Integrated Analog-Digital-Photonic Receivers

Matt Morgan
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Integration of Analog, Digital, and Photonic Front-End Components

**Re-optimizes front-end architecture to leverage modern advances in:**
- Integrated technology, and
- Digital Signal Processing (DSP).

**These concepts are complementary:**
- DSP delivers **precision** unmatched by analog techniques,
- while integration ensures **stability** in both amplitude and phase
  - more accurate and longer-lasting calibrations
  - crucial to high-dynamic range imaging

**To that end, we**
- digitize as close to the antenna feed as possible,
- transfer any functionality we can into the digital domain,
- and integrate into the front-end everything needed to lock-in the analog amplitude and phase drift and to get the data physically off the telescope (i.e. analog, digital, and photonic).
Orthomode Transducers (OMTs) Generally Work in Two Steps

- "Factorization"
  - separation of dual-polarized input into vector components
  - turnstile, Bøifot, etc.

- "Reconstruction"
  - Re-assembly of component vectors into orthogonal polarizations
  - Typically, E/H-Plane combiners, planar baluns, etc.
"Factorization" is still done by analog means.

But "Reconstruction" or synthesis can be done digitally
  - with greater accuracy, and
  - reduces loss in front of the cryogenic amplifiers.
Numerical Reconstruction Affords Additional Degrees of Freedom

- Center-probe couples in common-mode into all three channels, but not into a radiating mode on the sky.
- No added insertion loss (unlike calibration coupler).
- Signal drops out during digital polarization reconstruction.
  - Allows for strong omnipresent calibration signal that does not mask observations, and
  - Pilot-tone stabilization of amplitude fluctuations.
Polarization Performance and Stability

Isolation (Linear Pol.)  Axial Ratio (Circular)

- Polarization Isolation [dB]
  - X (30 C)
  - Y (30 C)
  - X (40 C)
  - Y (40 C)

- Axial Ratio [dB]
  - Left (30 C)
  - Right (30 C)
  - Left (40 C)
  - Right (40 C)
Digital Sideband-Separating
Downconversion
Benefits of Numerical Reconstruction

- Digital IF Hybrid is "better than ideal" in that it can compensate for analog RF-circuit imbalances.

- Allows precise, single-stage downconversion to baseband with only one system-wide LO.
  - Guards against spurious mixing products which integrated receivers are especially sensitive to.
Sideband-Separation Performance and Stability

Initial Calibration

After Temp. Excursion

Unwanted Sideband Suppression 28 Celsius

Unwanted Sideband Suppression 40 Celsius

28 °C

40 °C
Careful Step-by-Step Development

2008

Analog only

2009

Analog & Digital

2012

Analog, Digital, & Photonic
Internal ADCs Introduce No Measurable Interference

(expected clock harmonic)

(12.5 minute integration)
MMICs and Integration

Analog

Digital & Photonic
Miniaturization
Integration of Optical Transmitter

• Conventional digital fiber optic links come with a great deal of complex logic
  – bit scramblers
  – 8/10 encoding
  – packetizing/framing

• These functions add to the bulk and power dissipation of the front-end while increasing the risk of digital self-interference.

• But the known statistics of our signal may work to our advantage:
  – Well-characterized by Gaussian-distributed white-noise.
To realize a digital fiber-optic data link with minimal overhead, we use only
- a sampler,
- a serializer,
- a laser driver,
- and a laser.

Known statistics of radio astronomy signals allow link management to be performed entirely at the receive end.
- 1st Challenge: DC Balance
- 2nd Challenge: Clock Recovery
- 3rd Challenge: Word-Alignment
- (also channel synchronization, power, interleaving...)
Implementation

Analog-Digital-Photonic Front-End

Photonic Data Receiver
References

- M. Morgan, "Active Cascade Local Oscillator Distribution for Large Arrays," Electronics Division Technical Note #216, October 2010.
Want to know what's under the hood? (Backup slides follow...)

![Image of people looking under the hood of a car](image-url)
Vector Components Need Not Be Orthogonal/Independent

- Three-channel systems have advantages:
  - triangular/triple-ridged waveguides have broader mode-free bandwidth
  - extra degree of freedom permits common-mode calibration channel
Broad Mode-Free Bandwidth
Broad Mode-Free Bandwidth (cont'd)
N-Wire Model For Ridged Waveguides

• In the limit, all the fields are concentrated in the gaps.
• $N$-ridges become $N$-wires.
• Outer walls become "infinitely" far away.

• Low-order modes become like TEM modes.
• Their number is simply the number of ways you can assign currents to the wires while maintaining DC balance.
Triple-Ridged for Ultra-Wideband AND Low Noise?

• "Unlimited" single-mode bandwidth makes it easier to realize compact, abrupt transitions (e.g. thermal and vacuum)
• These junctions, along with smaller mass enable cryogenic cooling of electromagnetic components where other approaches cannot.
Laboratory Measurement Setup
Not Dependent on Bit Resolution

![Graph showing peak isolation and polarization isolation as a function of the number of active sampler bits and IF (MHz).](image)
Reflectionless Filters Enhance Stability

- New filter topology changes less with temperature (lower peak above) and more consistently with component values (less spread) than conventional designs.
  - fewer calibration points are required
  - calibration is far more stable
Even-/Odd-Mode Analysis (backwards)

Even-Mode excitation:

Odd-Mode equivalent circuit

Even-Mode equivalent circuit

symmetric two-port network

+ +

(open)

(短)

Allows you to solve two 1-port networks instead of one 2-port network.

Reverse application: Instead of solving for the performance of a given circuit, let us first prescribe the desired performance and then derive a circuit that achieves it...
Even-/Odd-Mode Equations for a Reflectionless Filter

\[ s_{11} = \frac{1}{2} \left( \Gamma_{even} + \Gamma_{odd} \right) = 0 \]
\[ \Gamma_{even} = -\Gamma_{odd} \]
\[ \frac{z_{even} - 1}{z_{even} + 1} = \frac{y_{odd} - 1}{y_{odd} + 1} \]
\[ \therefore z_{even} = y_{odd} \]
\[ s_{21} = \frac{1}{2} \left( \Gamma_{even} - \Gamma_{odd} \right) = \Gamma_{even} \]
Design a Reflectionless Filter

Even Mode equivalent circuit

Odd Mode equivalent circuit

"Reflectionless" if:
\[ z_{even} = y_{odd} \]
(normalized)

Full-circuit transmission coefficient
= even-mode reflection coefficient.
You Now Have a Symmetric Low-Pass Reflectionless Filter!
Low-Pass, High-Pass, Band-Pass, and Band-Stop
High-Order Designs are Possible as Well...
Integration of Samplers

L-Band Module

Analog Side
- Analog Inputs

Digital Outputs

Digital Side
- ADCs

Analog Inputs
- IF Channels
- RF Board
1st Challenge: DC Balance

Instantaneous Voltage vs. Time

Probability Density Function

Straight/Offset Binary

Two's Complement

\[ v_0 \]

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<th>Binary</th>
<th>Straight/Offset</th>
<th>Two's Complement</th>
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**1st Challenge: DC Balance**

- Actually, this is not a problem.
  - Individual samples are random with zero mean value.

- Common binary codes are symmetric about center.
  - Positive sample codes are mirror images of negative sample codes.
  - Thus, any given bit for any given sample has an equal chance of being a 1 or a 0.

- Only requires ADCs to have reasonably low offset voltage.
  - Small offsets lead to correspondingly small level shifts in the eye diagram.
  - Unlikely to break the serial link.
2nd Challenge: Clock Recovery

- Commercial deserializers can recover the clock from data streams that satisfy certain minimum transition density requirements.

- MAX3880 from Maxim:
  - "Tolerates >2000 Consecutive Identical Digits"

- VSC1236 from Vitesse:
  - signals Loss of Data when "transition density is less than 40%."

![Graph showing transition density vs. \( \sigma/\nu_0 \)]
3rd Challenge: Word Alignment

- The MSB has a predictable correlation with its neighboring bits in the most likely sample codes near the middle of the sampler range.

- This allows for the direct statistical determination of word boundaries in a serial data stream without any prior formatting.
Statistics Largely Immune to Passband Shape and External Interference
Strong Statistics Provide Very Reliable Operation

![Graph showing the relationship between the number of samples and the probability of word-lock failure.](image)
For Straight Binary, a Simple XOR Gate is Sufficient
4th Challenge: Synchronization

• Without framing, differential delays on parallel fibers may cause simultaneous data streams to arrive at the backend spectrometer or correlator out of sync.
  – In this regard, it is no different from an analog fiber optic link...

• But unlike analog links, the $\Delta \tau$ must be an integer multiple of the sample period, introducing a discrete-valued phase-slope into the correlation between channels.

• In-situ calibration signals provide an easy means for monitoring these slopes/delays.

• As long as they are stable (or tracked) within a sample period, the recovered synchronicity between parallel channels will be exact.
Final Challenge: Power Dissipation

Power Dissipation in an L-Band Integrated Analog-Digital-Photonic Receiver (3.7 Watts total per RF channel)

- ADC core (1.4 W)
- ADC interface (430 mW)
- LO amplifier (50 mW)
- IF amplifier (350 mW)
- RF amplifier (360 mW)
- Laser Driver (100 mW)
- VCSEL (30 mW)
- Serializer (1.0 W)
Combined ADC/Serializer Saves Power (and reduces the footprint)
Custom ADC/Serializer

• By combining the ADC and the serializer, we can replace the resistively-terminated, off-chip LVDS lines with on-chip high-impedance traces to save power.
  – In the process, reducing the pin count and package size by an order of magnitude.

• Could also save a lot of power simply by sampling at 4-bits resolution instead of 8-bits.
  – Gives wider bandwidth for the same aggregate bit rate.
  – Resolution-agnostic ADC architecture?
Proposed Custom Chipset for Unformatted Serial Links

- **ADC+Serializer**
  - High-speed
  - Low-power
  - Small footprint
  - Programmable bit-resolution

- **Deserializer**
  - Automatic, on-chip clock-recovery and word alignment
  - Adjustable word sequencing