Universal Beamforming Technology: Application and Tests

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Introduction

• Beam Pointing of Phased Arrays is not new
  – H/W phase-shifters still used widely
  – Full Digital Beamforming (DBF) is recent
  – ~ 2000, DBF began migrating into RF applications

• In 2004, CDSI designed a DBF TM subsystem
  – Installed on (2) USAF E-9A aircraft in 2008
    • 10 beams, 112 dual-pol elements, S-band, 11dB G/T
    • Replacing 5-beam conventional array (3x bigger)

• Since then, technology continues to advance…
  – We introduce “UBT” architecture/development
Sponsors to date

• Ongoing support from E-9A Program
  – Operational “testbed” for algorithms/operations

• Office Secretary of Defense
  – Test Resource Management Center (TRMC)
    • T&E/S&T Spectrum-Efficient Technology (SET), Edwards AFB, CA.
  – Navy, NAVAIR/NAWCWD Pt. Mugu, CA.

• Goals:
  – Hi-risk/Hi-payoff R&D for T&E
  – Technology transfer
  – Risk Reduction

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Background

• Experience with E-9A (operational since 2008):
  – Continuous functionality improvement:
    • Upgrade firmware (once)
    • Upgrade CPU (twice), software (many times)
  – Avoid obsolescence:
    • Entire DBF subsystem (2 racks) is replaceable:
      – Lower cost (ADC/FPGA devices evolve continuously)
      – Higher performance (channels, bandwidth, data rates)
      – Higher reliability (redundancy, fewer devices)
    • Augment antenna array (e.g., add C-band)
      – New S-band array ½ size of prior: more weight/space available
“Classic” DBF approach (E9)

• Each element RF signal is downconverted to IF
  – IF digitized synchronously (ADCs)
  – Processed digitally (FPGAs):
    • Filtering/DDC → baseband “channel-element” streams
      – Tuning frequency, bandwidth   – Calibration
    • Channel-elements combined into “beam” (each channel)
      – Simultaneous beams:  e.g.: Σ,Δ, Polarization, Low SL (weighted)
      – Acquisition: Sequential Search   – Tracking: Monopulse
  • Final output for each beam can be:
    – Analog IF (70 MHz) or Digital (Clock, Data)
Classic DBF Limitations

• As G/T increases:
  – Elements ↑ : cost increases as diameter$^2$
  – Acquisition time ↑ : beamwidth$^{-2}$
• Multipath
  – Destructive interference across array
• If aperture is fixed – (not on pedestal)
  – Scan Loss
  – Grating Lobes (element spacing >0.5λ)
Multipath

Mechanics of Multipath

- Line-of-sight (LOS) illumination provides predictable behavior
- Pointing algorithms usually created using LOS principles
- Conventional algorithm produces sub-optimal aggregate signal
- Primary effect: aggregation of bounce path (at random phase)
- Secondary effects like Aperture Surface waves

Notional Multipath scenario

Reflective surface
- Smooth ground
- Ocean

Antenna Position

Actual source position

Line-of-Sight Path

Reflection Path (Multipath)

Bounce point

Damaged spectrum

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UBT Improvements

• Digital Beamforming Module (DBM) concept:
  – Reduced cost, increased reliability/flexibility
  – Higher G/T = more DBMs (plug-n-play)

• DBM forms a Generic Intelligent Subarray:
  – Can handle single- or multi-band RF elements
  – Cost of available devices continuously reducing
  – Efficiency of available firmware increasing

• Local intelligence provides many advantages:
  – Optimal SNR, rapid acquisition/tracking
  – Multipath mitigation, conformal/disjoint apertures, ...
UBT RF Hardware

- Single-band or multi-band RF elements
  - LNA/LNB, Filters (EMI), limiters, ...
  - Many alternative downconversion approaches:
    - Block IF downconversion: entire band of interest (E-9)
      - Can handle many beams in each block with fewer devices
    - Individual beam (frequency) down-converters:
      - Can place beam anywhere in wide RF range (= many devices)
- Can be co-located with RF panel
  - Minimal cable loss
UBT RF Hardware

• UBT uses “Building block” approach: DBMs
  – Digital Beamforming Modules

• DBM contains
  – RF elements
  – Filters
  – Downconverters
  – DBF Processing
  – Interconnection
UBT Firmware

• DBM Firmware performs:
  – Subsystem hardware configuration
    • Channel parameters (tuning, bandwidth)
    • High-level functions (calibration, angle/freq scan, acq/track)
  – Dynamic operations:
    • ADC synchronous sampling
    • Channelization/Filtering (e.g., DDC)
    • DBF processing (algorithms, data transport, combination)
  – Hardware monitoring/control (interface to software)

• Final output Firmware:
  – Digital-to-IF upconversion
  – Any other output processing
UBT Software

• Subsystem configuration by User
  – Channels, scenarios
• Subsystem monitoring/control
  – Nominal health or fault diagnosis
  – Debug of firmware interface (essential)
• User interface
  – Graphical presentation
    • spectra, scans, maps
• Can be a single host (e.g., laptop)
UBT Digital Hardware

• ADC configuration (depends on RF choices):
  – Higher speed/cost required for “block” approach
  – Lower speed/cost for targeted frequency approach

• FPGA configurations
  – Each DBM: ADC inputs, DBM I/O (data and control)
  – Final Stage: produces digital or IF beam outputs

• DBF processing:
  – DBM intelligence: calibrate/acq/track/multipath
  – Physical: board-stack possible on each RF panel
Multipath Resilience

- Multipath scenario was purposely created
  - Mitigation is built into UBT
  - Conventional steering vs. UBT steering
Target Acquisition

• Spectrum Analyzer in Time-trace mode:
  – 13 dB SNR source
  – Tracking ~2 msec after signal appears anywhere in view
UBT implementation

- UBT Phase-1 proof-of-concept goal:
  - Tri-band multi-beam TM subsystem at TRL6
- Brassboard implemented in <12 mos, using:
  - Available COTS multi-purpose boards:
    - FMC transceiver boards + FPGA development boards
  - Available COTS firmware: DDC/filtering/DUC/SERDES cores
  - Prototype tri-band RF panel (First RF)
  - Some custom hardware required for integration:
    - Global Clock/sync/trigger, LO synthesis/distribution
8” square RF panel:
  4x4 dual-pol elements
  1.4–5.2 GHz

Rollaway (4x4 DBM):
  16 FPGA boards
  32 FMC boards

Providing:
  16 dual-pol beams
  250 MHz bandwidth
  over 0.4–6 GHz
  up to 125MHz/beam
UBT in-house testing

• “Wheel of Death” (WOD)
  – 6 RF sources mounted on suspended wheel
    • Rotation at 20RPM: >120deg/sec angular rates
  – One source transmitting SOQPSK at 30Mbps L/S/C
• Small drone: carrying SOQPSK source
• Multi-channel acquire: “instantaneous”
  – Despite multipath everywhere (indoors)
• Zero BER at 30 Mbps at all angular rates
  – Inside testing and drone flight (video taken)
UBT testing at EAFB

• UBT set up adjacent to 8’ TM dish at EAFB
  – 3 static sources: pole mounted
  – 1 flying source: 5 Mbps SOQPSK (L/S/C)
    • Flight path (blue) shown on map

• Pulsed interference:
  – Radar sweeps by...
    • Produce short error bursts
    • No front-end filtering installed

• Tracking Results:
  – Zero BER up to 45mi
    • Aircraft-aspect dependent
    • Discounting pulsed interference
    • Near theoretical limit For 8” aperture
  – Multipath mitigation demonstrated from flight-line
UBT vs. Reflector systems

• A specific DBM can be used in various ways, e.g.:
  – 8 beams for dual-pol 4x4 array (individual downconverters)
  – 1 beam for 16x16 single-pol array (different RF cabling)

• Decision-space model constructed:
  – Using today’s assumptions
  – Competes with dishes on cost
    • Up to 20’ for some cases
    • Could replace dish farm
  – Potential advantages, e.g.:
    • Multi-beam requirements
    • Limited or conformal space
Conclusions

• UBT concept demonstrated: TRL6 brassboard
  – Using available boards/firmware (risk reduction)

• Benefits:
  – Near-theoretical performance
  – Multipath resilience, “instantaneous” acq/track
  – High bandwidth/beam-count combinations
  – DBF has become cost-competitive vs. dishes
    • DBM cost continues to reduce over time
    • Potential ground, sea, airborne applications