Optimizing the Current-Mode Class D (CMCD) Amplifier for Decoupling in pTX Arrays

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Target audience: This work is relevant to those interested in parallel transmit amplifiers.

Purpose: A functional parallel transmit system must control the current in each element, independent of the load and the current on other elements. Thus the amplifier output should present the coil terminals with a relatively high effective impedance, implying a reflection coefficient near $\Gamma\approx1$[1]. This can be achieved using passive impedance transformation networks[2,3], but often at the expense of amplifier power capacity and efficiency. A second approach is to monitor the element current and use feedback (using either iterative[4] or real-time methods[5]) and an appropriate control law to enforce the desired element current. Previously we demonstrated the measurement of the large-signal behavior of a Current Mode Class D (CMCD) amplifier and found its effective output impedance to be significantly lower than that of the load impedance ($\mathrm{Re}(\Gamma)<0$)[6]. Here we attempt to use two similar methods in order to decouple the CMCD topology.

Methods: ***CNA:*** All experiments were performed using a coupled network analyzer (CNA) in an arrangement similar to previous work[6]. Both the device under test (DUT) and perturbation source (PS) were CMCD amplifiers driving coupled coils tuned to 63.3 MHz with known impedance parameters. The coupled network was driven across the full control space, while the RF coil current, DC bias voltage, and DC bias current were measured on each channel. This allowed the drain efficiency and effective output impedance of each amplifier to be measured quickly under large signal conditions. ***Experiment iterations:*** The DUT could either be connected to the DUT coil either directly or via a lumped element $\pi/2$ phase shifter with $Z_0=10\ \Omega$. This Z_0 was chosen so that it would not significantly transform the coil resistance ($R_C=10.3\ \Omega$) as presented to the DUT amplifier. The DUT could also be configured for closed loop control of the coil current magnitude using a custom current transformer on the DUT coil as described in[7]. These two methods were tested in four configurations. Configuration A lacked the phase shifter and its bias voltage was controlled open loop. Configuration B used the phase shifter and open loop control. Configuration C lacked the phase shifter but used closed loop bias control. Configuration D used both the phase shifter and closed loop bias control.

Results: Figs 2-4 show a reduced dataset corresponding to a single phase sweep of the PS for each DUT configuration (labels correspond to DUT configurations). For this phase sweep, the DUT and PS were biased for coil currents $|I_C|=0.8$ Arms and $|I_C|=0.5$ Arms respectively. Fig 2 shows scatter plots of the complex DUT coil current. Fig 3 shows Smith charts of the effective Γ calculated by defining $Z_0=R_C$ and Z_L as the impedance seen at the coil terminals looking towards the amplifier. Comparing the results from configurations A and B shows that the addition of the phase shifter does shift Γ towards the right side of the Smith chart, and thus suppresses deviation in the DUT coil current. The effect of closed loop current magnitude control can be seen in figs 2C and 2D. The control loop forces the DUT I_C to converge towards a contour of constant magnitude, but the phase of I_C is not controlled. Figs 3C and 3D shows that the $|\Gamma|$ of the closed loop configuration actually exceeds unity under some conditions. We believe this is due to RF power being directly injected from the PS into the DUT's feedback current transformer and into the RF carrier driving the DUT. Despite this, no instabilities were observed, likely due to the high resistance of the RF coils. Fig 4 shows a summary of the effect of the four configurations on the DUT's error vector magnitude (EVM) and the total power efficiency of the coupled amplifiers under the same biasing conditions. The phase shifter and current magnitude regulation methods both achieve nearly the same decrease in EVM. It was also found that under conditions with significant perturbation, the presence of the phase shifter actually increased mean overall power efficiency. Using both methods in configuration D showed a further decrease in EVM, and still provided improved mean efficiency over configurations A and C.

Discussion and conclusion: Both decoupling methods clearly offer significant reduction in the mean EVM of the DUT current. Additionally, the phase shifter showed an increase in total system efficiency in the presence of significant perturbations. It is likely that EVM could be further improved by increasing the Z_0 of the phase shifter, at the cost of some decrease in efficiency. The use of the closed loop current magnitude regulation exhibited $|\Gamma|>1$ under certain conditions. It is currently believed that this is due to the PS interfering directly with the DUT's control loop. Further experiments not shown here have also shown that the performance of the current magnitude control loop suffer in the presence of very strong perturbation due to saturation of its controller. Polar feedback and modulation is one possible solution to this limitation, though its severe nonlinearity presents a significant challenge to implementation.

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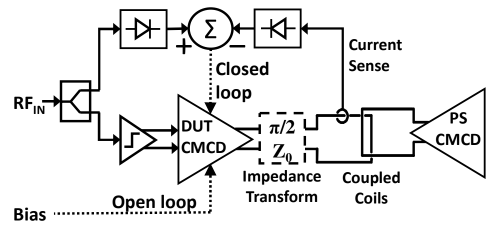

Figure 1: Diagram of DUT configuration

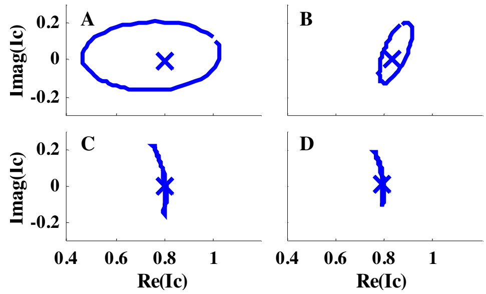

Figure 2: Plots of complex DUT RF current with (contours) and without (crosses) perturbation

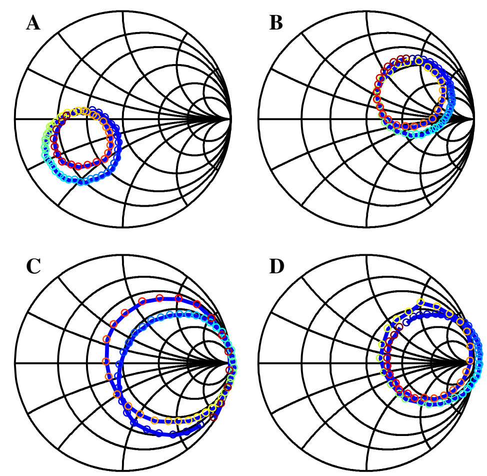

Figure 3: Plots of reflection coefficient Γ looking towards amplifier: $\Gamma=(Z_{amp}-R_C)/(Z_{amp}+R_C)$

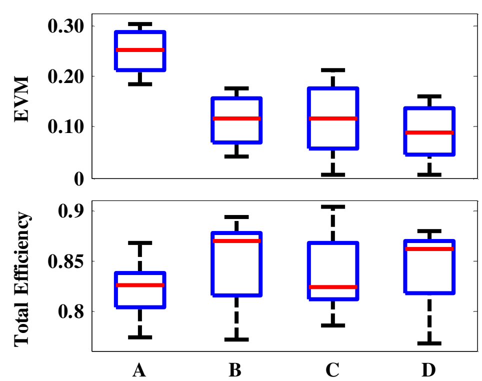

Figure 4: Box plots showing distributions of EVM and total system power efficiency for this phase sweep.

References: [1]Kurokawa, IEEE *ToMTT* 1964. [2]Kurpad et al, *CMR* 2005. [3]Chu et al, *MRM* 2009. [4]Stang et al, ISMRM 2009. [5]Hoult et al, *JMR* 2004. [6]Twieg et al, ISMRM 2014. [7]Twieg et al, ISMRM 2013.