Extensions to the Positive Feedback Pilot System for Second Loop Control of a Feedforward Compensated Amplifier

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Goal

• **Linear amplification of an RF signal.**
  – Large instantaneous bandwidths.

• **Compensate for amplifier degradations.**
  – Distortion, noise.
  – Linear impairments.

• **Adaptive.**
  – Optimize distortion cancellation.
Outline

• **Background**
  – Feedforward structure.
  – Loop alignment.

• **Pilot-based alignment of 2nd loop.**
  – Standard pilot systems.
  – Original positive feedback pilot system.
  – Extensions.

• **Summary**
Feedforward Structure

- **Two amplifiers**
  - Main amplifier (MA) determines the power capability.
  - Error amplifier (EA) determines linearity of system.

- **Optimization**
  - Adjust gains $g_1$ and $g_2$ to minimize the distortion power in the output signal $z(t)$. 
Feedforward Linearization

- **First cancellation loop (Path 1A-1B).**
  - Estimates of distortion $d(t)$ generated within the MA path.
  - Select gain $g_1$ to cancel linear signal within $\varepsilon(t)$.

- **Second cancellation loop (Path 2A-2B).**
  - Select gain $g_2$ to cancel distortion within $z(t)$. 
Pilot Assisted Second Loop Control

- Inject pilot into MA path.
- Adjust $g_2$ to minimize residual pilot in $z(t)$.
  - Optimum value is denoted $g_{2,\text{opt}}$.
- 2nd loop cancellation transfer function
  - $G_2 = 1 - g_{E_A}$
  - $g_2 = (g_{2,\text{opt}} - g_2) / g_{2,\text{opt}}$
  - Optimal value is $G_2 = 0$. 
Standard Pilot System

- **Pilot generation (bottom section)**
  - LO selects pilot frequency to be outside of carrier BW.
- **Pilot detection (top section)**
  - Band pass filter at IF blocks carrier.
  - Measures residual pilot power, $V_{det}$. 
**Pilot**

- **Pilot is located outside of input signal spectrum.**
  - Detected reliably by band pass filtering $z(t)$.
  - Injected pilot is independent of $x(t)$.
    - Able to adapt 2\textsuperscript{nd} loop when there is no input signal $x(t)$.

- **Drawbacks**
  - Residual pilot is considered a spurious emission.
  - 2\textsuperscript{nd} loop adaptation based on power minimization is slower than a gradient-based search.
Positive Feedback Pilot System

• **Self oscillating pilot signal.**
  
  – Generated from noise within a nonlinear feedback loop.
  
  – Oscillation occurs if loop gain is large enough that the soft limiter is clipping the fed back signal.
Positive Feedback Pilot System

• Key equations
  - \( V_{\text{det}} = k_a \log( |G_2| ) + k_b \).
  - \( \omega_{\text{pilot}} = \omega_o + \arg(G_2) / T_{\text{loop}} \).
  - \( T_{\text{loop}} \) is the loop delay.

• Advantages
  - Independent measurements of \( |G_2| \) and \( \arg(G_2) \).
  - Synchronous detection improves convergence.
  - Pilot shuts off automatically when \( |G_2| \) is small.
    - Residual pilot no longer discernible (24 dB reduction).
Magnitude and Frequency vs. Alignment $g_2$

- **Magnitude contours:** $V_{\text{det}}(g_2) = k_a \log|G_2| + k_b$
  - Convex, one minimum region.

- **Frequency contours:** $\omega_{\text{pilot}}(g_2) = \omega_0 + \arg\{G_2\} / T$
  - Freq is proportional to $\arg\{G_2\}$, except at discontinuity.
Pilot Spectrum

- **Pilot on state (oscillating)**
  - Single frequency tone, high amplitude.

- **Pilot off state**
  - Wide bandwidth, low amplitude.
Rate of Convergence

- **Synchronous detection.**
  - Gradient-based search, faster convergence.
- **Magnitude only.**
  - Coordinate descent, slower convergence.
Improved Positive Feedback Pilot System

• New features
  – Automatic level controller (ALC).
  – Digital phase lock loop (PLL).
  – Power spectrum measurement of pilot.
  – Adjustable pilot shut-off level.
• Replaces limiter and detector.
  – Variable attenuation based on a feedback loop.
    • Keeps pilot amplitude constant while VVA is in range.
  – VVA control measures residual pilot power (ATTN).
  – Pilot shut off begins when VVA reaches lower limit.
• Less harmonic content in pilot signal.
Digital PPL

- Frequency lock loop.
  - Variable phase shifter controls pilot frequency.
  - Loop keeps pilot frequency constant.
    - Compensates for frequency shifts associated with changes in $g_2$.
    - Phase control $\phi_{\text{loop}}$ measures $\text{arg}\{G_2\}$ directly.
- Phase shifter may be placed at LO port.
Power Spectrum of Pilot

- Part of the digital phase lock loop.
- Used to extend the residual pilot measurement.
  - Needed when the ALC-VVA reaches lower limit.
  - Allows control of $g_2$ within the pilot shut off region.
- Used to reduce the detection bandwidth.
  - Useful when the ambient noise level of the input signal to the feedforward PA is high.
  - Example: optically fed radio head amplifiers.
Adjustable Pilot Shut-off

- Adjustable gain stage placed before ALC.
  - Allows selection of the second loop cancellation level, $|G_2|$, when pilot shut off begins.
  - Increasing pilot shut off gain reduces $|G_2|$ shut off level.
Conclusion

• Positive feedback pilot system.
  – Direct measurements of a feedforward PA’s second loop cancellation transfer function.
  – Both amplitude and phase.
  – Improves second loop convergence.

• Extensions
  – Constant pilot frequency using PLL.
  – Variable detection bandwidth using power spectrum measurements.
  – Adjustable pilot shut-off threshold.
Thank You

• Questions?