APPLICATION NOTE

ANE025 | Signal Integrity – Loss Models for Internal Interfaces Connectors

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1. INTRODUCTION

In an ideal scenario, all electronics of a system can be integrated onto a single compact printed circuit board (PCB). In practice, however, designers often face constraints that make multiple PCBs necessary. In such cases, board-to-board connectors offer significant advantages due to their flexibility, mechanical robustness, and reliable signal and power handling capabilities. Board-to-cable-to-board (BTB) systems with flat cables allow a wider range of possibilities, supporting Human Machine Interfacex (HMI) and I/O panels away from the motherboards.

When two or more PCBs need to be interconnected, designers must select the appropriate connectors for their application. Given the large variation in available options, engineers must consider pin/pad counts, mechanical coding and the corresponding mating parts, housing style, mounting types (SMT vs. THT), and electrical specifications. A small consolation: The large number of variants allows great flexibility in PCB layout and placement. However, these nuances are often underestimated, and choosing the wrong connector can compromise the entire design—impacting form factor, signal integrity, or even long-term reliability in the field.

This application note examines key considerations when selecting such internal connectors, with a specific focus on signal integrity, then details their common applications.

Würth Elektronik offers BTB connectors with following pitches:

- WR-BTB 0.4 mm pitch High-Speed Low-Profile connectors series
- WR-BTB 0.5 mm pitch High-Speed connectors series
- WR-BTB 0.8 mm pitch Variable Mating Height connectors series
- WR-BTB 1.0 mm pitch Variable Mating Height connectors series

2. DESIGN CONSIDERATIONS

With the WR BTB series for high-speed applications, Würth Elektronik introduces precision manufactured BTB connectors in various configurations, distinguished by their high signal integrity. In particular, the 0.4 mm pitch series feature a very low-profile design, enabling it to reliably meet a wide range of requirements due to its small stacking height (0.9 mm height) allowing a very compact design.

Smaller pitches like 0.4 mm and 0.5 mm are significantly more demanding in terms of design and production. They require finer trace widths and spacings. This results in higher requirements for the PCB manufacturer, the assembly process (pick-and-place), and the soldering process. A pitch of 0.4 mm is often only realistically achievable with High Density Interconnect PCB (HDI PCB).

In contrast, larger pitches like 0.8 mm and 1.0 mm provide a bigger contact area, higher current-carrying capacity, and are more mechanically robust. The Würth Elektronik 1.0 mm BTB connectors series can be assembled with different mated heights, as well as the 0.8 mm pitch BTB connectors series which is available in different polarities.

3. TEST SETUP

Würth Elektronik engineers performed high frequency tests on the BTB connector series using customized test fixtures.

Measurements were carried out on specially developed test PCBs with 50 Ω (100 Ω differential) transmission lines. Calibration boards with exactly similar traces were also created to compensate for line losses and measured accordingly (Figure 1).

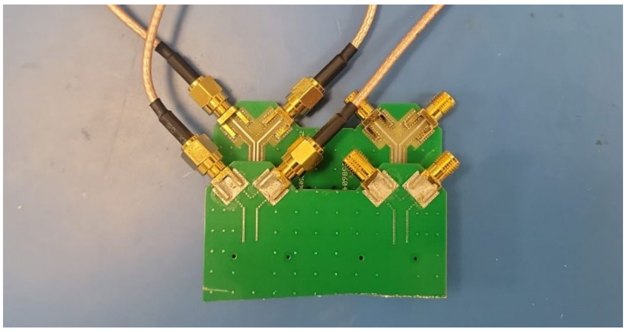


Figure 1: Test PCBs (left) and Calibration PCBs (right).

The test setup utilized a Rohde & Schwarz VNA ZVB 20 vector network analyzer with a frequency range from 10 MHz to 20 GHz (Figure 2).

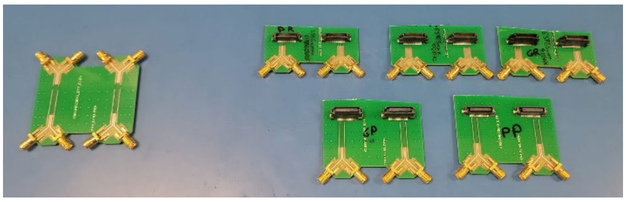


Figure 2: Test setup.

The input port is 1 (1 and 3 in differential mode) and the output port is 2 (2 and 4 in differential mode).

Return loss of the connector alone could not be isolated from fixture return loss in this test. A de-embedding procedure is planned for a future revision to provide S_{DD11}/S_{E11} connector-level data.

The signal characteristics described below apply to all pin positions except the outermost pins (Figure 2). It is recommended that these outer pins be assigned to low frequency signals, power rails, or ground return paths; an approach already implemented in many high-speed signaling standards.

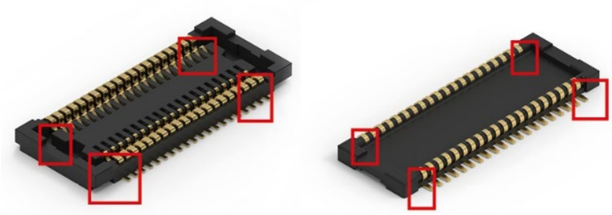


Figure 3: Outermost pins for BTB 0.4 mm.

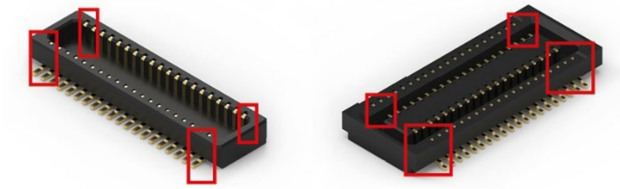


Figure 4: Outermost pins for BTB 0.4 mm and 0.5 mm connectors.

4. TEST RESULTS AND MODELS

4.1 Single mating distance

The loss models presented in this section are derived from measurements that include the contribution of the test fixture in addition to the connector itself. The calibration procedure compensates for the transmission line losses of the test PCB; however, residual fixture effects at the connector interface cannot be fully de-embedded with the current two-port setup. As a result, the models intentionally represent a conservative upper bound of connector insertion loss. This approach is suitable for system-level loss budget evaluation: a design that meets its loss budget using these models will have margin in practice.

The GSG (ground–signal–ground) single ended configuration assumes that the transmission path inside the connector consists of a signal pin (S) flanked by two ground or unrelated signal pins (G). In the GSSG (ground–signal–signal–ground) differential configuration, two adjacent pins (SS) form a differential pair, surrounded by two ground or unrelated signal pins (G) (Figure 5).

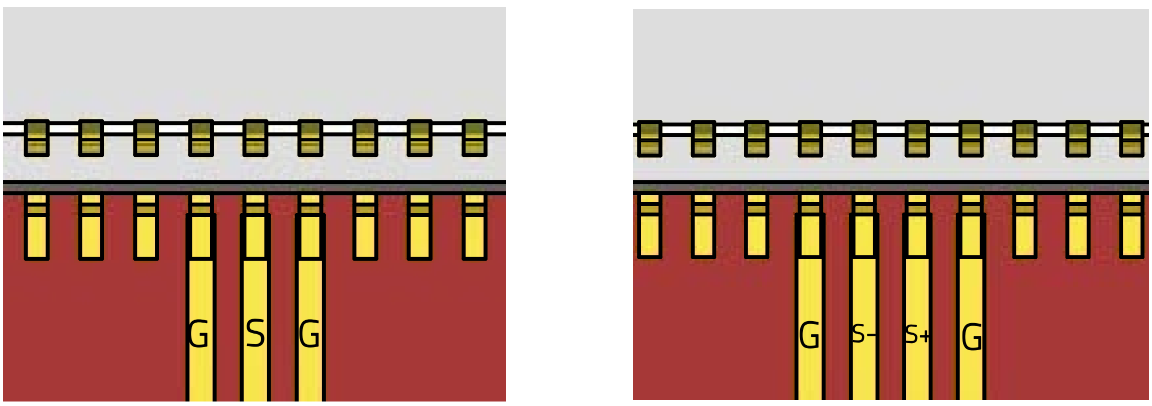


Figure 5: Ground-Signal-Ground (GSG) and Ground-Signal-Signal-Ground (GSSG) configurations.

These simplified pin-field configurations are used as representative measurement topologies and do not capture all routing-dependent coupling effects.

Note: Only insertion loss (S_{21}) is modeled in this test. Return loss (S_{11}) characterization at connector level is planned for a future revision.

Single-ended signaling

When testing a connector with a 50-Ohm transmission line in a GSG fixture, the insertion loss behavior can be approximated—using a conservative safety margin—by the equation:

$$IL(f) = Af^2 + Bf + C \qquad (1)$$

This quadratic approximation expresses the insertion loss (IL) dependence of the frequency f. The model intentionally overestimates losses slightly to allow conservative performance evaluation.

Parameter Explanation:

- C: constant term representing baseline DC loss, ideally near 0 dB but may include fixture offsets.
- Bf: linear term representing frequency dependent losses such as conductor losses and dielectric effects at low frequencies.
- Af^2: quadratic term representing dielectric losses, skin effect related losses, and dispersive effects.

The linear and quadratic terms capture the frequency-dependent increase in loss observed in measurement; they should be interpreted as empirical fit terms rather than as a strict separation of physical loss mechanisms.

As an example, using the following parameters (f in GHz), the values in Table 1 apply for the GSG configuration:

Profile	WR BTB 0.5 mm pitch
A	3.12×10^{-2}
B	4.61×10^{-1}
C	1.0×10^{-1}

Table 1: Parameter values for WR-BTB 0.5 mm pitch Serie (Single Ended).

Differential signaling

When tested in a 100 Ω GSSG differential fixture, insertion loss can again be approximated using as follows:

$$IL(f) = Af^2 + Bf + C$$

As an example, using the following parameters (f in GHz), the values in Table 2 apply for the GSSG configuration:

Profile	WR BTB 0.5 mm pitch
A	8.95×10^{-3}
B	0
C	1.84×10^{-1}

Table 2: Parameter values for WR-BTB 0.5 mm pitch series (Differential Signaling).

Attenuation curves

As a visual reference, attenuation curves can be used to easily compare the signal integrity of the connectors against the interface requirement:

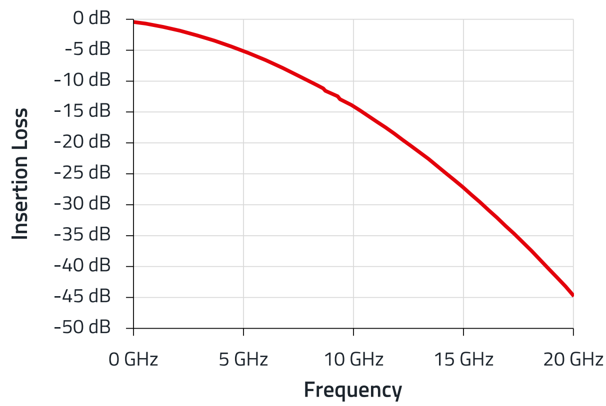


Figure 6: Attenuation curve of the 0.4 mm pitch BTB series in the GSG 50 Ω configuration.

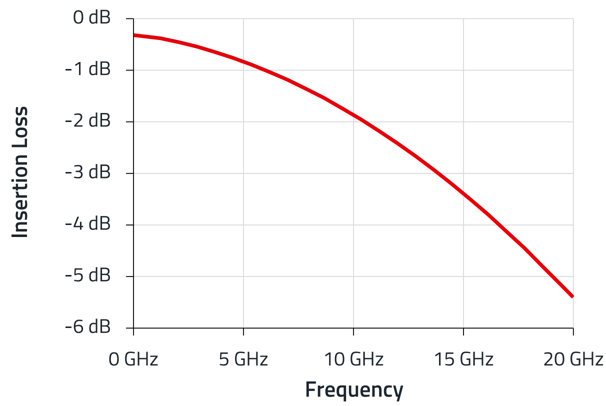


Figure 7: Attenuation curve of the 0.4 mm pitch BTB series in the GSSG 100 Ω configuration.

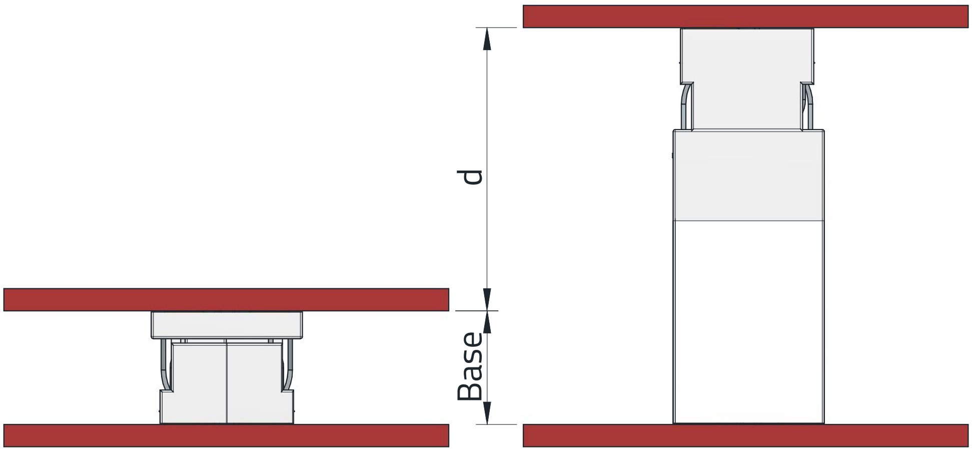


Figure 8: Variable mating height of the 0.8 mm pitch BTB connector series.

All that information can be found in the datasheets for each BTB connector series:

- WR-BTB Board-to-board 0.4 mm
- WR-BTB Board-to-board 0.5 mm

4.2 Variable mating distance

As mentioned in the introduction, and in Figure 8 shown, the WR-BTB connectors series with 0.8 mm and 1.0 mm pitches can be assembled with different mated heights. The lowest mated height possible of the WR-BTB 0.8 mm pitch is 5 mm, the highest is 20 mm. For the WR-BTB 1 mm pitch, the lowest mated height possible is 7.75 mm, the highest is 14.75 mm. This property allows designers to find the right mezzanine connector for their applications.

To consider the variable mating height in our model, we split the A, B and C values into 2 components: the value at the minimum mating height and the value of the increment. For both the 0.8 and 1.0 mm pitch series, the mating height increment is 1 mm. Each A, B and C value becomes then a A(n), B(n), C(n) function, n itself being the number of increments from the mating distance, or the difference between the minimum mating height and the desired mating height.

As an example, for a 5 mm minimum mating height series (WR-BTB 0.8 mm pitch):

$$IL(f) = (A_{5\,mm} + n \cdot A_{mm})f^2 + (B_{5\,mm} + n \cdot B_{mm})f + (C_{5\,mm} + n \cdot C_{mm}) \qquad (2)$$

where n = 0

For a mated height of 14 mm, n will be 9, so the model will be:

$$IL(f) = (A_{5\,mm} + 9 \cdot A_{mm})f^2 + (B_{5\,mm} + 9 \cdot B_{mm})f + (C_{5\,mm} + 9 \cdot C_{mm}) \qquad (3)$$

Using the test setup previously described, we measured the following parameters to use for the WR-BTB 0.8 mm pitch insertion loss model with f in GHz (Table 3 and Table 4). We can see that the C_{mm} parameter is at 0, which is normal as additional distance is supposedly free of fixture effects.

GSG Insertion Loss parameters			
...for 5 mm mated height		...for each additional 1 mm	
$A_{5\,mm}$	-1.45×10^{-2}	A_{mm}	7.51×10^{-4}
$B_{5\,mm}$	-4.87×10^{-1}	B_{mm}	-9.46×10^{-3}
$C_{5\,mm}$	-6.8×10^{-1}	C_{mm}	0

Table 3: Parameter values for WR-BTB 0.8 mm series (Single Ended Signaling).

GSSG Insertion Loss parameters			
...for 5 mm mated height		...for each additional 1 mm	
$A_{5\,mm}$	-1.08×10^{-2}	A_{mm}	8.50×10^{-4}
$B_{5\,mm}$	-6.55×10^{-2}	B_{mm}	-9.82×10^{-3}
$C_{5\,mm}$	-3.10×10^{-1}	C_{mm}	0

Table 4: Parameter values for WR-BTB 0.8 mm series (Differential Signaling).

Figure 9 and Figure 10 illustrate the corresponding attenuation curves for the WR-BTB connectors with 0.8 mm including the corresponding variable mating heights.

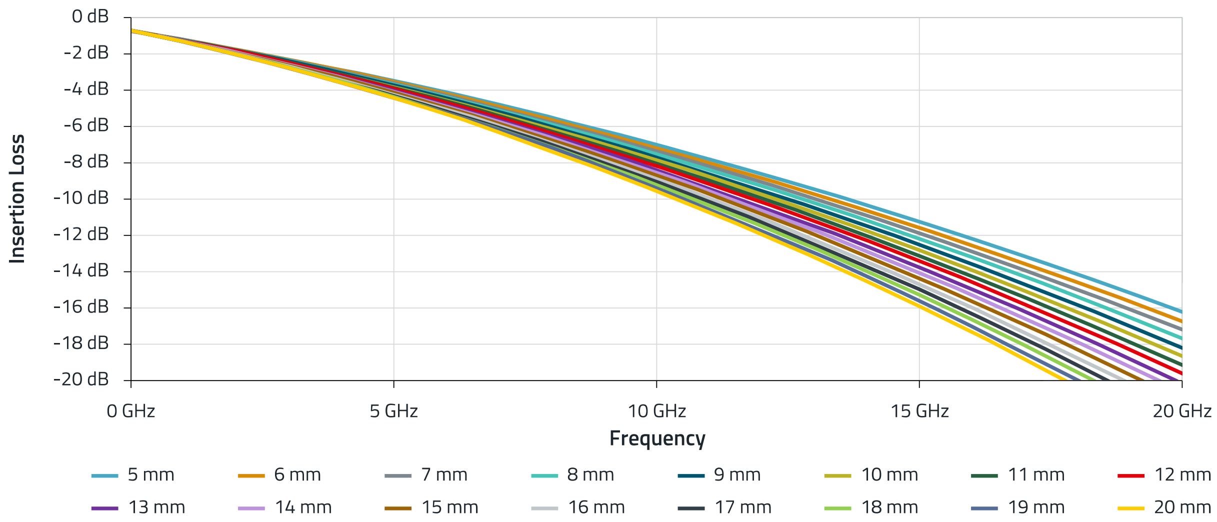


Figure 9: Attenuation curve of the WR-BTB 0.80 mm pitch GSG 50 Ω Insertion Loss profiles, viewing all variable mating heights.

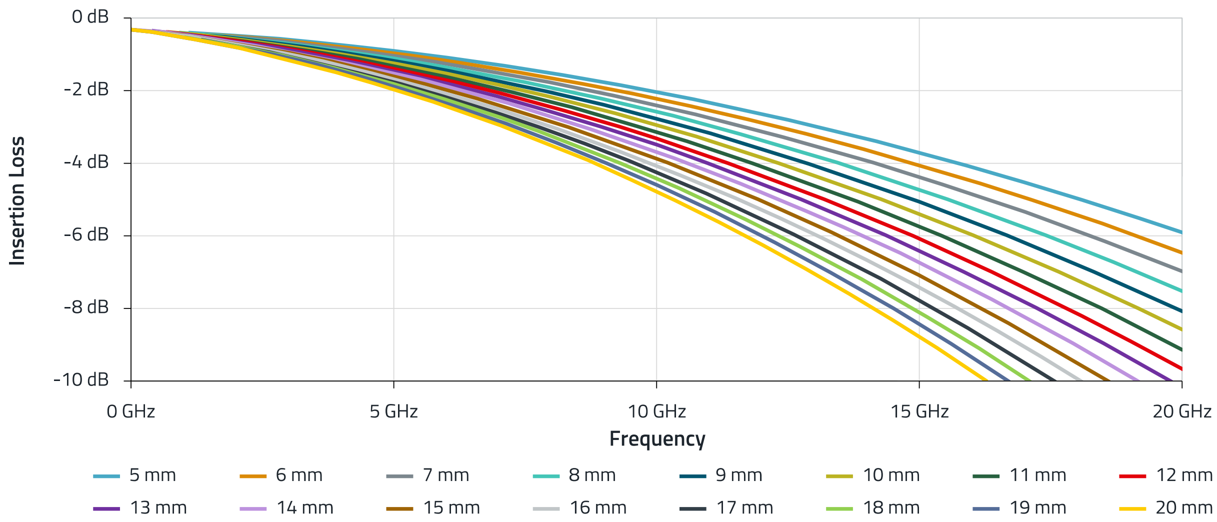


Figure 10: Attenuation curve of the BTB 0.80 mm pitch GSSG 100 Ω Insertion Loss profiles, viewing all variable mating heights.

All the information can be found in the datasheets for each mating height in the BTB connector series:

- WR-BTB Board-to-board 0.8 mm
- WR-BTB Board-to-board 1.0 mm

4.3 Right-angle board-to-board systems

Right-angle connection introduces another variable with a different pin design for each row. This section of the Application Note will later be expanded with the release of the WR-PHD series loss models.

4.4 Variable cable distance

Board-to-cable-to-board systems introduce a new problematic in this paradigm: the double connector/cable interfaces. This section of the Application Note will later be expanded with the release of the WR-FFC and WR-FPC series loss models.

4.5 Mixed cable/board-to-board systems

Mixed systems introduce another new problematic: the possibility of using the same PCB connector for board-to-board or board-to-cable-to-board. This section of the Application Note will later be expanded with the release of the WR-MM and WR-CAB series loss models.

5. COMPATIBILITY WITH DIGITAL SIGNAL CHAINS

While those models can be used to evaluate the distortion in analog signals, their use is maximal when used to evaluate the compatibility of the connector with digital signaling, whether single-ended or differential. Board-to-board setups feature a wealth of different protocols and interfaces for different uses and in different standards ecosystems.

This section aims to be a guide of what a designer can expect when using Würth Elektronik board-to-board connectors systems, based on comparing the modeled connector insertion loss against commonly accepted connector-level loss budgets within those interface ecosystems. This is not a replacement for proper standard and signal chain evaluation. Generally, the series are ranked from the least performing to the highest performing regarding high-speed digital signal integrity provided there are enough pins to map all signals. Later series can do everything the previous series can.

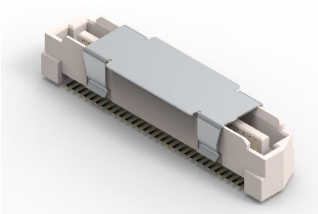
The compatibility assessments below are based on insertion loss models only. Return loss and crosstalk (NEXT/FEXT) are not characterized and should be independently validated for noise-sensitive or crosstalk-constrained interfaces (e.g., parallel buses).

5.1 WR-BTB 0.8 mm and WR-BTB 1 mm pitch (high mating heights)

Considering the outlined high-frequency signaling properties, the Würth Elektronik Board-to-Board 0.8 and 1 mm pitch connector series at high mating heights can be considered in the following interfaces:

PCI Express 2 as described with the standard connector loss budget. PCI Express 3 may even be considered if the rest of the channel has sufficient margins.

- USB High-Speed InterChip and USB Super-Speed InterChip up to 3.2 Gen 1
- XAUI Ethernet Media-Independent Interfaces
- Serial and parallel display and camera interfaces
- SPI, I^{2}C, and other serial and parallel internal buses



See the WR-BTB Board-to-board 0.8 mm and WR-BTB Board-to-board 1.0 mm datasheets.

5.2 WR-BTB 0.8 mm and WR-BTB 1 mm pitch (low mating heights)

Considering the outlined high-frequency signaling properties, the Würth Elektronik BTB 0.8 and 1 mm pitch connector series at low mating heights can be considered with all interfaces listed in the previous sections, plus the following:

- PCI Express 3 as described with the standard connector loss budget. PCI Express 4 may even be considered if the rest of the channel has sufficient margins.
- USB High-Speed InterChip and USB Super-Speed InterChip up to 3.2 Gen 2
- XFI/SFI Ethernet Media-Independent Interfaces
- D-PHY for MIPI CSI or MIPI DSI

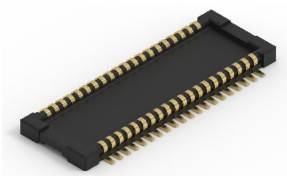
See the WR-BTB Board-to-board 0.8 mm and WR-BTB Board-to-board 1.0 mm series datasheets.

5.3 WR-BTB 0.4 mm pitch

Considering the outlined high-frequency signaling properties, the Würth Elektronik Board-to-Board connector 0.4 mm pitch series can be considered with all interfaces listed in the previous sections, plus the following:

PCI Express 4 as described with the standard connector loss budget. PCI Express 5 may even be considered if the rest of the channel has sufficient margins.

- USB High-Speed InterChip and USB Super-Speed InterChip up to 3.2 Gen 2
- M-PHY MIPI CSI or MIPI DSI



See the WR-BTB Board-to-board 0.4 mm series datasheet.

5.4 WR-BTB 0.5 mm pitch

Considering the outlined high-frequency signaling properties, the Würth Elektronik Board-to-Board connector 0.5 mm pitch series can be considered with all interfaces listed in the previous sections, plus the following:

- DDR4 SDRAM interfaces - subject to crosstalk validation; IL budget is met by the connector, but parallel bus deployment requires additional NEXT/FEXT characterization not covered in this revision.
- 25GBASE-KR Ethernet Media-Independent Interfaces

See the WR-BTB Board-to-board 0.5 mm series datasheet.

6. CONCLUSION

BTB connectors are available in numerous shapes, sizes, and configurations, allowing designers to reliably interconnect PCBs in a wide range of applications. Their mechanical durability and ability to support high-speed digital signals make them suitable for industrial and power control systems, display and camera interfaces, wearables and compact medical devices

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