Data processing system for denoising of signals in real-time using the wavelet transform

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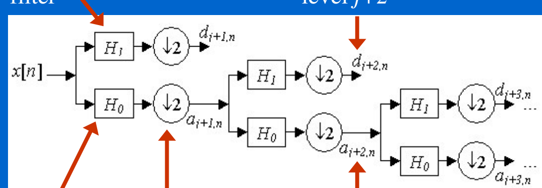
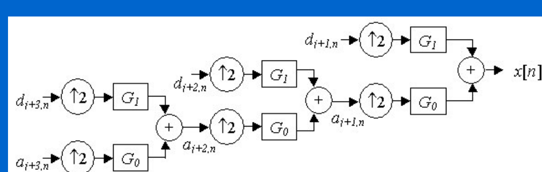
The discrete wavelet transform

- DWT as a time-frequency (scale) transform.
- DWT as an orthonormal transform:
  - perfect reconstruction capability;
  - decomposition without redundancy;
  - allows acting locally in the signal with minimal interference on its vicinity.
- DWT (and the WT) as an universal tool:
  - it found applicability in medicine, engineering, mathematics, geology, physics and so on.

The DWT algorithms

- DWT: performed by a filter bank that decomposes the signal in successively coarser approximations and details.
- IDWT: reconstructs the signal using a filter bank that is the mirror of the one used in the DWT.





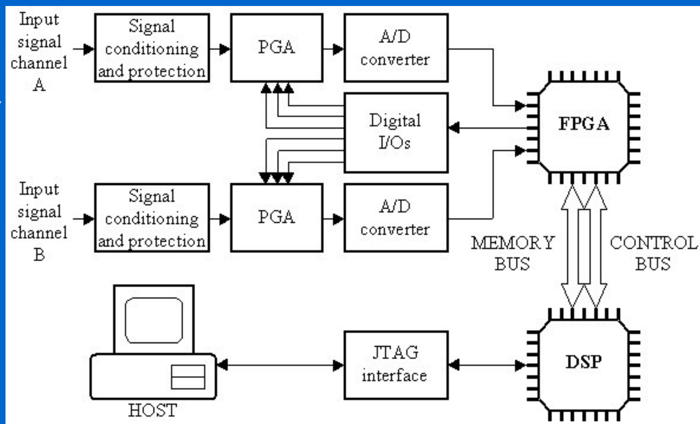
DWT implementation issues

- When high performance is a requirement the DWT is usually implemented through multi-processed systems or even dedicated hardware (e. g.: FPGA, ASIC):
  - these approaches offer the highest performances;
  - usually are harder to modify in the field;
  - compromise between system's performance and flexibility.
- As this system is under a prototype phase, we used in principle a monoprocessed approach to allow:
  - gathering information about algorithm's performance and efficacy;
  - using this information at later stages on the specification of newer systems.

Hardware overview

Two channels simultaneously sampled (70 MS/s @ 12 bits/S).

HOST computer.



FPGA bus interface (throughput of 17 MS/s).

DSP device: fixed-point, 720 MHz, 1 MB mem., superscalar, SIMD architecture.

DWT implementation in monoprocessed systems

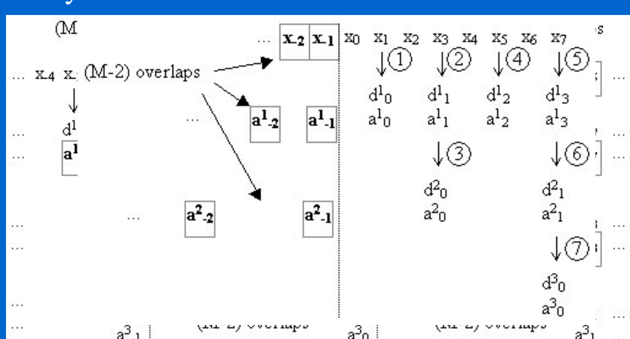
- First implemented by Stéphane Mallat and named the Pyramid Algorithm (PA).
- The PA works as a block processing algorithm:
  - when using blocks of size *N* it is possible to decompose the signal down to log_2N levels;
  - for a wavelet filter of size *M* it performs at most *2.N.M* multiplications and *2.N.(M-1)* additions ⇒ *O(N)* complexity;
  - when processing continuous streams of data it is necessary to deal with the borders of the sections (e. g. circular convolution, zero "stuffing") → over-computation and false information.
- Two new algorithms were developed to overcome the problems that arise with the traditional border dealing techniques.

The RunningDWT algorithm

- Inspired on the overlap-save convolution method and the Recursive Pyramid Algorithm.
- Advantage: capability to process the data through the borders as if they did not exist.

The input is divided into sections of size 2^J.

The algorithm keeps track of the borders through a matrix that store the overlapping segments.



The order of computation is changed to minimize storage requirements.

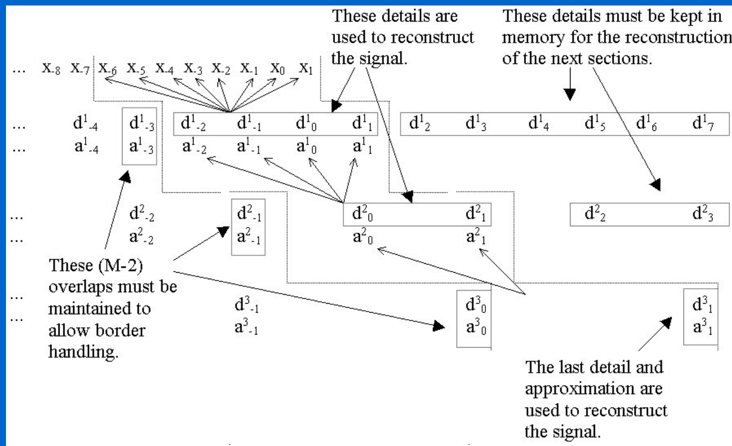
The RunningIDWT algorithm

- The reconstruction without extension techniques is harder to implement due to the delays introduced by the filters that compose the bank.
- It can be shown that, without extensions, it becomes progressively impossible to reconstruct the approximations of previous levels, thus making it impossible to recover the actual section.
- The only way to reconstruct without extensions is decomposing subsequent sections, the number of which depends on the filter size *M* and number of decomposition levels *J*.

The RunningIDWT algorithm

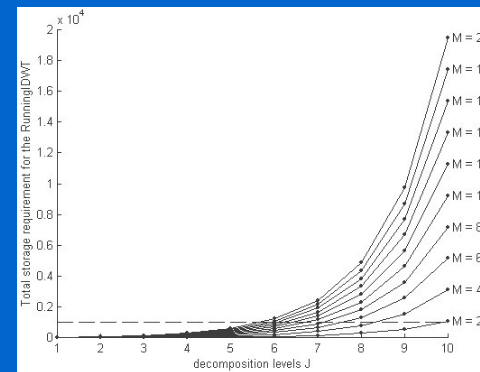
For each group it ... reconstruct ... M/2 approximations ... level, but delayed by (*M*-2) positions.

The reconstruction is performed by 2 matrixes, one for the details and the other for the approximations.



Performance and storage considerations

- The algorithms have the same computational load of the PA.
- One disadvantage: the storage can exceed the PA's requirement.
- They are still advantageous when decomposing only to intermediary levels.
- In real-time applications there will be a tradeoff between the available memory and the number of decomposition levels.



Denoising algorithms

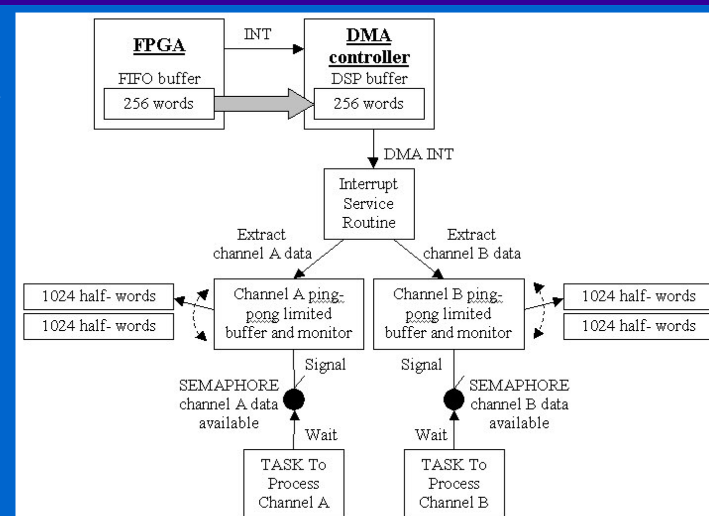
- The denoising algorithms based on wavelets follow a generic structure in which the wavelet coefficients are compared to a threshold level and modified if they are greater or smaller than that.
- Up to now we implemented only Hard and Soft-thresholding, but these will be expanded in the near future.

$$\hat{x}[n] = \begin{cases} x[n], & \text{if } |x[n]| \geq threshold; \\ 0, & otherwise. \end{cases}$$

$$\hat{x}[n] = \begin{cases} sign(x[n]) \cdot (|x[n]| - threshold), & \text{if } |x[n]| > threshold; \\ 0, & otherwise. \end{cases}$$

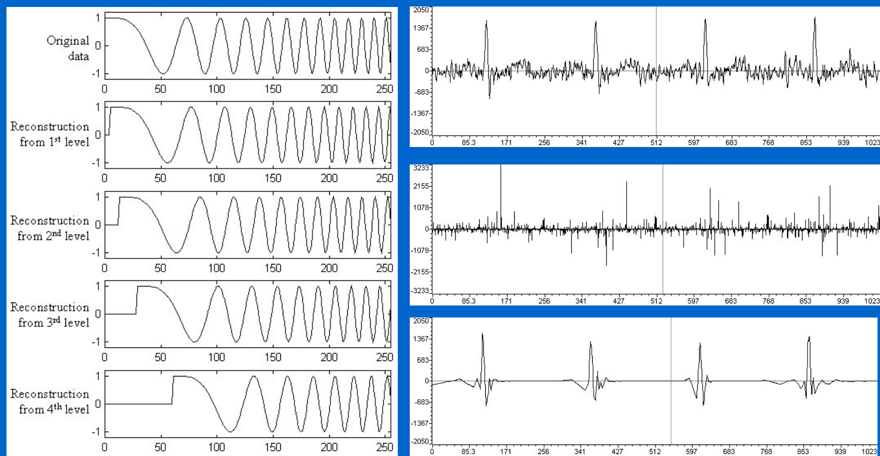
Software overview

- Data transfer controlled by the DSP DMA.
- Data are stored in two ping-pong circular and monitor buffers.
- Data are processed by two concurrent tasks.
- The system monitors the FPGA FIFO and the ping-pong buffers.



Results

Segmentation in 2^1, 2^2, 2^3 and 2^4



Results

- After an optimization stage the WCET of the algorithms were measured using the DSP's high-resolution internal clock.

Algorithm name	Execution time
RunningDWT	144.96 µs
RunningIDWT	152.80 µs
Hard threshold	1.10 µs
Soft threshold	1.70 µs
DMA ISR (data separation and storage)	1.26 µs

- The attained performance allowed real-time processing with sample rates up to 3 MS/s and 94 % of processor usage (using DB4 and 8 decomposition levels).

Conclusions

- The RunningDWT and RunningIDWT algorithms showed to be an advantageous alternative to the PA:
  - they remove the problems inherent to border dealing techniques;
  - they offer the same computational load of the PA;
  - they present a new way to see the wavelet coefficients;
- They have the disadvantage of storage structures that grows exponentially, solved by the judicious sectioning of the input.
- The DWT algorithms showed to be the bottleneck of the system:
  - the computational load is highly dependent on the chosen wavelet and number of levels;
  - data storage and thresholding are responsible by about 1% of the computational load;
  - it is safe to suppose that it is possible to increase the performance just working on these algorithms, maybe with a multiprocessed approach.

Conclusions

- Hard and Soft-thresholding showed to be very difficult to apply due to the fixed threshold value among the decomposition levels and empirical adjustments. In next stages other denoising methods will be evaluated.
- Potential applications of this system include on-line monitoring of high-voltage equipment, transmission line surge detection, real-time image processing, pattern recognition systems, automation and control systems and so on.