PAF Receiver Concepts

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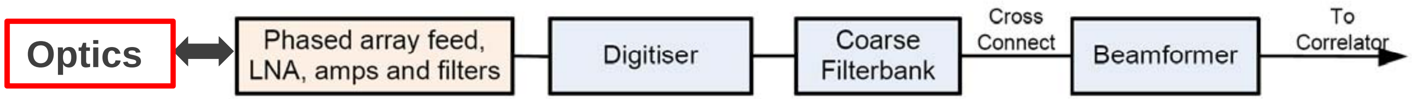
PAF sub-system overview

PAF presentations at CoDR

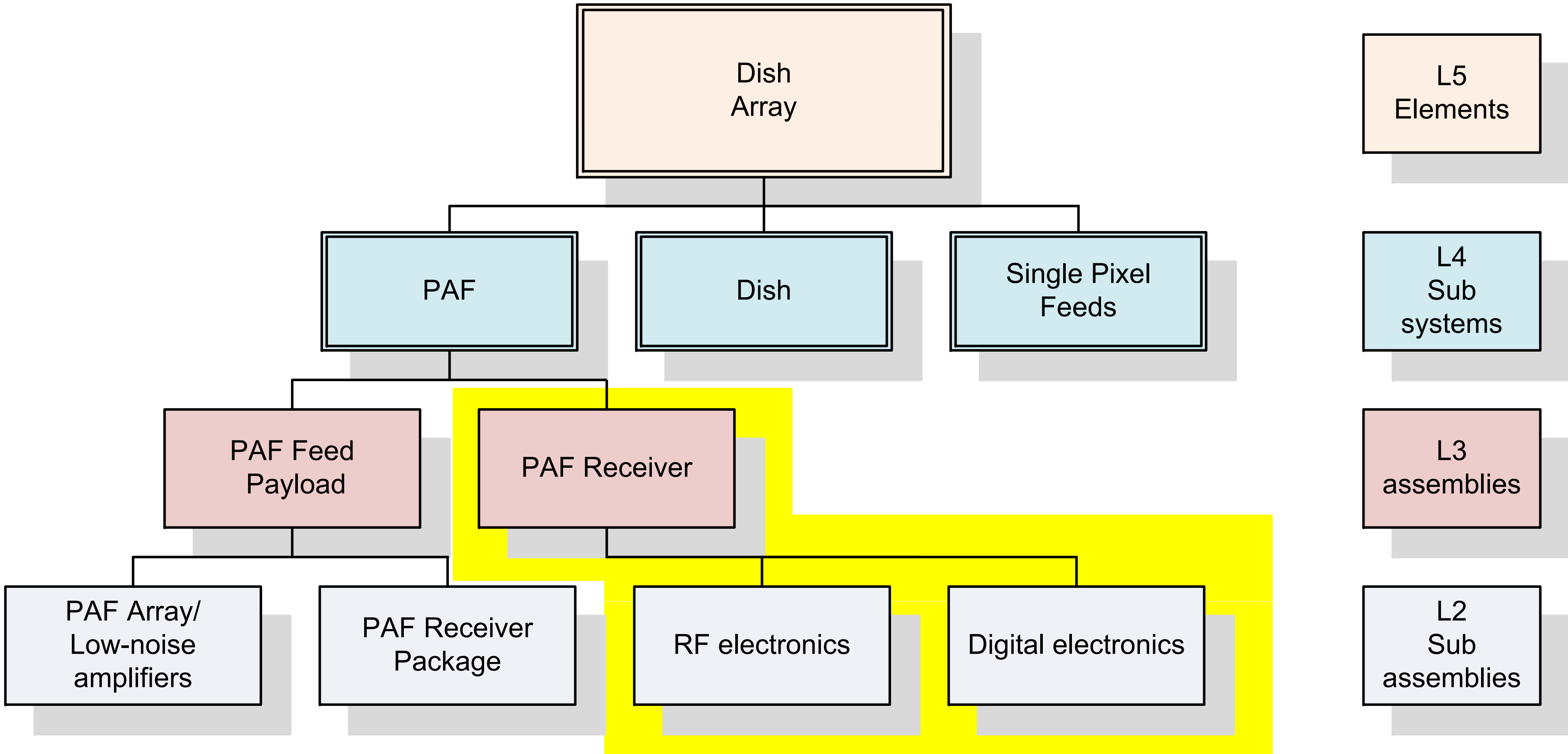


PAF SKA Context, addressing SKA requirements	Carole
PAF concept – PAF design (optics) feeds & LNA (PINK)	Stuart
PAF Concept PAF Receiver systems (BLUE)	**This presentation**
PAF Requirements, Risks and Logistics at the SKA scale	Mark
PAF Costs & plans for next phase	Carole

Summary
PAF Receiver Concepts for SKA Phase 1

- Introduction
  - PAF system requirements specifications
  - PAF receiver architectures
- PAF receiver assembly concepts
  - PAF receiver assembly (**Concept 1):**
    - Using RF-over-fibre signal transmission and direct sampling at RF but with switched narrowband anti-aliasing filters subassembly
  - PAF receiver assembly (**Concept 2)**:
    - Using an integrated IQ mixer architecture subassembly
  - PAF receiver assembly (**Concept 3)**:
    - Using wide-band direct sampling
  - Receiver gain calibration sub-assembly
  - Analog-to-digital conversion sub-assembly
  - Digital Filterbank sub-assembly
  - Digital transmission over optical fibre
  - Digital Beamformer sub-assembly
- Recommendations

The Dish Array Hierarchy



PAF System Requirements Specifications

PAF_REQ_0010	**Frequency range:** The PAF sub-systems shall cover the frequency range 450 MHz to 3 GHz.
PAF_REQ_0020	**Instantaneous bandwidth:** The instantaneous bandwidth sampled by the PAF sub-systems shall be comparable to the observing frequency.
PAF_REQ_0040	**Frequency band positioning:** If the PAF system is tuneable, it shall be possible to position the receiving band anywhere within the operating frequency band, with a positioning accuracy (TBD). The instantaneous observable frequency band is a contiguous (TBD) MHz band selected from the total frequency range.
PAF_REQ_0050	**Band selection resolution**: If the PAF system is tuneable, the resolution with which the frequency band, defined in requirement PAF_REQ_0020, can be selected shall be (TBD) or less.
PAF_REQ_0060	**Outputs**: The PAF sub-systems shall provide two simultaneously available digitised optical outputs for each beamformed beam, corresponding to nominally orthogonally polarised radio signals incident on the dish.
PAF_REQ_0070	**Polarisation frequency equality**: It shall not be possible to select different digitized bands for the two polarizations of each beamformed beam.
PAF_REQ_0080	**Passband flatness**: PAF sub-system passbands shall be flat to (TBD) dB.

PAF System Requirements Specifications

PAF_REQ_0090	**Passband stability**: PAF sub-system passbands shall be stable to within (TBD) over a period of 1000 hours.
PAF_REQ_0100	**Spectral dynamic range:** The performance of the PAF sub-system shall be consistent with a system spectral dynamic range of ≥43 dB in the band 450 MHz to 1.4 GHz
PAF_REQ_0150	**Beam stability:** The magnitude and phase variations of any of the PAF sub-system beamformed beams over a 12 hours period at any point of its half-power contour shall be less than 1% (TBD) relative to the beam peak.
PAF_REQ_0170	**Frequency agility:** If the PAF system is tuneable, it shall be able to tune to any frequency within the specified operating range within (TBD) minutes. This includes switching between PAF payloads and any tuning internal to the PAF receiver.
PAF_REQ_0180	**Beam polarization stability:** The polarization properties of the beams formed by the PAF sub-system shall be stable enough to allow their calibration to better than 0.5% (TBD)
PAF_REQ_0190	**Beam absolute pointing accuracy**. The required pointing accuracy of the beams formed by the PAF sub-system shall be TBD.

Receiver architecture considerations

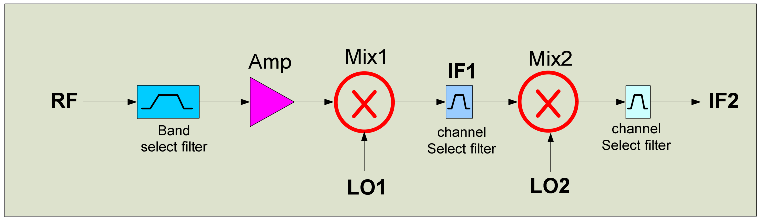
- Receiver architecture depends critically on:
  - RF (observing) band
  - IF (sampled) band
    - Sampled bandwidth is dependent upon digital processing capacity
- RF bandwidth
  - Up to 2.5:1 for Chequer-board array or Vivaldi array
- Possible RF bands (2.5:1) for SKA1 are:

HI Redshift (z)	RF Band (MHz)	RF Bandwidth (MHz)
0.3 – 2.2	440 – 1100	660
-0.1 – 1.4	600 – 1500	900
	1100 – 2700	1600

Possible Receiver Architectures

- Double heterodyne

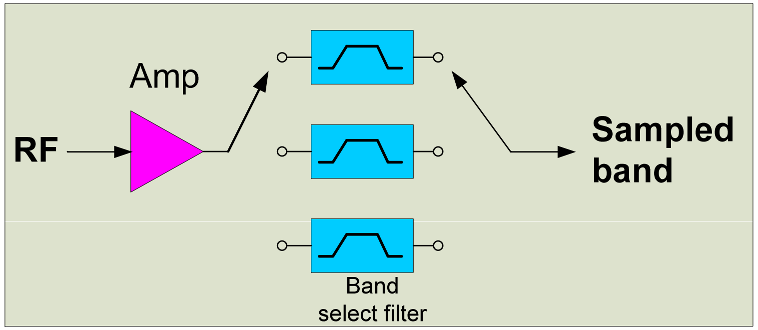
ASKAP: RF band 700 – 1800 MHz
IF 300 MHz bandwidth



APERTIF: RF band 1000 – 1750 MHz
IF 300 MHz bandwidth

- Direct RF sampling
  - with switched anti-aliasing filters

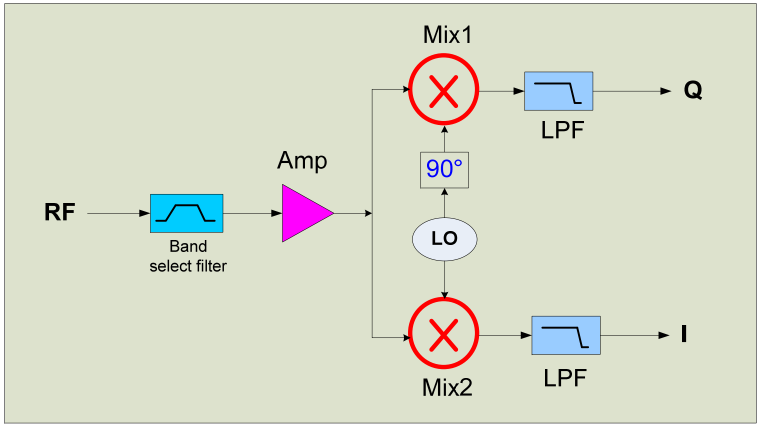
PAF Receiver assembly concept utilising RF-over-fibre signal transmission



Possible Receiver Architectures

- I/Q conversion

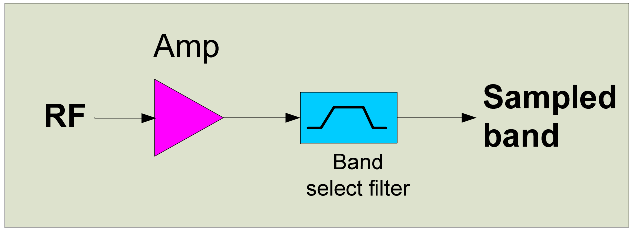
PAF Receiver assembly concept utilising an integrated IQ mixer architecture



- Direct RF sampling

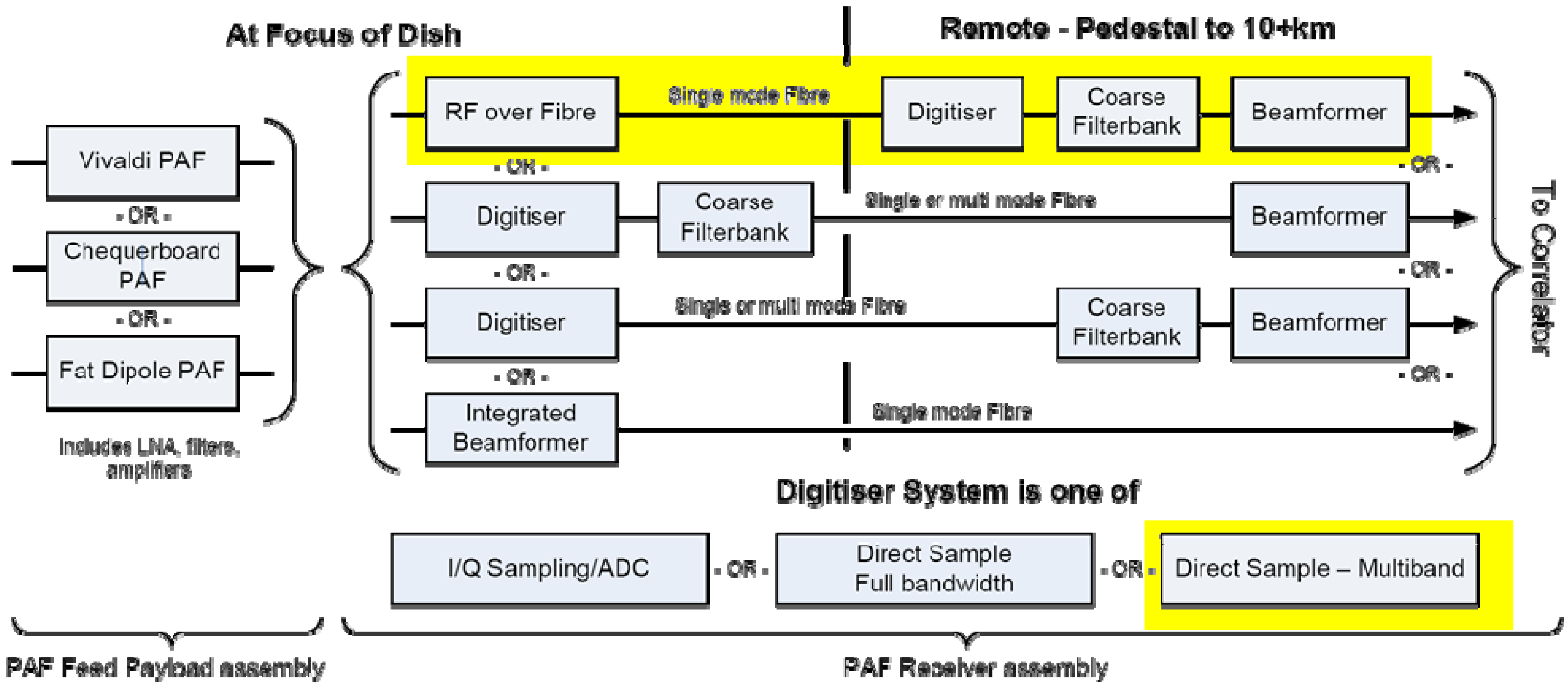
Receiver concept:

Using wide-band direct sampling



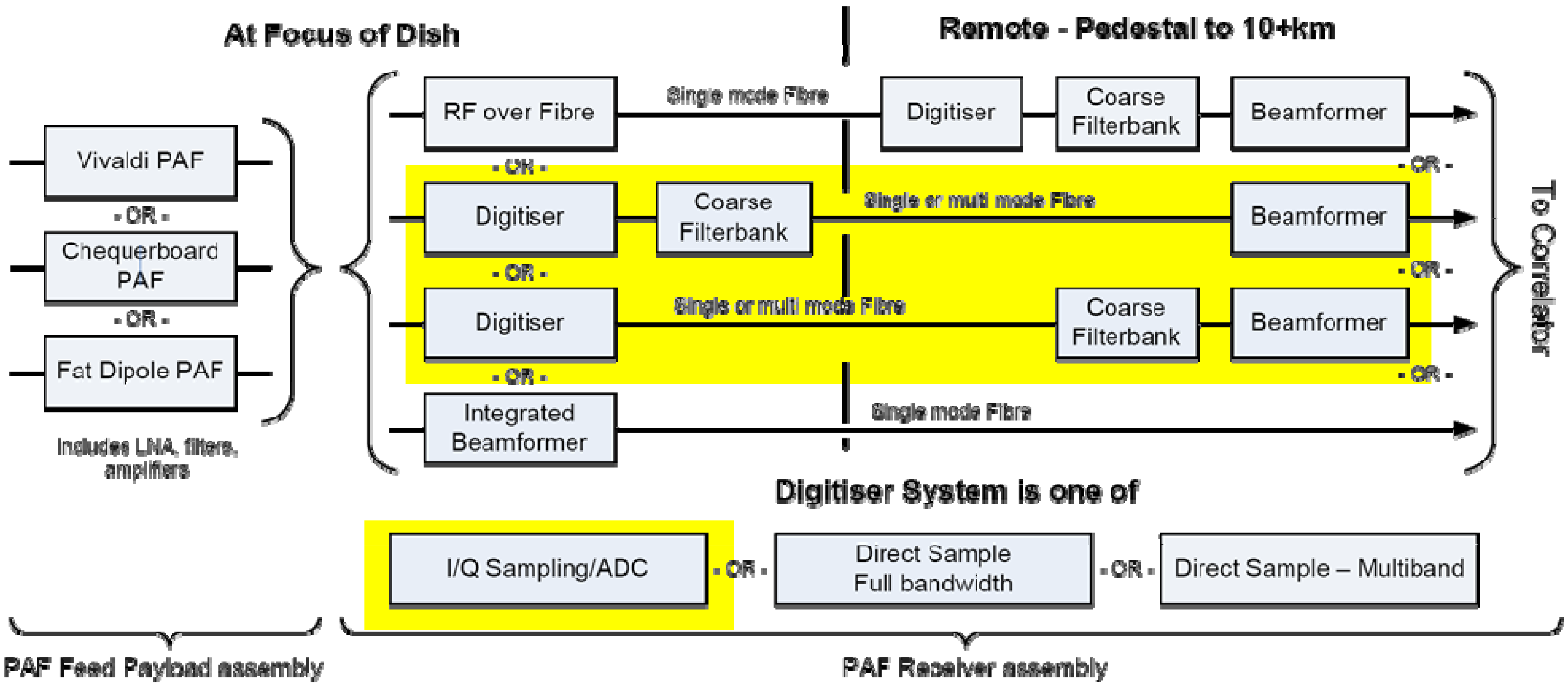
Possible Receiver Architectures

Concept 1: RF-over-fibre signal transmission



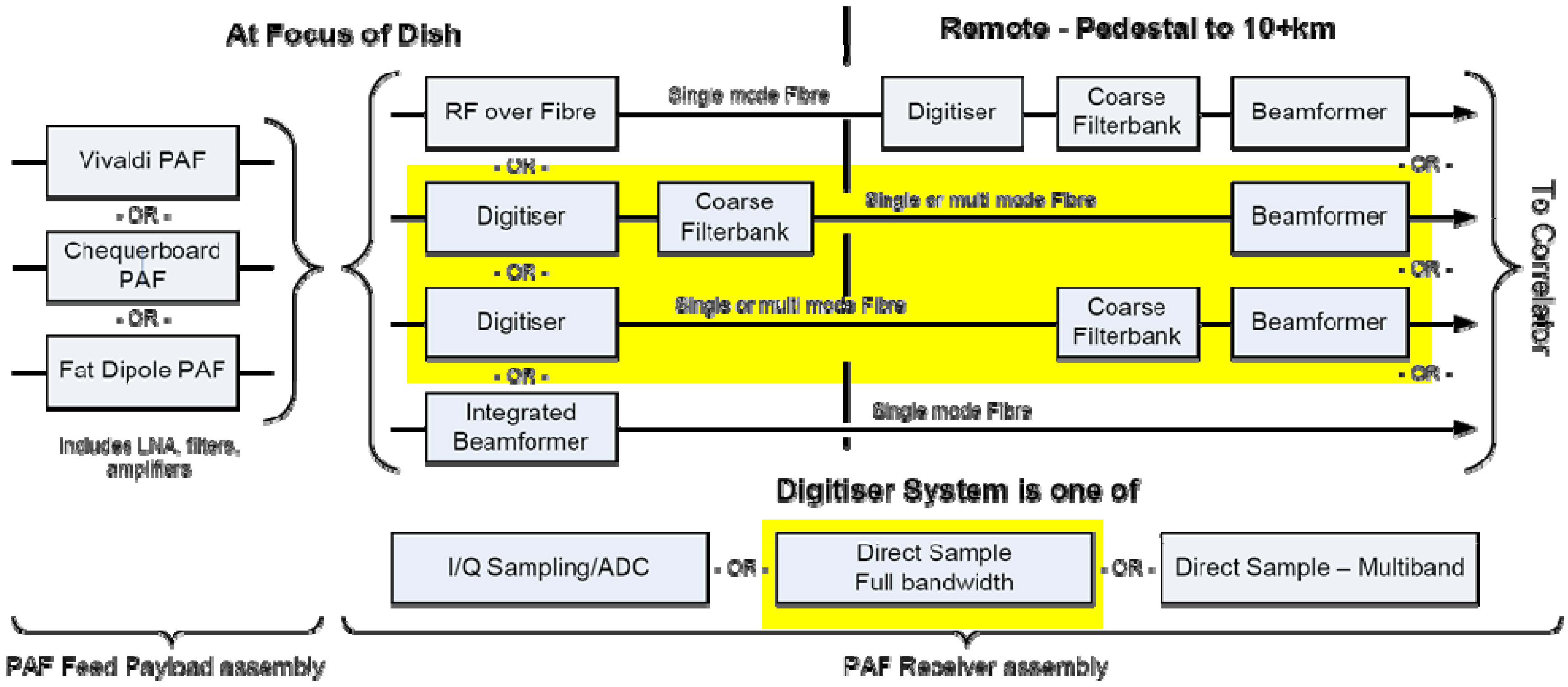
Possible Receiver Architectures

Concept 2: Integrated IQ mixer architecture

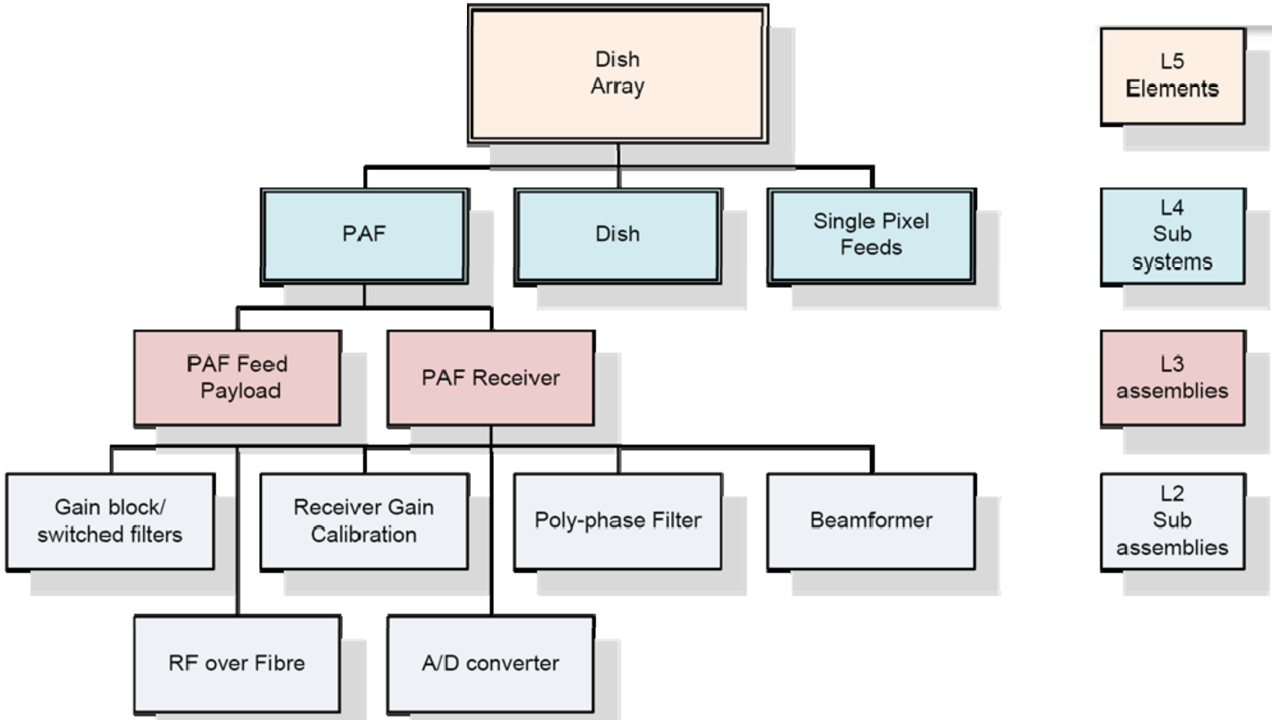


Possible Receiver Architectures

Concept 3: Wide-band direct sampling



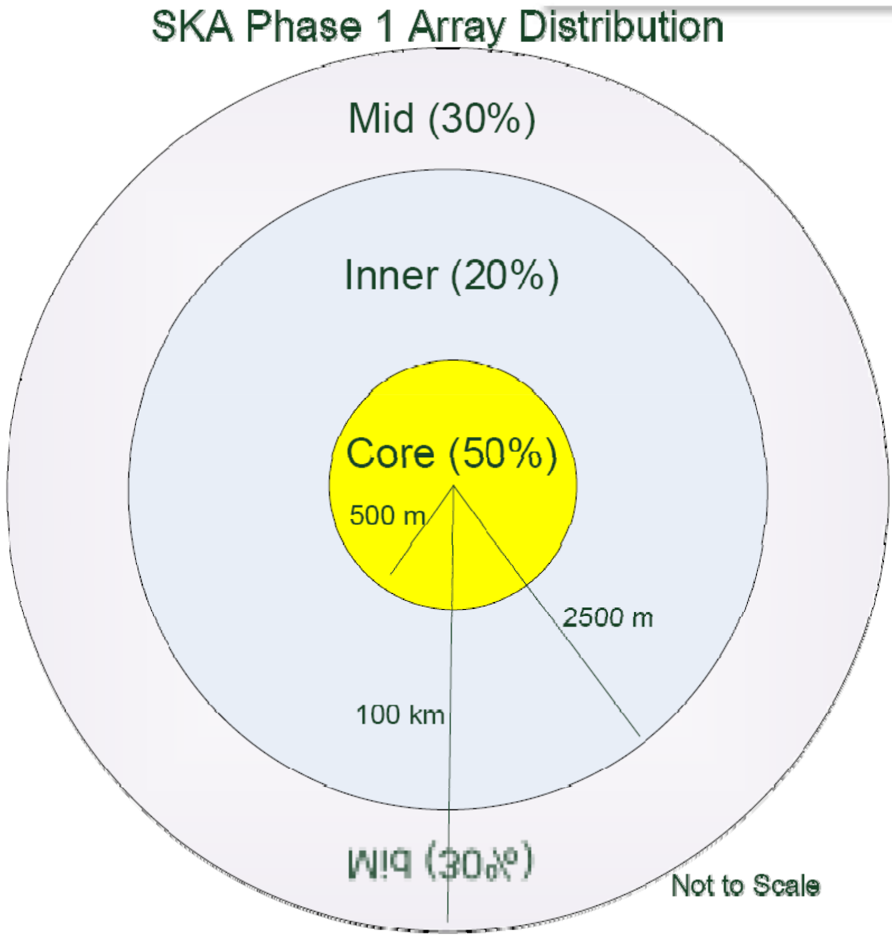
PAF Receiver assembly Concept 1: RF-over-fibre signal transmission



- Allows digitisation to occur up to 10 km from the antenna.
  - Digitisation and digital processing of the signals from the antennas in the "core" and "inner" regions (for SKA Phase 1) could be at the central site;
  - for antennas in the "Mid" region, the digitisation and digital processing of signals from one or more "clusters" of antennas could be centralised in RFI shielded "nodes" and the resulting data trunked to the central site.

SKA Phase 1 Array Distribution (Memo 130)

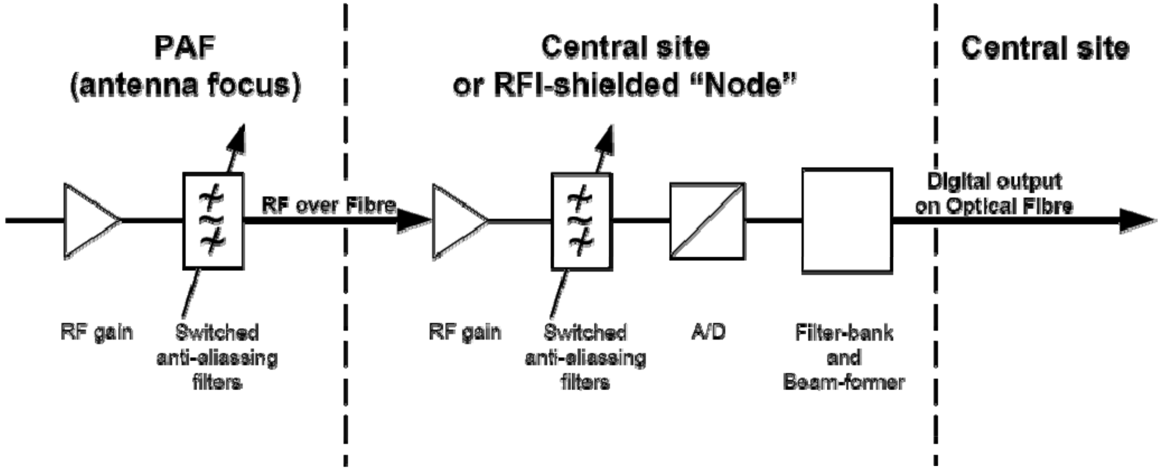
- 250 dishes total;
  - 175 in the core and inner regions,
  - 75 in the mid region.
- In the core and inner regions
  - Dishes are <2.5 km from centre
- In the mid region
  - (~200 km dia.)
  - there are 5 dishes per cluster
  - there are 15 clusters.



PAF Receiver assembly Concept 1: RF-over-fibre signal transmission

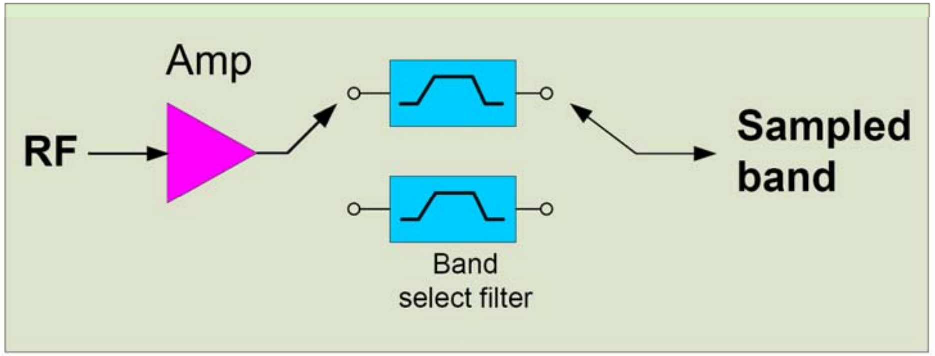
PAF receiver assembly concept includes the following components:

- A set of two switched anti-aliasing filters to cover the whole 600 – 1500 MHz RF band,
- Transmission of the RF over fibre to the Analog-to-digital conversion block,
- Gain calibration to correct for minor variations in gain and phase of the RF channels,
- Analog-to-digital conversion using the EV8AQ160 or similar,
- Digital processing in the Filterbank/Beamformer, and
- Digital transmission within the Filterbank/Beamformer using optical fibre.



PAF Receiver assembly Concept 1: RF-over-fibre signal transmission

- Cost competitive RF over Fibre systems are currently limited to at most octave bands due to second order intermodulation.
- The PAF covers more than an octave so this requires sub-octave band filters after LNA and RF amplification in the PAF



RF Band	RF Band (MHz)	RF Bandwidth (MHz)	Sample rate (MS/s)
Band 1	600 – 1000	400	1100
Band 2	900 – 1500	600	1650

RF Band	RF Band (MHz)	RF Bandwidth (MHz)	Sample rate (MS/s)
Band 1	600 – 1100	500	2500
Band 2	900 – 1500	600	1650

PAF Receiver assembly Concept 1: RF-over-fibre signal transmission

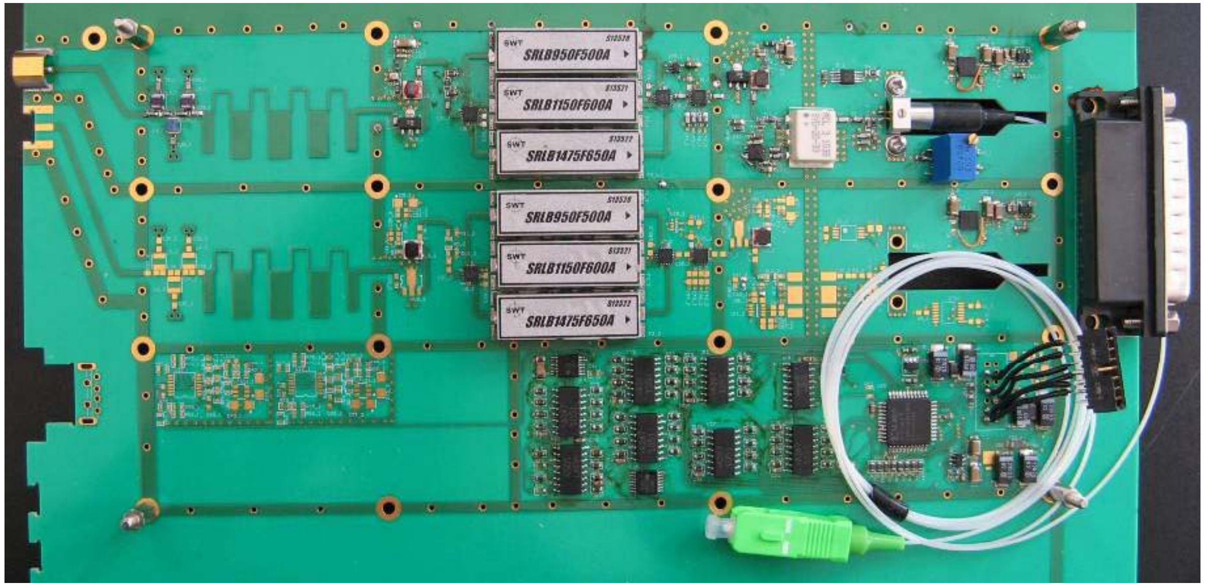
- Single mode transmission of RF requires
  - good Optical Return Loss (ORL),
  - low back reflection connectors.
- Mass termination Multiple Parallel Optical (MPO) connectors are preferable.
  - Can be used in 12 wide MPO configurations with Angled Physical Contact (APC) high ORL ~ 60 dB (designed for single-mode ribbon fibre).
  - Multiple MPO connectors can be mounted in the same connector shell making for rapid field replacement of the PAF.
- Single mode fibre loose tube could also be used

  (rather than newer ribbon fibre based distribution)

PAF Receiver assembly Concept 1: RF-over-fibre signal transmission

- Technical Progress to date
  - Gain block sub-assembly with switched filters
    - 2-channel prototype gain block subassembly
    - with 3 switched filters for the ASKAP RF band: 700 – 1800 MHz
    - 300 MHz band overlap

RF Band	Frequency range
Low band	700 – 1200 MHz
Mid band	850 – 1450 MHz
High band	1150 – 1800 MHz

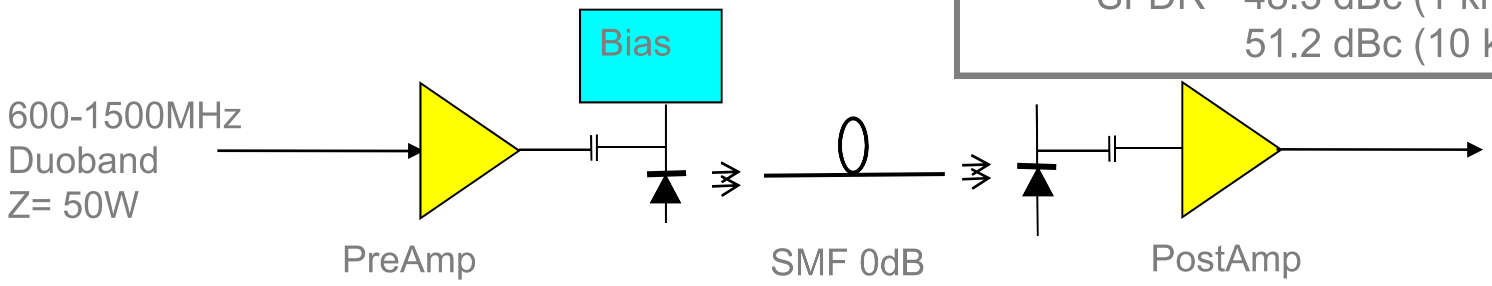


PAF Receiver assembly Concept 1: RF-over-fibre signal transmission

- Technical Progress to date
  - RF over fibre sub-assembly

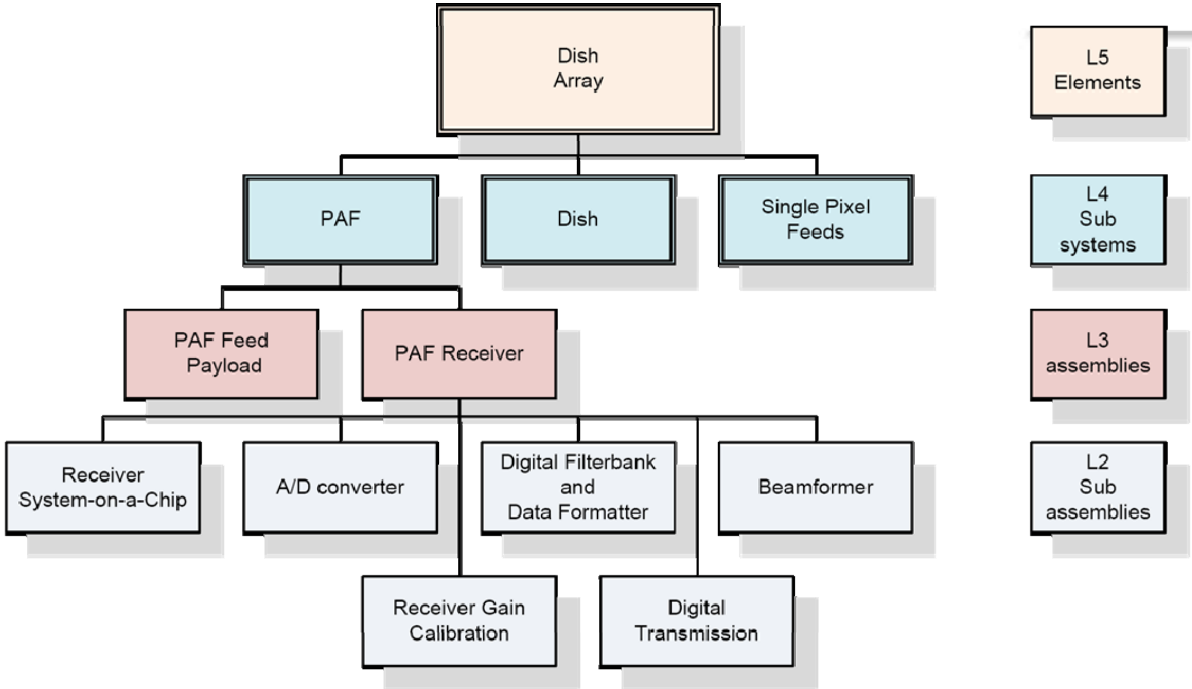
Link NF	< 2 dB
SFDR	> 110 dB.Hz [2/3]
Link Gain	> 18 dB
Flatness	+/- 1 dB

Gain	21.5-26.1 dB
NF	1.6 to 2.4 dB (band average)
IP2	6 dBm
IP3	-12.8 dBm
1dB gain compression	-20 dBm
SFDR	47.9 dBc (1 meter fibre), 48.3 dBc (1 km fibre), 51.2 dBc (10 km fibre)



	Band 1 (700-1200MHz)		Band 2 (850 to 1450MHz)		Band 3 (1150 to 1800MHz)	
Optical power at receiver	**Gain (dB)**	**Noise Figure (dB)**	**Gain (dB)**	**Noise Figure (dB)**	**Gain (dB)**	**Noise Figure (dB)**
-0.1dBm	20.84	1.63	20.05	1.92	19.56	2.56

PAF Receiver assembly Concept 2: Integrated IQ mixer architecture



- Allows digitisation of the received signals at the antenna and the beamformer digital processing to occur up to 10 Km from the antenna
  - Beamforming of the signals from the antennas in the “core” and “inner” regions (for SKA Phase 1) could be at the central site;
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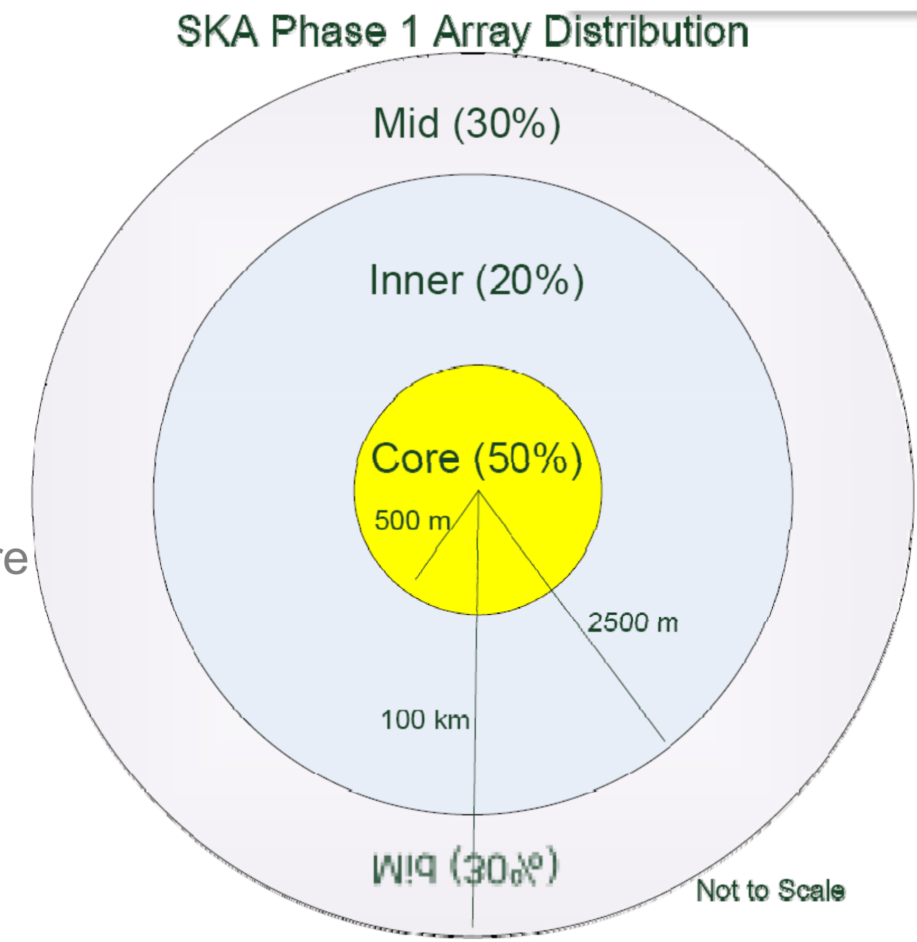
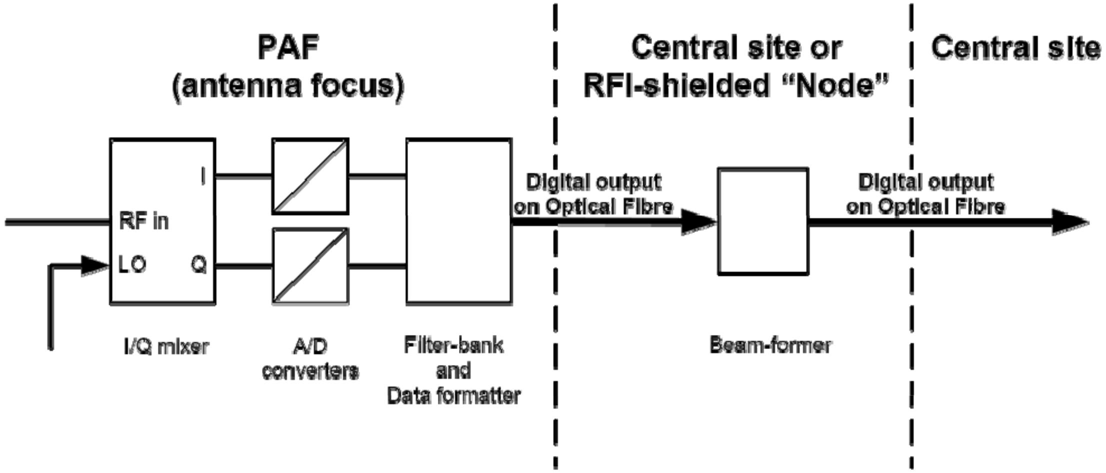


PAF Receiver assembly Concept 2: Integrated IQ mixer architecture

PAF receiver assembly concept includes the following components:

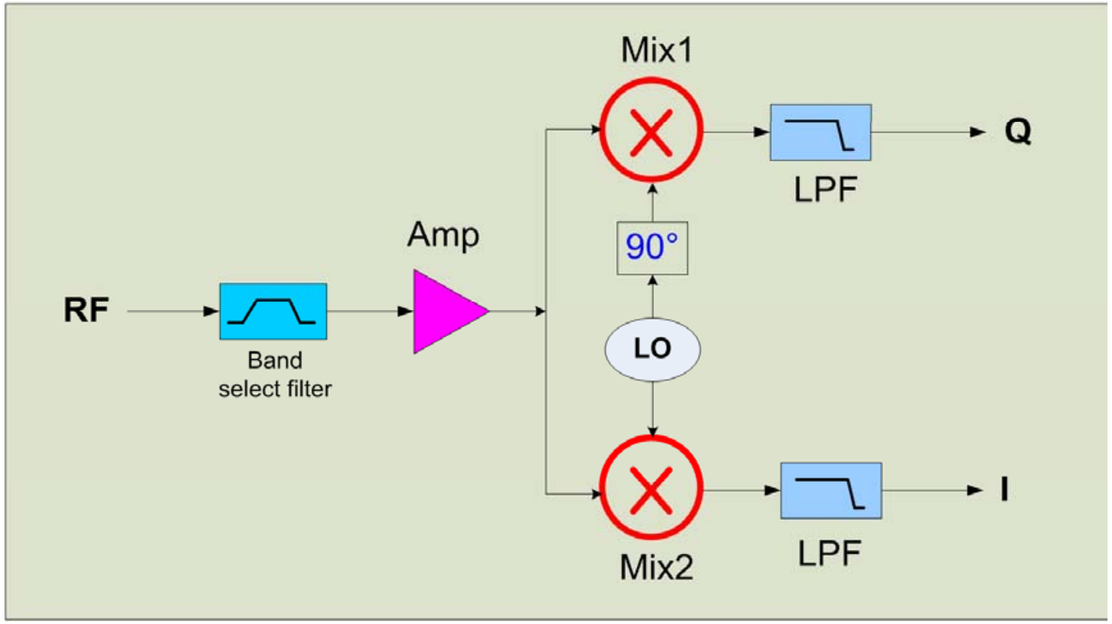
- An integrated "Receiver System-on-a-Chip" that includes RF gain, RF filters, I/Q direct quadrature down conversion, IF gain and anti-aliasing filters.
- Analog-to-digital conversion using the EV8AQ160 or similar,
- Gain calibration to correct for minor variations in gain and phase of the RF channels,
- Digital Filterbank signal processing and data formatting for transmission to the Beamformer.
- Transmission of the Filterbank digital output to the Beamformer over optical fibre,
- Digital processing in the Beamformer, and
- Digital transmission within the Beamformer using optical fibre.



PAF Receiver assembly Concept 2: Integrated IQ mixer architecture

Critical System-on-a-chip specifications are:

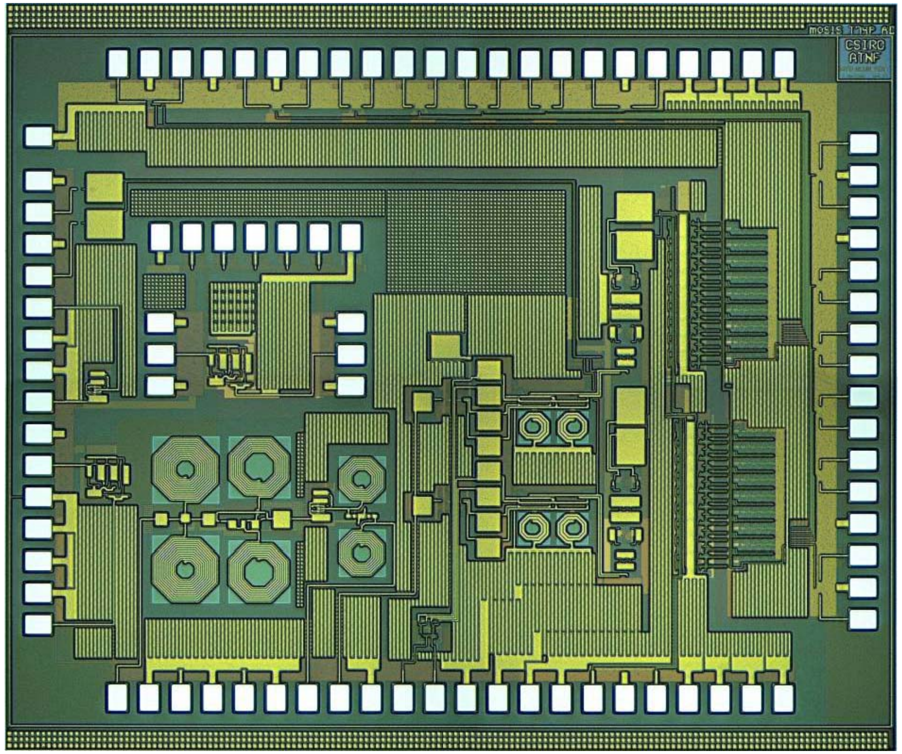
- 600 MHz to 1500 MHz RF range.
- Onboard RF filters: 600 MHz HP and 1500 MHz LP.
- 2 dB input noise figure.
- I/Q direct quadrature down conversion
  - 600 MHz instantaneous bandwidth
  - 2 x 450 MHz anti-aliasing filters,
- Tight I/Q amplitude and phase matching
- Onboard LO synthesiser and ADC driver.
- RF and broadband gain adjustment:
  - 15 – 40 dB RF gain range, 5 dB steps.
  - 8 – 20 dB BB gain range, 2 dB steps.



PAF Receiver assembly Concept 2: Integrated IQ mixer architecture

- Technical progress to date
  - RF-CMOS proof-of-concept development

RF frequency range	200 MHz – 2000 MHz
RF filters	300MHz - 1800MHz or 500MHz - 1800MHz
Instantaneous bandwidth	300MHz
Dynamic range >	30 dB (6 bit on-board ADCs)
RF input noise figure	2 dB (180K Tn)
RF gain	30 dB
Baseband gain	10 dB
I/Q mismatch	< 1 degree and 0.1 dB (35 dB image suppression)

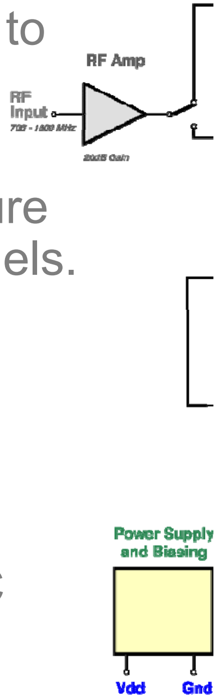


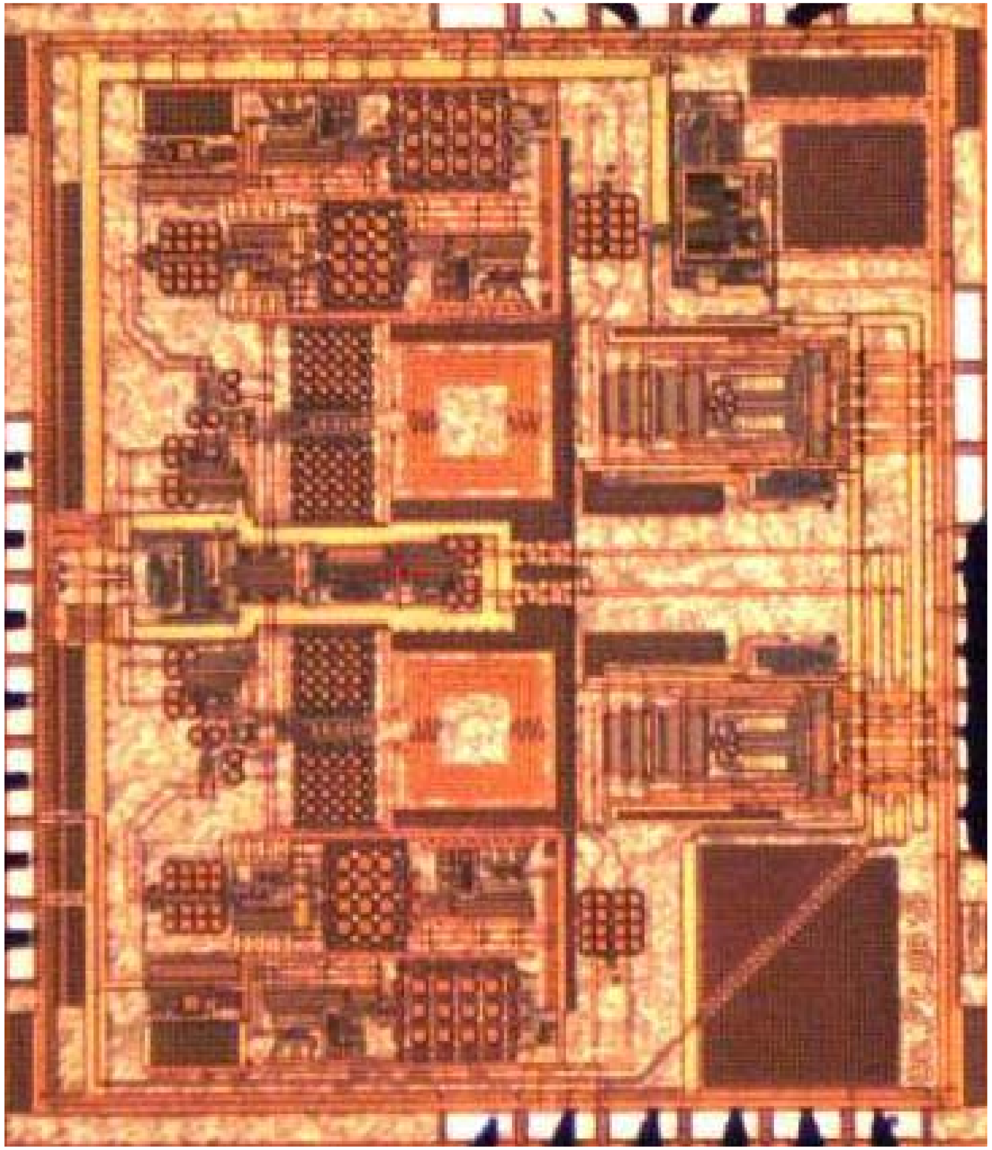
PAF Receiver assembly Concept 2: Integrated IQ mixer architecture

- Technical progress to
  - Silicon-on-sapphire inte

The critical Silicon-on-sapphire chip sp

- RF tuning range 200 MHz to 2000 MHz range.
- 300 MHz instantaneous bandwidth, using quadrature 150 MHz baseband channels.
- Integrated quadrature LO generator
- 14 dB of baseband gain adjustability in 2 dB steps,
- Integrated differential ADC driver.

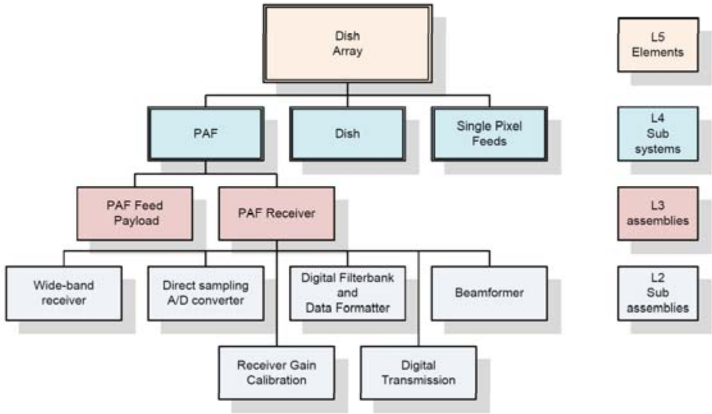


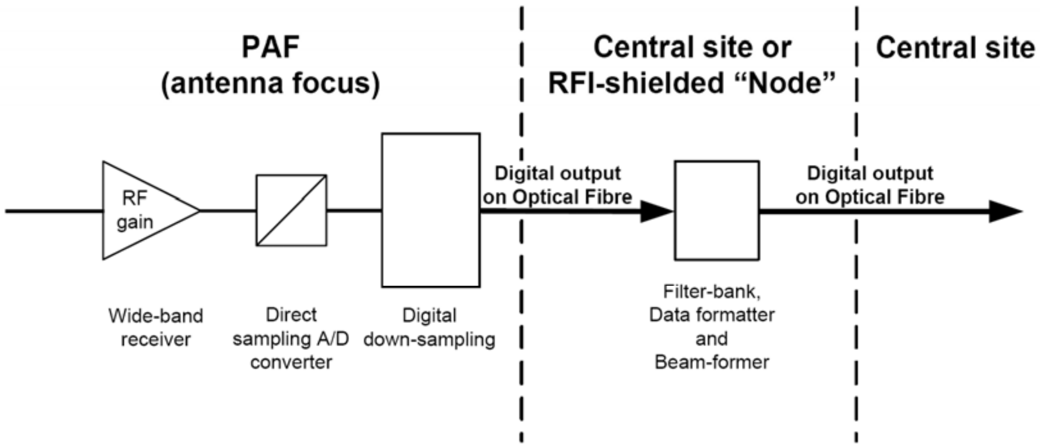


PAF Receiver assembly Concept 2: Integrated IQ mixer architecture

- Plans for further development
  - Receiver broadbanding
    - to increase the instantaneous bandwidth by developing anti-aliasing filter with a cutoff frequency of 450 MHz
  - On-chip PLL for LO generation
    - Tuning range: 1000 MHz to 1100 MHz.
    - Harmonics of the synthesiser to be suppressed by -40 dBc.
    - Spurs to be suppressed by -80 dBc.
    - Phase noise at 10 KHz offset < -90 dBc.
    - Reference input: 16 MHz, differential 100 ohm input.
  - System integration
    - The current silicon on sapphire I/Q receiver will be integrated into a full receiver system making use of existing ASKAP PAF hardware wherever possible.
  - RF circuitry
    - Complete system-on-chip design by including:
      RF gain stages, RF filters, RF switches and attenuators

PAF Receiver assembly Concept 3: Wide-band direct sampling



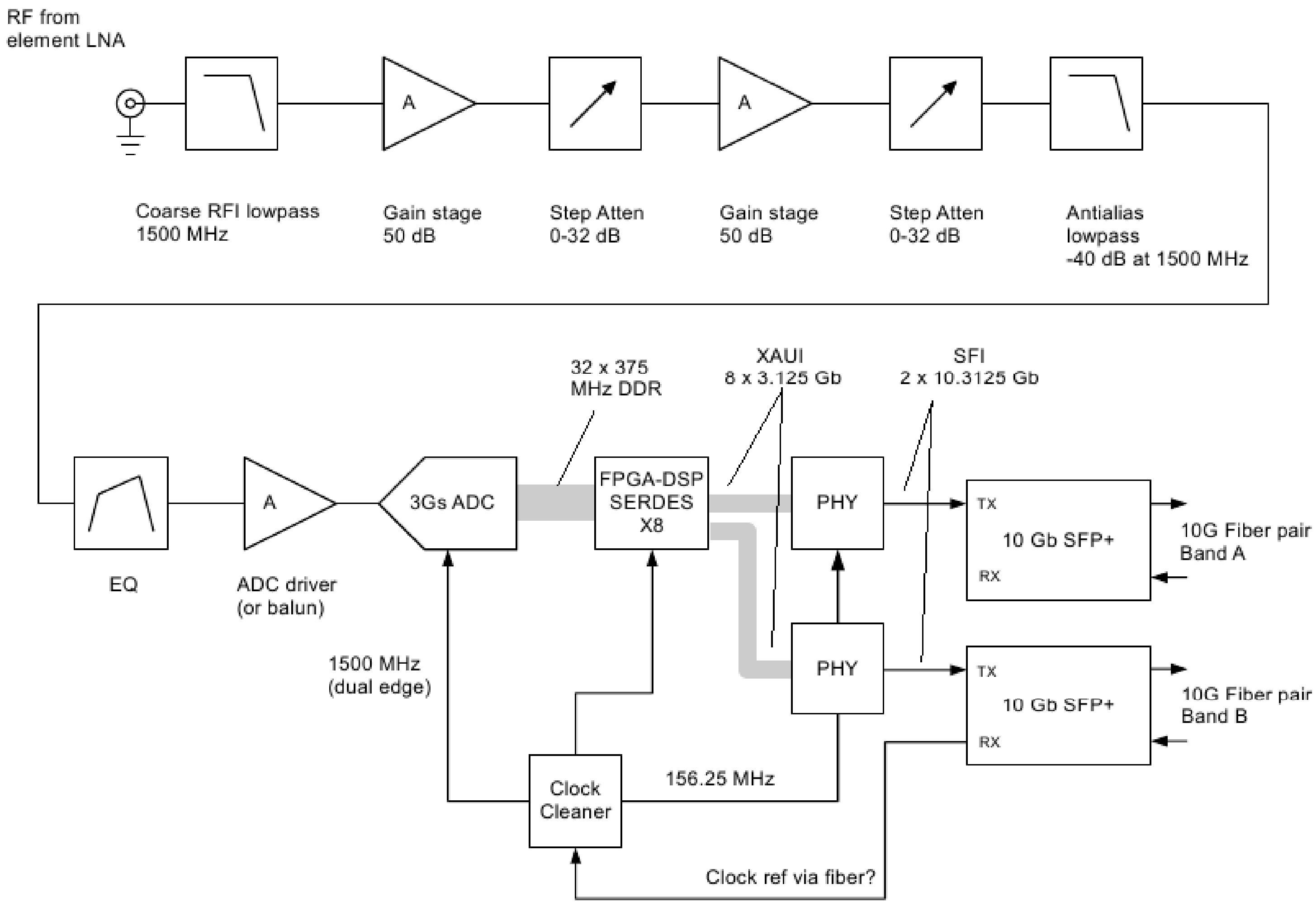


PAF Receiver assembly Concept 3: Wide-band direct sampling

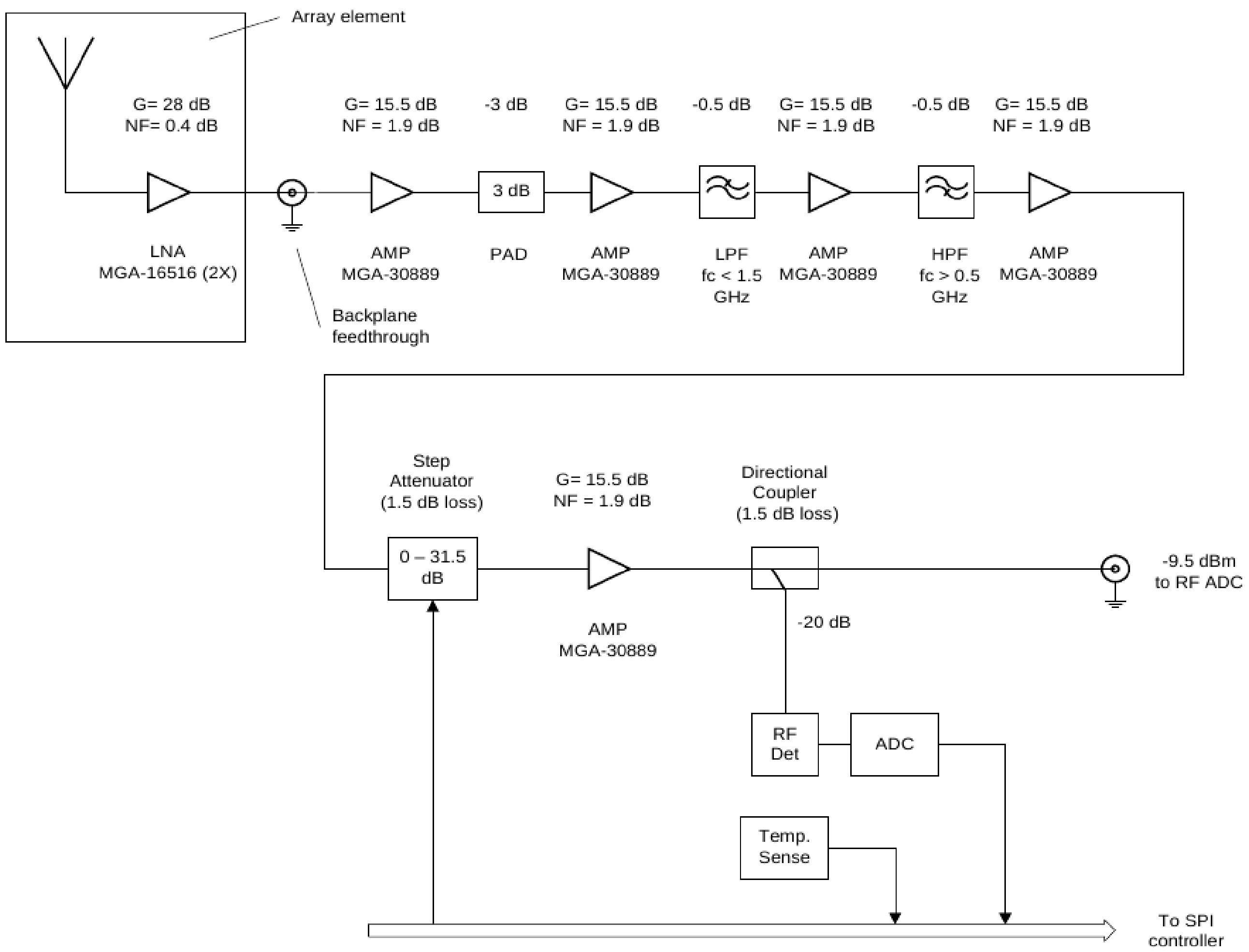
Introduction

- Amplify and filter are the only analogue functions in the signal chain
- No frequency conversions
- Sample at signal frequency
- Further filtering and frequency shifting applied in digital domain
- Much like “Software-Defined Radio”
- Appropriate at L-band
- Decreasing costs make this technique viable

PAF Receiver assembly Concept 3: Wide-band direct sampling

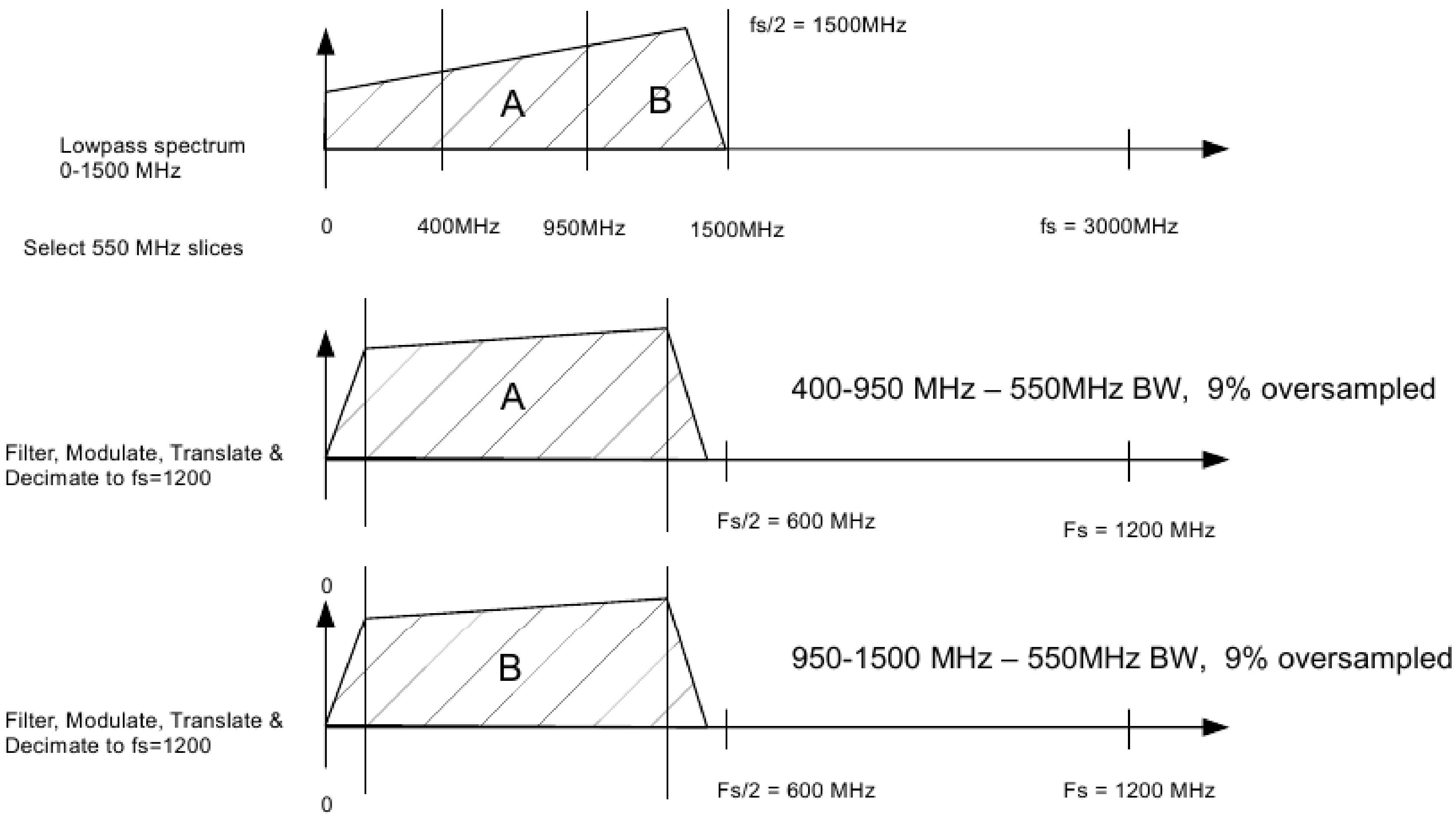


PAF Receiver assembly Concept 3: Wide-band direct sampling



Exploring the Universe with the world's largest radio telescope

PAF Receiver assembly Concept 3: Wide-band direct sampling



PAF Receiver assembly Concept 3: Wide-band direct sampling

Advantages

• Minimise number of analogue components
⇒ reduce time-varying effects
⇒ improve stability
• Reduced complexity compared with conventional rx
• Avoid up/down conversions with super-het
• Eliminate local oscillators
• ADC clock is fundamental frequency reference

PAF Receiver assembly Concept 3: Wide-band direct sampling

Disadvantages

• Currently too expensive but this should change
• Shielding effectiveness critical because input and output signals in RF chain at same frequency

PAF Receiver assembly Concept 3: Wide-band direct sampling

Example: AFAD receiver system

- Frequency range ~700–1500 MHz
- ADC: National Semiconductor ADC083000 8-bits @ 3 GS/s
- Lattice ECP3-95EA FPGA to filter/extract 500 MHz bands
- One 10 GS/s optical fibre per band to beamformer
- Total cost ~$1900/element (2011)
- Power ~12W/element (2011)

		RF	Digital	Optical
Trend	Cost	10%	70% ↓	20%
Trend	Power	15%	50% ↓	35%

PAF Receiver assembly Concept 3: Wide-band direct sampling

SQUARE KILOMETRE ARRAY

Technology Trends

- Analogue/RF: little change in cost or performance
- Analogue/RF: higher degree of integration

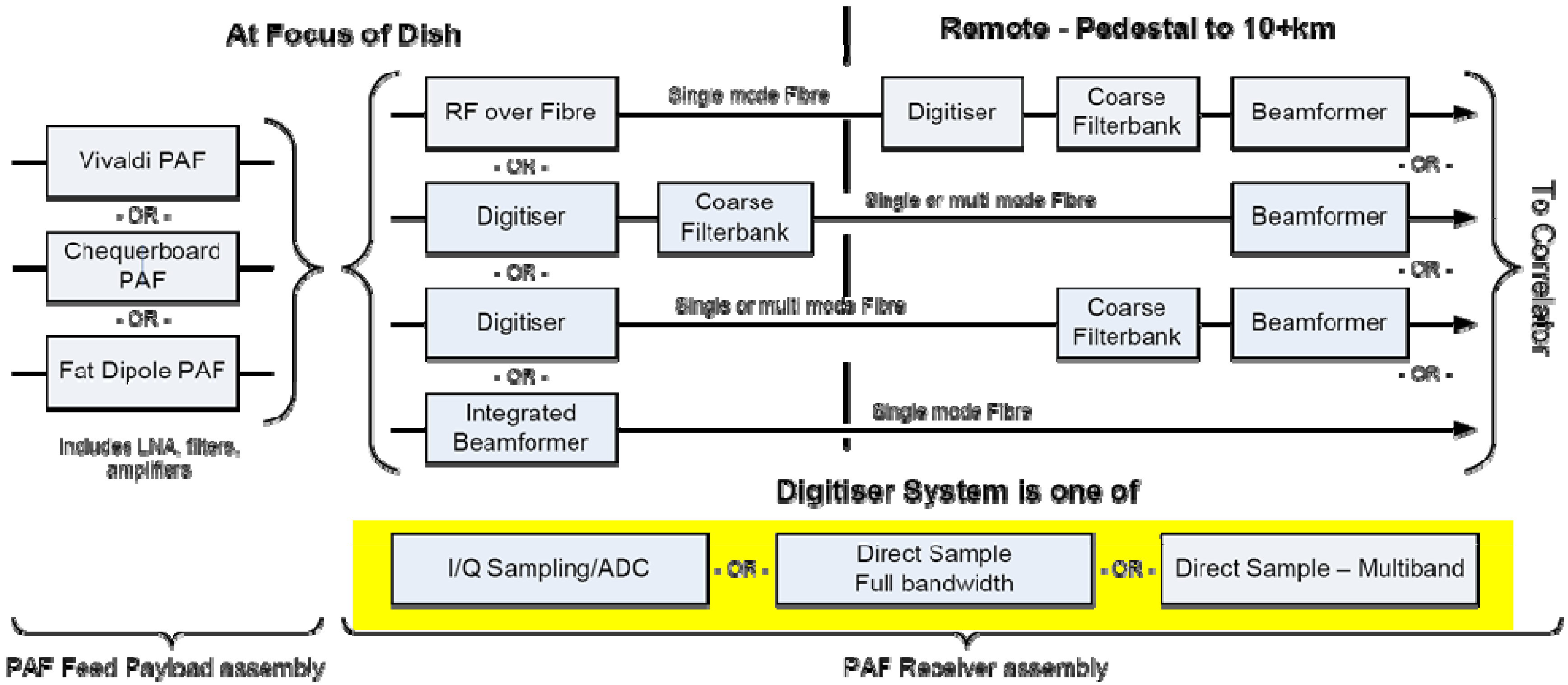
- Optical: trend to lower cost

- Digital: Reduction in cost with increase in clock speed
- Digital: Higher levels of integration in ADC
- Digital: ADCs with power consumption ~10 to 100 mW
- Digital: FPGAs with integrated 10G transceivers so that external PHYs no longer required

Receiver gain calibration sub-assembly

- Uses noise radiated from the dish surface or rim
  - To measure and track the relative complex gains of the individual receiver channels
    - from the low-noise amplifier through to the digitiser.
  - A sample of the radiated noise
    - is also digitised using a spare channel of the receiver.
    - is correlated with the output of each of the RF channels
      - to measure and track the relative complex gains of the individual receiver channels.
  - Relative complex gains of the individual receiver channels
    - used to compensate for channel gain and phase variations
    - by adjusting the weights fed to the beamformer

Analog-to-Digital Conversion



Analog-to-Digital Conversion

- ADC requirements
  - Usual suspects ENOBs, SFDR, SNR, INL, etc.
  - RF bandwidth (and gain flatness)
  - Sample rate typically GSPS, depends on many factors:
    - Desired bandwidth, multiple bands
- "System" costs also a driver!
  - Not only ADC but signal processing costs
    - Faster ADCs require more DSP (filterbanks)

Available ADCs 2011

- GSPS ADCs are not common place
  - Few vendors (growing)
  - Volume low in commercial world (growing)

- Interleaving ADCs to get higher speeds?
  - Calibration and dynamic performance issues

- Possible candidate:
  - NatSemi 12-bit, 1.6GSPS, 2W, 1.9V, RFBW 2.8GHz, ~few $100, 2 per package

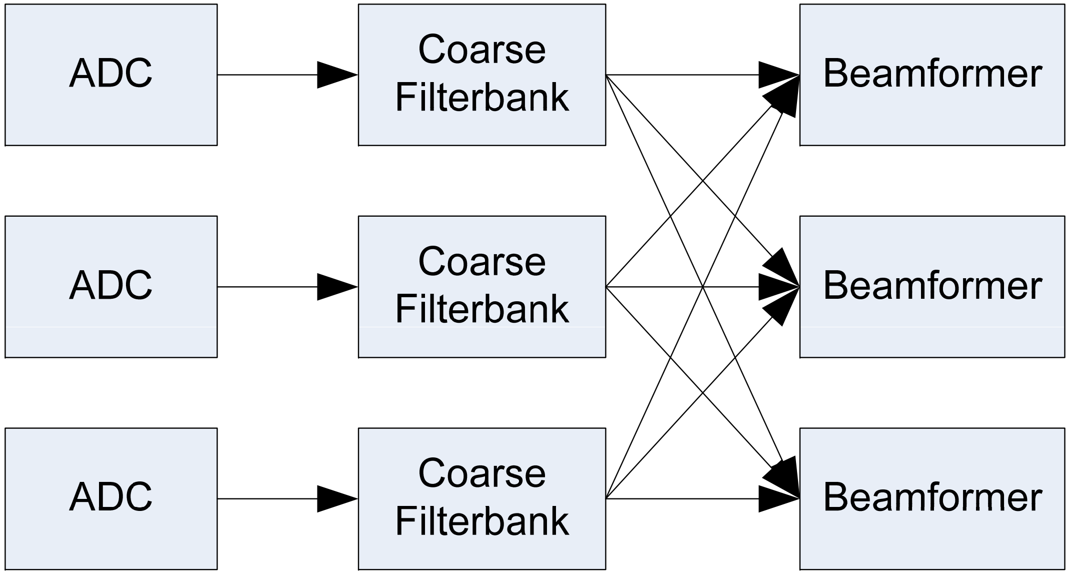
Digital Filterbanks

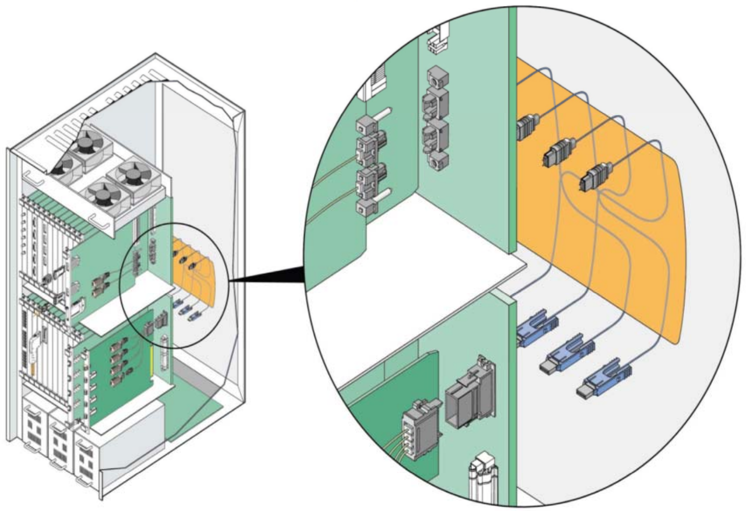
- After the analogue data is digitised it is processed by a Digital Filterbank
  - Divides input BW into finer sub-bands
  - Frequency selection occurs
    (not all data processed by beamformer)

- Each filterbank is ultimately connected to each of the beamformer boards
  - For N beamformer boards each connection carries data for 1/Nth the frequency channels

Optical Cross-connect

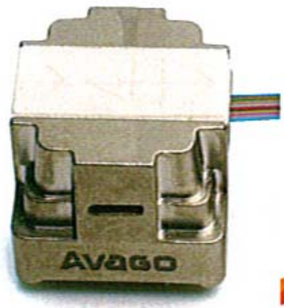
- For the Phase 1 SKA beamformer, multiple processing boards are needed for the beamformer and a cross connected beamformer is used
  - Optical cross connect requires less power, has lower EMI, longer distances than copper, faster data rates

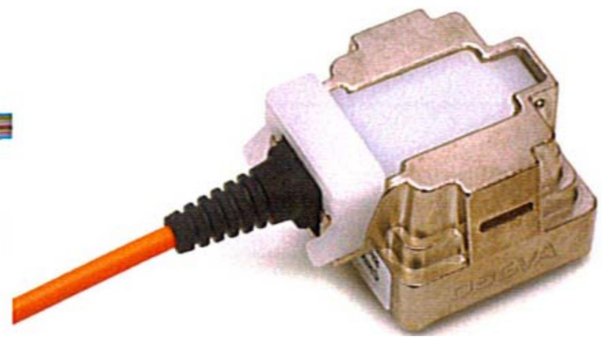




Digital Communications

- Low cost short spans with multi-mode ribbon fibre and parallel optical modules
  - Avago Minipod, ~$3/Gbps, 50mW per channel





- For distances up to 10 km (central site to the “core” and “inner” regions (for SKA Phase 1) use single-mode fibre and SFP+ modules
  - 1W per channel, much larger form factor, ~$16/Gbps

Digital Beamforming

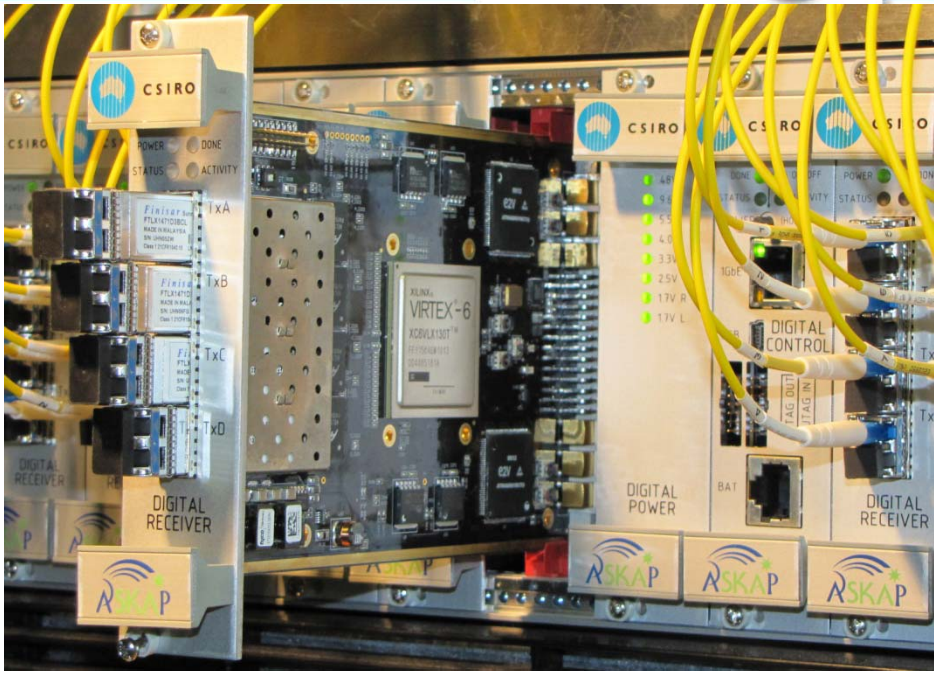
- Beamformer core is FPGAs
  - Using larger FPGAs requires fewer FPGAs
  - FPGAs achieving better balance of IO and processing
  - Number of FPGAs per board needs to be reasonable
    - Larger PCBs are more expensive
  - Low number of FPGAs – ASIC NRE costs too high
- Need to watch system costs
  - FPGAs themselves are not super expensive items
  - FPGA support important – the hidden costs
    - PCBs, assembly, power, connectors, control and monitoring, system packaging, metal work

Beamforming Computations

- Beamformer based on CMAC
  - CMAC = complex multiply accumulate
  - Computations proportional to bandwidth, number of PAF ports, number of beams
  - Frequency resolution at beamforming is ~1MHz
- Hidden items
  - Data communications – major cost
  - Array covariance matrix for calibration
  - External memory controller required – added processing
    - Enables Fine filterbank and transient buffer
  - Coarse delay and fringe stopping
  - Control and monitoring

ASKAP ADC & Filterbank Example

- Dragonfly-2 (2010)
  - 4-ports per board
  - 768MSPS IF sampling
  - SFP+ outputs
  - ~$700/input



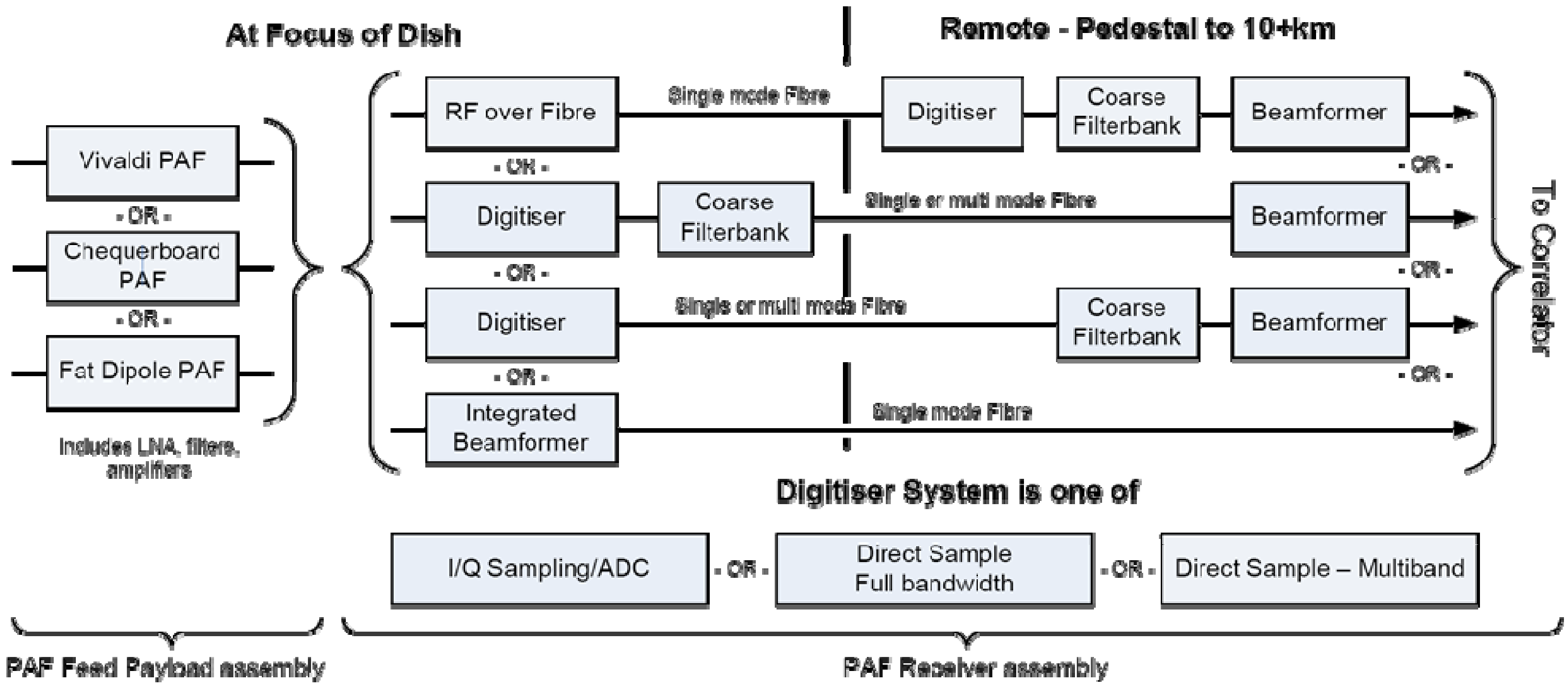
- Dragonfly-3
  - 16-ports per board, 1536MSPS RFOF Sampling, parallel optical outputs, 2-V7 FPGAs
  - ~$700/input (including RFOF receiver)
- Cost is neutral even with double BW and RFOF!

ASKAP Beamformer (& Correlator) Example

- Redback-2 (2010) (~$13/MHz-Beam)
  - – 4-V6 FPGAs per board, ATCA form factor, 16-boards + 16 optical RTMs to receive Dragonfly-2 outputs

- Redback-3 (~$6/MHz-Beam)
  - – 6-V7 FPGAs per board, 6-boards, parallel optics on board, 1U “ATX” motherboard form factor
- Half the cost – 2014 Redback-4 could halve again!

Summary of PAF Receiver Concepts



Summary of PAF Receiver Concepts

Analog

RF-over-fibre

- Is viable now
- And is currently being investigated for implementation in ASKAP

Integrated IQ mixer architecture

- Has much promise but needs to be demonstrated

  The challenges are:
  - NRE associated with integrated circuit development
  - Digitising in the receiver package

Wide-band direct sampling

- Should be seen as the ultimate solution
  - It will potentially enable observations that encompass the whole RF bandwidth

The receiver concepts presented here are at varying levels of technological readiness.

- They will become more mature as time progresses
- The choice of receiver concept depends, ultimately, on the affordable digital processing bandwidth

Summary of PAF Receiver Concepts

Digital

- Cost analysis of sampled BW
  - Power needs to be investigated and compared with other schemes
- Largest data rates should go shortest distance
  - Optical backplanes have significant advantages
- Beamformer is not only beamforming
  - Many other “bits” of firmware required
  - Larger FPGAs require less interconnections
- Next generation hardware reduces cost significantly
  - Keep the development path alive!

Thank you