KERPEN
DATACOM

WHITE PAPER
ZERO PEAK BANDWIDTH

Peak-Free Transmission Bandwidth for Reliable Multi-Gigabit Networks

www.kerpen-data.com

WHITE PAPER

ZERO PEAK BANDWIDTH (ZPB)

Effect of Attenuation and Impedance on PAM-16 Ethernet Transmission over Twisted Pair Copper Cables

Modern multi-gigabit networks rely on advanced modulation schemes such as PAM-16, which require stable and interference-free transmission over twisted-pair copper cables. These increasing demands call for a new generation of cabling technology. The quality of signal transmission depends largely on the physical properties of the cables used, particularly their attenuation and impedance characteristics across the relevant frequency range.

Technical Background

Ethernet Standards and PAM Encoding

With the introduction of 2.5GBASE-T, 5GBASE-T and 10GBASE-T, data transmission over twisted pair cables is approaching physical limits. These standards rely on multi-level modulation schemes such as PAM-16, which allows up to 4 bits per symbol. However, this increases sensitivity to reflections, attenuation fluctuations and inhomogeneities within the cable. Especially at higher frequencies, consistent impedance characteristics and a peak-free attenuation profile are essential to avoid signal distortion and bit errors.

Ethernet standards employ different modulation methods depending on the desired data rate and transmission technology. Likewise, the choice of cabling medium is decisive. An overview:

Standard	Speed	Recommended Cable	Modulation
100BASE-TX	100 Mbit/s	Cat.5	4B5B + MLT-3
1000BASE-T	1 Gbit/s	Cat.5$_e$ / Cat.6	PAM-5
2.5GBASE-T	2.5 Gbit/s	Cat.5$_e$ / Cat.6 / Cat.6$_A$	PAM-16
5GBASE-T	5 Gbit/s	Cat.6 / Cat.6$_A$	PAM-16
10GBASE-T	10 Gbit/s	Cat.6$_A$ / Cat.7 / Cat.7$_A$	PAM-16
25GBASE-T	25 Gbit/s	Cat.7$_A$ / Cat.8	PAM-16 (adapted)

Table: Overview of Ethernet Standards, Transmission Speeds and Modulation Methods

- -

- **100BASE-TX:** Does not use PAM but instead relies on 4B5B encoding combined with MLT-3 signaling. This technique is sufficient for transmission rates up to 100 Mbit/s but is not scalable to higher data rates.

- **1000BASE-T (1 Gbit/s):** Uses PAM-5, which transmits five discrete amplitude levels per symbol. This theoretically allows for the transmission of 2 bits per symbol. Additionally, certain signal states are reserved for error detection and correction (e.g., trellis coding). Transmission takes place symmetrically over all four twisted pairs, which increases receiver complexity but ensures efficient bandwidth utilization.

- **2.5G/5G/10G/25GBASE-T (2.5–25 Gbit/s):** These standards use PAM-16, i.e., 16 discrete amplitude levels, allowing the transmission of 4 bits per symbol. The increased number of levels enables higher data throughput within the same time period. However, the signal-to-noise ratio (SNR) becomes significantly more critical. The reduced amplitude spacing between individual symbols makes the signal highly sensitive to even minimal distortion, noise, or reflections, which can lead to symbol misinterpretation.

The choice of PAM-16 encoding is a response to the need for ever-higher data rates over existing, bandwidth-limited cabling infrastructures. However, this approach places high demands on:

- The linearity and symmetry of the transmission channel
- The temporal stability of the channel's impulse response
- The control and mitigation of inter-symbol interference (ISI)
- The receiver's ability to perform real-time error correction (e.g., LDPC codes in 10GBASE-T)

In particular, systems using PAM-16 require significantly more sophisticated digital signal processors (DSPs) for equalization, adaptive level calibration, and precise clocking and synchronization mechanisms. As a result, the demands on the physical quality of the cabling increase: consistent impedance profiles, minimal attenuation fluctuations, and low crosstalk are essential for reliable high-speed data transmission.

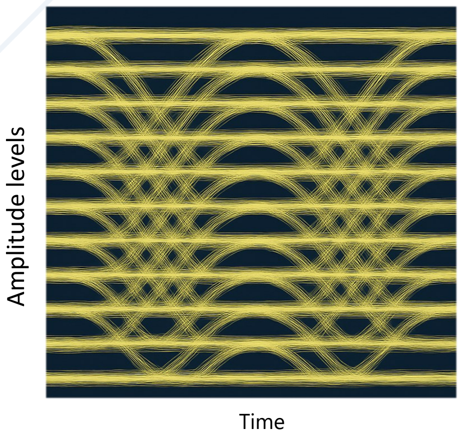


Figure: Example of an Eye Diagram for a PAM-16 Signal

Transmission Channel Requirements
For reliable transmission of PAM-16 signals, the following parameters are critical:

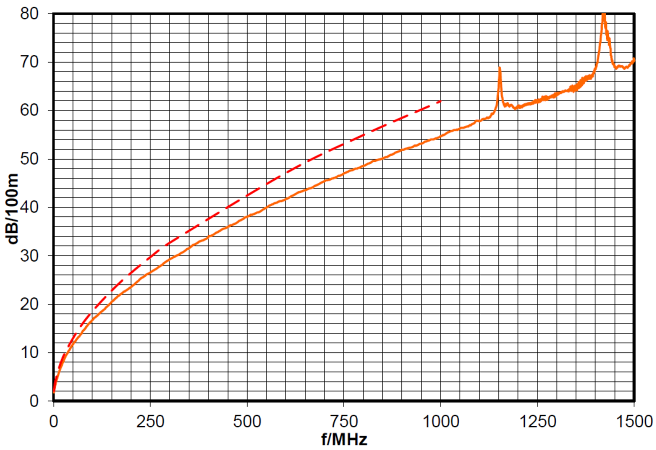
- **Signal-to-Noise Ratio (SNR):** A high SNR is necessary to reliably distinguish the narrow amplitude levels used in PAM-16 transmission.
- **Impedance Consistency:** Deviations from the characteristic impedance lead to reflections and signal distortion.
- **Attenuation Profile:** A consistent attenuation profile across the frequency range prevents selective frequency losses and inter-symbol interference (ISI).
- **Crosstalk (NEXT, FEXT):** Low near-end and far-end crosstalk between the wire pairs is essential for maintaining signal integrity.

Comparison of Two Category 7_A-Cables
Use Case: Two suppliers offer Category 7_A cables with a normative frequency limit of 1000 MHz. Cable A is specified up to 1500 MHz according to datasheet but shows significant peaks in the frequency range above 1000 MHz. In contrast, Cable B from KERPEN DATACOM GmbH, utilizing ZPB technology, guarantees peak-free transmission up to 1300 MHz.

Example Scenario:
In a direct comparison, two Category 7_A cables are evaluated. Particular attention is given to the data cable from KERPEN DATACOM GmbH featuring ZPB (Zero Peak Bandwidth) technology, which has been specifically optimized for peak-free high-frequency transmission.

Data Cable A (Supplier XYZ):

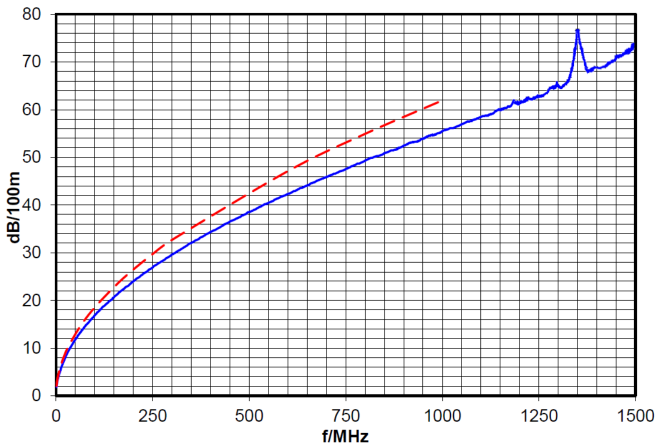
- Frequency range: Specified up to 1500 MHz, significant above the requirements for Category 7_A
- Measured performance: Displays several pronounced peaks in attenuation and impedance, particularly between 1000 and 1500 MHz, with noticeable resonance behaviour when changing frequencies
- Standards compliance: Compliant with Category 7_A in terms of maximum specified frequency (1000 MHz), but exhibits unstable transmission performance in critical frequency ranges



Data Cable A: Attenuation characteristic across the frequency range 1–1500 MHz

Data Cable B (KERPEN DATACOM GmbH with ZPB Technology):

- Frequency range: Specified up to 1300 MHz, clearly exceeding Category 7_A requirements
- Performance: Fully peak-free attenuation profile from 1 to 1300 MHz, no resonance effects, no frequency jumps
- Technological background: Based on ZPB technology, developed through AI-assisted optimization of twisted-pair data cables
- Unique feature: ZPB-optimized cables ensure not only compliance with standards but also superior high-frequency performance by eliminating peaks
- Measured performance: Linear, continuous attenuation profile without significant peaks.



Data Cable B: Attenuation characteristic across the frequency range 1–1500 MHz; peak-free performance up to approximately 1340 MHz enabled by ZPB technology.

In direct comparison, clear differences become apparent in the frequency-dependent performance characteristics: While Data Cable A exhibits significant irregularities in the upper frequency range between 1000 and 1250 MHz, the ZPB cable from KERPEN DATACOM GmbH demonstrates a largely consistent and stable attenuation profile. This has a particularly positive impact on signal integrity and system stability, especially in applications requiring high data rates from 10 Gbit/s onwards.

The peaks occurring in the upper frequency range of Cable A cause localized reflections and signal distortion. This significantly increases the likelihood of bit errors, especially with complex modulation schemes such as PAM-16, as used in 10GBASE-T. In practice, this means that although Data Cable A formally meets the standard, a noticeably higher bit error rate must be expected. As a result, transmission rates of 10 or 25 Gbit/s may prove unstable or cannot be reliably maintained. Consequences include renegotiation of link speeds, packet loss, or reduced overall system performance — particularly under high network loads or in critical real-time applications.

In professional network environments, such issues can lead to unexpected system outages, increased maintenance efforts, or even the need for costly retrofits.

Effects of Attenuation and Impedance Peaks

Peaks in attenuation and impedance — i.e., abrupt changes in the frequency-dependent transmission properties — have a direct impact on data transmission quality and are particularly critical in the context of high-bitrate modulation schemes such as PAM-16.

- **Reflections and Return Loss:** Impedance discontinuities cause partial reflections at points where the cable deviates from characteristic impedance. These reflected signals overlap with the original signal, resulting in constructive or destructive interference. The effects manifest as jitter and amplitude distortion in the received signal.
- **Distortion of the Channel Impulse Response (CIR):** A uniform impulse response is essential for low-loss transmission. Local maxima in attenuation within certain frequency bands affect group delay, leading to group delay distortion. This causes temporal smearing of the signal and leads to inter-symbol interference (ISI) as consecutive symbols overlap.
- **Reduced Signal-to-Noise Ratio (SNR):** Frequency-dependent losses caused by attenuation peaks selectively weaken certain spectral components. This locally reduces the SNR and impairs the decoding accuracy of the PAM-16 amplitude levels, whose narrow spacing allows only minimal noise margins.
- **Nonlinear Equalization Required:** To compensate for the distortions caused by peaks, complex adaptive equalizers must be used at the receiver. This significantly increases the complexity of digital signal processing (DSP), leading to higher power consumption and latency.

In summary, attenuation and impedance peaks lead to unstable and more error-prone transmission, especially at higher frequencies and with narrow symbol spacing as used in PAM-16. A peak-free transmission profile - as ensured by ZPB cables - makes a decisive contribution to the stability and efficiency of data transmission.

Benefits of a Consistent Frequency Response

A cable with a consistent attenuation and impedance profile exhibits uniform transmission behavior in the frequency domain, free from pronounced spectral fluctuations. This uniformity minimizes reflections (low return loss), reduces the need for complex equalization algorithms, and results in an improved channel impulse response, which is reflected in lower levels of inter-symbol interference (ISI).

In contrast, Data Cable A, with documented attenuation and impedance peaks, exhibits selective losses in specific frequency bands. These lead to locally degraded signal-to-noise ratio (SNR) and may cause asymmetric group delay. The resulting group delay distortion impairs the temporal resolution of the received symbols, which is particularly problematic for PAM-16 transmission, as the narrow amplitude levels are highly sensitive to signal distortion and require precise decoding.

The ZPB data cable from KERPEN DATACOM GmbH has been specifically developed to provide a uniform transmission characteristic across the entire frequency range up to 2000 MHz, free from significant peaks. This promotes symmetrical time-domain behaviour, stable impedance transitions, and consistent SNR conditions throughout the utilized spectrum.
From a physical perspective, this behaviour offers clear advantages in the following areas:

- **Stable Signal Transmission:** Consistent attenuation and constant impedance minimize reflected signal components and resonance effects.
- **Scalability of Data Rates:** The absence of spectral bottlenecks enables robust implementation of higher modulation schemes such as PAM-16 or even PAM-32.
- **Future-Proofing:** Cables with a flat, peak-free frequency response offer greater system margins and are therefore better suited for future Ethernet generations.

Visualisation: Eye Diagrams

Eye diagrams are a proven method for analysing and visualising signal quality in high-speed digital transmission systems. They represent an overlay of many individual bit or symbol transitions within a given time window and allow for a direct assessment of the quality of the physical transmission channel.

Significance of Eye Diagrams

The analysis of an eye diagram provides valuable insights into typical effects caused by attenuation and impedance disturbances, such as those resulting from peaks in the frequency response. An ideal transmission channel presents a wide-open eye with clearly separated amplitude levels (e.g., for PAM-16: 16 horizontal eye openings), stable transitions, and minimal jitter effects. This is indicative of high signal integrity, a favorable signal-to-noise ratio (SNR), and low inter-symbol interference (ISI).

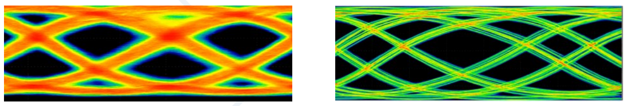


Figure: Eye Diagrams, The diagram on the left shows a PAM signal with a high bit error rate (BER), while the diagram on the right illustrates a PAM signal transmitted over ZPB-optimized twisted pairs, demonstrating significantly improved signal quality.

If irregularities occur within the transmission path — for example, due to attenuation peaks or impedance deviations — the eye openings progressively close. The amplitude thresholds become blurred, transitions lose sharpness, and signal overlaps occur. This is reflected in the eye diagram by blurred, noisy signals, asymmetric transitions, and ultimately a reduced eye opening.

The visual representation clearly demonstrates the impact of an inconsistent physical transmission path on the signal — regardless of whether these effects are caused by cables, connectors, or external disturbances. As a result, cable types like the ZPB cable, with ist consistent attenuation profile, can be verified by a stable and symmetrical eye diagram, whereas cables exhibiting pronounced peaks will show a significantly less stable representation.

WHITE PAPER

Technological Background of ZPB Data Cables

The Zero Peak Bandwidth (ZPB) technology was developed by KERPEN DATACOM GmbH as a technological response to the continuously increasing demands on data transmission capacity, driven by modern applications such as 10GBASE-T, 25GBASE-T, and future high-speed standards. The primary objective of this development was to achieve a transmission characteristic that ensures consistently high signal integrity beyond the normative frequency range, particularly with regard to frequency-dependent disturbances such as attenuation peaks and impedance discontinuities.

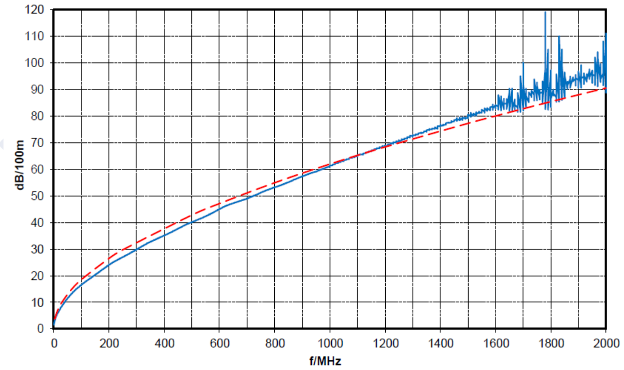
ZPB exceeds the requirements of conventional standards and establishes a new benchmark for quality: a continuously peak-free attenuation profile across the entire specified frequency range. The technology is based on scientific findings from a publicly funded research and development project, in which AI-based models were used to precisely control the frequency-dependent transmission characteristics.

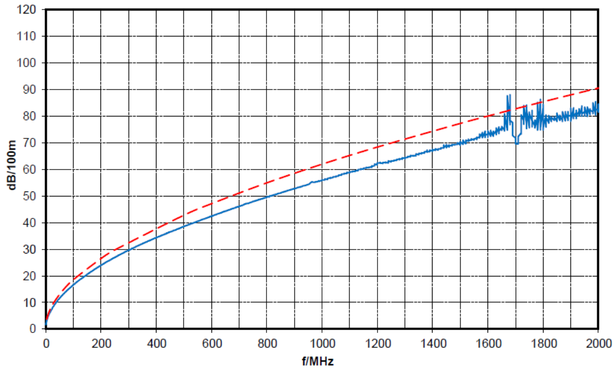
Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

The result is data cables for structured cabling with outstanding signal integrity, ideally suited for PAM-16-based Ethernet applications up to 25GBASE-T — and with future potential beyond.





These two diagrams illustrate the effectiveness of the Zero Peak Bandwidth (ZPB) technology within the development process.
Left: *The original attenuation profile of an AWG22 data pair barely meets the normative requirements up to 1000 MHz, but shows a noticeable increase in attenuation and distinct peaks beyond this range.*
Right: *Through targeted adjustments to lay length, capacitance, and impedance, the optimized data pair demonstrates a uniform, peak-free attenuation profile up to 1650 MHz — with up to 7 dB headroom compared to normative limits. This optimization is based on AI-based prediction models integrated into the development process.*

Conclusion

For high-speed Ethernet transmission using PAM-16 encoding, the choice of the right cable is critical. Cables with a consistent attenuation and impedance profile across the entire specified frequency range provide more reliable signal transmission, lower error rates, and greater future readiness. Therefore, the Zero Peak Bandwidth (ZPB) data cables from KERPEN DATACOM GmbH, with their guaranteed peak-free transmission performance up to 2000 MHz, represent the first choice for demanding Ethernet applications. They combine outstanding electrical properties with a reproducibly uniform frequency response, providing a robust and future-proof solution for modern network infrastructures. The high consistency of their transmission characteristics ensures error-free, stable data transmission without frequent interruptions, featuring low bit error rates (BER) and minimal packet loss. These cables are particularly suitable for professional users who prioritize stability, operational reliability, and sustainable performance of their network infrastructure.

Would you like to learn more about ZPB technology and the available cable variants?

Get in touch with us - via www.kerpen-data.com/en/sales-network/ by phone at +49 2402 17 1 or via email at info@kerpen-data.com.

V2 07-2025