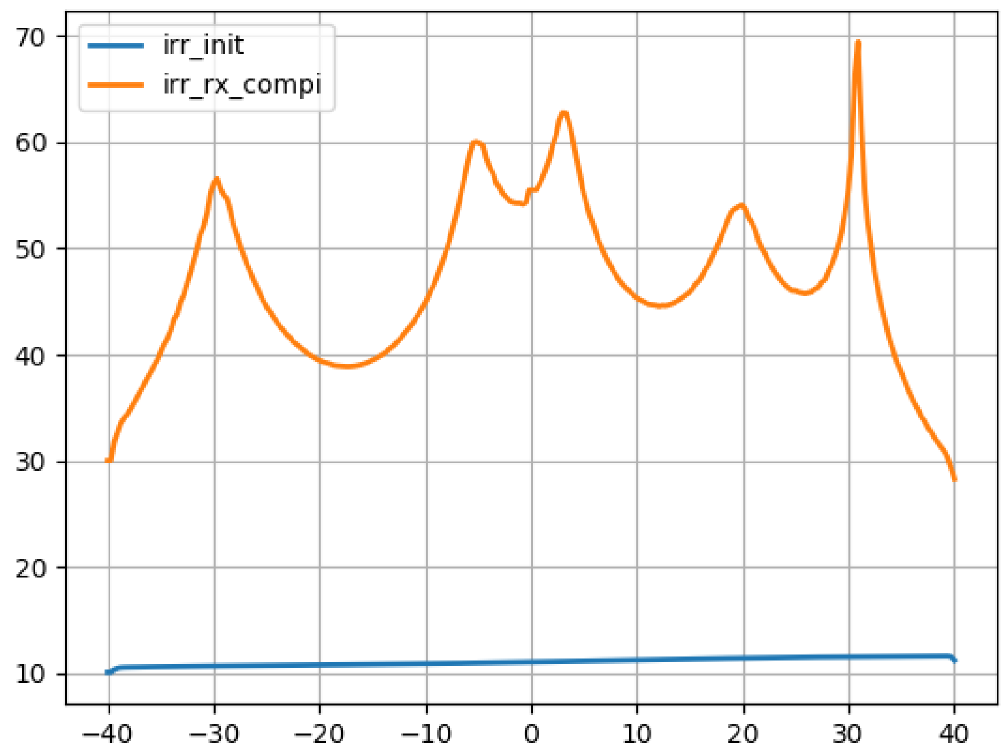
- Procedure:
  - For each estimation

        - AGC: fix TX gain, adjust RX gain to make minimum Noise
        - Estimate TRXIQ jointly: iteratively doing the approach
            - Estimate gain offset of two path using time domain Golay sequence with compensated TX,RX IQ mismatch
            - Estimate TX iq compensation using two paths with gain offset
            - Compensate TX, Estimate RX iq compensation using one path.
    - Collect all estimation results => separation of TX/RX mismatch
- Training Pattern
    - Calibration Training sequence

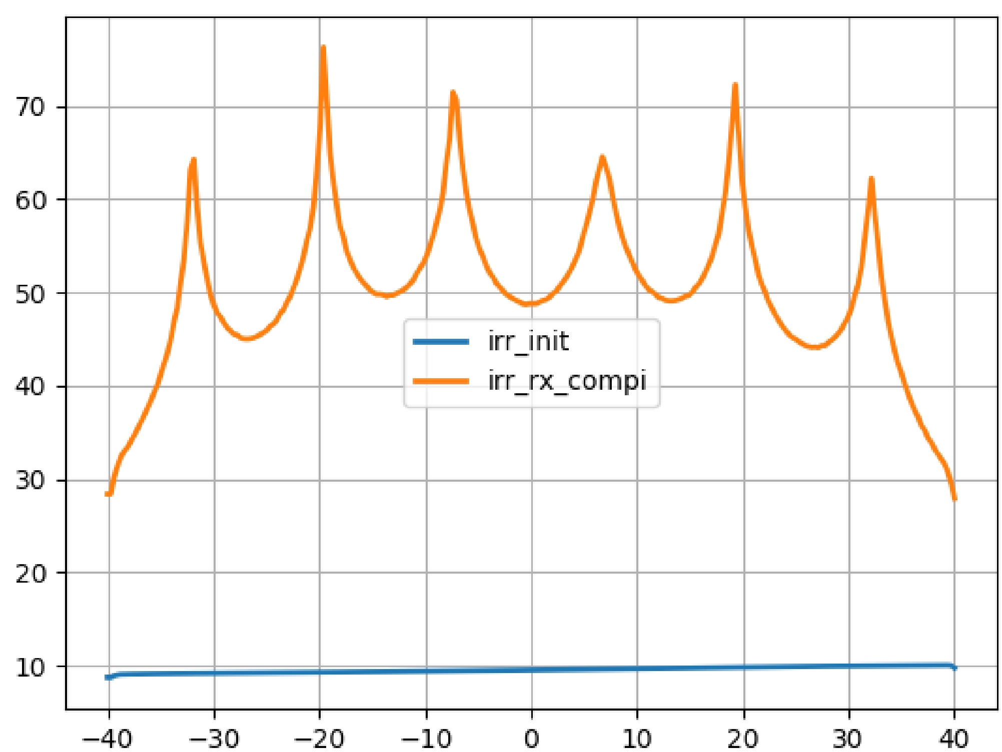
- Calibration receiver procedure:
    - Average per symbol and DC removal
    - FFT get frequency response
    - Estimate response by Golay Sequence
    - Generate compensator coefficients by IFFT

Exercise

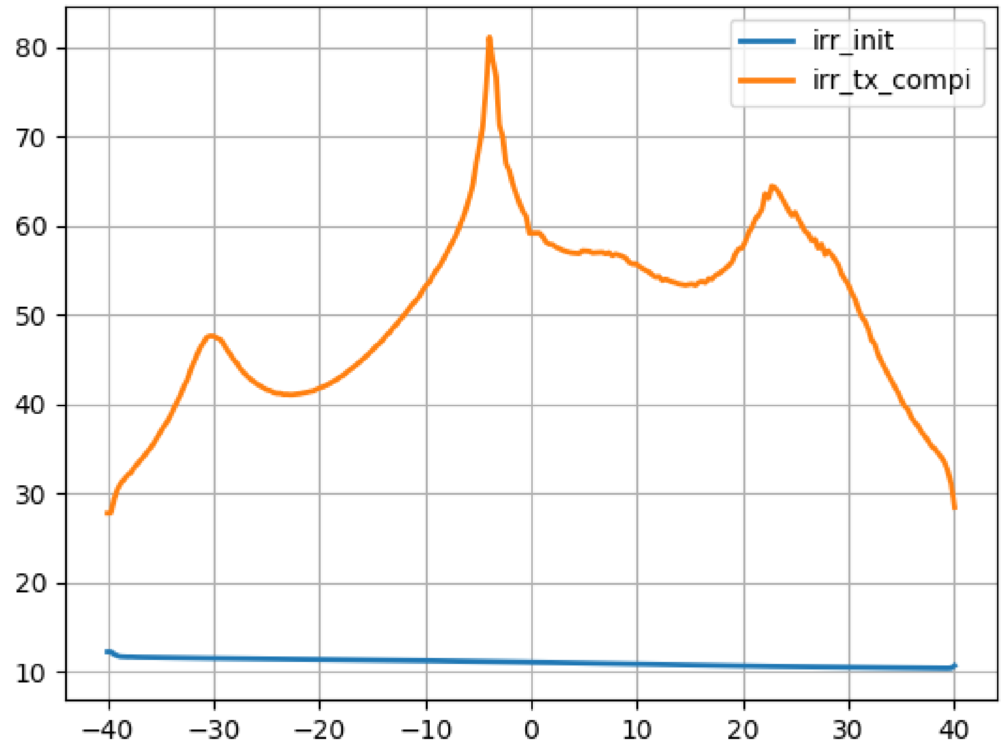
- setting:
    - compensator 6 taps, sysBW=“BW80”,256pt FFT used
    - IRR = $10 \times \log 10(|S(k)|^2/|I(k)|^2)$
        - $S(k) = F(k)s(k)$, $I(k) = B(k)s^*(-k)$
- case 1: rx-only calibration
    - IQmismatch: +3dB,25deg,5% corner var, cheby1,SNR=15dB



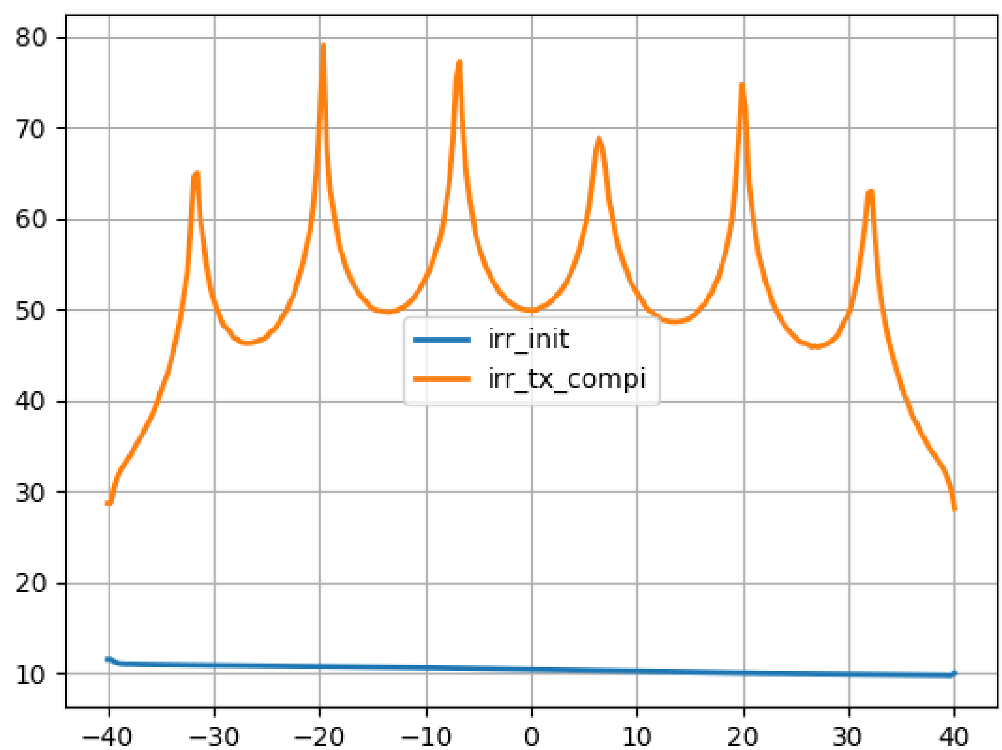
- IQmismatch: +3dB,32deg,5% corner var, cheby1,SNR=30dB



- case 2: tx-only calibration
  - IQmismatch: -3dB,-25deg,5% corner var, cheby1,SNR=15dB

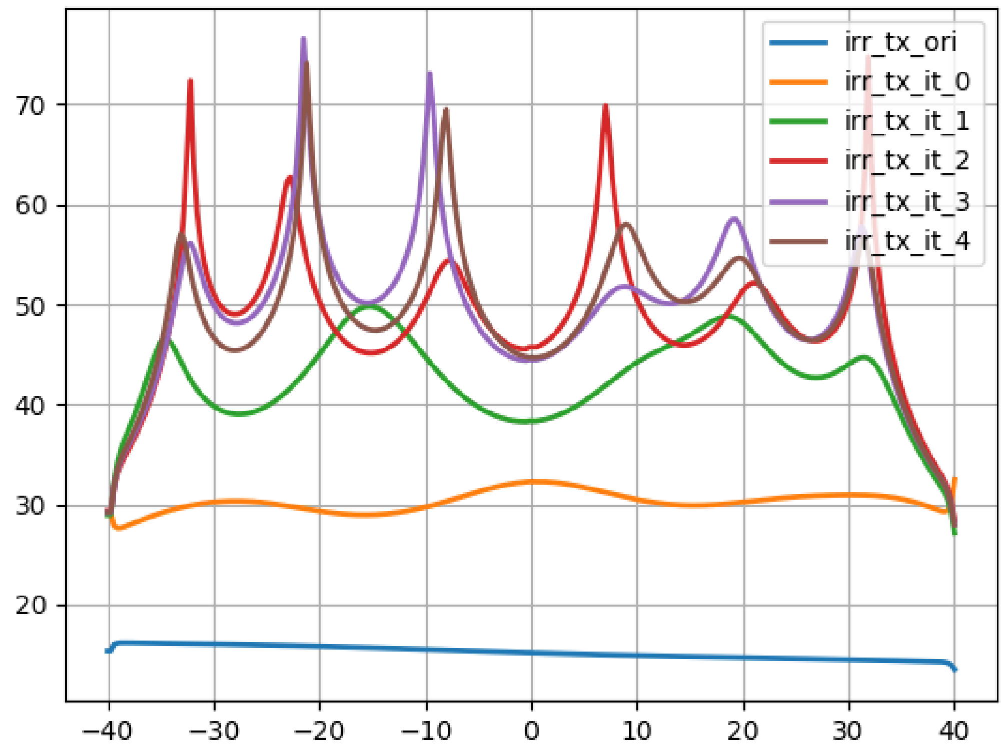


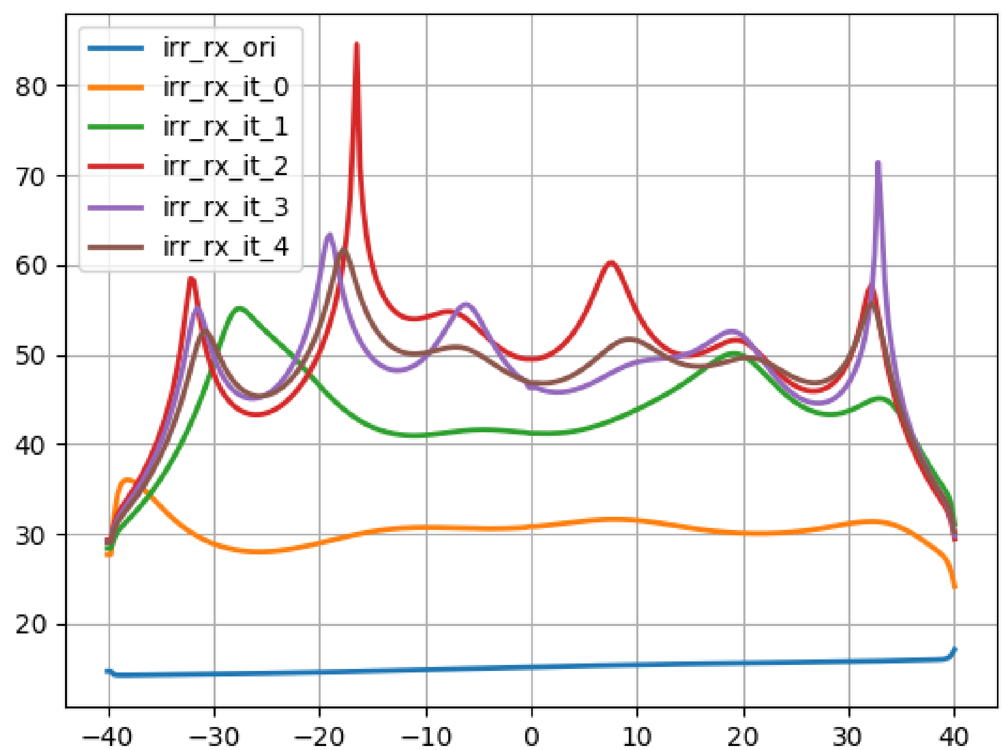
- IQmismatch: -3dB,-28deg,5% corner var, cheby1,SNR=30dB

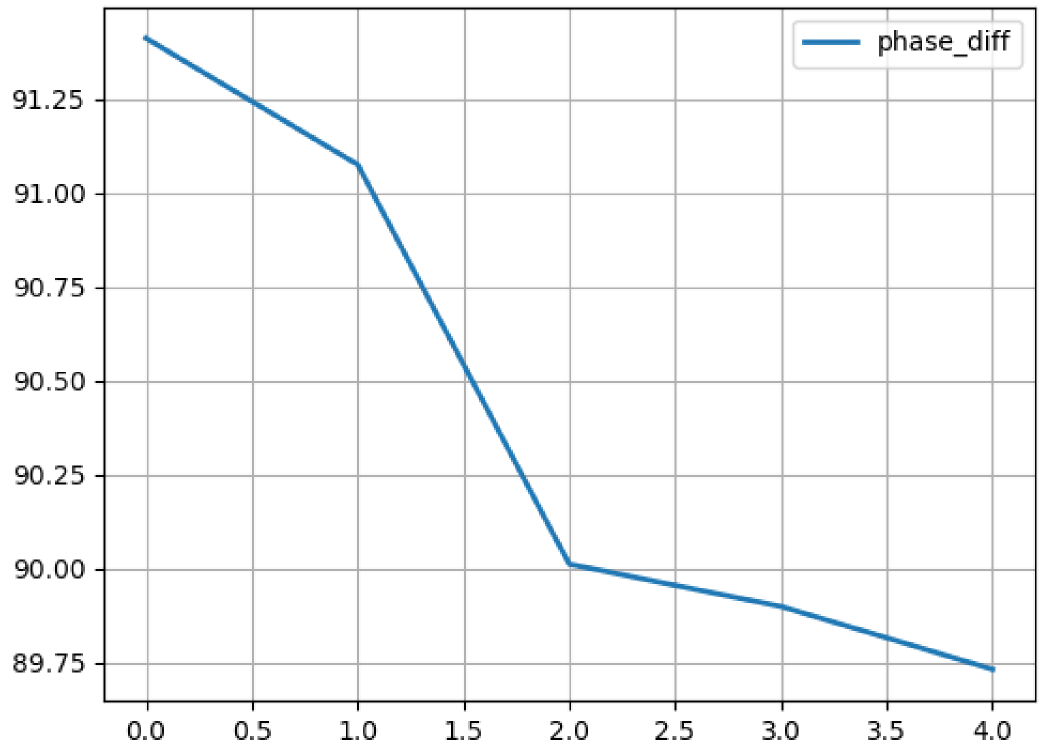


- case 3: joint tx/rx
    - TX IQmismatch: +2dB,-15deg,5% corner var, cheby1

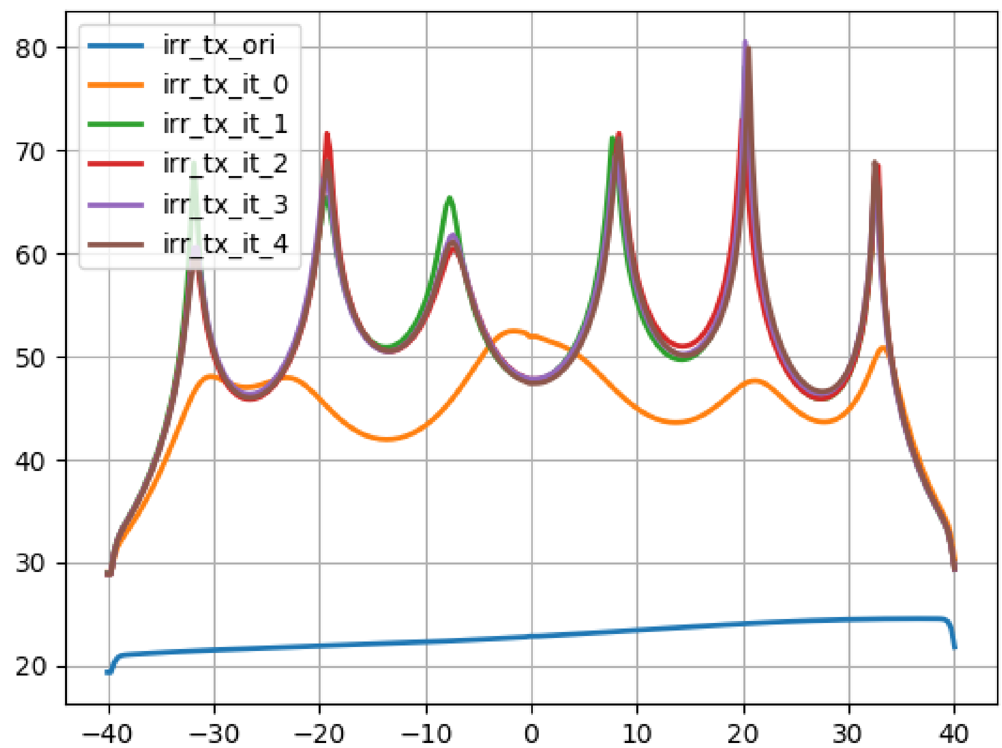
- RX IQmismatch: -2dB,15deg,-5% corner var, cheby1
- SNR = 20dB







- case 4: joint tx/rx
  - TX IQmismatch: +1dB,5deg,5% corner var, cheby1
  - RX IQmismatch: -1dB,-5deg,-5% corner var, cheby1
  - SNR = 30dB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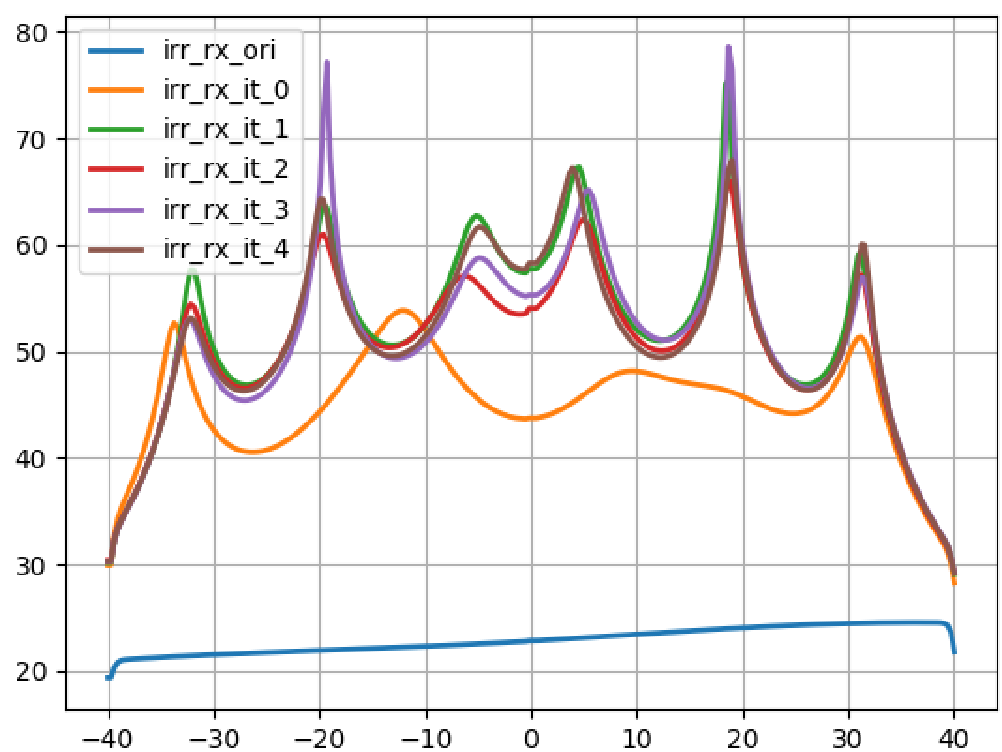
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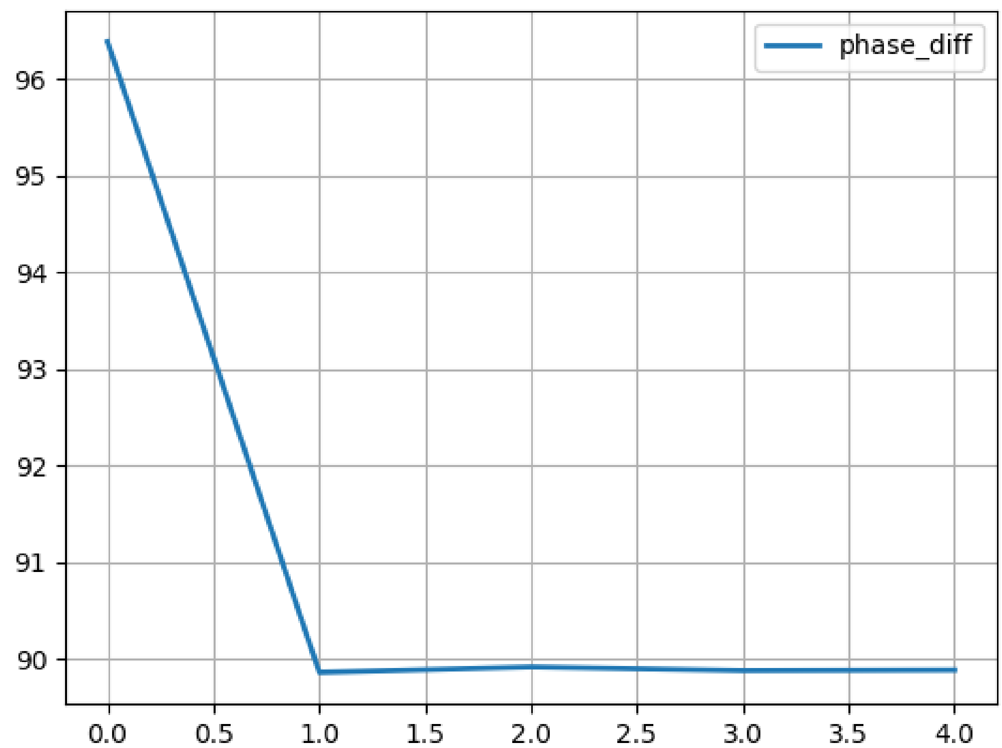
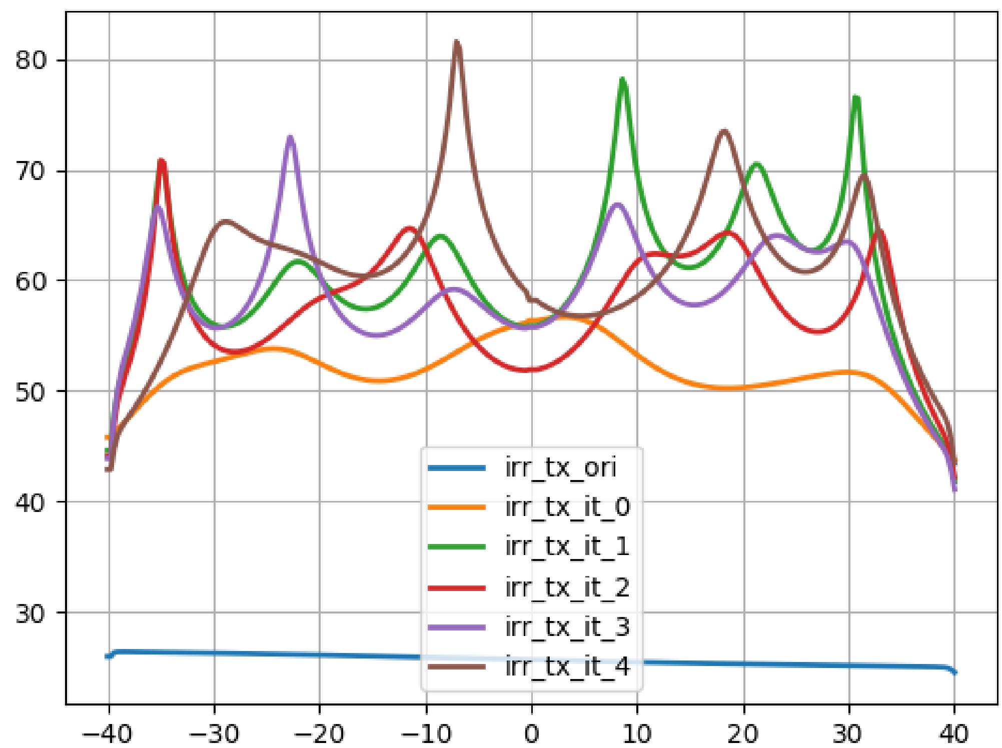


- case 5: joint tx/rx
    - TX IQmismatch: +0.5dB,5deg,1% corner var, cheby1
    - RX IQmismatch: -0.5dB,-5deg,-1% corner var, cheby1
    - SNR = 30dB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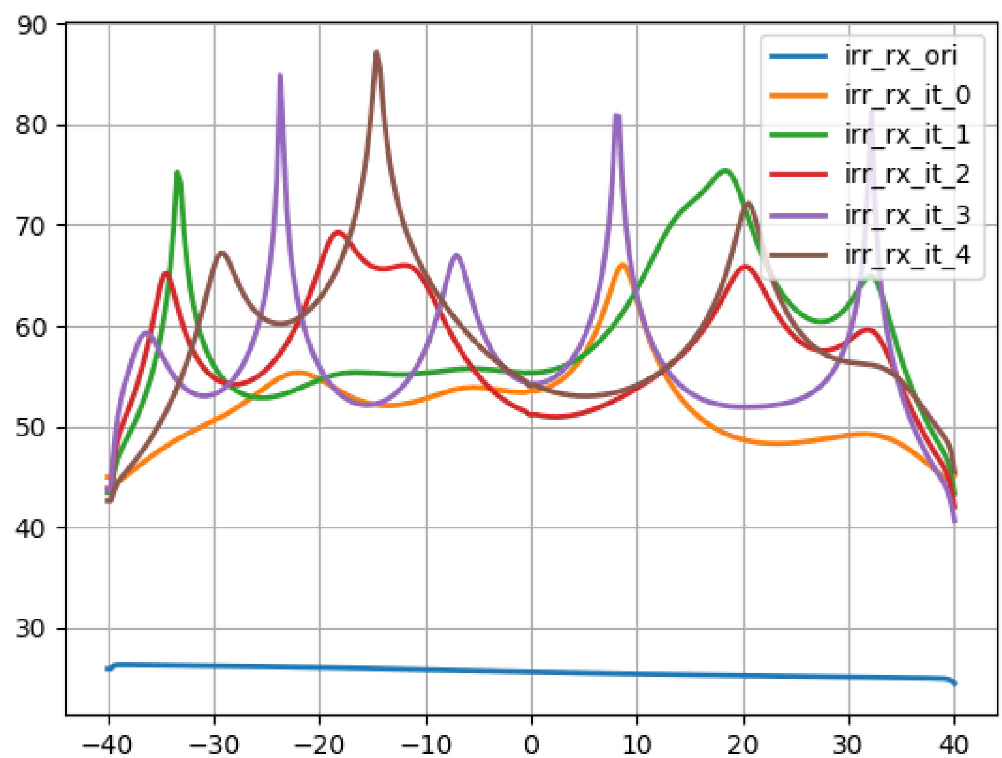
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70
60
50
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−10
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40

Conclusion:

- Joint TX/RX cal is possible, need to introduce different channel response for separate TX/RX
- Approach of iteratively estimate channel response and TRX iqcal is proposed.
- 6 taps compensators can provide approaching >50dB IRR(worst case ~ 45-48)
  - SNR requirement is not significant
  - Even very bad iq mismatch, its estimation and compensation still okay to reach ~48-50dB

Open discussion :

- TX/RX architecture spec:
  - TX: filters, iq-mismatch properties/dependency, DAC properties, loop-back path properties(attenuation,rotation,…)
  - RX: filters, iq-mismatch properties/dependency, LNA/LPF, gain partition, properties
- Calibration requirements:
  - cal time, power-on, channel switch, thermal change,…

References:

- [WLS] Bernard Picinbono, Pascal Chevalier. Widely Linear Estimation with Complex Data. IEEE Transac-tions on Signal Processing, Institute of Electrical and Electronics Engineers, 1995, 43, pp.2030 - 2033.
  - https://hal-centralesupelec.archives-ouvertes.fr/hal-01756249
- [GolaySeqEst] R. Rodrıguez-Avila,et.al. “Frequency-Selective Joint T x/Rx I/Q Imbalance Estimation Using Golay Complementary Sequences”, IEEE RANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 12, NO. 5
  - 10.1109/TWC.2013.040213.120622
- [TXSelfMixing] “Built-In Self-Test of Transmitter I/Q Mismatch and Nonlinearity Using Self-Mixing Envelope Detector”, IEEE TRANSACTIONS ON VERY LARGE SCALE INTEGRATION (VLSI) SYSTEMS
  - 10.1109/TVLSI.2014.2308317
- [TXSelfmixing] Ainhoa Rezola, et.al., “Built-in-Self-Calibration for I/Q Imbalance in Wideband Millimeter-Wave Gigabit Transmitters”, IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES 2017
  - 10.1109/TMTT.2017.2712145
- [TXDiodeTwoTone] Wei Li, et.al., “Self-IQ-Demodulation Based Compensation Scheme of Frequency-Dependent IQ Imbalance for Wideband Direct-Conversion Transmitters”
  - IEEE TRANSACTIONS ON BROADCASTING, VOL. 61, NO. 4
- [TRXFdelta] Björn Debaillie, et.al, “Calibration of Direct-Conversion Transceivers,” IEEE JOURNAL OF SELECTED TOPICS IN SIGNAL PROCESSING, VOL. 3, NO. 3
- [TRXFdelta] Chen-Jui Hsu and Wern-Ho Sheen, “Joint Calibration of Transmitter and Receiver Impairments in Direct-Conversion Radio Architecture”, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 11, NO. 2, FEB. 2012