Large-N Correlators for SKA

Speaker: Roger Capallo, MIT Haystack Obs.
Large - N Correlators
for SKA

~ or ~

"How much Moore can we expect?"

Roger Cappallo
MIT Haystack Observatory
29 February, 2000
## International Technology Roadmap

(1999 edition – SEMATECH)

<table>
<thead>
<tr>
<th>Year</th>
<th>Line Widths (nm)</th>
<th>ASIC trans/chip (Millions)</th>
<th>ASIC local freq (MHz)</th>
<th>ASIC Cross-chip freq (MHz)</th>
<th>DRAM size (Gb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>180</td>
<td>160</td>
<td>1250</td>
<td>500</td>
<td>1.1</td>
</tr>
<tr>
<td>2002</td>
<td>130</td>
<td>432</td>
<td>2100</td>
<td>700</td>
<td>3</td>
</tr>
<tr>
<td>2005</td>
<td>100</td>
<td>1064</td>
<td>3500</td>
<td>900</td>
<td>6.1</td>
</tr>
<tr>
<td>2008</td>
<td>70</td>
<td>2624</td>
<td>6000</td>
<td>1200</td>
<td>24</td>
</tr>
<tr>
<td>2011</td>
<td>50</td>
<td>6488</td>
<td>10000</td>
<td>1500</td>
<td>69</td>
</tr>
<tr>
<td>2014</td>
<td>35</td>
<td>16000</td>
<td>13500</td>
<td>1800</td>
<td>194</td>
</tr>
</tbody>
</table>

- note: Mark 4 correlator chip uses ~700K transistors to implement 512 lag registers and 8 delay & phase trackers, at a max. 64 MHz clock rate


**Historical Extrapolation**

- **Moore's Law** (variation #17): *The cost per given IC function is halving every 18 months.*

- Moore's Law was based on observations of the mass-market for IC's, but a similar relationship seems to hold for radio-astronomy correlators as well.

- chip **density** increasing at 1 order of mag / 7 years, doubling each 25 months.

- chip clock **speed** increasing at 1 order of mag / decade, doubling every 36 months.

- **speed \times density** doubling time is only 15 months, but is offset by increasing cost / chip, resulting in Moore's 18 months.

- in comparing correlators, a useful **figure of merit** is the number of lag operations (multiply & accumulate) per second.
Correlator Throughput Comparison

**Mark 3**
- 84 boards
- 1 baseband pair / board
- 8 complex lags / baseband pair
- 4 Ms / s (1 bit / sample)
- $5.4 \times 10^9$ lag_ops / s

**Mark 4**
- 16 boards
- 128 baseband pairs / board
- 64 complex lags / baseband pair
- 32 Ms / s (VLBI mode)
- $8.4 \times 10^{12}$ lag_ops / s ($\equiv 1600 \times \text{Mk3}$)

**SMA**
- same custom correlator IC and board as Mark 4
- 96 boards
- 16384 real lags / board
- 53 Ms / s
- $8.3 \times 10^{13}$ lag_ops / s ($\equiv 10 \times \text{Mk4}$)
Correlator Throughput Comparison
(cont’d.)

ALMA (Preliminary Design Review)
- 64 antennas = 2016 baselines
- 8 2-GHz basebands / antenna
- 4 Gs / s
- 2048 real lags / bb-pair for 1 bb, 1 pol, 2GHz BW
- 128 lags for 8 bb’s, & full polarization
- optional cross polarization
- $1.7 \times 10^{16}$ lag_ops / s ($\equiv 200 \times$ SMA)

SKA Strawman
- 1000 stations $\rightarrow$ $5 \times 10^5$ baselines / tertiary beam
- 4 Gs/s (2 GHz BW)
- 64 complex lags / baseline (at full BW w/ cross-pol.)
- 12800 lags at 10 MHz BW w/o polarization; yielding 1.6 KHz res.= 0.08 km/s at 6 GHz
- 2 bit / sample
- 3 tertiary beams
- optional cross polarization
- $1.5 \times 10^{16}$ lag_ops / s ($\equiv 90 \times$ ALMA)
## Correlator Throughput Summary

<table>
<thead>
<tr>
<th></th>
<th>Mark 3</th>
<th>Mark 4</th>
<th>SMA</th>
<th>ALMA</th>
<th>SKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>stations</td>
<td>8</td>
<td>16</td>
<td>8</td>
<td>64</td>
<td>1000</td>
</tr>
<tr>
<td>baselines</td>
<td>28</td>
<td>120</td>
<td>28</td>
<td>2016</td>
<td>499500</td>
</tr>
<tr>
<td>boards</td>
<td>84</td>
<td>16</td>
<td>96</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>basebands/board</td>
<td>1</td>
<td>128</td>
<td>128</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>basebands</td>
<td>84</td>
<td>2048</td>
<td>12288</td>
<td>16128</td>
<td>499500</td>
</tr>
<tr>
<td>lags/baseband</td>
<td>8</td>
<td>64</td>
<td>128</td>
<td>128</td>
<td>64</td>
</tr>
<tr>
<td>counters/lag</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>speed (Msamp/s)</td>
<td>4</td>
<td>32</td>
<td>53</td>
<td>4000</td>
<td>4000</td>
</tr>
<tr>
<td>bits/sample</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>polarization products</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>correlator beams</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>throughput (lag_ops/sec)</td>
<td>5.4E+09</td>
<td>8.4E+12</td>
<td>8.3E+13</td>
<td>1.7E+16</td>
<td>1.5E+18</td>
</tr>
</tbody>
</table>
Cost Projections

- marginal replication cost (excluding NRE)
- 2000 US dollars

**Mark 3**
- built in 1979
- 84 modules
- \(\approx $3K / \text{module}\)
- \(\approx $300K\) including rack & power supplies
- \(6 \times 10^{-5} \$ / \text{lag}_\text{op}\)

**Mark 4**
- built in 1997
- \(\approx $220K\) (16 corr. bds., 2 input bds., cntl. bd., rack, power supplies)
- \(\approx $480K\) for 16 station units @ \(\approx $30K / \text{SU}\) (omitting tape-related modules)
- \(\approx $700K\) system total
- \(8 \times 10^{-8} \$ / \text{lag}_\text{op}\)

**ALMA**
- to be built in \(~2006\)
- \(\approx $15M\) system total (PDR, Feb. 2000)
- \(8.8 \times 10^{-10} \$ / \text{lag}_\text{op}\)
Cost Projections (cont’d.)

**Mk 3 – ALMA comparison**

- 16.1 performance / price ratio doublings in 27 years
- = 1 doubling / 20 months
- **Moore’s Law** predicts 18 month doubling time for CPU’s (over the past 3 decades)

**Mk4/SMA → SKA extrapolation**

- assume manufacture in 2012
- assume 20 month Moore’s Law for Mk4/SMA→SKA
- extrapolated cost per function: $5 \times 10^{-11}$ $/ \text{lag_op}$
- extrapolated cost for strawman SKA: $75$ M
SKA Signal Hierarchy

(1 of N stations)

N ~ 1000

correlator array
Correlator Array with Optical Signal Distribution
Correlator Array Characteristics

- ~500K baselines are distributed through 64 correlator racks, each rack having about 8k baselines

- the 8k baselines to be correlated are half of the 16k product baselines in the off-diagonal racks

- the racks along the diagonal only have 8k baselines to correlate, since both sets of 128 signals are the same

- there are 256 optical fibers entering each rack, terminating directly on the appropriate circuit boards (perhaps through an optical backplane connector)

- in order not to duplicate the delay stages for correlator beam formation, the delay function(s) could take place at each station

- if the rack were comprised of 512 correlator chips, such as the Mark 4 rack, each chip would have to perform 4.5E13 lag_ops/s

- a 1 GHz ASIC correlator chip would need to have 45,000 lags, a factor of 90 greater than the Mark 4 chip.

- the 2011 projection for transistors/chip would predict the lag capacity to increase by a factor of 8000 (relative to the Mk4 chip), easily accommodating the increased number of lags
Comparison of FX and XF Correlators

- **XF correlators:** time samples are cross-correlated by baseline and (usually) summed in hardware (sec timescale), then Fourier transformed into cross-power spectra in software.

- **FX correlators:** time samples are Fourier transformed by station, the resultant transforms cross-multiplied (ms timescale) and summed.

- except for station deformatting and possibly fringe-rotation, XF correlators do everything for $\sim N^2 / 2$ baselines, while FX correlators do only $N$ FFT's, and $\sim N^2 / 2$ cross-multiplies.

- in FX correlators, there is no penalty for large spectra…

- …*but* FX correlators multiply data rate at FFT output by perhaps a factor of 32, increasing demands on signal routing.

- NRAO chose XF for the ALMA correlator, citing costs of interconnection and 2 custom chip designs (FFT, Xmult).

- DSP's will likely affect future decisions, though.
FX Strawman based on DSP’s

- year 2000 implementation using Analog Devices Tiger-SHARC (0.9 Gflop/s; 1024 pt. FFT in 69 µs; ~$150)

- need 270 TS’s per station-beam to do FFT’s (total 810,000)

- complex cross-multiply requires 5 TS’s per baseline-beam (total 7.5 x 10^6)

- current cost of 9 million TS’s: ~ $1300M!

- in 2012 Moore’s law predicts equivalent DSP cost of $5.2M in 12K chips
Conclusions

- Moore's law applies to correlator systems with a 20 month doubling time

- a 1000 station SKA correlator looks buildable, and economically feasible, albeit expensive

- in this decade, DSP's may become an attractive alternative to ASIC's, especially for FX correlators

- optical interconnection technology will probably be both necessary and sufficient

- control software to manage 500,000 baselines should employ many of us well into retirement!