

Method for expanding the dynamic range of the analog-to-digital path of jitter analyzers in fiber-optic transmission systems

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ABSTRACT

The analog-to-digital path represents one of the key components in signal jitter analyzers used in fiber-optic transmission systems, significantly defining their performance limits in terms of dynamic range. To enhance the dynamic range of such analyzers, a technique involving random switching between conversion channels within the analog-to-digital path has been proposed, followed by frequency-domain processing of the output signals. A structural diagram of a parallel analog-to-digital path incorporating random channel switching has been developed. The efficiency analysis of the proposed method demonstrates that it enables an extension of the dynamic range of an 11-bit parallel analog-to-digital path by 8 to 14 dB, depending on the level of timing instability present in the output signal of the converter.

Keywords: fiber-optic transmission systems, jitter analyzer, analog-to-digital path, dynamic range, signal jitter, time instability, digital spectrum

1. INTRODUCTION

In modern fiber-optic transmission systems (FOTS), signal jitter is one of the primary challenges encountered during both the design and operation phases. To ensure high-quality communication, it is essential to evaluate jitter at the output of each digital component within the FOTS¹. At the same time, the advancement of new fiber-optic technologies imposes increasing demands on the efficiency of jitter evaluation in such systems^{2,3}.

A key factor determining the efficiency of jitter evaluation in FOTS is the quality of the signal processing path used for jitter analysis. Jitter parameters can span a wide dynamic range². The analog-to-digital path (ADP), which constitutes one of the most critical components in both current and next-generation jitter analyzers for FOTS, significantly defines their performance limits in terms of both speed and dynamic range³. Therefore, improvements to the ADP in jitter analyzers focus on increasing the bandwidth of the converted signals as well as expanding the dynamic range. In recent years, however, the landscape of high-speed analog-to-digital converter component offerings has changed dramatically. A rapid breakthrough is underway in the development of ultra-high-speed analog-to-digital converters⁴. As a result, developers of jitter analyzers for FOTS are increasingly concentrating on enhancing the dynamic range of the ADP.

High-speed ADPs used in jitter analyzers for signals in FOTS employ a method of parallelizing analog-to-digital conversion channels, followed by their multiplexing at the output processing stage. This method involves the use of multiphase sampling across M parallel-connected analog-to-digital conversion channels, which makes it possible to increase the sampling rate of the parallel ADP by a factor of M ⁵. In ADP built on the basis of parallel-connected analog-to-digital channels, the sampling of the input signal is accompanied by uncontrolled timing delays in the parallel ADPs. The instability of these timing delays in each analog-to-digital conversion channel results in the degradation of the noise characteristics of such converters. As a result, these timing instability errors in the ADP output signal lead to a reduction of the actual dynamic range of the ADP⁶. The development of jitter analyzers for signals in FOTS underscores the relevance of studying parallel ADPs with an extended dynamic range^{6,7,8}.

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The study of timing instability errors in the output signal of high-speed parallel-type ADPs is the focus of research⁷ that has demonstrated that the timing uncertainty of output signals affects the effective number of bits of the ADP, and that as the operating frequency bandwidth expands, the dynamic range of high-speed analog-to-digital converters deteriorates. The works^{8,9} present methods for correcting timing instability errors in the ADP output signal. It should be noted that the accuracy of such correction is limited by the time interval during which the timing instability values of individual channels in parallel ADPs are estimated. To improve the dynamic range of parallel ADPs, this study proposes the use of a random channel switching mode for analog-to-digital conversion channels^{10,11,12}. Moreover, the methodology of correcting output signal timing instability in the frequency domain using random channel switching appears more promising and may provide a broader dynamic range for parallel ADPs used in jitter analyzers for FOTS. The aim of this work is to expand the dynamic range of ADPs in jitter analyzers by using random channel switching, followed by output signal processing in the frequency domain^{13,14,15}.

2. MATHEMATICAL MODEL OF THE ADP OUTPUT SIGNAL IN THE FREQUENCY DOMAIN

In the classical structure of a parallel ADP, M conversion channels are used, each characterized by a sampling period of MT_s . On the ADP output bus, the output signal samples $y[n]$ are generated with a sampling period of T_s . When random channel switching is applied, in order to maintain the minimum sampling period T_s , it is necessary to add R additional conversion channels to the ADP structure. The structure of the analog-to-digital conversion process demonstrating the principle of random channel switching is shown in fig. 1. In this case, $M = 2$ and $R = 1$, meaning that one additional conversion channel is used so that the sampling interval T_s is not limited. In the first two clock cycles, the ADP channels operate sequentially: first ADP1, then ADP2. In the third cycle, either ADP1 or ADP3 can be connected, and in the fourth cycle, if ADP1 was used in the previous cycle, either ADP2 or ADP3 can be connected.

ADP1	ADP2	ADP1	ADP2
			ADP3
		ADP3	ADP1
			ADP2
I	II	III	IV
Sampling intervals			

Figure 1. Structure of the Analog-to-Digital Conversion Process with Random Switching of ADP Channels

To analyze the output signal spectrum of an ADP with random channel switching, let us consider the well-known expression for the output signal of a parallel ADP characterized by timing jitter errors Δt_m in each conversion channel¹¹

$$Y(e^{j\omega T_s}) = \frac{1}{T_s} \sum_{k=-\infty}^{\infty} F_k \left[j \left(\omega - \frac{k\omega_s}{M} \right) \right] X_a \left[j \left(\omega - \frac{k\omega_s}{M} \right) \right], \quad (1)$$

$$\text{where } F_k(j\omega) = \frac{1}{M} \sum_{m=0}^{M-1} e^{-j\omega \Delta t_m} e^{-jkm\omega \frac{2\pi}{M}}.$$

The presented expressions allow us to assert that the digital spectrum of the output signal of a parallel ADP contains M groups of frequency components, which overlap and are uniformly distributed along the frequency axis, making it impossible to separate the input signal components from the parasitic spectral components. An ADP with random

channel switching generates a sequence of samples $z_n \in [0, 1, \dots, M + R - 1]$. The total number of ADP samples depends on the size of the output buffer memory and is equal to

$$N = (M + R)L. \quad (2)$$

Taking this into account, the transfer function of the ADP in the frequency domain takes the following form:

$$F_k(j\omega) = \frac{1}{N} \sum_{n=0}^{N-1} e^{-j\omega \Delta t_{z_n}} e^{-jkn\omega \frac{2\pi}{N}}. \quad (3)$$

It is necessary to shape the spectrum of the output signal of the parallel ADP in such a way that, during further processing in the frequency domain, conditions are created for suppressing groups of parasitic spectral components. Let us represent expression (3) using the first two terms of the Taylor series expansion:

$$F_k(j\omega) = \delta[k] - \frac{j\omega}{N} \sum_{n=0}^{N-1} \Delta t_{z_n} e^{-jkn\omega \frac{2\pi}{N}}, \quad (4)$$

where $\delta[k]$ – the discrete impulse function in the frequency domain.

Taking into account the symmetry of the digital signal spectrum with respect to the central frequency, the size of the analyzed array can be reduced by half. Expression (4) can then be written in the following form:

$$F_{N/2}(j\omega) = -\frac{j\omega}{N} \sum_{n=0}^{N/2-1} (\Delta t_{z_{2n}} - \Delta t_{z_{2n+1}}). \quad (5)$$

From the entire group of available channels of the parallel ADP: $[0, 1, \dots, M + R - 1]$, we construct two subgroups with corresponding timing jitter errors Δt_{m_a} and Δt_{m_b} . The size of each subgroup is $0,5 \cdot (M + R)$. Assuming that all even indices z_{2n} are elements of subgroup $\mathbf{a}$, and all odd indices z_{2n+1} are elements of subgroup $\mathbf{b}$, expression (5) can be represented in the following form:

$$F_{N/2}(j\omega) = -\frac{j\omega}{N} \sum_{m=0}^{\frac{M+R}{2}-1} (\Delta t_{m_a} - \Delta t_{m_b}). \quad (6)$$

From expressions (5) and (6), it is evident that $F_{N/2}(j\omega)$ is determined by the difference between the total timing jitter errors of the channels in subgroup $\mathbf{a}$ and those in subgroup $\mathbf{b}$. It should be noted that forming the subgroups requires only an approximate estimation of the ADP channels timing jitter errors, so the error estimation process itself does not require significant time. The structure of the analog-to-digital conversion process with random channel switching and the formation of two channel groups with corresponding timing jitter errors is shown in fig. 2.

ADP1a	ADP2b	ADP1a	ADP2b
			ADP3b
		ADP4a	ADP2b
			ADP3b
I	II	III	IV
Sampling intervals			

Figure 2. Structure of the Analog-to-Digital Conversion Process with Random Switching and Formation of Two ADC Channel Subgroups

In this case, the ADC channels operate alternately: first from subgroup *a* , then from subgroup *b* . Fig. 3,a shows the output signal spectrum of the parallel ADC in the deterministic channel switching mode, while fig. 3,b shows the spectrum for the random switching mode with the formation of two channel subgroups.

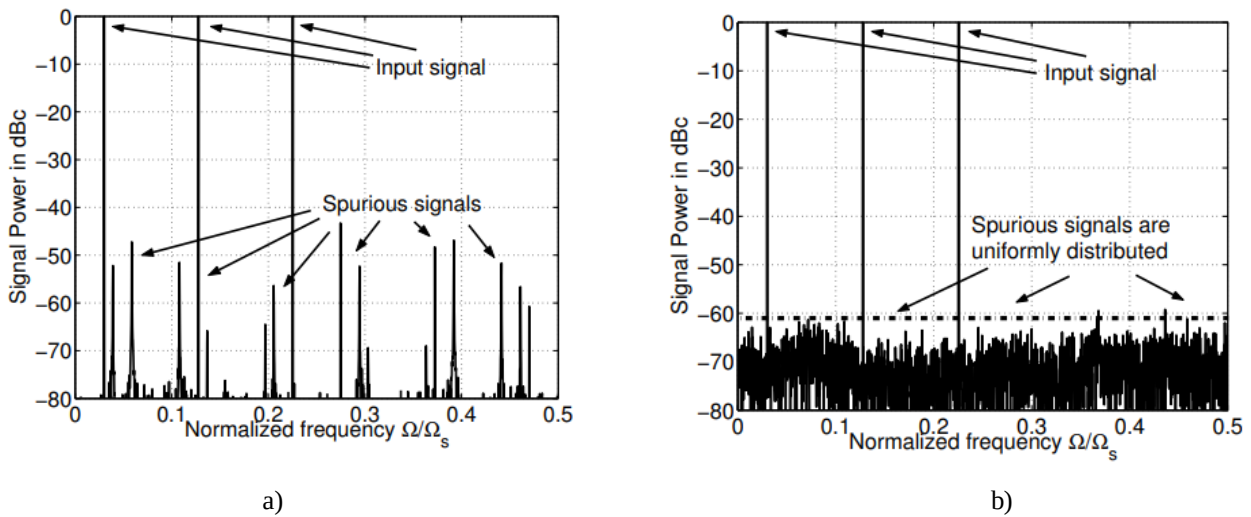


Figure 3. The spectra of the output signal of a parallel ADP

The spectrum of the output signal of a parallel ADP contains three harmonic components of the input signal and a number of spurious components caused by timing jitter errors (fig. 3,a). The output spectrum of the ADP will include N overlapping groups of frequency components, with the center of each pair spaced T_s/N apart from the center of the next pair. The number of spectral component pairs along the frequency axis from $\omega_{\min} = 0$ to $\omega_{\max} = 0,5\omega_s$ depends on the number N of ADP channels. In the mode of random switching and the formation of two subgroups of ADP channels, the power of the spurious components in the output signal is reduced and becomes more evenly distributed along the frequency axis. To suppress these components, it is proposed to use a low-pass filter on the output bus of the parallel ADP.

3. STRUCTURE OF A PARALLEL ADC WITH RANDOM CHANNEL SWITCHING

Fig. 4 shows the block diagram of a parallel ADC with random channel switching.

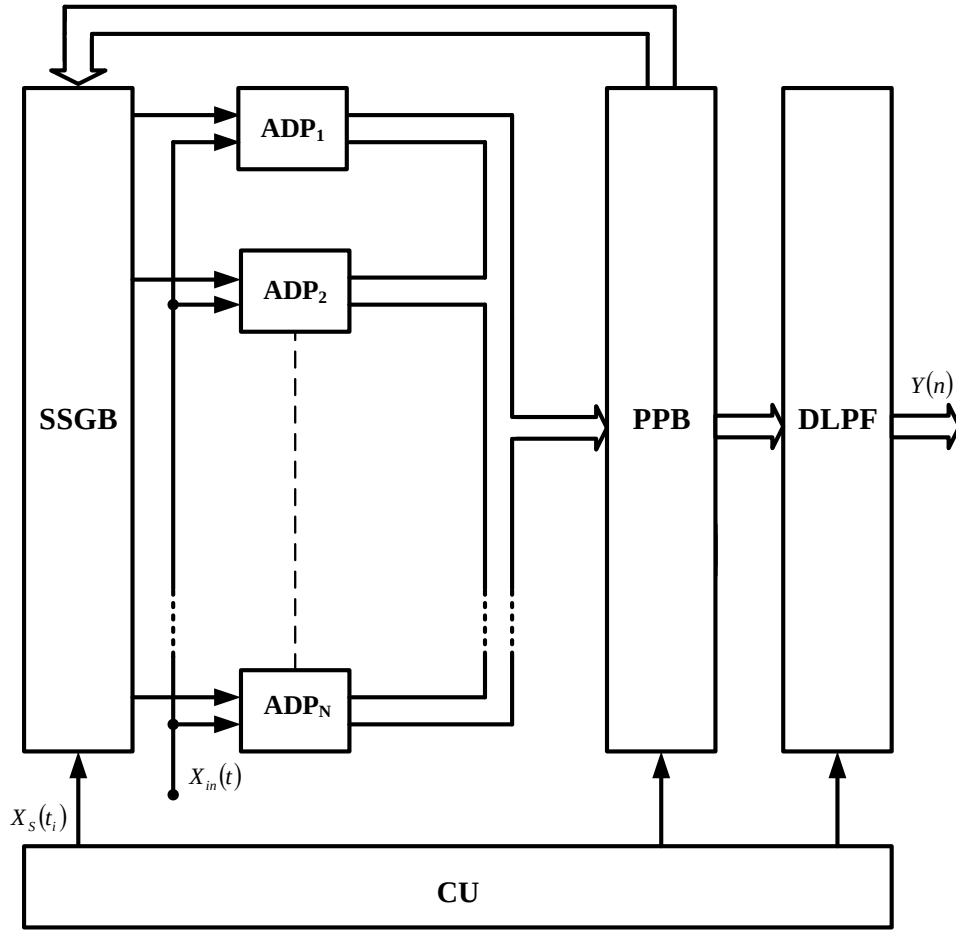


Figure 4. Block diagram of a parallel ADP with random channel switching

Sampling pulses $X_s(t_i)$ from the output of the Control Unit (CU) are fed into the Sampling Signal Generation Block (SSGB), where, according to a random law, sampling pulses are generated for each ADP channel. The output signals from the analog-to-digital conversion channels (ADP1...ADPN) are sent to the Primary Processing Block (PPB), which performs a rough estimation of timing jitter values. These values are then fed back through a feedback loop to the control input of the SSGB. Final signal processing and the formation of its spectral characteristics are carried out using a Digital Low-Pass Filter (DLPF), from which the digital signal $y[n]$ is sent to the output bus of the ADP.

4. ANALYSIS OF THE DYNAMIC RANGE OF THE PROPOSED PARALLEL ADP

Let us analyze the dynamic range of the proposed parallel ADP. The expression for estimating the dynamic range of an n -bit ADP with timing jitter correction is known¹²:

$$D_T = 6,02n - 20 \lg \frac{1}{m_t} - 10 \lg \frac{4\pi^2(N-1)}{N} + 1,8, \quad (7)$$

where $m_t = \frac{\Delta t_s - \Delta t_m}{\Delta t_s}$ – the relative timing jitter of the ADP output signal, Δt_s – the nominal time delay of the ADP output signal.

Based on the obtained expression, it is possible to plot the dependence of the dynamic range of an 11-bit ADP on the number N of channels for different values of m_t . Fig. 5 shows these graphs for the case when a sinusoidal signal is applied to the input of the ADP.

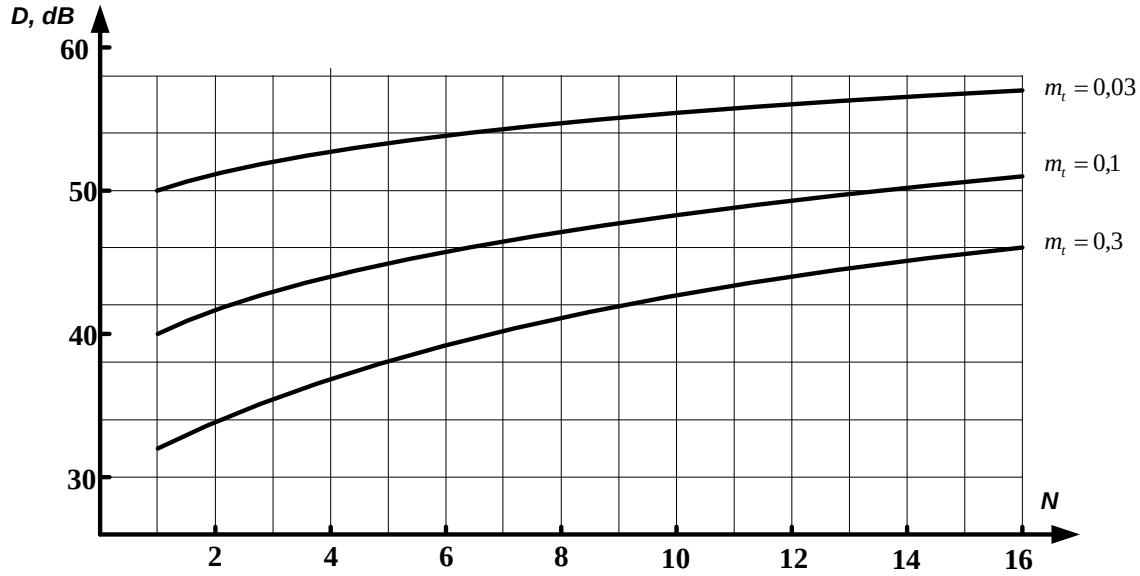


Figure 5. Dependence of the dynamic range on the number of ADP channels for a sinusoidal input signal

From fig. 5, it can be seen that as the number of ADP channels increases, the dynamic range improves. In the case where $m_t = 0,03$, this parameter increases from 50 dB for a 2-channel ADP to 58 dB for a 16-channel ADP. In the case where the relative timing jitter $m_t = 0,3$, an even better growth trend of the dynamic range is observed, specifically: from 33 dB to 47 dB.

5. CONCLUSIONS

This paper presents a method for improving the dynamic range of ADPs used in jitter analyzers for FOTS. It has been established that analog-to-digital conversion in multichannel parallel-type ADPs is accompanied by instability in the formation of output signal samples in the time domain. As a result, timing instability errors appear in the output signal of the parallel ADP. This leads to the emergence of spurious frequency components in the output signal spectrum of the ADP, which reduce its dynamic range. A solution is proposed that involves random switching of conversion channels with the formation of two subgroups of channels, followed by processing of the ADP output signal in the frequency domain. A structural diagram of the parallel ADP with random channel switching has been developed. An analysis of the efficiency of the proposed method confirmed that the developed approach allows for an increase in the dynamic range of an 11-bit parallel ADP by 8 to 14 dB, depending on the level of timing instability in the output signal of the converter.

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