



Article Time-Variant Front-End Read-Out Electronics for High-Data-Rate Detectors

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Abstract: The foreseen incremental luminosity for near-future high-energy physics experiments demands evolution for the read-out electronics in terms of event data-rate. However, the filtering necessary to reject noise and meet the signal-to-noise-ratio requirements imposes a restriction on the operational speed of the conventional read-out electronics. The stringent trade-off between signal-to-noise-ratio and the event data-rate originates from the time-invariant behavior of the conventional systems. In this paper, the cases of time-variant systems are addressed, studying a benchmark with the RC-CR shaping function used in time-over-threshold methods. It was demonstrated that the time-variant systems enable a higher data-rate for the given noise performance. Moreover, taking advantage of time-variant systems, the proposed rising-edge method enables further data-rate enhancement with respect to the traditional time-over-threshold technique by reading the data from the rising edge of the analog output waveform. A comparison between the conventional time-invariant time-over-threshold technique, its time-variant equivalent and rising-edge method confirms the better performance of the latter one in terms of data-rate enhancement for a target noise performance. Moreover, design challenges for time-variant systems are briefly discussed, considering the ATLAS Monitored Drift Tube detector as a design case.

Keywords: read-out channel; time-over-threshold; time-invariant; time-variant; rising-edge front-end

1. Introduction

The luminosity of the Large Hadron Collider (LHC) accelerator at CERN will be upgraded by a factor of about seven compared to its previous performance. While the upgraded LHC accelerator is expected to go into operation in the second half of this decade, a more powerful accelerator is already on the drawing board, which is envisaged to be constructed in the second half of the next decade [1,2].

Detector technology for high-energy physics experiments must cope with ever-increasing signal rates, as the performance of particle accelerators is evolving to higher luminosity. Monitored drift tube (MDT) detectors are a prime candidate for the required high-accuracy tracking of charged particles due to their high spatial resolution for ionizing particles and their simple and rugged construction [3,4]. However, signal pile-up events in MDT detectors caused by secondary spurious pulses result in multiple crossings in the signal tail of the read-out-channel for each muon track.

In the current MDT chambers, muon detection is performed by a read-out-channel composed of an ASD (amplification–shaper–discriminator) to evaluate the charge arrival time and the amount of charge by time-over-threshold (ToT) encoding [5–7]. To prevent pile-up events, small time constants and/or bipolar shaping are used in the read-out-channel [8]. Moreover, an additional dead-time after event detection (up to 750 ns) is adopted to disable the detection of multiple crossings.



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). In small-diameter MDT (sMDT) chambers using 15 mm diameter drift tubes (instead of 30 mm), the maximum drift time is reduced to 180 ns, offering about ten times higher rate capability [9]. To fully profit from the sMDT performance, the read-out electronic is required to exploit shorter dead-time, increasing the risk of pile-up effects of muon signals.

In the read-out chain of sMDT, high-bandwidth analog-channels are demanded to obtain a short baseline recovery (BLR) tail, and accordingly, a short time interval between consecutive events. However, the signal-to-noise-ratio (SNR) of the read-out output is improved with the high noise filtering of the analog-channel. To meet the SNR requirements, low-bandwidth analog-channels are demanded. As a result, the conventional ASD read-out chains suffer from a severe trade-off between data-rate and SNR originating from the time-invariant (TI) nature of the analog-channels' operational behavior.

In this paper, time-variant (TV) analog-channels were considered, which allow the transfer function optimization of both the event measurement (EM) phase and BLR tail. During the EM phase, high noise filtering (with a long time constant) is implemented, while during BLR, the time constant is dramatically reduced (or nulled) to minimize tail and provide a high-data-rate.

The comparison between TI and TV analog-channels is studied considering the known RC-CR transfer function as a benchmark with the ToT method for event amplitude measurement. Both TI and TV methods are modeled and behaviorally simulated to be compared in terms of SNR, BLR, and consequently, experiment data-rate. The results indicate the competitiveness of TV analog-channels in the optimization of the SNR versus BLR trade-off. Moreover, the rising-edge (RE) method for event amplitude measurement is presented, which by utilizing TV analog-channels, further decreases BLR. It is demonstrated that for a target SNR required in a defined application/experiment, the time-variant rising-edge (TV-RE) system presents a shorter BLR, enabling a higher data-rate, outperforming the TV/TI-ToT systems. Therefore, the proposed solution is attractive for high-data-rate experiments.

2. Time-Invariant ToT Technique Trade-Offs

A typical structure for a time-invariant read-out-channel is composed of an analogchannel (formed by a charge-sensitive-preamplifier (CSP) and a shaper) and a discriminator, as shown in Figure 1. In this analysis, it is assumed that for a given event, an impulsive input charge (Q_{in}) is injected into the analog-channel, where a CSP operates as an ideal integrator and produces an ideal step at its output. This corresponds to assume that the CSP time-constant is much shorter than the shaper time-constant. Regarding the shaper, among the several possible transfer functions [10], in this analysis, the typical RC-CR one is used as a benchmark, with a transfer function of:

$$TF_{RC-CR}(s) = \frac{s\tau}{(1+s\tau)^2} \tag{1}$$

where τ is the shaper time constant. The shaper produces an output signal V_{out}(t) given by

$$V_{out}(t+\tau) = -\frac{Q_{in}e^{-1}}{\tau^2} t e^{-t/\tau}$$
(2)

The peak value of V_{out} and the peaking-time-delay (PTD), i.e., the time that the peak value occurs, are extracted from impulse response as

$$V_p = \frac{Q_{in}e^{-2}}{\tau}, \quad PTD = \tau \tag{3}$$

The incoming charge amount can be measured with different methods. The popular time-over-threshold (ToT) detection method is here considered [5]. It is based on the measurement of the time interval between double-crosses of the analog-channel output with a proper threshold voltage V_{TH} , as shown in Figure 2. The pulse-width of the ToT signal (ToT-PW) is used to measure the input charge amplitude Q_{in} .



Figure 1. A typical structure of a TI-ToT read-out-channel.



Figure 2. (**a**) Analog-channel output waveform indicating PTD, EM and BLR times; and (**b**) extracted ToT signal from the analog-channel output.

For a given event, the main operations of the read-out-channel are EM and BLR phases. As presented in Figure 2, the EM phase is the required time to produce the ToT-PW signal indicating the input charge amount, i.e., it starts at the event arrival time and ends a bit after the instant of the second crossing of the analog-channel waveform with the threshold voltage, V_{TH} :

$$EM_t = T_2 + \epsilon \Rightarrow EM_t = f(\tau, Q_{in}) \tag{4}$$

where ϵ is a small amount of time to assure proper ToT-PW detection. Based on Equations (2) and (4), EM time is a function of τ and input charge amount. Accordingly, the ToT-PW, i.e., the time interval between V_{out} double-crosses with V_{TH} , is also a function of τ and Q_{in} . For a given τ , the plot of ToT-PW versus Q_{in} is shown in Figure 3. The amount of ToT-PW is reported as a factor of the given τ . Moreover, V_{TH} is considered as 80% of V_p for the minimum Q_{in} .



Figure 3. ToT-PW versus Q_{in} for a given τ and $V_{TH} = 0.8 \times V_p$.

After the EM phase, i.e., the ToT-PW signal generation, the analog-channel time evolution decreases, returning to zero to prepare for the next event processing. In order to avoid event pile-up, a new event can be applied only when the analog-channel output signal is sufficiently decreased [11,12]. For instance, in this analysis, damping down to 1% of the V_p is considered. The time to reach such a condition is defined as the BLR phase. Hence, BLR_t is the time interval between the event occurrence and the instant that the analog output is decreased down to 1% of its peak value.

$$BLR_t = t|_{(V_{out}=0.01 \times V_p)} - t|_{(V_{out}=0)}$$

$$BLR_t \times e^{-BLR_t/\tau} = 0.01 \times e^{-1} \times \tau \Rightarrow BLR_t = f(\tau)$$
(5)

where, unlike the EM phase, the period of BLR is only a function of τ . Thus, the ToT-PW detection is studied as a function of time constant τ .

For simplicity, two τ values are considered, as shown in Figure 4, where the solid and dashed curves refer to the cases with long- τ and short- τ , respectively. The long- τ case corresponds to longer EM and BLR phases, requiring longer time between two events, and consequently resulting in a lower possible experiment data-rate. On the other hand, for the short- τ case, the situation is the opposite, i.e., faster EM and BLR, and accordingly, higher experiment data-rate.

Moreover, the noise effect on the ToT-PW signal is studied. A series noise is applied at the input of the analog-channel with a standard deviation (SD) equal to 3% of the input amplitude ($\sigma_{noise} = 0.03$). Such a noise affects the analog-channel output time evolution, and hence, the ToT-PW evaluation. The gray curves in Figure 4 show the resulted noisy evaluations for 100 transient iterations, where the noisy analog-channel evolution is superimposed to the no-noisy ideal output shown in black curves. The noise effect on the analog-channel outputs and ToT-PW signals is shown for both τ cases. To study the noise effect, the SNR of the ToT-PW is defined as

$$SNR_{ToT} = 20 \times log(\frac{ideal\ ToT - PW}{SD(noisy\ ToT - PW)})$$
(6)

A 100-sample Monte Carlo analysis with a 0.03-SD for the input noise is performed to evaluate the SNR for each τ value. Figure 5 shows the SNR_{ToT} as a function of the τ , where threshold voltage V_{TH} is considered as 80% of V_p and the amount of τ in the horizontal axis is normalized to τ_{max} . Longer- τ corresponds to higher noise filtering and accordingly lower output noise, achieving better SNR. However, based on Figure 4, the BLR and ToT-PW demonstrate that the high-data-rate system requires shorter τ , resulting in lower SNR. Thus, the ToT technique imposes a severe trade-off between data-rate and SNR of the system, being unable to meet both the speed and noise requirements of the state-of-the-art high-data-rate high-SNR detectors. To overcome this problem, alternative signal processing approaches are under development.



Figure 4. (a) Time domain outputs of the two analog-channels with different τ specifications; and (b) extracted ToT signals from the analog-channel output.



Figure 5. SNR of the ToT signal versus τ of the analog-channel output, for $V_{TH} = 0.8 \times V_p$ and $\sigma_{noise} = 0.03$.

3. Time-Variant Solutions

In the previous analysis, the time-invariant ToT (TI-ToT) method exhibited a severe limitation due to the fact that the same transfer function processes the signal for both EM and BLR phases, resulting in a critical SNR versus data-rate trade-off.

In fact, the analog-channel requires a high-filtering transfer function only for the input signal detection and measurement (EM phase, i.e., until the generation of the ToT-PW signal). After this instant, the following time domain evolution, i.e., BLR tail, is adversely affected by such and amount of high filtering. However, the BLR tail does not affect the signal detection accuracy. Thus, a high filtering operation is not required for this phase. To optimize this inefficient situation, time-variant solutions are presented, which means that the transfer function in the BLR tail is modified with respect to the transfer function in the EM phase to reduce the BLR period.

3.1. Time-Variant ToT Method

In a time-variant system, the transfer function is re-arranged (with proper solutions for hardware implementation) to optimize system performance in every operational phase. For TV read-out electronics, a long- τ is used in the EM phase to reach a high SNR, while during the BLR phase, the τ is shorter or even null to minimize the BLR tail.

The TV concept is here applied to the ToT method. To perform a time-variant ToT (TV-ToT) signal processing, after achieving the second threshold crossing, the analog-channel is reset to the baseline (i.e., the null τ), preparing to process a new event, as shown in the dashed curve of Figure 6a. There is a small delay between crossing the second threshold and resetting the analog-channel to guarantee a proper operation.



Figure 6. (**a**) Analog-channel time domain outputs for TI-ToT, TV-ToT and TV-RE techniques; (**b**) extracted ToT and RE signals of the analog-channel waveform.

In the EM phase, the TV-ToT transfer function is unchanged with respect to the TI-ToT case; thus, all considerations for the signal detection accuracy in the conventional TI-ToT are also valid for TV-ToT signal processing. Accordingly, the ToT signal and ToT-PW are the same for both TI-ToT and TV-ToT techniques, as shown in Figure 6b.

Figure 7a illustrates a significant improvement in the BLR_t by plotting it as a function of τ for TI-ToT and TV-ToT techniques. The BLR period is reported as a factor of the maximum τ (τ_{max}), and the amount of τ in the horizontal axis is also normalized to τ_{max} . The TV-ToT system presents shorter BLR times than the TI-ToT case, which corresponds to a significant improvement in terms of the optimization of the SNR versus data-rate trade-off.

3.2. Time-Variant Rising-Edge Method

In Section 3.1, a reset operation after the EM phase is exploited to reduce BLR time and then increase the possible data-rate. In this sub-section, more development is used to reduce the EM time, further increasing the possible data-rate. Therefore, as a further evolution, the input charge Q_{in} is read from the information stored in the rising-edge (RE) of the analog-channel output waveform. Compared to the analog-channel output with two threshold voltages (named V_{TH} and V_{THE}), the pulse width between the two crossings (RE-PW) is extracted as the output signal, as shown in Figure 6a (analog-channel output) and Figure 6b (comparison of the TV/TI-ToT-PW with the RE-PW).



Figure 7. (a) BLR_t versus τ of the analog-channel for TI-ToT, TV-ToT and RE techniques; (b) the pulse width of ToT and RE signals versus τ ; and (c) SNR_{RE} and SNR_{ToT} versus τ . All are plotted for $V_{TH} = 0.8 \times V_p$, $V_{THE} = 0.4 \times V_p$ and $\sigma_{noise} = 0.03$.

The resulting RE method for the Q_{in} amplitude measurement exploits the RE-PW versus Q_{in} plot as depicted in Figure 8, which reports the amount of RE-PW as a factor of the given τ . In this analysis, V_{TH} and V_{THE} are assumed to be 80% and 40% of V_p , respectively.

Increasing Q_{in} enhances the peak value of the analog-channel waveform, resulting in a steeper rise time, and consequently, shorter RE-PW. Thus, in the RE process, unlike ToT-PW versus Q_{in} as shown in Figure 3, the RE-PW decreases by increasing the Q_{in} amount.

In the TV-RE analog-channel, by a small delay after the crossing point of the second threshold voltage (V_{TH}) and generating the RE-PW amount, the system is reset to be ready to process a new event, as shown in Figure 6a. This presents a significant boost to the data-rate, even in comparison to the TV-ToT technique.



Figure 8. RE-PW versus Q_{in} for a given τ and $V_{TH} = 0.8 \times V_p$, $V_{THE} = 0.4 \times V_p$.

The BLR time of the TV-RE method versus τ is plotted in Figure 7a to compare the RE data-rate to TI-ToT and TV-ToT cases. Moreover, Figure 7b shows the pulse width of the ToT and RE signals versus τ , indicating much shorter pulse width for the RE method in comparison to TI/TV-ToT cases. To make a proper comparison, the BLR, ToT-PW, and RE-PW are reported as a factor of τ_{max} .

To study the noise effect, the same 100-sample Monte Carlo analysis with 0.03-SD for the input noise is performed for the RE method. The SNR of RE-PW (SNR_{*RE*}) versus τ is plotted in Figure 7c. Furthermore, SNR_{*ToT*} versus τ reported in Figure 5 is repeated in Figure 7c for comparison. For the same τ , SNR_{*ToT*} and SNR_{*RE*} are in the same range, however, the ToT technique exhibits a much longer BLR_{*t*}, as depicted in Figure 7a. To make a better comparison, the SNR of ToT and RE signals versus BLR_{*t*} for TI-ToT, TV-ToT, and RE methods are plotted in Figure 9a. Hence, to meet the same BLR which corresponds to the system data-rate, the RE architecture presents a higher SNR than both ToT techniques.



Figure 9. SNR of ToT-PW and RE-PW versus BLR_t for TI-ToT, TV-ToT and RE techniques for optimizing V_{TH} and V_{THE} .

In the SNR versus BLR curves, the deeper analysis addresses the optimization of V_{TH} and V_{THE} . Therefore, in Figure 9b, V_{THE} is changed for the TV-RE method for the three values of 30%, 40%, and 50% of V_p , while V_{TH} is fixed to 80% of V_p . As indicated, TV-RE outperforms TI/TV-ToT for all values of V_{THE} and SNR_{RE} is improved by decreasing V_{THE} .

Obviously, TV-ToT has a better performance than TI-ToT in terms of SNR versus BLR. Therefore, to study the effect of the V_{TH} value, Figure 9c plots SNR versus BLR curves for TV-ToT and TV-RE methods, while V_{THE} is fixed to 40% of V_p . A study of the results for V_{TH} equal to 70%, 80%, and 90% of V_p shows that in any case, TV-RE outperforms the TV-ToT method. Nonetheless, significant SNR improvement is achieved by proper V_{TH} adjustment to a higher value.

4. Time-Variant Read-Out-Channel Design Discussion

Time-variant architectures outperform the conventional TI-ToT technique improving baseline recovery time and data-rate to achieve the same SNR. However, time-variant systems need to be reset after each EM phase, introducing new challenges and concerns to the design of read-out electronics—which are briefly discussed in this section.

4.1. Time-Variant Read-Out-Channel Architectures

The architectures of the TV-ToT and TV-RE methods are shown in Figure 10a and Figure 10b, respectively. Comparing them to the TI-ToT scheme shown in Figure 1, an additional logic unit is demanded to implement the reset phase. Moreover, the TV-RE scheme requires an extra discriminator to detect the V_{THE} crossing. Nevertheless, TV read-outs necessitate a limited hardware penalty with small power consumption growth.



Figure 10. The simplified schematic of the (a) TV-ToT; and (b) TV-RE architectures.

A deeper analysis would be necessary to address the effects of implementation inaccuracy. For instance, any timing inaccuracy is detrimental to measurement precision because all the proposed methods are based on time measurements. Among them, the discriminator latency introduces time inaccuracy, which is more critical for small Q_{in} in the ToT method and large Q_{in} in the RE method. Hence, specific design consideration is necessary depending on the target experiment.

4.2. ATLAS MDT Detector Design Case

Considering the ATLAS MDT detector with an impulsive output charge of 5–100 fC, the time constant of the RC-CR shaper in the read-out channel can be set to 50 ns. Consequently, the BLR time for the TI-ToT case (assuming waveform decay down to 1% of the peak amplitude) is 380 ns, which is sufficient for the large-tube detectors with the maximum drift-time of 750 ns.

Although in small-diameter detectors, the maximum drift-time is reduced to 180 ns demanding high-data-rate read-out electronics. For the same shaper time constant of 50 ns, BLR time is reduced to 110 ns for the TV-ToT case, while TV-RE method requires only 44 ns BLR time. Assuming a reset phase of about 50 ns, the TV-RE method still enables an experiment data-rate of up to 10 MHz, which is sufficient even for the small-diameter MDT detectors.

5. Conclusions

In this paper, the trade-off between SNR versus data-rate for advanced read-outchannels is studied, using a traditional RC-CR transfer function as a benchmark with conventional time-invariant ToT method for input charge amplitude measurement. The intrinsic trade-off between SNR and data-rate in TI-ToT is significantly relaxed by innovative time-variant architectures. The presented rising-edge method outperforms TI/TV-ToT techniques with a substantial improvement of SNR versus data-rate trade-off.

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Abbreviations

The following abbreviations are used in this manuscript:

LHC	Large Hadron Collider
MDT	Monitored Drift Tube
sMDT	Small-Diameter MDT
SNR	Signal-to-Noise-Ratio
ASD	Amplification-Shaper-Discriminator
CSP	Charge-Sensitive-Preamplifier
BLR	Baseline Recovery
EM	Event Measurement
PTD	Peaking-Time-Delay
ТоТ	Time-over-Threshold
TI	Time-Invariant
TV	Time-Variant
TI-ToT	Time-Invariant Time-over-Threshold
TV-ToT	Time-Variant Time-over-Threshold
RE	Rising-Edge
TV-RE	Time-Variant Rising-Edge
PW	Pulse-Width
SNR _{RE}	SNR of Rising-Edge Pulse-Width
SNR _{ToT}	SNR of Time-over-Threshold Pulse-Width
SD	Standard Deviation

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