Trigger with Sampled Signals

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Collecting and analyzing events

- Rare events hidden in large backgrounds (DIS, DVCS, charm,....)
  (the simple experiments have already been done ...)

- Limits in data acquisition bandwidth and storage volume

- Preselection of data to be finally converted and stored
  called first level trigger systems

  - needs fast processing since intermediate storage is finite
  - High purity
  - High efficiency
  - watch out for absolute acceptance calibration (x-section measurements)

- Trigger strategy

- select “simple” observables (available quickly, not too much calibration effort, good stability)
- correlate the features of different signals and requiring necessary conditions for the event type in focus
- Example: Horoscope timing and coincidences, mean times, time differences, pulse height windows

Traditional Method

- Use trigger discriminators (comparators) on signals to generate a Boolean function B(t)
- Use comparators for pulse height selection to generate more Boolean functions
- Feed them into a Boolean network and wait for a preselected condition to become true ->trigger
- Obviously configurable gate arrays (" Matrices") will be used.
- The trigger will be used to start conversion of signals stored in analog manor (cables, buckets, or S&H signals)

- Or retrieve signals from sampled values stored in FIFOs

Limitations

Configurable Boolean networks now allow high complexity of networks and flexible configuration and control

but:

- need hardware "feature extractors" or discriminators with finite dead time and double pulse resolution
  - only one feature per box e.g. leading edge, CFT, integrator. Requires analog splitters and appropriate filters
  - very demanding additional hardware for pile-up detection
- need dedicated hardware for simple operations like mean timing or coincidences
- fine grained quantitative comparison only after TDC/ADC conversion (2nd level triggering, filtering)

Alternatives

- immediate digitization of primary signals to a binary data stream
- parallel derived filter streams
- extraction of signal **features**
  - timing (LE,CFT,Zero-crossing,extrapolated strobe of rising and falling edge(s)
  - pulse height and integrals
  - double pulse detection and analysis
  - quality tags (error estimates)
- numbers to be correlated by processors
  - Coincidences: $|t_1 - t_2| < \delta t_c$

- mean times $t_m = (t_1 + t_2)/2$
- Veto $|t_{tr} - t_{Veto}| > \delta t_v$
- Additional fine grained conditions

Limitations: sampling rates, sampling accuracy (ENOB), processing speed, ...
(We believe in Moore's law ...)

Signals and their features

- Signals reflect properties of events seen by detectors

- There is a chain of processes leading to signals
  - beam & target interact at the vertex position at the event time
  - particles and quanta are produced and emerge from the vertex with different momenta
  - particles traverse passive and active material of finite extension
  - space time distribution of energy loss processes and excitation of the material
  - photons or charged particles propagate, diffuse or drift to a detection electronics with amplifiers
  - we assume that an elementary excitation produces a standard response of the detecting electronics
    - the single photo electron response of a multiplier

  * the current produced by a single ion/electron or electron/hole pair on an electrode

- we assume the response of the detector to be linear such that the signal caused by an ensemble of primary excitations is the folding of the elementary signal with the transport-time and/or arrival time.

Horoscopes

- the primary excitations produced by a ionizing track have a life time $\tau_{sz} \approx 1 - 5ns$

- propagation times vary as a function of emission angle and the number of internal reflections
  - the arrival-time distribution of photons at the photo cathode can be characterized by an edge, a centroid, a width an obliqueness ..
  - the elementary response of PMs depends on the divider chain and the voltage. Transit time fluctuations at every stage will fold into the elementary excitation.
  - ..

Pulse shapes

- in many cases the signals are mono-polar, tailing off exponentially to provide a finite width
- pulses are **causal**
- Signals are noisy and may also exhibit imperfections caused by transmitting cables (reflections etc.)
- For simulations I have used elementary responses of "Poissonian" shape

$$f(t) = t^{\nu} e^{-t/\tau} H(t)$$

- They are signals caused by the $\delta-$ function in system with a ν fold real pole at $s = -\tau$

- they are strictly causal, enforced by the Heaviside $H(t)$, the are $\nu - fold$ continuous at t=0

- the can be easily folded with "box-like" arrival time distributions (mimicking the effect of long scintillator bars)
  If $f(x) = \frac{d}{dt}F(x)$, then the box responses are $\tilde{f}(t) = (F(t) - F(t-T))/T$

integrale_pulsform.pdf

- Freiburg colleagues prefer the non causal Moyal shape

$$f_M = e^{-\frac{1}{2}(\frac{t}{W} + e^{-t/w})}$$

versch-puls.pdf

Feature extraction with templates

- If there is a template pulse shape with shape parameters τ, T describing the observed pulse shapes well

- then the amplitude A the time shift t_{tr} and the pulsshape parameters can be determined by least square fitting
  - overlay the template to the measured samples
  - determine the $\chi^2 = \sum \frac{(y_i - A \cdot \tilde{f}(t_i - t_{tr}, T, \tau))^2}{\sigma_i^2}$ (assuming uncorrelated errors)
  - minimize χ^2 with respect to $\{A, t_{tr}, T, \tau\}$ and get the (correlated) errors
  - This is the optimum way of feature extraction making best use of the signal information
  - if τ turns out to be constant (within errors), we can "freeze" it and only use one shape parameter

- if we could also express the other parameter by its average and a few neighboring values $T_n = \bar{T} + n\Delta T$

- we can set up a **Filter** moving along the time axis calculating χ^2 for each position t_r and amplitude A
  - if we apply the filter only at discrete times we will (generally) miss the minimum !
  - but: we will find the i_th time before and the i+1_th after the minimum
  - we can perform an interpolation (making use of the pulse shape and its derivatives)

- filtering the search of the minimum can be made on streaming data: -> no dead time

- But:

- needs a minimum "activity" threshold to protect feature extractor from noise (and overload)
- the method needs "learning" of pulse shape parametrization and setup of several parallel filters for each T_n

The cubic extractor

- continuous cubic functions are are very effective to approximate general smooth functions (see splines)

- we fit (least sq ares) a cubic function one a finite interval right and left of a given sampling point by minimizing

$$\chi^2 = \sum_{k=-m}^{+m} \frac{(y_{i+k} - \{a_i t_k^3 + b_i t_k^2 + c_i t_k^1 + d_i\})^2}{\sigma_{i+k}^2}$$

If the errors σ_{i+k}^2 are independent of the sampled value the minimizing χ^2 leads to the four coupled linear equations for the coefficients

$$\sum_{k=-m}^{+m} y_{i+k} \quad = \quad \sum_{k=-m}^{+m} [(a_i(k \cdot \Delta t)^3 + b_i(k \cdot \Delta t)^2 + c_i(k\Delta t) + d] =$$

$$b_i \Delta t^2 \sum_{k=-m}^{m} k^2 + d_i \Delta t^0 \sum_{k=-m}^{+m} 1$$

$$\sum_{k=-m}^{+m} y_{i+k}(k \cdot \Delta t) \quad = \quad \sum_{k=-m}^{+m} (k \cdot \Delta t)[(a_i(k \cdot \Delta t)^3 + b_i(k \cdot \Delta t)^2 + c_i(k\Delta t) + d] =$$

$$a_i \Delta t^4 \sum_{k=-m}^{+m} k^4 + c_i \Delta t^2 \sum_{k=-m}^{+m}$$

$$\sum_{k=-m}^{+m} y_{i+k}(k \cdot \Delta t)^2 \quad = \quad \sum_{k=-m}^{+m} (k \cdot \Delta t)^2 [(a_i(k \cdot \Delta t)^3 + b_i(k \cdot \Delta t)^2 + c_i(k\Delta t) + d] =$$

$$b_i \Delta t^4 \sum_{k=-m}^{+m} k^4 + d_i \Delta t^2 \sum_{k=-m}^{+m} k^2$$

$$\sum_{k=-m}^{+m} y_{i+k}(k \cdot \Delta t)^3 \quad = \quad \sum_{k=-m}^{+m} (k \cdot \Delta t)^3 [y_{i+k} - (a_i(k \cdot \Delta t)^3 + b_i(k \cdot \Delta t)^2 + c_i(k\Delta t$$

$$a_i \Delta t^6 \sum_{k=-m}^{+m} k^6 + c_i \Delta t^4 \sum_{k=-m}^{+m} k^4$$

the relation of the moments and the coefficients a_i, b_i, c_i, d_i is given by

$$< yx^0 >_i^m = b_i \Delta t^2 L_2^m + d_i \Delta t^0 L_0^m$$

$$< yx^1 >_i^m = a_i \Delta t^3 L_4^m + c_i \Delta t^1 L_2^m$$

$$< yx^2 >_i^m = b_i \Delta t^2 L_4^m + d_i \Delta t^0 L_2^m$$

$$< yx^3 >_i^m = a_i \Delta t^3 L_6^m + c_i \Delta t^1 L_4^m$$

We now can express the coefficients a_i, b_i, c_i, d_i of the locally fitted cubic polynomial by the discrete moments $< yx^n >_i^m$ and the numbers L_j^m as

$$a_i = \frac{1}{\Delta t^3} \frac{1}{L_4^m \cdot L_4^m - L_6^m \cdot L_2^m} [L_4^m < yt^1 >_i^m - L_2^m < yt^3 >_i^m]$$

$$b_i = \frac{1}{\Delta t^2} \frac{1}{L_2^m \cdot L_2^m - L_4^m \cdot L_0^m} [L_2^m < yt^0 >_i^m - L_0^m < yt^2 >_i^m]$$

$$c_i = \frac{1}{\Delta t} \frac{1}{L_2^m \cdot L_6^m - L_4^m \cdot L_4^m} [L_6^m < yt^1 >_i^m - L_4^m < yt^3 >_i^m]$$

$$d_i = \frac{1}{L_0^m \cdot L_4^m - L_2^m \cdot L_2^m} [L_4^m < yt^0 >_i^m - L_2^m < yt^2 >_i^m]$$

Feature extraction from the cubic filter

- the extracted cubic coefficients can be regarded as the numerical values of the average values of a smooth function and their first 3 derivatives

- remembering school mathematics **features** have to be expressed by **zeroes** of the function and its derivatives
  - the maximum is where the first derivative is zero
  - the inflection points are where the second derivative is zero ..
  - the are independent of amplitude (like CFT which can be found as a zero of $f(t_{cft}) - \mathrm{f}f^{max} = 0$
  - extrapolated zero times $t_e = Max(t - f/f')$
  - curvature at the maximum
  - (partial)integrals

- Interpolation between i and $i+1$ can use linear interpolation (systematic errors due to curvature of the function are of order $1/10$ of sampling time)

The Holy Grail - Pile-up analysis

- different pile-up situations
  - close pile-up (pile-up within the arrival time width) no chance!
  - pile-up time $<$ rise time: only distortion of shape parameters detectable
  - some unperturbed features of the underlying first pulse exist
  - multiple features emerge: additional inflection points or maximum depends on pile-up ratios eg 1:10 or 10:1