Data Compression Techniques

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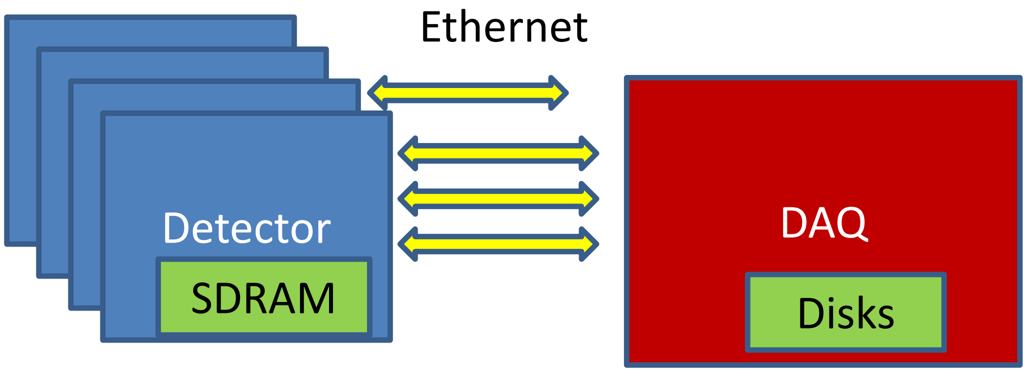
Need for compression

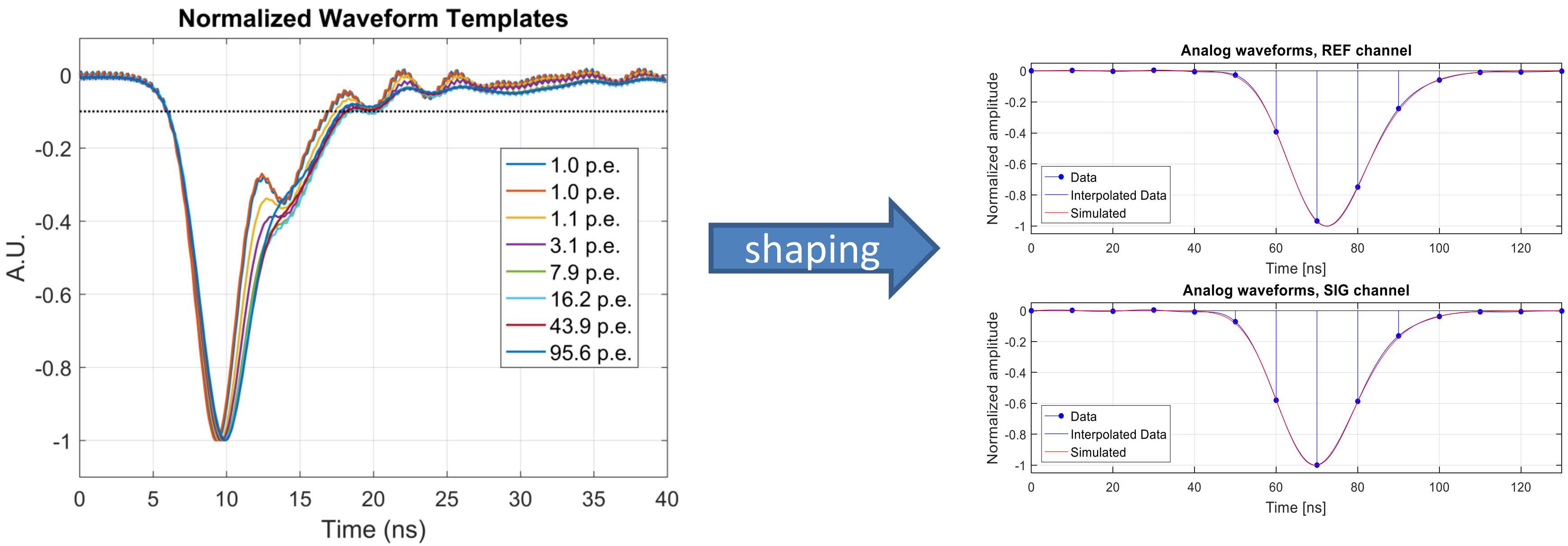
- Saving disk space for the archiving
- Limited bandwidth between detectors and the data acquisition system (DAQ)
- Saving RAM capacity in detector modules



- Constraints on resources and power

Input Signals

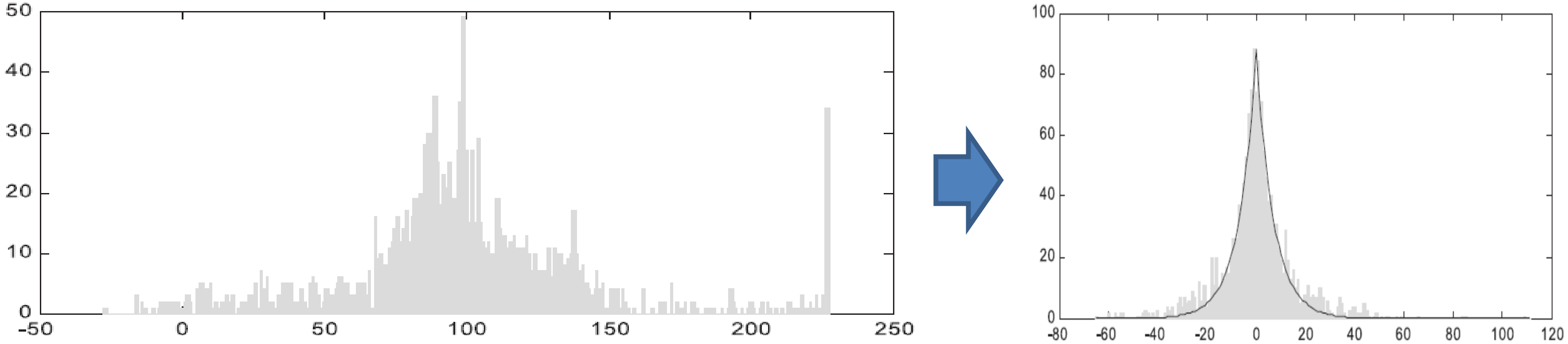
- Acquired PMT signals:
  - seems to be similar,
  - Stability is limited,
  - Shaping changes original signal from PMT.
- Allowable losses in processing should be small to preserve key signal features
- How strong is the correlation of signals from neighboring PMTs?

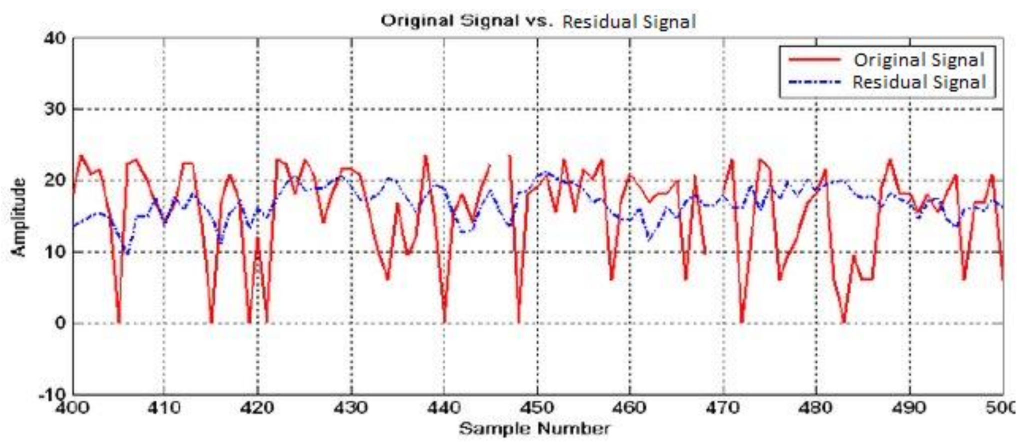


Compression Methods

- Modeling
  - Linear Prediction
  - Signal Models
  - Transforms
- Quantization
  - Scalar quantization
  - Vector quantization – using signal models
- Entropy Coding
  - Variable length coding
  - Arithmetic coding – more complex and better compression

Signal Modelling





- Predictions, Transformations decrease the dynamics
- Distributions of residual signal concentrated around zero
- Signal reconstruction using reverse operations

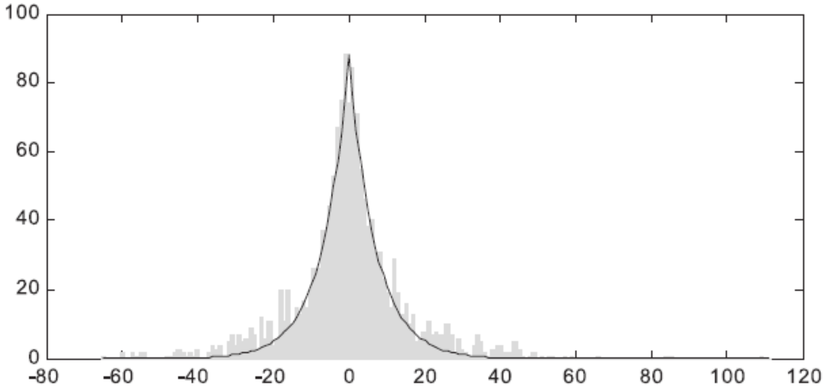
Linear Prediction

- Prediction as a sum of previous samples multiplied by coefficients

$$x_{predicted}[t] = \sum_{i=1}^{N} a_i x[t-i]$$

- Residuals (equal to difference between input samples and their predictions) have much lower values and energy

$$\Delta x[t] = x[t] - \sum_{i=1}^{N} a_i x[t-i]$$



- Coefficients must be known at the decoder -> precomputed or sent with residuals
- Error energy:

$$E = \sum_{t=0}^{T} (\varepsilon[t])^2 = \sum_{t=0}^{T} \left(x[t] - \sum_{i=1}^{N} a_i x[t-i] \right)^2$$

Signal Models

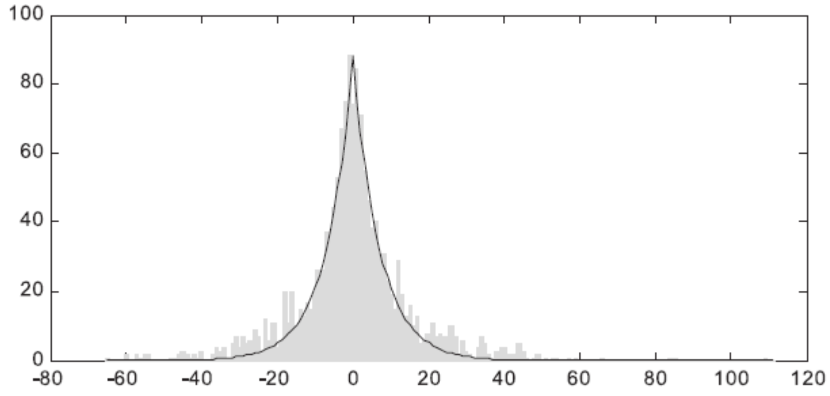
- Set of representative sample sequences are compared with acquired samples to find the best matching in terms of SAD or MSE

$$i = \arg\min\left(\sum_t |x[t,i] - x[t]|\right)$$

$$i = \arg\min\left(\sum_t (x[t,i] - x[t])^2\right)$$

$$x_{predicted}[t] = x[t,i]$$

- Residuals (equal to difference between input samples and their predictions) have much lower values and energy

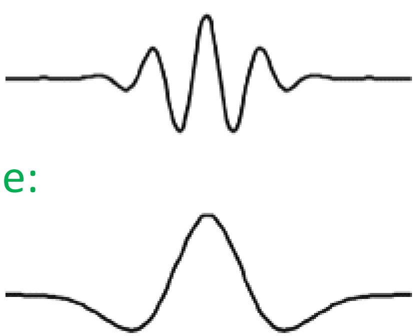


- In vector quantization residuals are neglected

Transforms

- Karhunen-Loeve Transform (KLT)
  - Best efficiency expected
  - Computed based on a number of signal sequences
  - Required similarity of signals to obtain better energy compaction
- DWT, FFT, and DCT seems to be less efficient

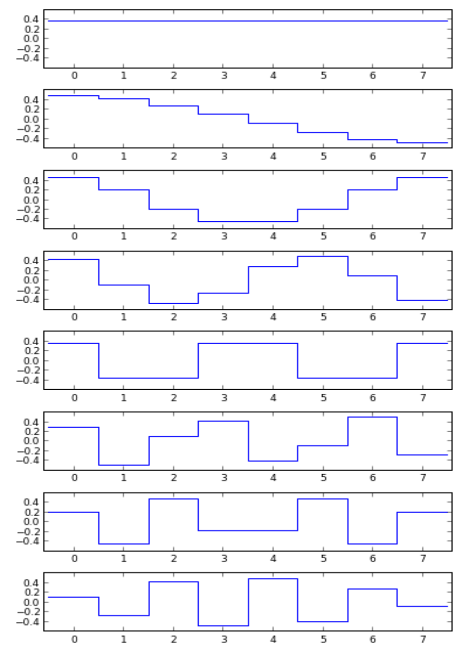
DWT base:



H wavalet

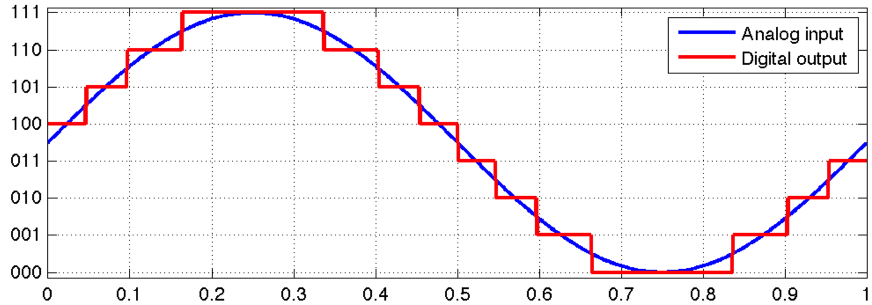
L wavelet

DCT base:



Quantization

- Scalar Quantization – division by quantization step
- Scalar Dequantization – multiplication by quantization step
- Quantization step can be dependent on charge to keep sufficient SNR



- Possible to apply quantization from video coding
  - Quantization parameter (6 bits) determines quantization step
  - Increments decrease SNR by about 1dB
  - Division replaced by equivalent multiplication

Quantizer:

$$X_q(i,j) = \text{sign}\{X(i,j)\}\left[\left(|X(i,j)|\,A(Q_M,i,j) + f2^{17+Q_E}\right) \gg (17+Q_E)\right]$$

Dequantizer:

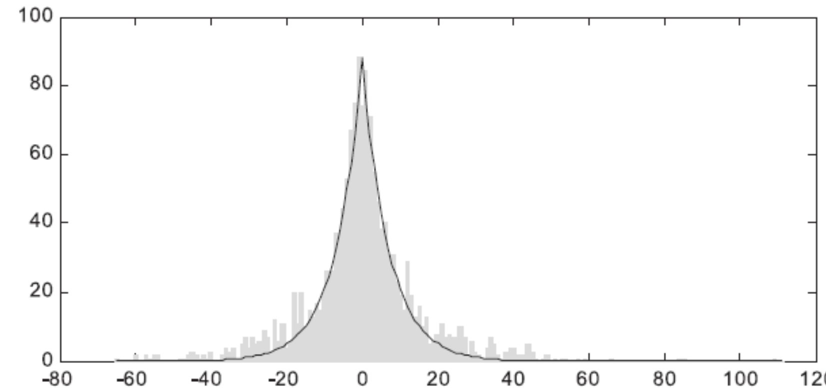
$$X_r(i,j) = X_q(i,j)\,B(Q_M,i,j) \ll Q_E$$

Entropy coding (1)

- Assignment of input values to codewords
- Codewords with variable lengths inversely proportional to probabilities
- Bit rate greater than the information entropy by a fraction of bit per sample
- Variable Length Coding is simple in implementation
- Arithmetic Coding achieve entropy at higher implementation complexity

Entropy coding (2)

- Golomb/Rice codes suitable for geometric distribution
- Exp-Golomb codes suitable for exponential distribution

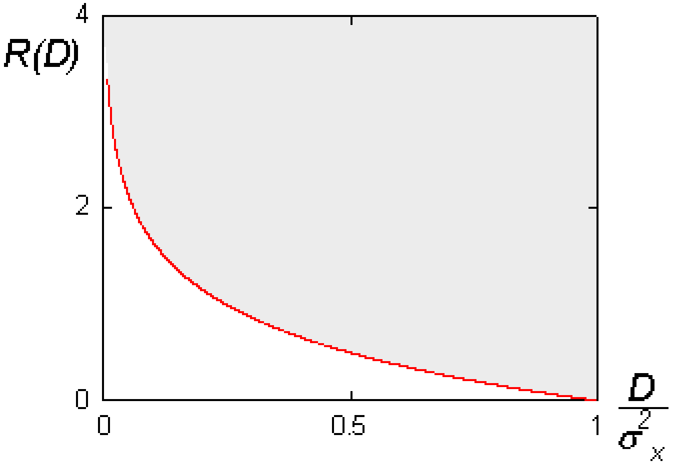


Golomb Codewords for different orders

i	$m=1$	$m=2$	$m=3$	$m=4$	$m=5$	$m=6$	$m=7$
0	0	0|0	0|0	0|00	0|00	0|00	0|00
1	10	0|1	0|10	0|01	0|01	0|01	0|010
2	110	10|0	0|11	0|10	0|10	0|100	0|011
3	1110	10|1	10|0	0|11	0|110	0|101	0|100
4	11110	110|0	10|10	10|00	0|111	0|110	0|101
5	111110	110|1	10|11	10|01	10|00	0|111	0|110
6	1111110	1110|0	110|0	10|10	10|01	10|00	0|111
7	11111110	1110|1	110|10	10|11	10|10	10|01	10|00
8	111111110	11110|0	110|11	110|00	10|110	10|100	10|010
9	1111111110	11110|1	1110|0	110|01	10|111	10|101	10|011
10	11111111110	111110|0	1110|10	110|10	110|00	10|110	10|100
$\vdots$	...	...	...	...	...	...	...

Compression Efficiency

- Lossless Coding of signals
  - Compression ratio: about 2-3
- Lossy Coding of signals
  - Compression ratio: more than 3, e.g. 10
  - Distortion (D) and bit rate (R) depend on quantization step
  - RD Tradeoff

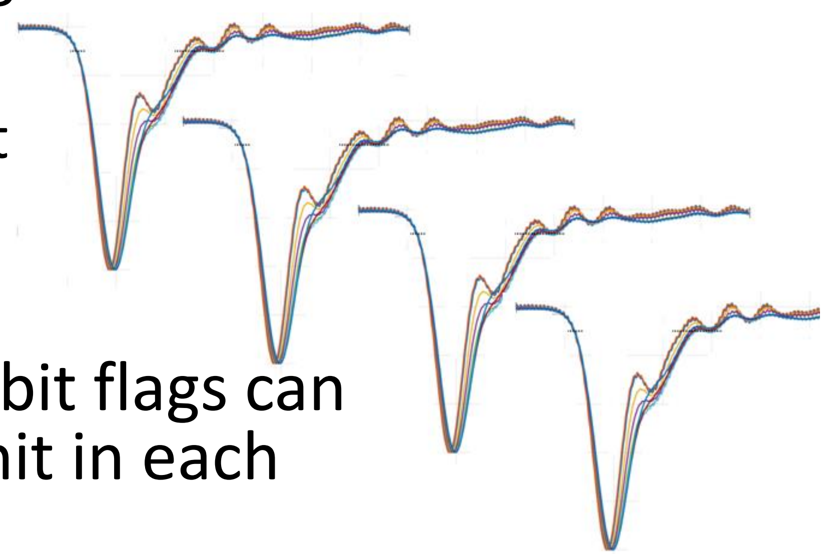


More accurate estimation of compression ratios after the statistical analysis

Multi-channel Compression

- Neighboring PMTs may be excited in similar moments
  - each separate time descriptor consumes about 32 bits
  - common time descriptor (offset) for 19 channels is useful
  - Time Delta values for each channel should be close to zero ->suitable variable length coding

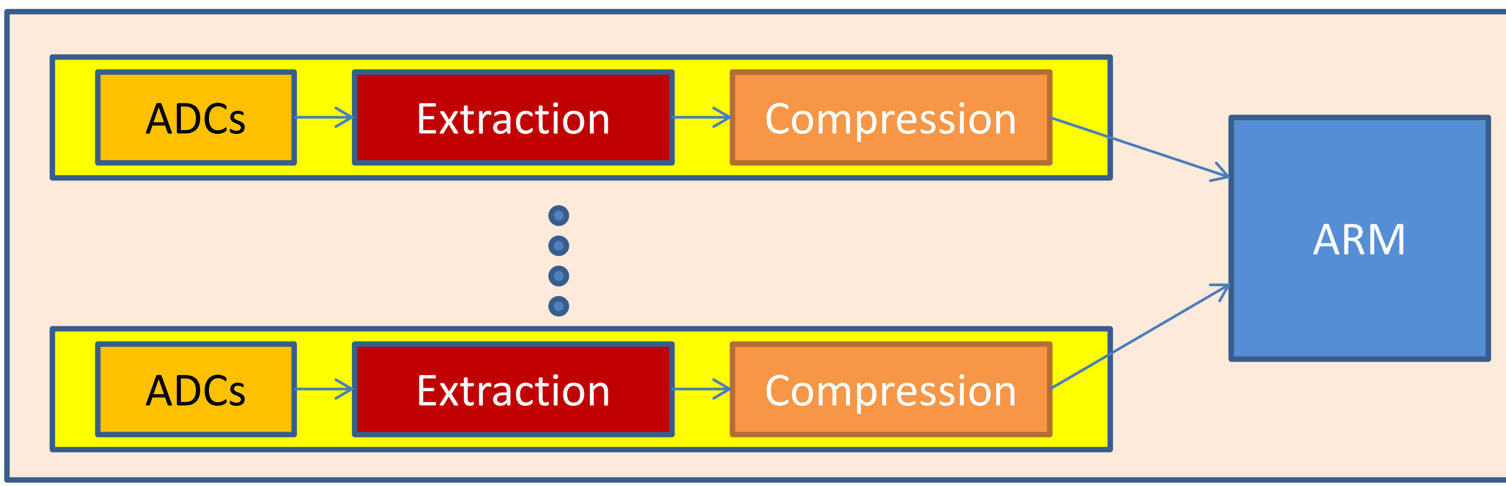
- Waveforms from neighboring PMTs may be similar
  - Use of one channel to predict others



- Common packets where one-bit flags can indicate the presence of the hit in each channel

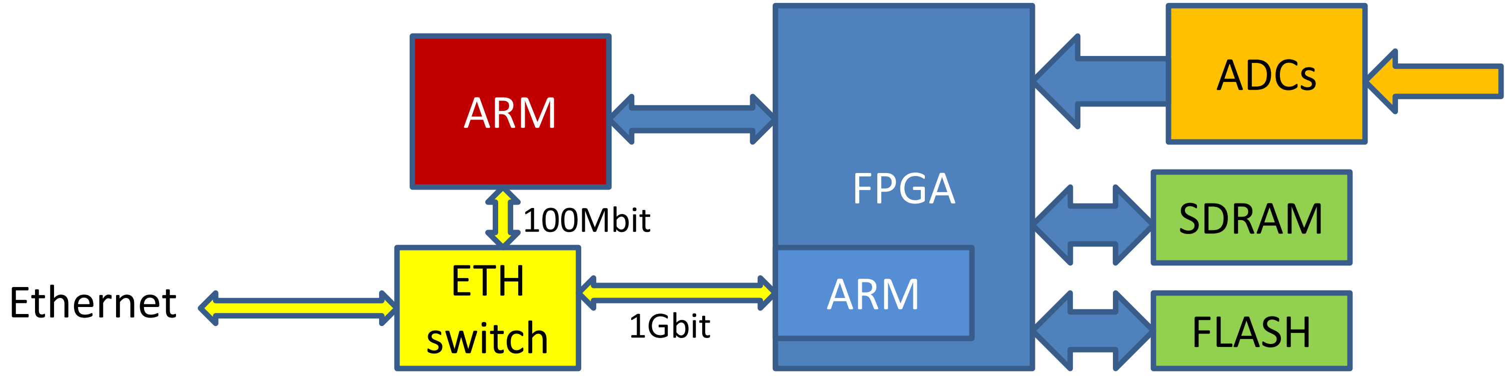
FPGA – architecture

- Compression in basic version is not complex
- Parallel processing for 19 PMTs significantly increases requirements on resources and power
- Extraction of time stamps will make the architecture more complex – filters utilize multiplications



FPGA – power consumption

- Strong limitations on power consumption – 4/10 W
- The digital system should include:
  - FPGA device – 2W
  - SDRAM memory – 1W
  - External ARM microcontroller – 0.5W - 1W
  - DC/DC converters – 0.5W
- Low-power modes should be used when data are not acquired
- 1Gbit Ethernet requires switch and more complex FPGA with internal ARM – higher power consumption by 1W-2W



Summary

- A number of compression methods must be examined
- The level of loss must be decided
- Architecture must be reduced to keep power at minimum