Outphasing Elements for Hybrid Analogue Digital Beamforming and Single-RF MIMO

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Overview

Motivation

Fully digital (massive) MIMO transmitter design confronts with the following challenges:

- RF-chains are costly
  - One digital-to-analogue converter and power amplifier per antenna
  - RF-chains need to be synchronised (sampling clock, oscillator phase)
- Power Amplifiers are inefficient if required to be linear

Outphasing Architectures

These problems can be mitigated by outphasing architectures (passive networks):

- Outphasing Precoder Architecture (OPA)
  - Hybrid analogue digital precoder architecture with amplitude and phase control
  - Number of RF-chains is reduced to a few
  - Beamforming weights are updated once per coherence interval

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- Outphasing Precoder Architecture (OPA)
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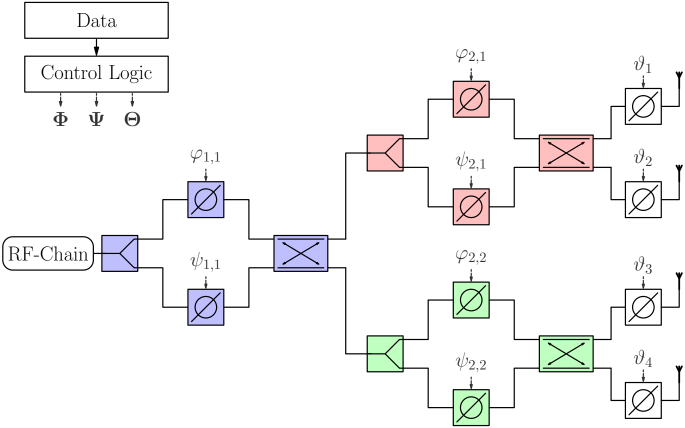
  - Number of RF-chains is reduced to a few
  - Beamforming weights are updated once per coherence interval
- Outphasing MIMO Architecture (OMA)
  - Single-RF architecture
  - Single/no RF-chain: just a simple ‘power oscillator’
  - Modulation (e.g. PSKH) is accomplished by an analogue network $\Rightarrow$ update rate $\geq$ symbol rate

The Outphasing Network



OMA / single sub-array branch of OPA

Advantages of OMA/OPA

- No power deliberately dissipated or reflected
- Reflections caused by mismatched antennas cannot couple into another branch
- Insertion losses scale with logarithm of the number of antennas
- Only three standard components used: Wilkinson dividers, (switched line) phaseshifters, 90°-hybrid couplers

Overview

1. Introduction
2. Sensitivity Analysis – Definitions
3. Sensitivity Analysis – Results
4. Measurements
5. Summary

Motivation for Sensitivity Analysis

- Single outphasing element: One block comprised by a power divider, two phase shifters (φ, ψ), and a power combiner
- For proper function, amplitudes *and* phases at both output ports of an outphasing element need to be controlled
- Cascading leads to error propagation

Which are the most critical components?
Which specifications are important?

Transfer Function Definition

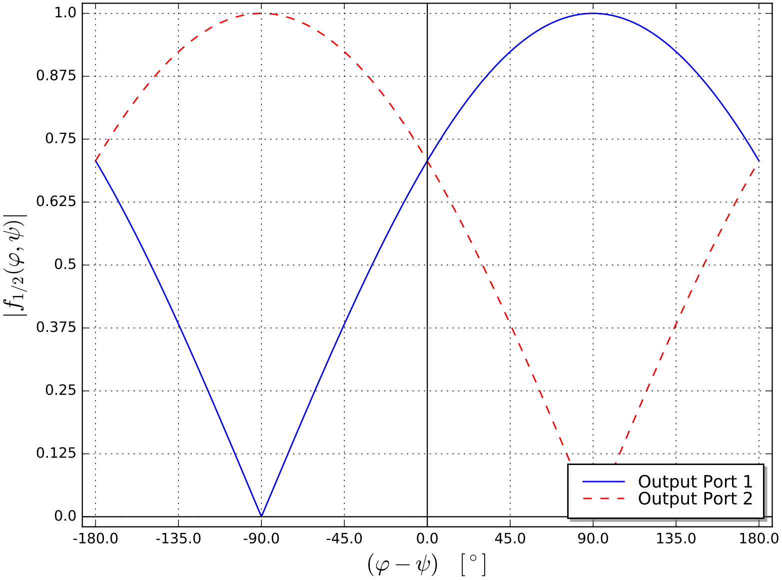
"Transfer function" of outphasing element: $\frac{\underline{s}_{\text{out},p}}{\underline{s}_{\text{in}}} = f_{\text{p}}\left(\varphi, \psi, \boldsymbol{x}\right)$, where:

$\underline{s}_{\text{out},p}$: signal at upper $(p = 1)$ or lower $(p = 2)$ output port

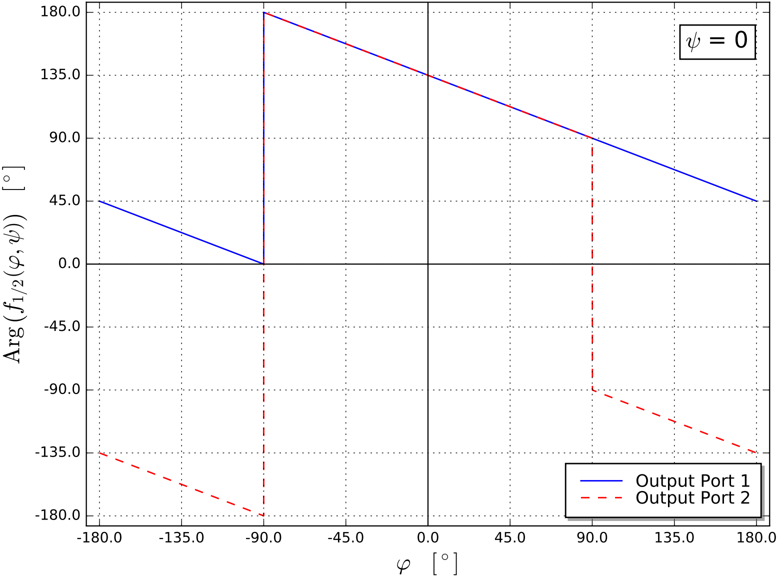
$\underline{s}_{\text{in}}$: input signal at Wilkinson divider

$\boldsymbol{x}$: Vector of parameters to be included in the sensitivity analysis (Wilkinson/hybrid coupling coefficients, transmission line impedances, attenuations)

Error-free Amplitude Response



Error-free Phase Response



Sensitivity Definition

One-at-a-time partial derivative approach:

- Sensitivity is separately calculated for each parameter x_i as partial derivative of $f_\mathrm{p}\left(\varphi, \psi, \boldsymbol{x}\right)$ with respect to x_i, evaluated at the design parameters $\boldsymbol{x}_0$
- Separate sensitivities for amplitude and phase:
  - $S_{\mathsf{mag},x_\mathrm{i},\mathrm{p}}(\varphi, \psi) = \left.\dfrac{\partial \left|f_\mathrm{p}\left(\varphi, \psi, \boldsymbol{x}\right)\right|}{\partial x_\mathrm{i}}\right|_{\boldsymbol{x}_0}$
  - $S_{\mathsf{arg},x_\mathrm{i},\mathrm{p}}(\varphi, \psi) = \left.\dfrac{\partial \arg\left(f_\mathrm{p}\left(\varphi, \psi, \boldsymbol{x}\right)\right)}{\partial x_\mathrm{i}}\right|_{\boldsymbol{x}_0}$

Notes

- Due to symmetry, only $S_{\mathsf{mag},x_\mathrm{i},1} \overset{!}{=} S_{\mathsf{mag},x_\mathrm{i}}(\varphi,\psi)$ and $S_{\mathsf{arg},x_\mathrm{i},1} \overset{!}{=} S_{\mathsf{arg},x_\mathrm{i}}(\varphi,\psi)$ are shown
- Some quantities are expressed in dependence of $\delta \overset{!}{=} \varphi - \psi$ for readability

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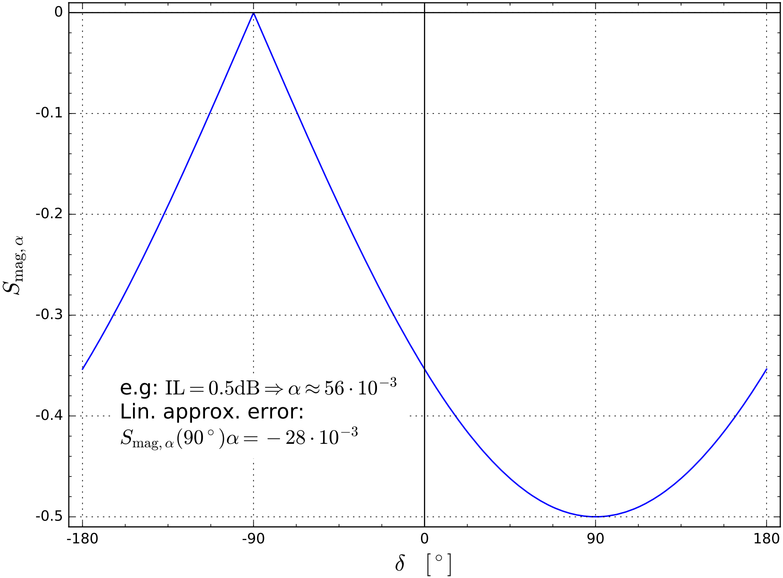
Unequal Insertion Loss of Phase Shifters

- Cause: Different transmission line lengths, variations in insertion loss of switches
- Model: Output signal of phase shifter "ψ" multiplied by $(1-\alpha)$
- $S_{\mathsf{mag},\alpha}(\delta) = -\dfrac{\sin(\delta)+1}{2\sqrt{2\sin(\delta)+2}}$
- $S_{\mathsf{arg},\alpha}(\delta) = -\dfrac{\cos(\delta)}{2(\sin(\delta)+1)}$

Insertion Loss – Amplitude Sensitivity

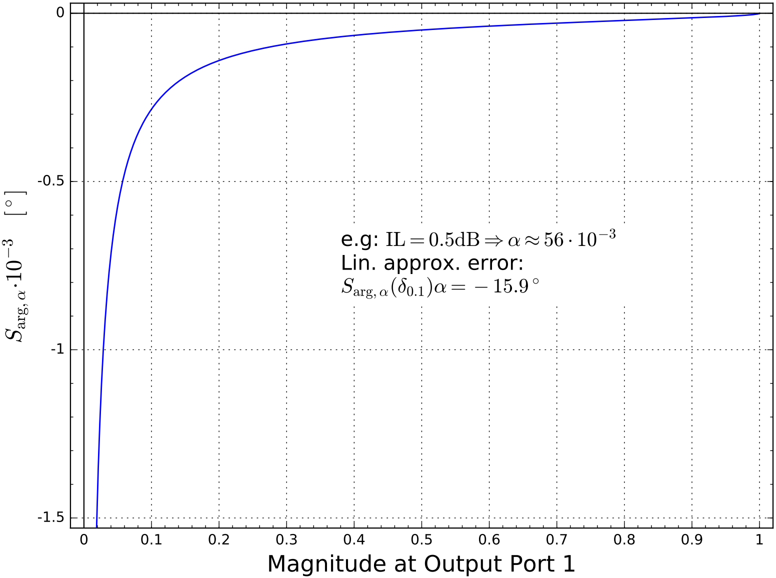


e.g: $\mathrm{IL} = 0.5\mathrm{dB} \Rightarrow \alpha \approx 56 \cdot 10^{-3}$

Lin. approx. error:

$S_{\mathrm{mag},\,\alpha}(90^\circ)\alpha = -28 \cdot 10^{-3}$

Insertion Loss – Phase Sensitivity

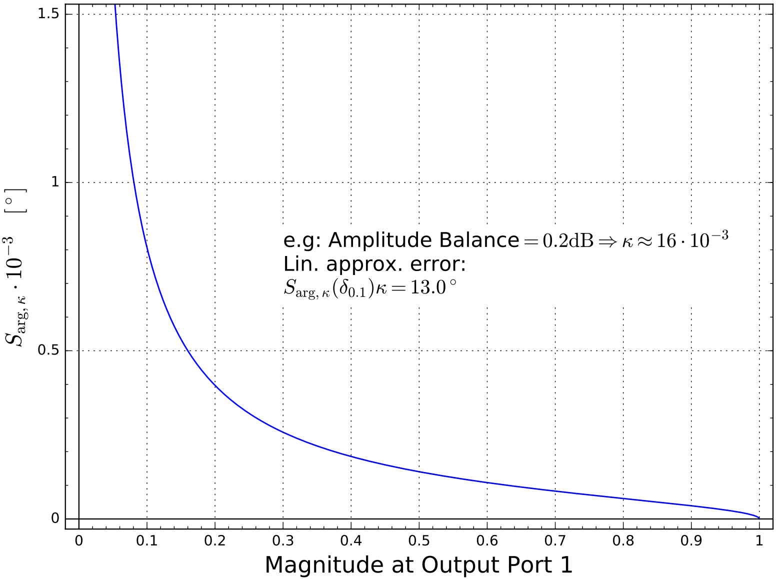


e.g: $\mathrm{IL} = 0.5\mathrm{dB} \Rightarrow \alpha \approx 56 \cdot 10^{-3}$
Lin. approx. error:
$S_{\mathrm{arg},\,\alpha}(\delta_{0.1})\alpha = -15.9^\circ$

Deviation of ideal 3 dB-*Coupling Coefficients*

- Cause: non-ideal, non-frequency flat hybrid coupler and Wilkinson combiner
- Model: Coupling coefficients $-\mathrm{j}(k+\kappa)$ for upper branch (Wilkinson)/through path (hybrid), $-\sqrt{1-(k+\kappa)^2}$ for lower branch (Wilkinson)/coupled path (hybrid), where $k=\frac{\sqrt{2}}{2}$
- $S_{\mathsf{mag},\kappa}(\delta)=0$
- $S_{\mathsf{arg},\kappa}(\delta)=\dfrac{\sqrt{2}\cos(\delta)}{\sin(\delta)+1}$

Coupling Coefficients – Phase Sensitivity



e.g: Amplitude Balance $= 0.2\mathrm{dB} \Rightarrow \kappa \approx 16 \cdot 10^{-3}$
Lin. approx. error:
$S_{\arg,\,\kappa}(\delta_{0.1})\kappa = 13.0\,^\circ$

Mismatched Phase Shifters

- Cause: Poorly specified substrate (e.g. FR-4)
- Model: $Z_{\text{Phaseshifter},\varphi} = Z_{\text{System}} + \zeta$
- $S_{\text{mag},\zeta}(\delta) = 0$
- $S_{\text{arg},\zeta}(\delta) = 0$
- Diminishing errors caused in amplitude and phase also for large deviation

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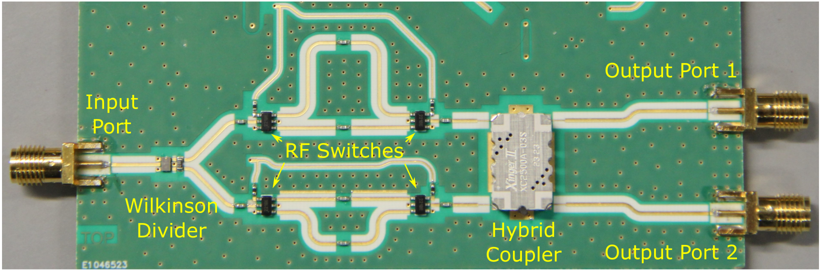
Outphasing Element under Test

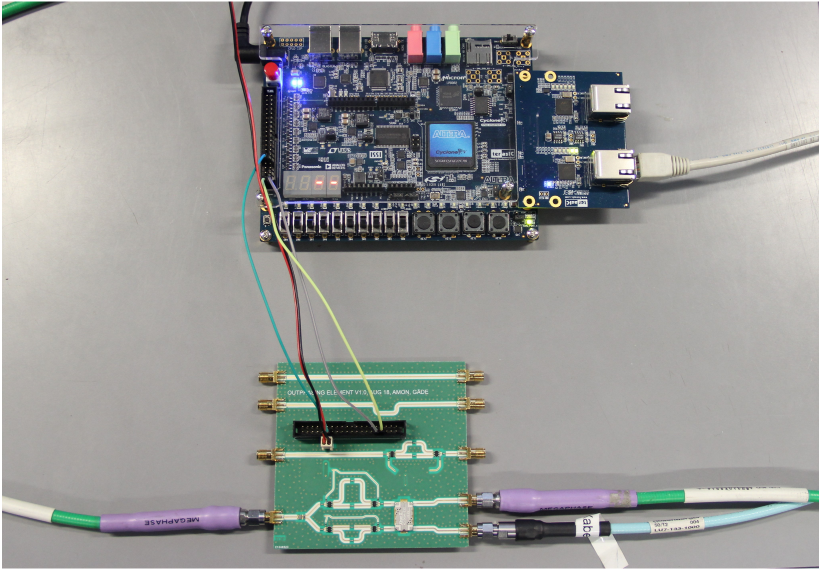
- Design frequency: 2.45 GHz
- Phase shifts:
  - $\varphi \in \{90°, 180°\}$
  - $\psi \in \{90°, 120°\}$

  $\Rightarrow \delta \in \{-30°, 0°, 60°, 90°\}$
- Components:
  - Hybrid: Anaren XC2500A-03S (Amplitude balance ±0.15 dB)
  - Divider: Anaren PD2328J5050S2HF (Ampl. bal. ±0.3 dB)
  - Switches: Analog Devices HMC221BETR
- Control unit: Alter Cyclone V GX Starter Kit connected to Octave via Ethernet

PCB Image


Input
Port
Wilkinson
Divider
RF Switches
Hybrid
Coupler
Output Port 1
Output Port 2
Xinger II
XC2500A-03S
TOP
E1046523

Measurement Setup



Measurement Results – Static Behaviour

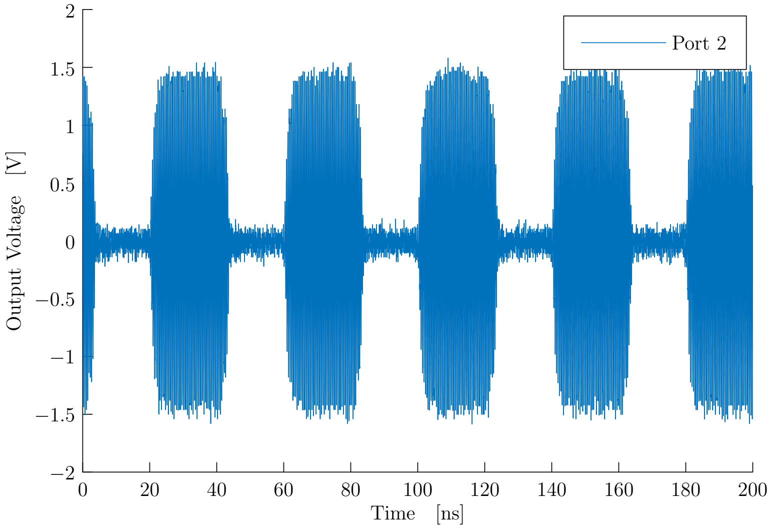
All measurements are taken at design frequency

- Design vs. measured power splits:

δ	Design	Measurement
$-30°$	0.25 : 0.75	25.6 : 74.4
$0°$	50 : 50	50.2 : 49.8
$60°$	93.3 : 6.7	94.4 : 5.6
$90°$	100 : 0	100 : 0

- Phase error $< 2°$ except for off-port at $\delta = 90°$ (error: 147°)
- Insertion loss: $\approx 2\,\text{dB}$

Measurement Results – Dynamic Behaviour



Toggling between states 1 and 2 at 50 Msym/s

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Summary and Consequences

- Magnitude is reasonable robust against tolerances
- Phase is very sensitive at low output magnitudes
  - Dividers and Couplers have to be chosen for best amplitude balance
  - Insertion losses must be made equal for both branches
  - If possible, large power split ratios should be avoided in the first stages
- Measurements show good agreement with theoretical results
- High symbol rates are feasible

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Thank you for your attention!

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