A Feedforward Amplifier using a Modulation Pilot and Bi-Orthogonal Demodulation for Loop Alignment Control

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Goal

- Linear amplification of RF signals with large instantaneous bandwidths.
  - 100 MHz BW planned for LTE-Advanced.
- Pilot-based adaptive feedforward compensation.
  - Out-of-band pilots measurements are too far away from the actual signal for large BW's.
  - In-band pilots are acceptable.
- Reasonable cost.
  - Implement a modulation pilot approach.

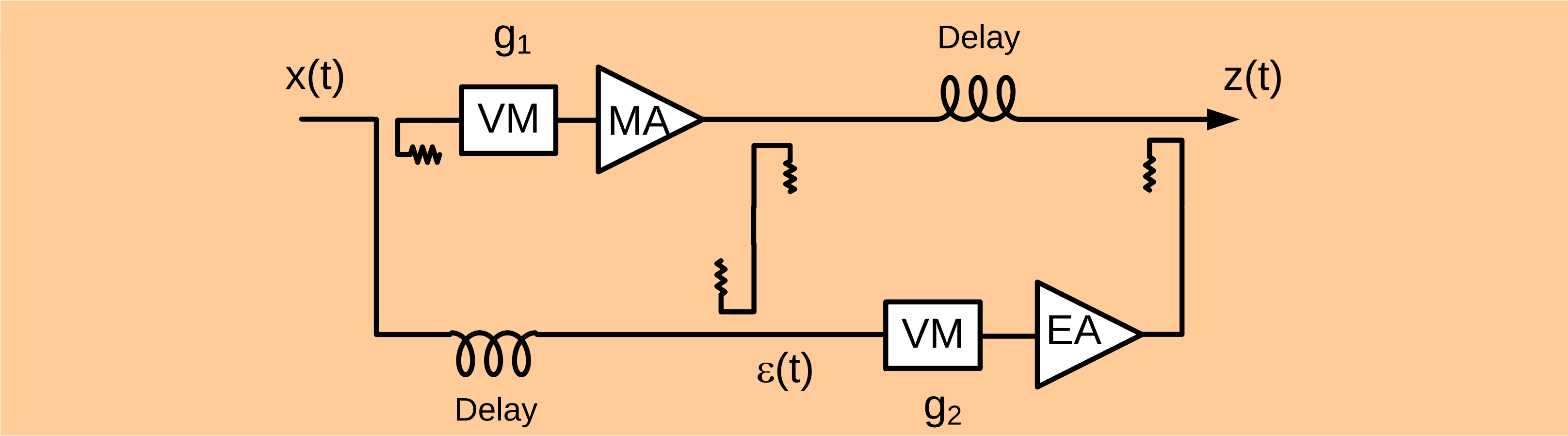
Other Goal

- Seeking collaboration.
  - The math shows potential for LTE.
  - Need to build a prototype and test.
- Warning.
  - This technique has been abandoned numerous times.

Outline

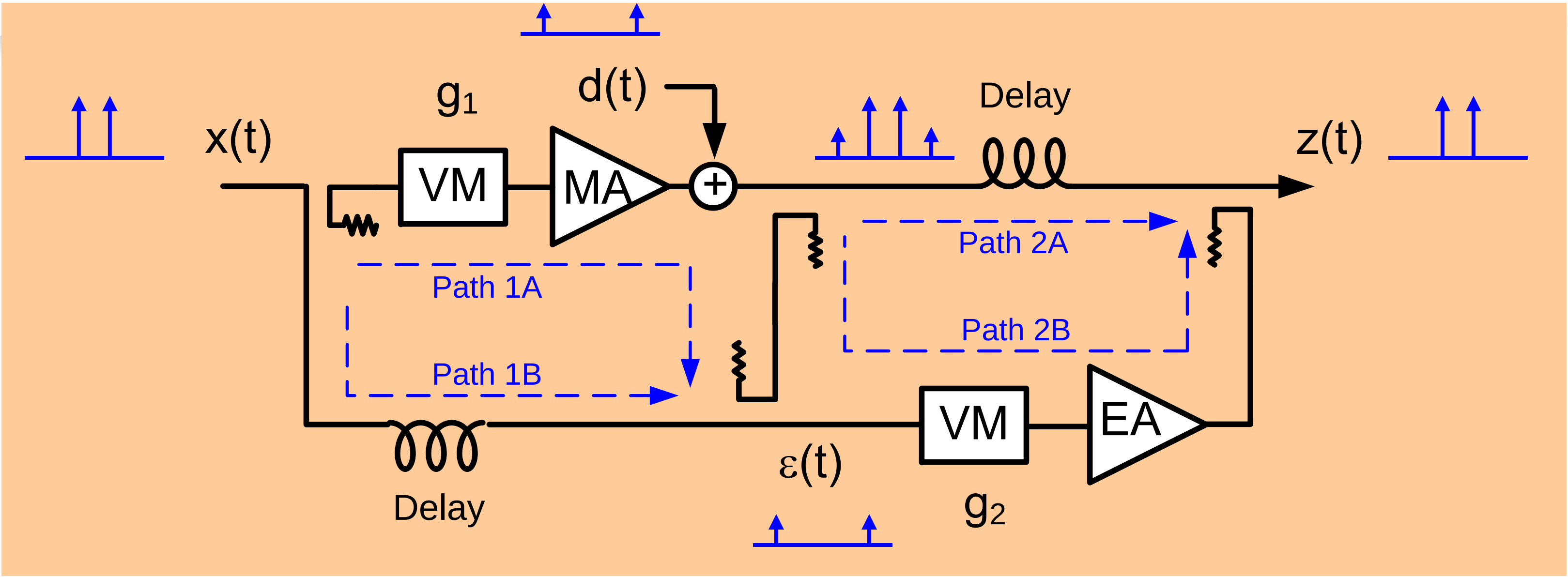
- Background
  - Feedforward structure for linearization.
- Modulation pilot approach to 2^{nd} loop adaptation.
  - Review original method proposed by Matz.
  - Discuss the short-comings which include biases.
- Propose a new modulation approach.
  - Use bi-orthogonal demodulation to avoid biases.
- Summary

Feedforward Structure



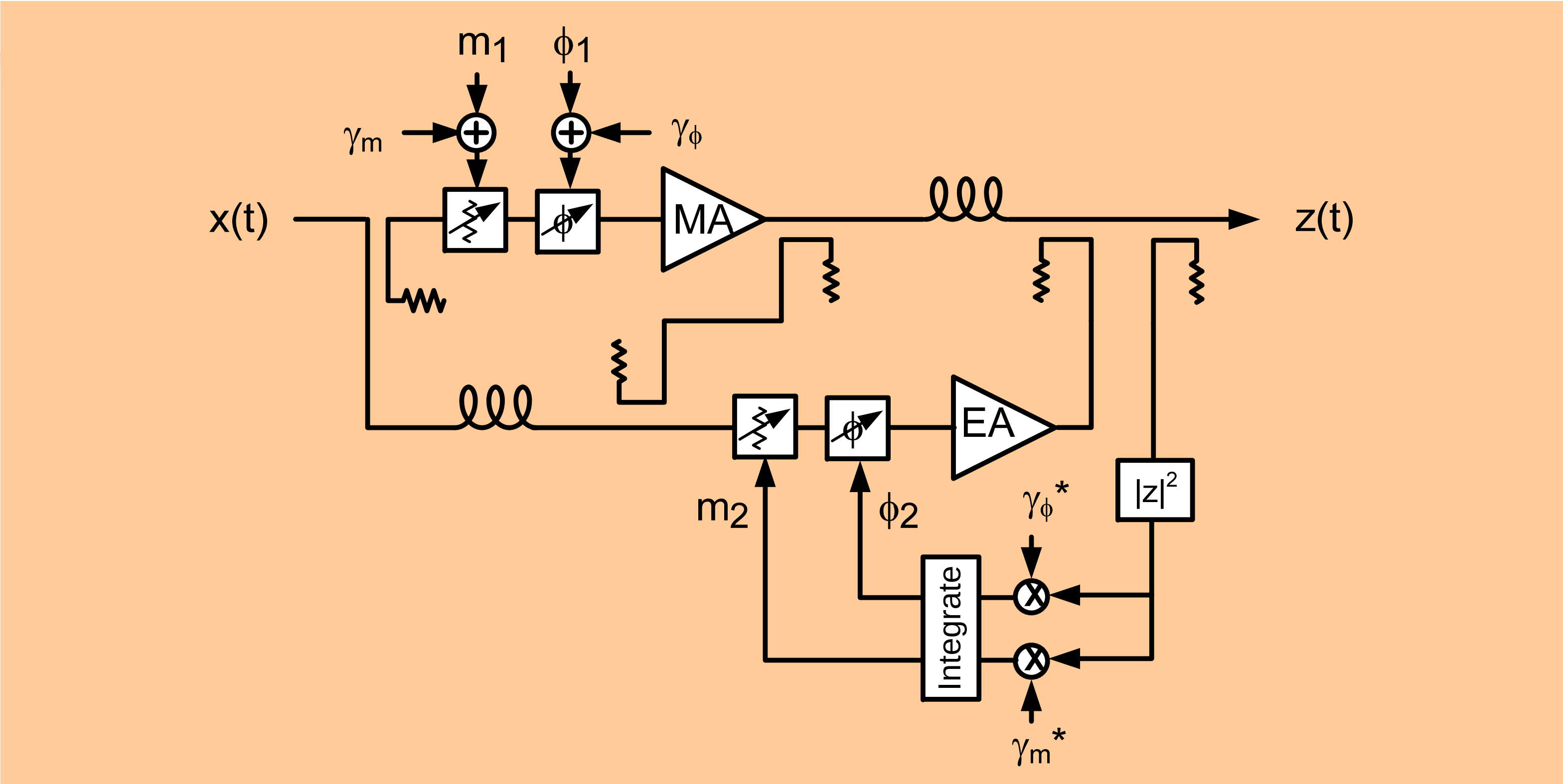
- Two amplifiers
  - Main amplifier (MA) determines the power capability.
  - Error amplifier (EA) determines linearity of system.
- Optimization
  - Adjust gains g_1 and g_2 to minimize the distortion power in the output signal z(t).

Feedforward Linearization



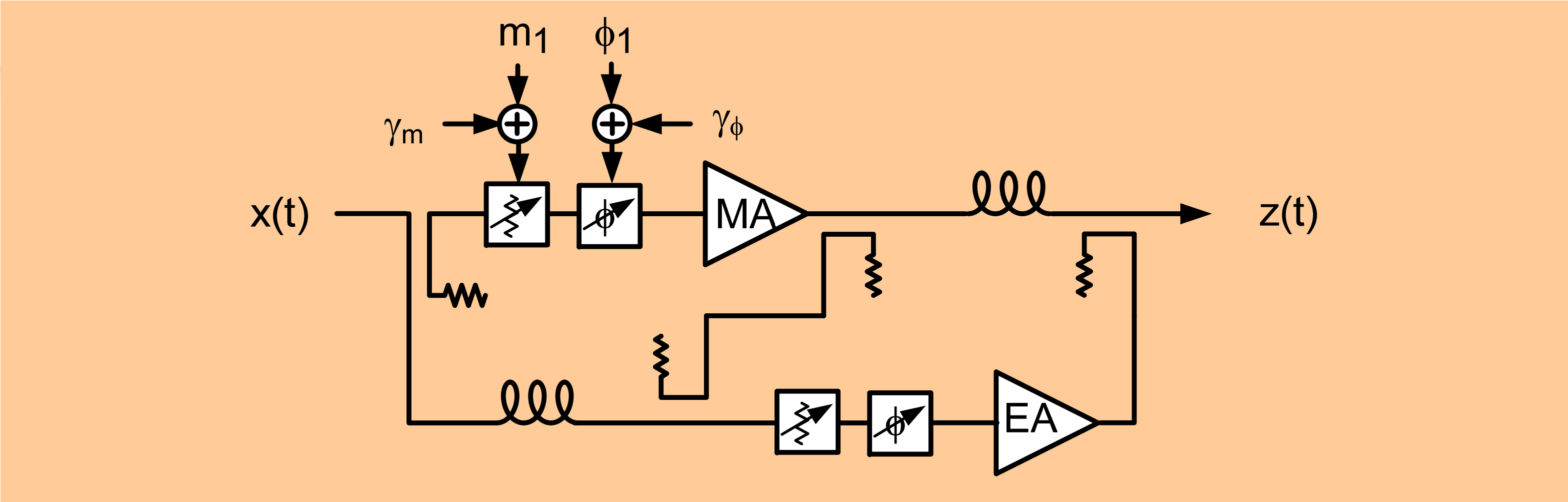
- First cancellation loop (Path 1A-1B).
  - Estimates of distortion d(t) generated within the MA path.
  - Select gain g_1 to cancel linear signal within $\varepsilon(t)$.
- Second cancellation loop (Path 2A-2B).
  - Select gain g_2 to cancel distortion within z(t).

Modulation Pilot (Matz, US Patent 5491454)



- Modulate 1st loop to control 2nd loop alignment.
  - Two modulation pilots, γ_m and γ_ϕ (sine waves, ω_m and ω_ϕ).
  - Control (m_2,ϕ_2) by demodulating $|z|^2$ with γ_m and γ_ϕ.

Modulation Pilot (Matz)



- Amplifier gain
  - Main amplifier + coupling loss: G_o.
  - Error amplifier + coupling losses: g_{EA}.
- First loop alignment
  - $g_{1,static} = \exp\{ m_1 + j\ \phi_1 \}$
  - γ_m and γ_ϕ are modulation pilots.
  - $g_1 = g_{1,static} * \exp(\gamma_m + j\ \gamma_\phi)$

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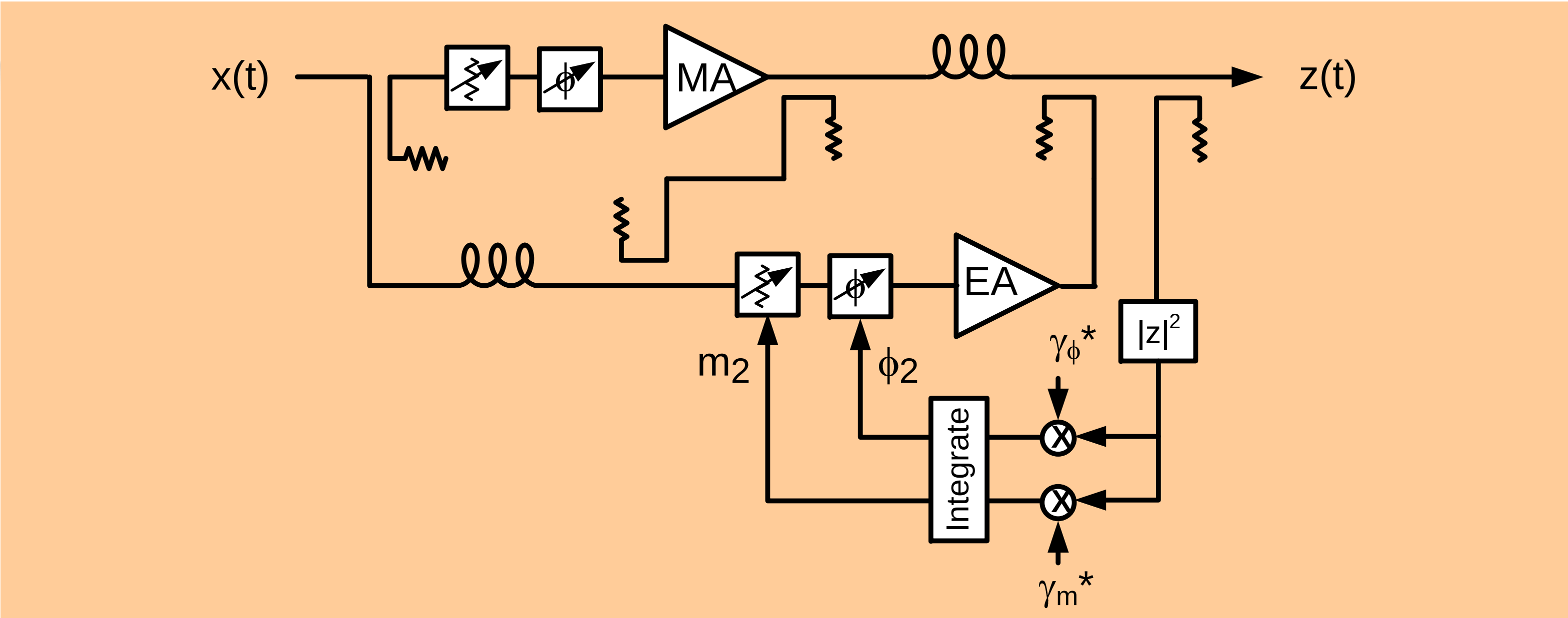
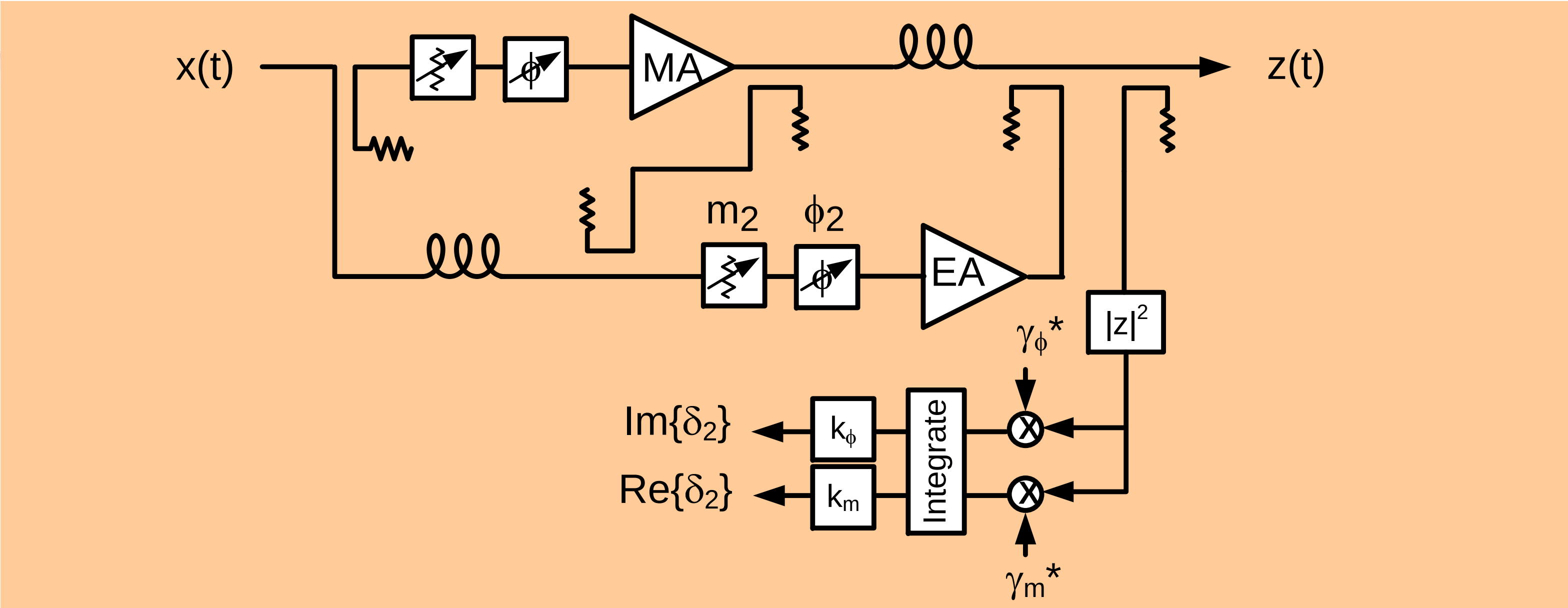
Second Loop (Matz)



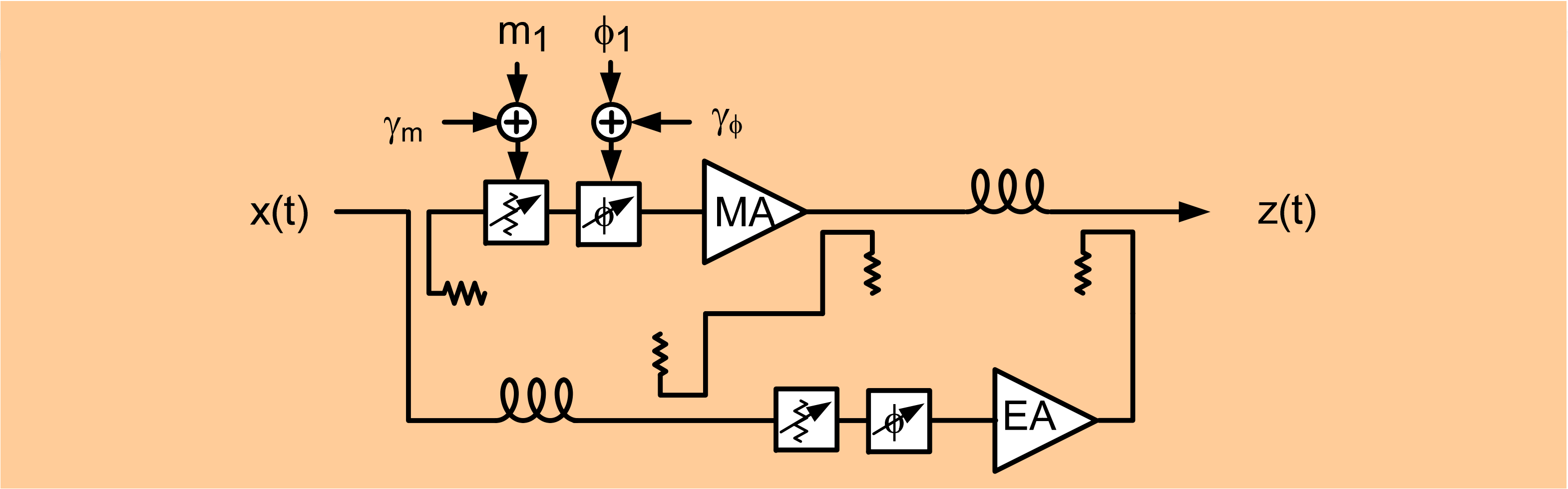
- 2^{nd} loop alignment.
  - Optimal alignment denoted by $g_{2,opt}$ where $g_{2,opt} * g_{EA} = 1$.
  - Actual misalignment denoted by $\delta_{2,actual}$.
  - $g_2 = \exp\{ m_2 + j\ \phi_2 \} = g_{2,opt} * \exp(-\delta_{2,actual})$.
- 2^{nd} loop cancellation.
  - $G_2 = (1 - g_2 * g_{EA}) \approx -\delta_{2,actual}$

2^{nd} Loop Misalignment Estimate (Matz)



- Measured estimate of misalignment: δ_2.
  - $\mathrm{Re}\{\delta_2\} = k_m \int |z|^2 \gamma_m^* \, dt$
  - $\mathrm{Im}\{\delta_2\} = k_\phi \int |z|^2 \gamma_\phi^* \, dt$
- where
  - $k_m^{-1} = |G_o|^2 [2 \int |x|^2 |\gamma_m|^2 \, dt]$; $k_\phi^{-1} = |G_o|^2 [2 \int |x|^2 |\gamma_\phi|^2 \, dt]$

FF Output (Matz)



- FF output z(t)
  - z(t) = linear signal + residual in-band pilot
  - $z(t) = G_o * x(t) + \delta_2 * (\gamma_m + j\,\gamma_\phi) * G_o * x(t)$
- Residual pilot
  - Modulation index $|\gamma_m + j\,\gamma_\phi|$
  - 2nd loop misalignment $|\delta_2|$.

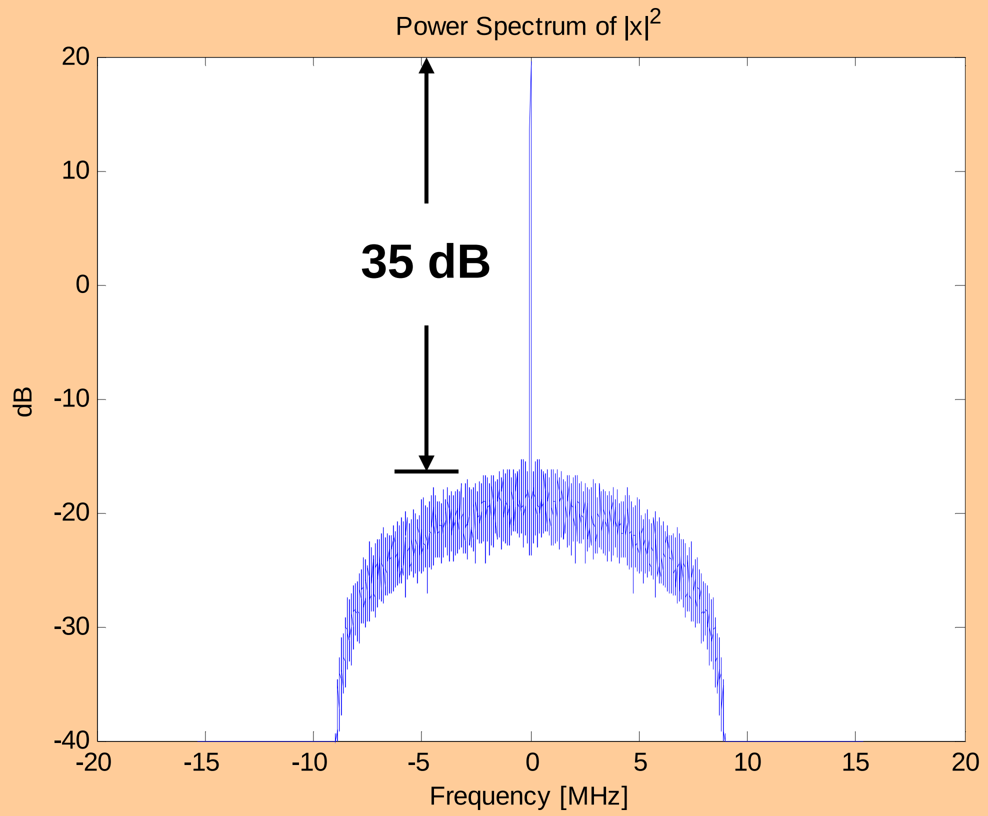
Demodulation Offsets (Matz)

- Demodulated squared magnitude of FF output
  - $\int |z|^2 \gamma_m \, dt = |G_o|^2 * [\, A_1 + |\delta_2|^2 * (A_2+A_6) + \mathrm{Re}\{\delta_2\} * B_1 \,]$
  - $\int |z|^2 \gamma_\phi \, dt = |G_o|^2 * [\, A_3 + |\delta_2|^2 * (A_4 + A_5) + \mathrm{Im}\{\delta_2\} * B_2 \,]$
- Offset terms
  - $A_1 = \int |x|^2 \gamma_m{}^* \, dt$ $\quad A_2 = \int |x|^2 |\gamma_m|^2 \gamma_m{}^* \, dt$
  - $A_3 = \int |x|^2 \gamma_\phi{}^* \, dt$ $\quad A_4 = \int |x|^2 |\gamma_\phi|^2 \gamma_\phi{}^* \, dt$
  - $A_5 = \int |x|^2 |\gamma_m|^2 \gamma_\phi{}^* \, dt$ $\quad A_6 = \int |x|^2 |\gamma_\phi|^2 \gamma_m{}^* \, dt$
- A_1 and A_3 are the most significant offset terms.
  - $B_1 = 2 \int |x|^2 |\gamma_m|^2 \, dt > 0$ $\quad B_2 = 2 \int |x|^2 |\gamma_\phi|^2 \, dt > 0$

Steady State Bias (Matz)

- Measured estimate of δ_2
  - $\int |z|^2 \gamma_m \, dt / (B_1 * |G_o|^2) \approx (A_1 / B_1) + \mathrm{Re}\{\delta_2\}$
  - $\int |z|^2 \gamma_\phi \, dt / (B_2 * |G_o|^2) \approx (A_3 / B_2) + \mathrm{Im}\{\delta_2\}]$
- Steady state
  - Alignment bias: $|\delta_{2,ss}| = |\ (A_1 / B_1) + j\ (A_3 / B_2)\ |$
  - Second loop cancellation: $|G_{2,ss}| = |\delta_{2,ss}|$
- Important terms
  - $A_1 = \int |x|^2 \gamma_m^* \, dt$; $A_3 = \int |x|^2 \gamma_\phi^* \, dt$
  - $B_1 = 2 \int |x|^2 |\gamma_m|^2 \, dt$; $B_2 = 2 \int |x|^2 |\gamma_\phi|^2 \, dt$

Power Spectrum of $|x|^2$ for DL-LTE



- Magnitude pilot
  - $\gamma_m = \sin(2\pi f_m t)$
  - f_m = 100 kHz
- Phase pilot
  - $\gamma_\phi = \sin(2\pi f_\phi t)$
  - f_ϕ = 120 kHz

- Assume $|\gamma| = |\gamma_m| = |\gamma_\phi| = 0.1$ and 1 kHz RBW
  - $|G_{2,ss}| = E[|\delta_{2,ss}|] \approx -35\text{ dB} - 20\log|\gamma| = -15\text{ dB}$
  - Residual pilot at FF output = -35 dB.

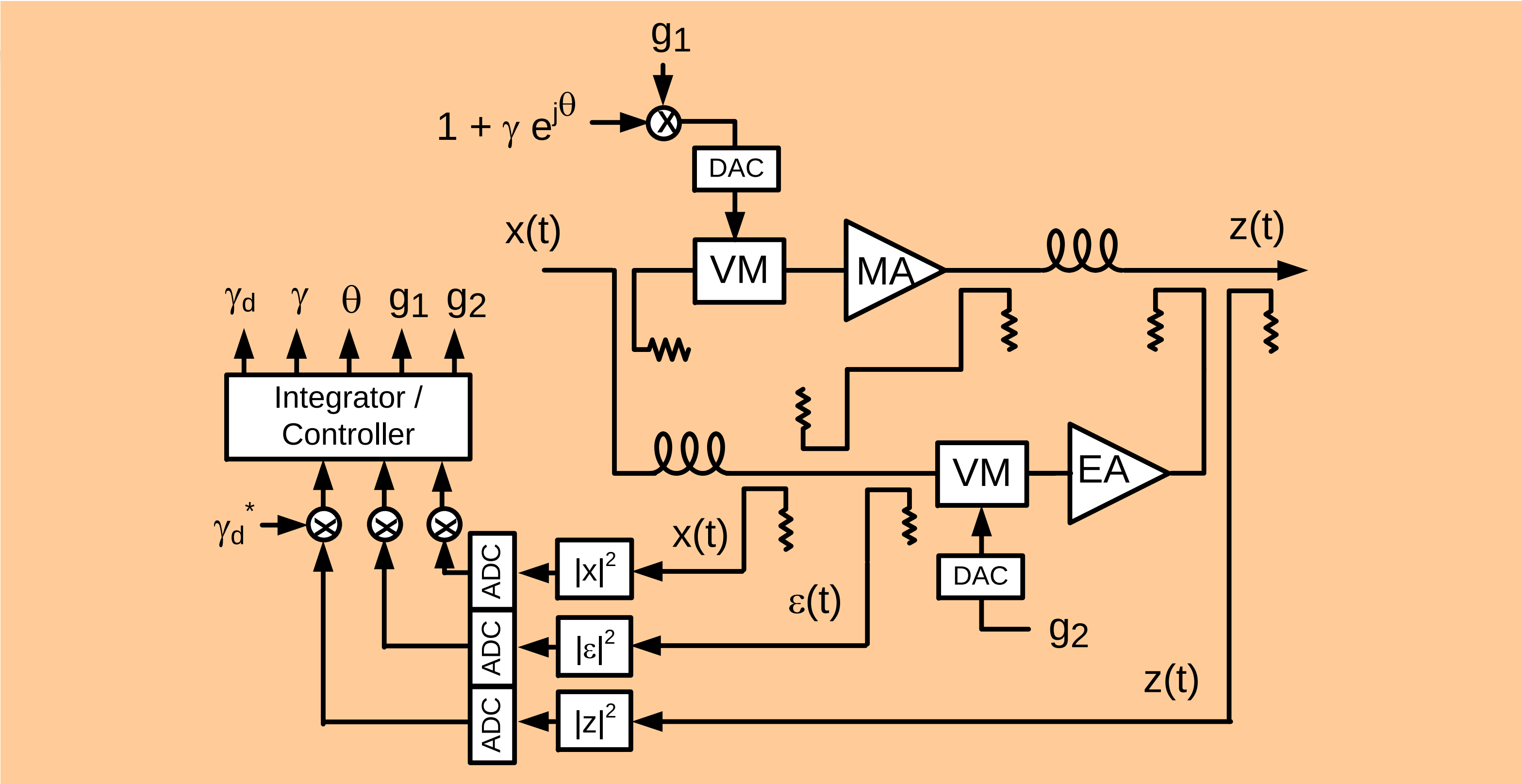
Summary (Matz)

- Steady state offset
  - Fundamental limitation of Matz approach.
  - Pilots are not orthogonal to $|x|^2$.
- Distortion cancellation
  - Determined by steady state offset.
  - Can be improved by increasing pilot modulation level $|\gamma|$.
- Residual pilot
  - Determined by the power spectrum of $|x|^2$ and pilot frequency.
  - Independent of pilot modulation level.
  - Increases EVM of transmitted DL-LTE.

Avoiding Biases (Matz)

- Conditions on γ_m and γ_ϕ to avoid bias in g_2.
  - $[A_1 \dots A_6] = [0\ 0\ 0\ 0\ 0\ 0]$.
  - $[B_1\ B_2] > [0\ 0]$.
- In general, the conditions are not met.
  - $A_1 = 0$ and $B_1 > 0$ requires γ_m to be orthogonal to $|x|^2$.
  - $A_3 = 0$ and $B_2 > 0$ requires γ_ϕ to be orthogonal to $|x|^2$.
- Important terms
  - $A_1 = \int |x|^2\, \gamma_m^*\, dt$; $A_3 = \int |x|^2\, \gamma_\phi^*\, dt$
  - $B_1 = 2 \int |x|^2\, |\gamma_m|^2\, dt$; $B_2 = 2 \int |x|^2\, |\gamma_\phi|^2\, dt$

Modulation Pilot and Bi-orthogonal Demod.



- Alternative to Matz.
  - Use separate pilots for modulation γ and demodulation γ_d.
  - Select pilots to be bi-orthogonal to $|x|^2$.
  - Digital controller.

Differences from Matz's Implementation

- Modulate g_1 along one dimension at a given time.
  - Modulation direction θ.
  - Fewer orthogonality conditions to fulfill.
- Select a modulation and demodulation pilot pair (γ,γ_d) such that

$$A_1 = \int |x|^2 \gamma_d^* \, dt = 0$$

$$A_2 = \int |x|^2 |\gamma|^2 \gamma_d^* \, dt = 0$$

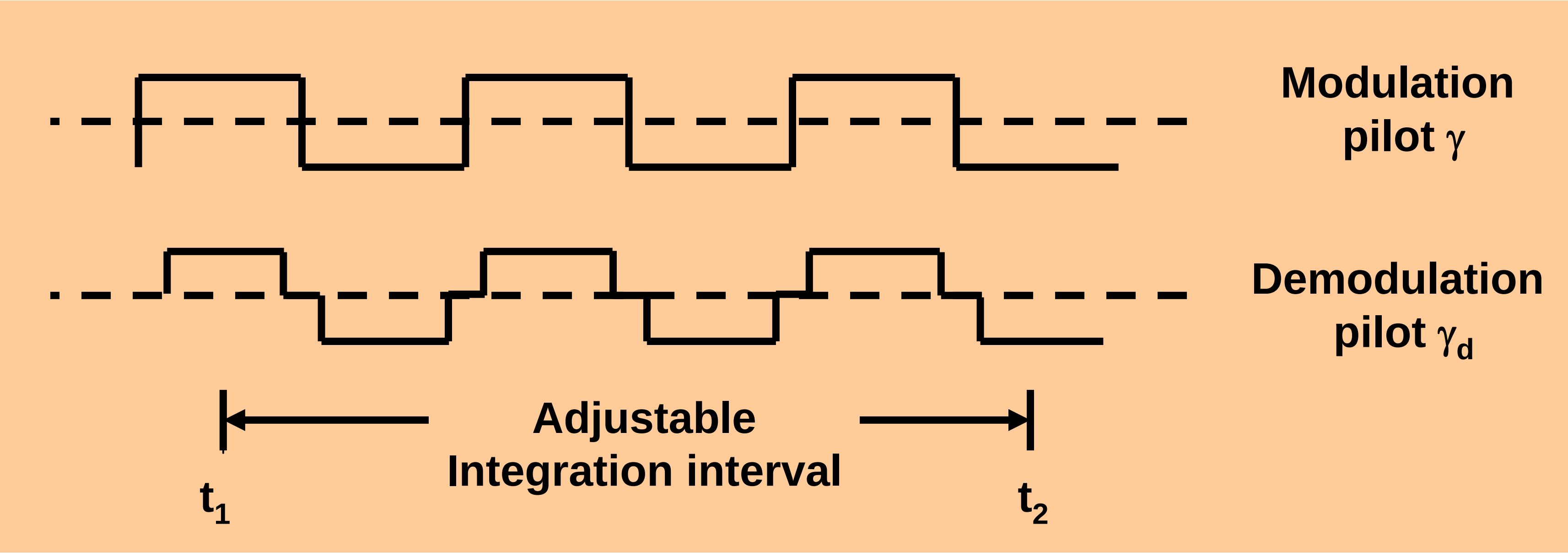
$$B_1 = 2 \int |x|^2 \gamma \gamma_d^* \, dt > 0.$$

- Choose γ_d as a function of $|x|^2$ to fulfill orthogonality condition.

Bi-Orthogonal Pilot

- Select binary modulation pilot $\gamma = \pm\rho$.
  - Reduces orthogonality to one equation.
  - $A_2 = |\rho|^2 A_1$
- Select demodulation pilot γ_d
  - $\gamma_d(t) = \gamma(t)$ or 0 (masked).
  - $\gamma\gamma_d^* = |\gamma_d|^2$ which makes $B_1 > 0$.
    - $B_1 = \int_{t1}^{t2} |x|^2 |\gamma_d|^2 \, dt > 0$.
  - Adjust t_1, t_2, and masking of γ_d to make offset zero.
    - $A_1 = \int_{t1}^{t2} |x|^2 \gamma_d^* \, dt = 0$.
  - Adjustments made in DSP after $|x|^2$ and $|z|^2$ have been digitized and captured.

Modulation and Demodulation Pilots

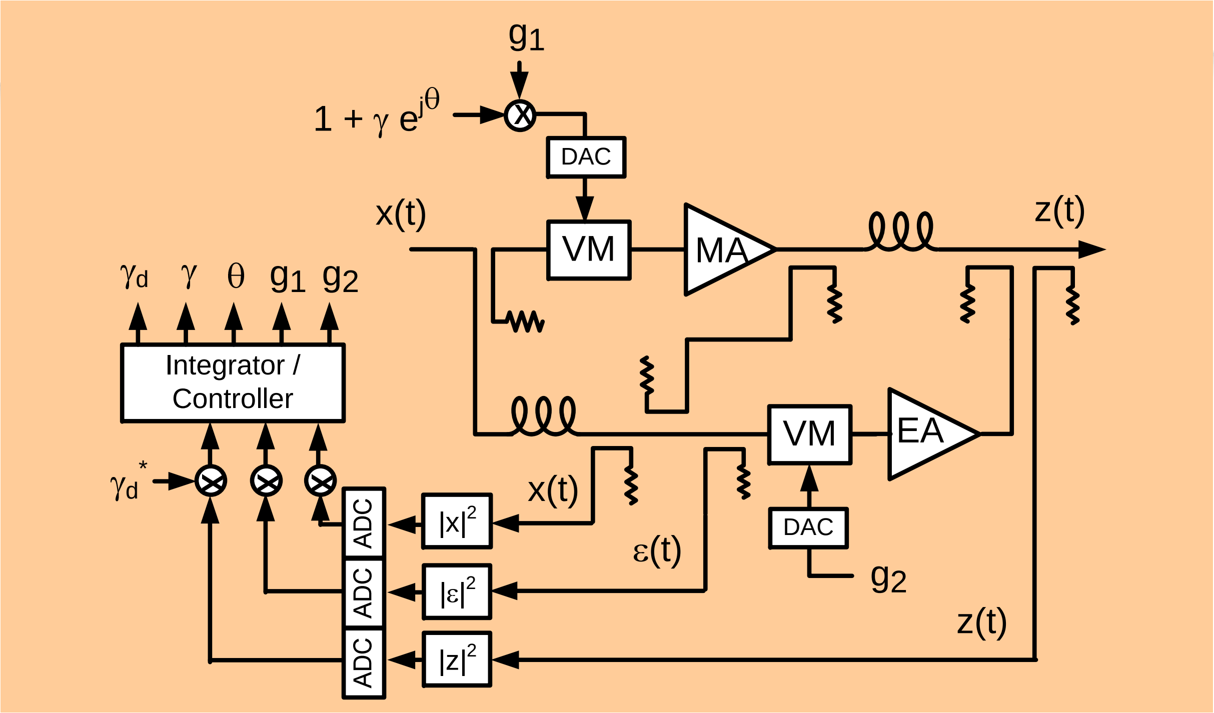


- Integration interval adjusted so that
  - $A_1 = \int_{t1}^{t2} |x|^2 \gamma_d^* \, dt = 0.$
- Masking shown above reduces sensitivity to time misalignments between $|x|^2$ and $|z|^2$.

Alignment Update (Bi-Orthogonal Pilot)

- 2^{nd} loop misalignment estimate
  - $\Delta_2 = \mathrm{Re}\{\delta_2{}^*\exp(j\theta)\} = k \int_{t1}^{t2} |z|^2 \gamma_d{}^* \, dt$
  - $k^{-1} = |G_o|^2 * \int_{t1}^{t2} |x|^2 |\gamma_d|^2 \, dt$
- 2^{nd} loop alignment update
  - $g_2(t_{n+1}) = g_2(t_n) * [\, 1 + \Delta_2 * \exp(j\theta) \,]$
- Alternate modulation directions
  - $\theta(t_{n+1}) = \mathrm{mod}\{\, \theta(t_n) + \pi/2, \pi \,\}$

Challenges



- Square law responses, $|x|^2$ and $|z|^2$, need to be matched.
- Signals need to be time aligned.
- Distortion from main amplifier not considered in analysis.
- Masking and calibration can reduce these problem.

Conclusion

- Second loop control of a feedforward PA
  - In-band pilot obtained by modulating the alignment control of the first loop.
- Bi-orthogonal demodulation pilot
  - Avoids steady state alignment offsets.
- Has potential for DL-LTE Advanced applications.

Thank You.

- Questions?