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Sampled Analog Video Transport: High Accuracy, Zero Visible Compromise

Technology delivers 10× greater bandwidth efficiency than conventional display drivers, enabling future high-performance displays within existing power and cost constraints.

By **Alex Henzen, Todd Rockoff, Rob Hannebauer, and Siddhartha Chatterjee**

CONSUMER DEMAND FOR HIGHER RESOLUTION, FASTER frame rates, and greater color depth is driving video data rates beyond the capacity of conventional transport solutions. High-end displays, such as 4K gaming at 360 Hz or 8K TVs at 120 Hz, require multiple parallel data pairs per driver integrated circuit (IC), complex equalization, and sometimes data compression. These demands raise costs, power consumption, and system complexity. As the industry moves toward 8K at 120 Hz, 4K at 240 Hz, and advanced light-field displays, traditional video transport becomes increasingly strained.

HYPHY's Sampled Analog Video Transport (SAVT) addresses these bandwidth challenges by transmitting video information as accurately sampled analog levels rather than as streams of digital bits. By representing the equivalent of multiple digital values in a single transmitted level, the approach can significantly improve transport efficiency compared with conventional digital links. This provides several generations of headroom to accommodate future bandwidth requirements for high-performance displays.

The long-held consensus that video transfer must be free of bit errors is eroding as modern interfaces increasingly rely on techniques that introduce controlled errors, including compression in High-Definition Multimedia Interface (HDMI) links and in-panel processing. This shifts the comparison: Small analog transfer errors can now be evaluated alongside so-called "lossless" digital links and compressed digital streams.

Bit errors can arise anywhere and may affect any of the 10 transmitted bits, whereas compression artifacts typically distort groups of pixels (e.g., visible as Moving Picture Experts Group [MPEG] block errors). In contrast, analog-transfer errors mainly influence only the lowest-order bits of a single pixel. The frequency and impact of these defects are examined later.

Perceived Image Accuracy

In data networking, even a single bit error in a symbol stream is typically unacceptable because the transmitted data must be preserved exactly. Human visual perception, however, is far more tolerant of small inaccuracies. Double-blind studies[1] have shown that one video signal may be measurably superior to another while still appearing indistinguishable to even attentive viewers. As a result, designing video transport systems to meet bit-perfect requirements may impose bandwidth, power, and complexity overheads that deliver little or no perceivable benefit.

More specifically, the acceptable error rate for digital communication is effectively zero; even a 1 part per billion (ppb) error rate can cause critical failures within seconds. By contrast, a 1-ppb error rate in a video stream would produce only one incorrect subpixel every 40 frames on a 4K display, which would be imperceptible. Even a 1 percent random error rate can still yield good video quality.

To quantify the effects of imperfect video transmission and compare the visual impact of errors, digital and SAVT video signals were sent through identical channels, allowing the resulting inaccuracies—and their visual consequences—to be directly compared.

In a traditional digital signal, interference that reduces the bit-eye opening (the time where the difference between logical "1" and logical "0" can be discerned without ambiguity) to the point where the receiver can no longer reliably detect the bit state—typically at approximately 30 percent of the signal level—can cause loss of synchronization, requiring several frame intervals for recovery.

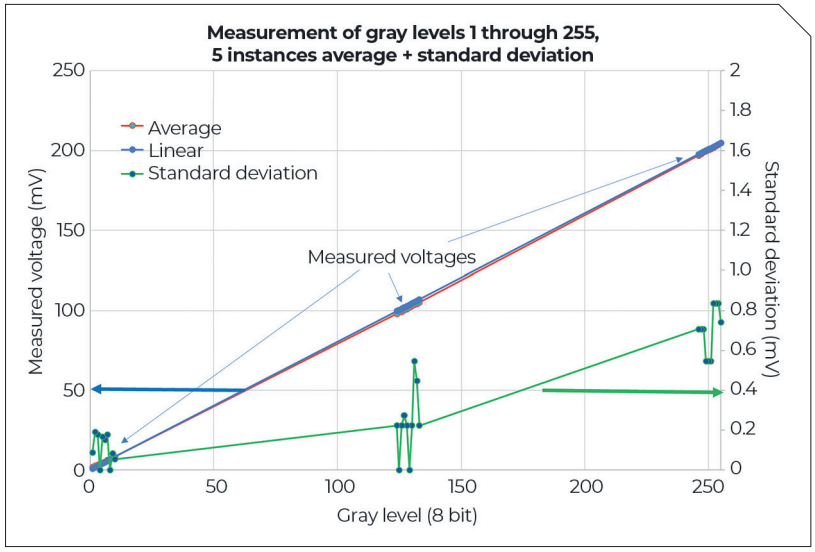

Fig. 1.

► Measured signal levels of a SAVT stream.

In a SAVT signal, even an error large enough to shift a subpixel value by 100 percent affects only that single subpixel during a one frame interval. The correct value is restored in the next frame, synchronization is maintained, and the error remains imperceptible to the viewer.

Electro-Optical Transfer Function Optimization

In current display architectures, the electro-optical transfer function (EOTF) and gamma correction are typically implemented within the display driver IC (DDIC) using a resistor-ladder digital-to-analog converter (DAC) with a set of nonlinearly spaced reference voltages. This approach has limitations:

- The number of reference voltages is typically limited to 18.
- The interpolation between the reference points is usually linear.
- The reference voltages are usually hard-wired, although some metadata-driven exceptions exist.

SAVT technology takes a different approach by performing the digital-to-analog conversion at the transmission end of the chain rather than in the DDIC. As a result, EOTF and gamma correction can be applied with the same accuracy as the DAC, enabling reproduction of the display transfer function with accuracy exceeding 12 bits and reducing the limitations imposed by conventional reference-voltage architectures.

Pre-Compensation for Wiring Harness Electromagnetic Propagation Errors

When an analog signal is applied at the input terminal of a wiring harness, impedance discontinuities can introduce attenuation and reflections that are observable at the harness output. Because these effects are deterministic and unchanging, they can be accurately characterized and compensated for, allowing the signal path to be adjusted so that any distortion does not affect the sampling timing or voltage levels of the SAVT DDIC. Disturbances occurring outside the sampling window are therefore excluded from the recovered signal and have no impact on the displayed image. In contrast, such prefiltering is impossible in conventional digital transmission due to its higher speed and the lack of a reference channel.

Results

Improved Video Transport Principle: Perceived Image Accuracy

To evaluate the impact of transmission errors on image quality, a system model was created that combines basic signal-transmission equations, information theory, and models of visual perception. A transmission-line model of the electrical circuitry estimates attenuation, transient shapes, and the effects of interference sources such as thermal noise and power-supply fluctuations. These electrical-transmission deviations are then used to calculate symbol error rates, demonstrating the resilience of SAVT technology to channel-induced distortions. Finally, visual perception models account for the low-pass filtering characteristics of the human eye, translating electrical errors into perceived image accuracy across the operating conditions of current and future display systems.

To confirm the reproduction of exact voltage levels, verification measurements were initially conducted using an oscilloscope. However, the required accuracy is beyond the reach of most measurement devices of this type because the noise at the input amplifiers exceeds the signal levels being measured. Instead, a spectrum analyzer was used in combination with a dedicated test signal that alternates between 0 V and the voltage to be measured. This approach enabled measurement accuracy limited only by the noise floor, typically on the order of several tens of microvolts (**Fig. 1**).

Simplified Gamma Implementation Greatly Improves Reproduction of EOTF

Existing LCD technologies have markedly different transmission–voltage (T–V) curves, requiring technology-specific compensation to achieve a linear optical response. Twisted nematic, vertical alignment, and in-plane switching panels each need distinct correction curves. Although partial compensation can be implemented using multiple gamma reference voltages within the DDIC, a complete correction would require a unique reference level for every pixel value—256 support voltages for an 8-bit system. Furthermore, each color channel would exhibit slightly different optical responses due to wavelength-dependent variations in the refractive index.

HYPHY implements per-primary EOTF and gamma correction with 4,096 levels of precision, enabling unprecedented color accuracy and efficient light transmission.[2] This advantage can be seen using a multidomain vertical alignment (MVA) LCD (**Fig. 2**).

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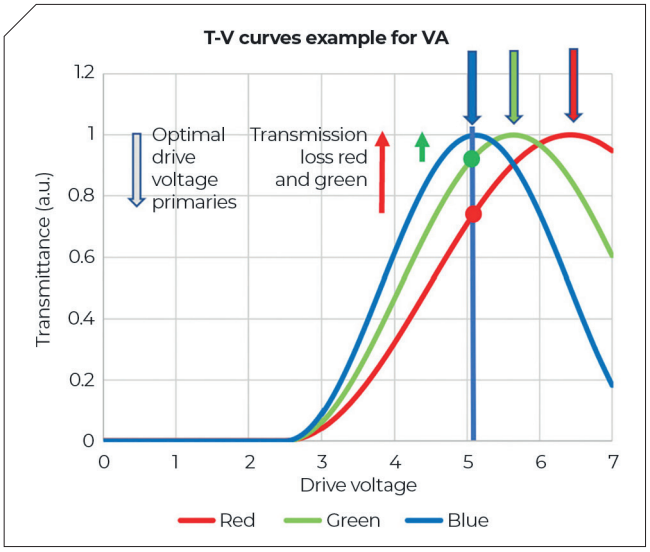

When a single EOTF is applied to all three color channels, the transfer function is constrained to a single monotonic region of the T–V curve (blue arrow and red and green dots), limiting the usable portions of the red and green response curves.[3] By contrast, separate EOTF curves for the red, green, and blue primaries allow each channel to operate across a larger region of its respective T–V characteristic. The result is higher total transmission and better efficiency.

Prefiltering and Correction for Wiring Harness Transmission Errors

Preprocessing the transmitted signal with finite impulse response (FIR) filtering in its digital form at the transmitter introduces minuscule adaptations. As a result, transmission-line distortions can be pre-distorted at the transmitter so that the correct value arrives at the receiver. Thus, for given differential traces and wiring-harness design, an inverse reflection filter can be applied to pre-distort the signal so that the reflections self-correct and present the proper value to the input of the DDIC. With this approach, the voltage amplitude sampled by the DDIC can achieve better than 1:1,000 accuracy.

Fig. 2.

◀ T–V curves of the MVA display at primary wavelengths.

In signal-processing terminology, *noise* generally refers to any unwanted component superimposed on the desired signal. These unwanted effects are made up of two main components:

- Statistical sources, such as Johnson and shot noise, typically on the order of 40 µV, that arise from inherent physical processes.
- Distortions in the signal, such as reflections, attenuation, and bandwidth restrictions.

These artifacts are controllable through manufacturing and pre-distorting the signal. The distinction is important: Noise is statistical, and distortion is not statistical.

Distortion introduces an interaction between manufacturing and the coefficients used in the FIR filter to pre-distort. For example, if a connector reflection occurs in the signal path at a critical point, such as during the sampling interval, the wiring can be adjusted to introduce a slight delay, moving the problematic reflection away from this critical area. This has no impact on volume manufacturing cost and simplifies the FIR filter design.

By doing this, we reduce these artifacts to linear, first-order artifacts that can be corrected using FIR filtering. The FIR filter operates at the video sample rate and is designed to compensate only those channel characteristics that influence the sampled signal value.

The objective is not to correct the complete waveform shape, which would be mathematically impossible. Rather, the goal is

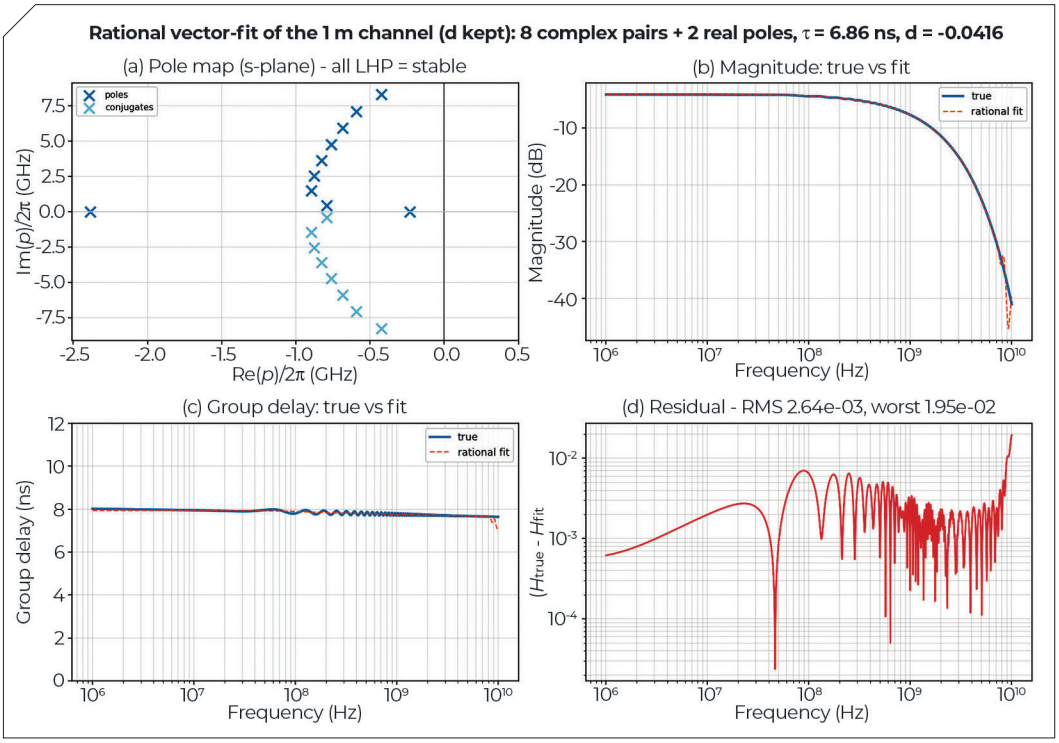

Fig. 3.

▶ Transmission-line transfer function and its rational approximation. (a) Pole map, (b) magnitude: true versus fit, (c) group delay: true versus fit, and (d) residual on magnitude.

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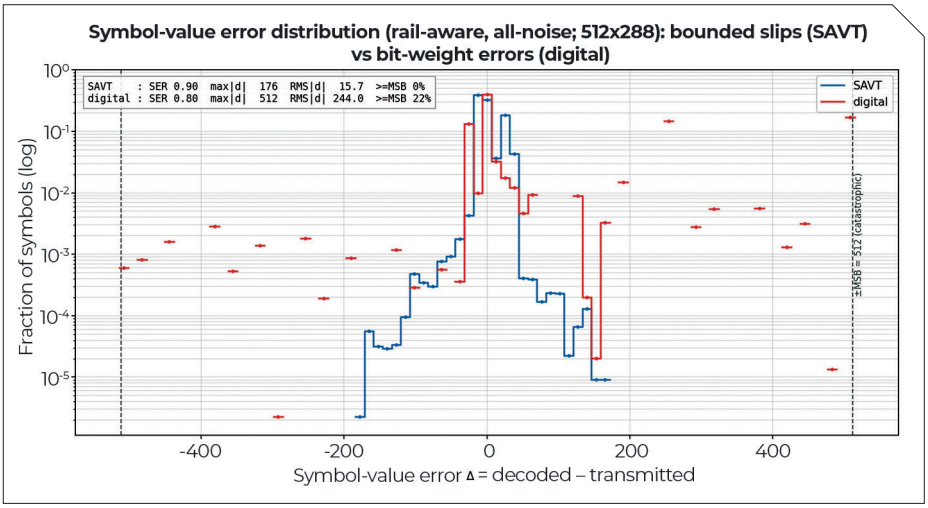

Fig. 4.

◀ Symbol errors on the reference image with all noise sources active, digital and SAVT.

to ensure that the signal at the point of sampling at the receiver is the intended transmitted value after transiting the channel.

Ab Initio Modeling and Simulation

To better understand the relation between unwanted and desired signals in both digital and analog systems, the video transmission system was modeled as an asymmetric differential coplanar stripline (ADCPS). To model the transmission line, the physical cross-section and material properties were translated into frequency-dependent per-unit-length resistance, inductance, conductance, and capacitance (RLGC) parameters.

- Dielectric substrate: a causal, wideband Djordjević–Sarkar dispersion model[4] yielding a Kramers–Krönig-consistent complex permittivity for the FR-4 substrate,[5] anchored to the specified relative permittivity (4.6) and loss tangent (0.02) at a 1 GHz reference. The resulting effective loss tangent, and hence the shunt conductance, varies with frequency rather than remaining constant.
- Conductor: a DC series resistance from the trace cross-section and bulk conductivity, plus a causal skin-effect contribution scaling as √f together with its associated internal inductance.
- Capacitance: the stripline self-capacitance to the upper and lower ground planes and the sidewall coupling to the adjacent coplanar guard traces, together with the inter-trace mutual capacitance of the differential pair; all scaled by the frequency-dependent permittivity.

The simulation builds a rational model by using vector fitting,[6] which is then implemented in the time domain through recursive convolution,[7] with computational complexity that scales linearly with stream length. The bulk delay is handled as an integer-sample shift buffer.

An 18-pole rational approximation is used to model the transfer function. The resulting model includes a direct feedthrough of −0.0416 and poles in the negative half-plane at frequencies from 250 MHz to 8 GHz. **Fig. 3** summarizes both the analytic characteristics of the transmission line and the fidelity of its rational approximation.

The parameters used in the full system model are shown in **Fig. 4**, along with the governing parameters of these sources. Five sources of noise and distortion were considered: thermal noise, supply ripple, code-division multiple access (CDMA) crosstalk, power delivery network (PDN) voltage droop, and power-supply-induced jitter (PSIJ). The corresponding simulation parameters are listed in **Table 1**.

Fig. 5 illustrates the end-to-end effect of the two systems, including a model of the human visual system (HVS). Perceptual error is evaluated using the just-noticeable-difference (JND) model of Zhang et al.[8] to show the perceptual error of the two schemes.

Although the simulation results should be interpreted as being directionally correct (indicative) rather than predictive, they illustrate the different characteristics of the two signaling modes and

Table 1.

▶ Corresponding simulation parameters.

Group	Parameter	Value
Channel	Transmission line	1 m differential stripline, FR-4
	Dielectric	rel. permittivity 4.6, loss tangent 0.02
SAVT	Modulation	PAM-1024 (10-bit amplitude), bipolar
	Symbol rate	400 MHz (2.5 ns UI), 10% rise
Digital	Modulation	Binary NRZ, 10 bits/symbol serialized
	Bit rate	4 GHz (250 ps UI), 10% rise
Hardware	Supply rail	±0.6 V, 25 Ω source
Noise	Thermal	300 K
	Supply ripple	30 mV at 100 MHz
	Crosstalk	-30 dB FEXT
	PDN droop	L 0.8 nH, C 5 pF, R 50 mΩ
	Sampling jitter (PSIJ)	5 ps/mV, supply-driven
Equalization	TX pre-emphasis	4-tap FIR (1 pre / 1 main / 2 post), rail-aware MMSE
	TX taps (SAVT)	[+0.01, +0.98, -0.01, +0.00]
	TX taps (digital)	[+0.13, +0.87, -0.09, -0.02]
	RX	Feed-forward + decision-feedback
Perceptual	Display	Relative luminance, $\gamma = 2.2$
	Error metric	Per-pixel error vs local just-noticeable difference

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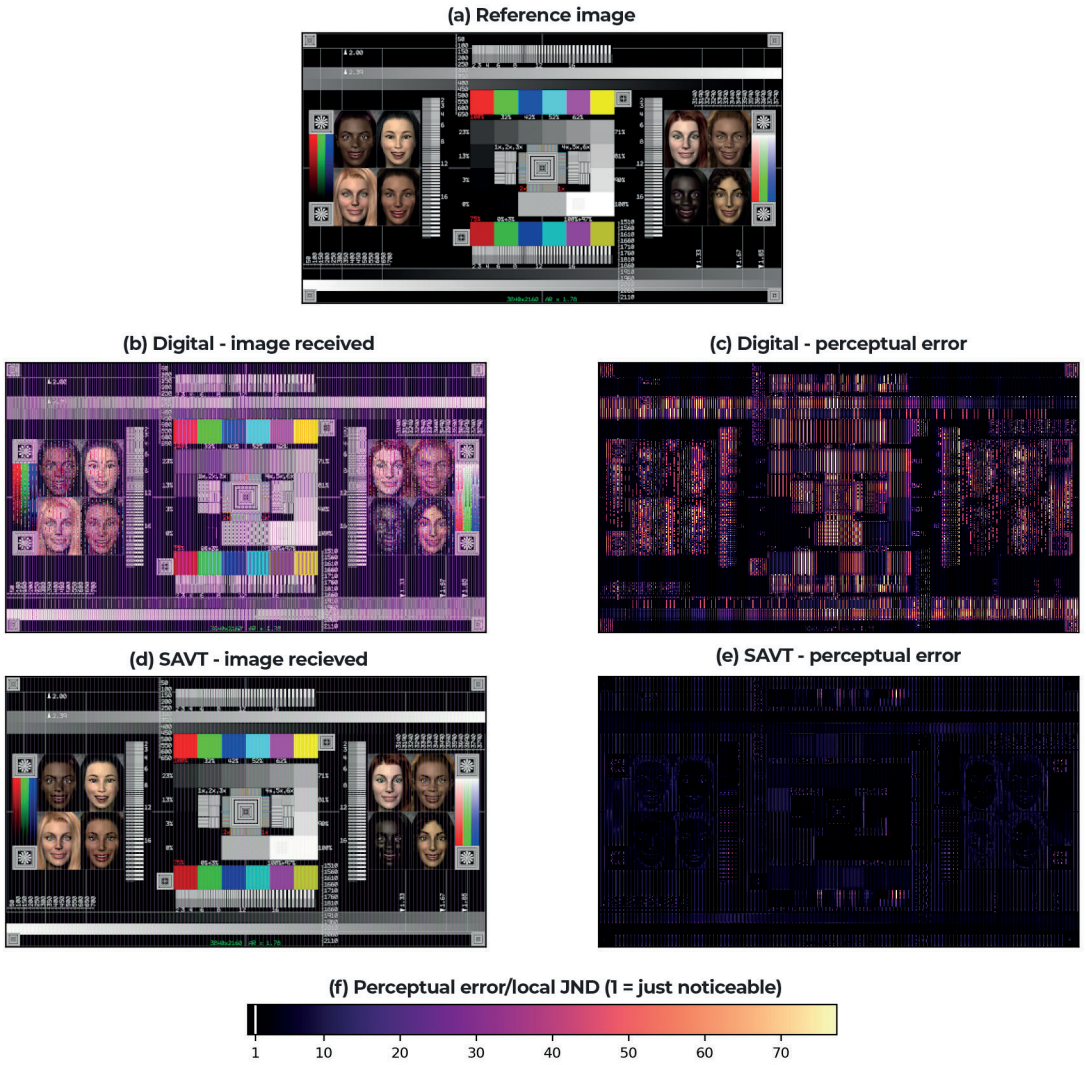

Fig. 5.

▲ Image transmission with all noise sources active. (a) Reference image at transmitter end. (b) Decoded image at receiver end, digital transmission. (c) Perceptual error at receiver end, digital transmission. (d) Decoded image at receiver end, SAVT. (e) Perceptual error at receiver end, SAVT. (f) Perceptual error color bar for (c) and (e).

how those differences influence the delivery of identical image data through the transmission channel.

Digital signaling employs two well-separated signal values but requires a signaling rate approximately 10× that of SAVT. Although the use of two well-separated levels generally makes digital systems robust to the voltage-induced noise sources, it also increases their susceptibility to timing impairments, such as PSIJ. Further, digital transmission errors are unbounded in symbol magnitude: The impact of an error depends on which bit is corrupted. Assuming random bit errors, every bit position is about equally likely to flip, but the effect scales with the weight of the flipped bit (1 MSB = 1,024 LSBs). Consequently, although digital errors may occur infrequently, their visual impact can vary dramatically depending on the affected bit position.

SAVT transmits data using 2^{10} discrete levels while operating at only one-tenth the rate of digital. This makes it more susceptible to voltage-induced errors than digital transmission. However, SAVT errors are magnitude-bounded. A level slip is overwhelming to an adjacent level because turning 15 into 31 requires an excursion of 16 levels, which is exponentially less likely than a ±1 slip.

Consequently, when errors occur in an SAVT system, they tend to be small and localized. The JND characteristics of the HVS further suppress these small errors, making the perceptual error concentrated at the 1-JND threshold. **Fig. 5c** and **5e** demonstrate the final perceptual error for both schemes. **Fig. 5f** shows the different distribution of symbol errors for the two schemes.

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Discussion

SAVT technology offers several advantages in display driving and color accuracy. The examples demonstrate that image transport to the DDICs is much more robust, and small errors—when present—have no perceptible impact on image quality. In addition, SAVT technology improves the accuracy of the column voltages applied to the LCD source drivers, enabling more precise reproduction of the intended optical output.

Color reproduction also benefits from the architecture. EOTF and gamma correction can be implemented with greater than 10-bit precision, providing more accurate mapping between input signal levels and displayed luminance. Optical efficiency is further improved through independent native EOTF optimization for each primary color channel, allowing the display to make more effective use of its transmission characteristics. Finally, SAVT technology has been shown to support reliable image transport over longer transmission distances than conventional digital display interfaces.

Conclusion

The results presented in this article suggest that SAVT technology offers an alternative approach to addressing increasing video bandwidth demands in high-resolution display systems. By reducing transmission-rate requirements while maintaining image fidelity, the technique has the potential to alleviate some of the constraints associated with conventional digital video transport.

The analyses and demonstrations indicate improvements in transmission robustness, signal accuracy, color reproduction, and optical efficiency. The approach also enables more precise EOTF and gamma correction, supports longer transmission distances, and may facilitate higher color depth, resolution, and frame rates without a corresponding increase in channel bandwidth requirements.

If successfully implemented in commercial products, SAVT technology could provide a practical means of improving video transport efficiency and display performance across a range of display technologies and applications.

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