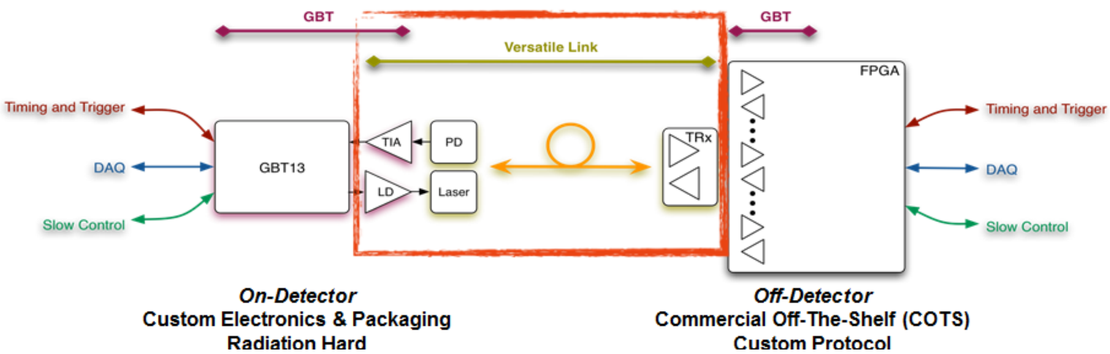
The Versatile Link Application Note



Abstract:

This application note describes how to implement a Versatile Link-based system in a typical High Energy Physics experiment. It summarizes the most relevant Versatile Link features and available options, and points to the relevant documentation. It guides the optical system designer in his/her engineering effort, highlighting in particular those system aspects that are not directly or fully covered by the Versatile Link specification.

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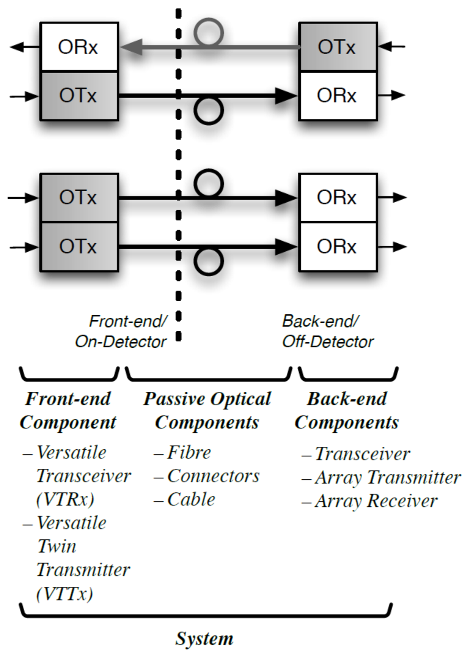
1 Introduction

The Versatile Link is a bi-directional digital optical data link operating at rates up to 4.8 Gbit/s and featuring radiation-resistant, magnetic field tolerant, low-power and low-mass front-end components. The system is proposed in multimode (MM) or singlemode (SM) versions operating at 850nm or 1310nm wavelength respectively. It has serial data interfaces and is protocol-agnostic, but is targeted to operate in tandem with the GigaBit Transceiver (GBT) serializer/deserializer chip at the front-end, and with a GBT core instantiated in an FPGA at the back-end.

The Versatile Link project was started jointly by ATLAS and CMS in 2008 [1]. It developed and qualified components for LHC experiments upgrades with two grades of radiation resistance: Tracker-grade and Calorimeter-grade [2]. However, as it became clear that the timescale for the upgrades of the ATLAS and CMS trackers was shifting beyond 2020, only the Calorimeter-grade option was continued to the pre-production readiness stage. Thus, this document refers only to Calorimeter-grade Versatile Links as envisaged for use in the phase I upgrades of the LHC experiments.

This application note is written for teams intending to use the Versatile Link in their experiment, but who were not involved in the project from the beginning. It intends to explain the principles underlying the design of a Versatile Link based system and to help them take the relevant engineering decisions.

2 Versatile Link features and options



Front-end VTRx	Fiber	Back-end TRx
EE Laser, 1310 nm InGaAs PIN, 1310 nm	SM G.652a G.652b	LR-SFP+ TRx Board-edge Tx, Rx, TRx Mid-board Rx
VCSEL, 850 nm GaAs PIN, 850 nm	MM OM3 OM4	SR-SFP+ TRx Board-edge Tx, Rx, TRx Mid-board Tx, Rx, TRx

Figure 1: Versatile link generic architecture (left) and implementation options (right)

The Versatile Link generic architecture and its implementation options are presented schematically in Figure 1. In its basic point-to-point configuration, the link is driven by two optical transceivers (OTx and ORx), one at each end of the link. At the front-end, the Versatile Transceiver (VTRx) is a bi-directional custom-developed module loosely following the SFP+ form-factor [3]. At the link back-end, the backend transceiver (TRx) can be either of the SFP+ type, or be based on parallel optics (array Transmitters or Receivers). In the latter case, it can take the form of board-edge optics (such as for instance SNAP12 [4], QSFP+ or CXP modules) or of mid-board optics (also frequently referred to as optical engines). Multi-channel modules are typically only interfaced to Multi Mode (MM) fibre ribbons. However, Single Mode (SM) devices have been identified and are also available from a few suppliers.

Most experiments have asymmetric bandwidth needs in the up- and downstream directions. This typically results in applications requiring many more front-end transmitters than receivers. To cover this need, a uni-directional Versatile Twin Transmitter (VTTx) module is also available, consisting of two transmit channels instead of one in exactly the same package as the VTRx. Most experiments will thus design systems including both VTRx and VTTx modules at the frontend. For the sake of simplicity, this document generally refers to VTRx-based links only. However, the extension of its recommendations and conclusions to VTTx-based links is straightforward.

2.1 Front End components

Whereas the transceivers located at the Versatile Link back-end sit in a standard crate environment and can be selected from a range of Commercial Off The Shelf (COTS) modules, the front-end VTRx must withstand radiation, operate in a magnetic field and in many cases be as small and lightweight as possible. The quasi-SFP+ module developed for the Versatile Link front-end is thus a customized device integrating a radiation hardened transceiver chipset along with a radiation-qualified laser diode and photodiode. The module housing was also customized to reduce as much as possible its material budget while maintaining both EMI susceptibility and emissions within acceptable limits.

2.2 Passive components

The passive optical components must fit the requirements of the experiment, both in terms of legacy cable plant (if any) and in terms of topological routing constraints. The final choice of fibre, cable and connector types are thus left to each experiment. Typically, only experiments with a legacy SM plant will select a SM Versatile Link variant. All others will select a MM Versatile Link variant that will result in a more cost effective implementation for short distance and moderate bandwidth links.

2.3 Backend components

The choice of fibre type (SM or MM) will determine the type of VTRx to be selected: either SM-VTRx or MM-VTRx. Both SM and MM VTRx modules are custom devices that can only be sourced from CERN.

The choice of backend TRx component will be greatly influenced by the design of the backend electronic board and is thus left in the hands of the designer. However, care should be taken that the selected TRx device meets the Versatile Link requirements.

To summarize, the Versatile Link system is built from a CERN supplied VTRx or VTTx (see section 4) and from user selected passive and backend components meeting the Versatile Link specifications. Recommendations for selecting the proper fibre, connector and backend TRx type are given in section 5.

3 Versatile Link specifications

The Versatile Link specifications are available to users as a full set of electronic documents from the CERN EDMS server [5]. All components selected to be used as part of the Versatile Link system must comply fully with these specifications to guarantee that the system will meet its requirements over its entire operating range, over component performance spread, and during the lifetime of the experiment. Users wishing to deviate from the listed specifications are encouraged to contact the Versatile Link team to discuss the possible impact of non-compliances on operation margins.

3.1 Operational and environmental specifications

The system-level operational and environmental specifications are shown in Table 1 and Table 2 below for quick reference. The full specification set must however be used whenever system details need to be investigated.

Table 1: Versatile Link operating specifications

	Parameter	Min	Typ	Max	Units
3.1.1	Max Bit Rate	4.8			Gbit/s
3.1.2	Bit Error Ratio[1]			10^{-12}	
3.1.3	Max. link length	150			meter

Note 1: Test patterns for the BER measurement should be reasonably stressful. Thus PRBS23-1 patterns or longer record lengths are preferred.

Table 2: Versatile Link environmental specifications

4.1.1.1	Radiation resistance (frontend)	10 kGy Dose 5 x 10^{14} n/cm^2 fluence (1Mev n. equivalent)			
4.2.1	Temperature range				
4.2.1.1	VTRx	-30	to	60	°C
4.2.1.2	Passives	-30	to	70	°C
4.2.1.3	backend	0	to	70	°C
4.3.1	Magnetic field tolerance (frontend)	4T			

Bit rate, link length and radiation resistance requirements all have a direct impact on the selection of link components. Experiments with different requirements may re-optimize the component selection proposed in section 5, provided they have sufficient resources to qualify a different component set (see for instance section 0).

3.2 Power budget

The Versatile Link power budget is presented in Table 3 below for the two data propagation directions and the two proposed fibre types. The VTRx specifications are in grey-background cells to indicate that they are imposed by the CERN supplied module and are fixed. The other specifications (backend TRx OMA and sensitivity, fibre attenuation, Insertion loss) are dependent on the finally selected components (backend transceiver, fibre, connectors) while the penalties depend on the exact link operating conditions (bitrate, length) and environment (radiation). It is worth noting that all specifications are based on worst-case component performance, meaning that a typical link will operate with much higher margins than shown here.

Table 3: Versatile Link power budget in upstream (VTx_Rx), or downstream (Tx_VRx) directions, for SM or MM links

	MM_VTx_Rx	MM_Tx_VRx	SM_VTx_Rx	SM_Tx_VRx
Min. Tx OMA	-5.2 dBm	-3.2 dBm	-5.2 dBm	-5.2 dBm
Max Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	**5.9 dB**	**9.9 dB**	**7.4 dB**	**10.2 dB**
Fibre attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
VTx rad. penalty	0 dB	-	0 dB	-
VRx rad. penalty	-	2.5 dB	-	2.5 dB
Fibre rad. penalty	0.1 dB	0.1 dB	0 dB	0 dB
Margin[1]	**2.7 dB**	**4.2 dB**	**3.8 dB**	**4.1 dB**

Note 1: Error coding scheme, for example the GBT coding, can result in in an additional 1-2 dB gain in margin.

The values indicated in Table 3 are representative of a generic Versatile Link system, but will need to be more finely adjusted if they are to reflect the exact implementation in an experiment. Globally, one can see that a power margin in excess of 2.7dB exists in all cases, thus confirming the robustness of the design even under worst-case assumptions. A power margin of at least 3dB is usually recommended to ensure resiliency of optical systems used in long lifetime applications.

The link penalties are derived from the 10GbE link model [6], a physical layer power margin calculation model developed by the IEEE802 standard working group to account for the effects of intersymbol interference, mode partition noise, modal noise, extinction ratio and relative intensity noise. The calculated penalties are valid for most link implementations and should in principle not be changed.

The fibre radiation penalties are based on experimental data gathered during qualification tests of specific fibre types. They apply only to the tested fibre types, in the specified environmental conditions, and cannot be generalized to different conditions (see section 5 below).

Users selecting passive and backend components should ensure that those meet or exceed the generic specifications listed in Table 3. For instance:

- MM Fibre attenuation: <4dB/km max (150 m link length)
- SM fibre attenuation: <0.4dB/km max (150m link length, rounded up to 0.1dB)
- MM connector Insertion Loss: <0.5dB max per breakpoint (3 breakpoints)
- SM connector Insertion Loss: <0.65dB max per breakpoint (3 breakpoints)
- MM backend TRx: >-3.2dBm OMA min, <-11.1 dBm sensitivity max
- SM backend TRx: >-5.2dBm OMA min, <-12.6dBm sensitivity max

3.2.1 Saturation of SM VTRx Receivers

Excessive optical modulation amplitude can saturate the amplifier stage of a VTRx receiver. The saturation shows as increased jitter in the receiver’s electrical output, which in turn can increase the bit error rate of the link. This is a concern in case of single-mode systems, if too powerful transmitters are used without sufficient attenuation.

A typical sensitivity range of a SM VTRx receiver using the specified data rate of 4.8 Gbps and PRBS23 pattern (comparable to GBT encoding) is shown in Figure 2. If the received optical modulation amplitude is higher than -2 dBm, the error-free operation is lost. Therefore, the user should ensure that the VTRx receiver input OMA does not exceed -2 dBm. If a commercial transmitter with high OMA has to be used, the user can mitigate the saturation problem by installing an inline attenuator that reduces the OMA to the safe region below -5 dBm.

The saturation depends strongly on the maximum run length of the data stream, and therefore the user must verify the possible penalty if imbalanced data streams are used. On the other hand, in case of short run lengths (e.g. 8b/10b encoding) saturation does not occur even when receiving an OMA of +3 dBm. Note that this saturation effect has never been observed in MM links.

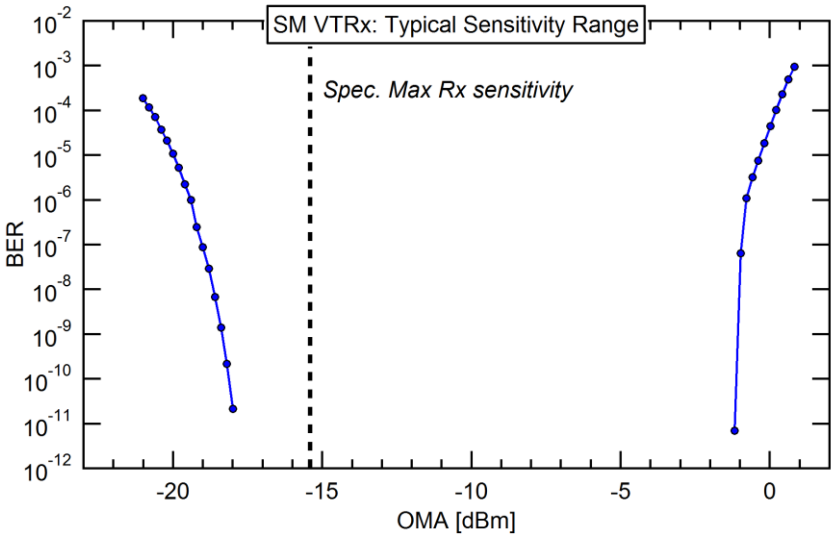


Figure 2: Typical sensitivity range of a single-mode VTRx receiver for error-free transmission with GBT encoding scheme.

4 Versatile Transceiver mechanical dimensions and electrical connectivity

The Versatile Transceiver (VTRx) module format is loosely based upon the SFP+ multi source agreement. It uses the same card-edge connector and has similar dimensions as its commercial counterpart, but doesn't fit into a standard card cage and doesn't use the same power supply rails. It must thus be mounted on custom-built host boards. Figure 3 and Figure 4 illustrate the VTRx (VTTx) module. Full specifications can be found in [7]. Useful publications by the Versatile Link team are: [8],[9],[10],[11],[12],[13] and [14].

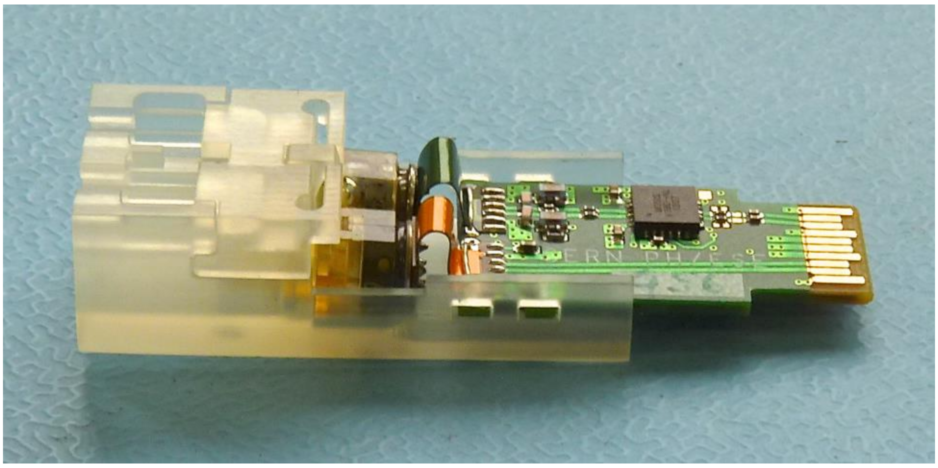


Figure 3: Photograph of a fully assembled VTRx

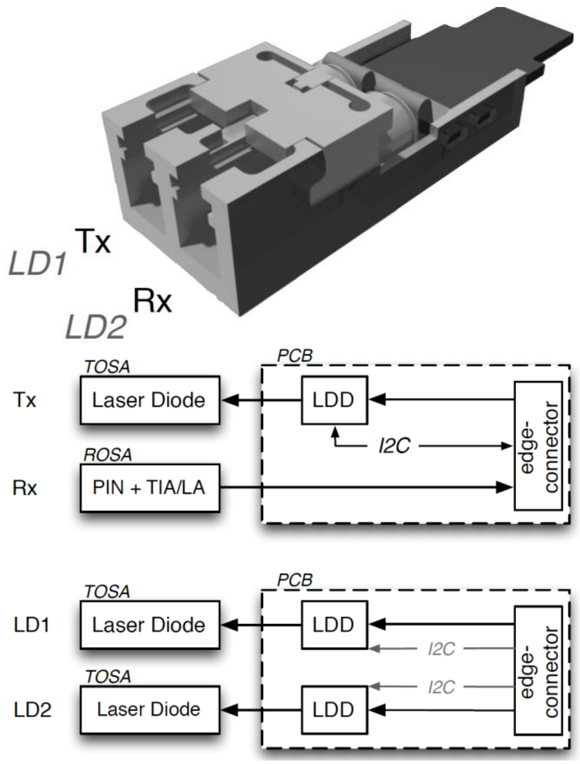


Figure 4: Sketch and block diagram of VTRx and VTTx modules

4.1 Mechanical dimensions

The VTRx module mechanical specifications are summarized in Table 4 below.

Table 4: VTRx module mechanical specifications

#	Specification	Min	Typ	Max	Unit	Notes
2.1	Length		55		mm	From optical connector boot to electrical edge-connector
2.2	Width		14.5		mm	Across both connectors
2.3	Height		10		mm	With connector mated
2.4	Mass		5		g	VTRx
			4		g	VTTx
2.6	Optical Interface					Receptacle for LC connector, 1.25mm ferrule

Mechanically, the VTRx module is fixed to its host board in three points: the card-edge electrical connector and two 3mm diameter, 1mm high standoffs. These allow aligning and fixing the module with two M1.4 screws, once inserted into its electrical connector. Four 3D views of the module are shown in Figure 5 below. The full engineering drawing can be downloaded from [15].

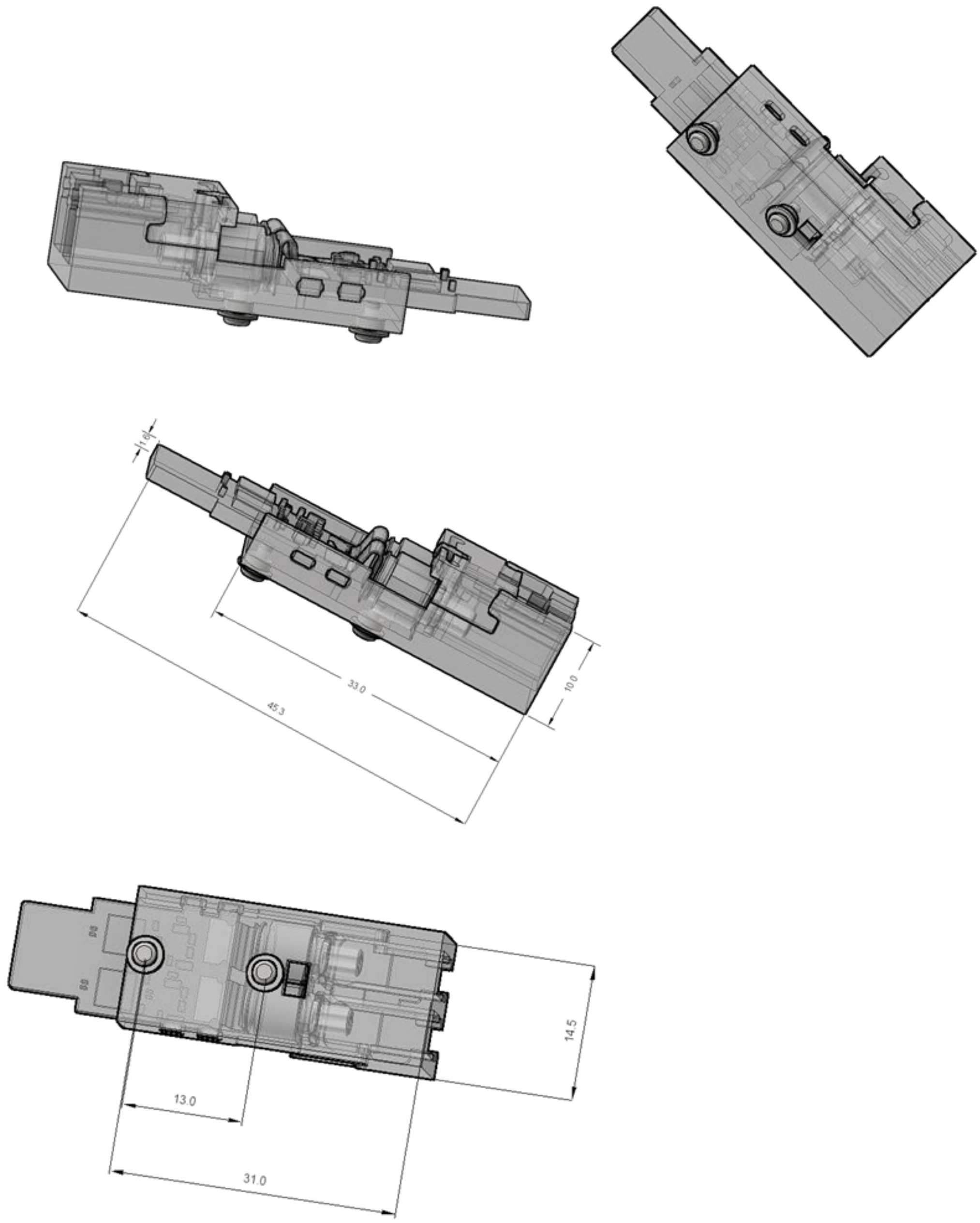
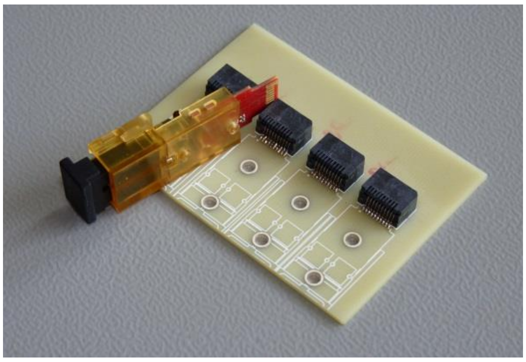
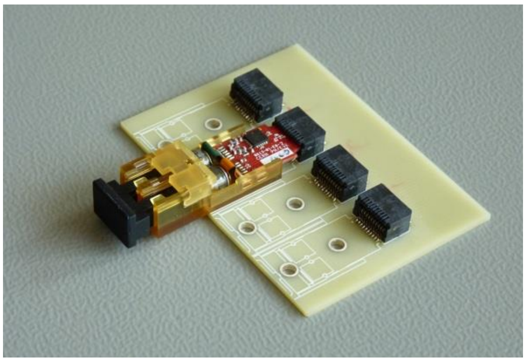


Figure 5: 3D views of VTRx or VTTx module from different view points

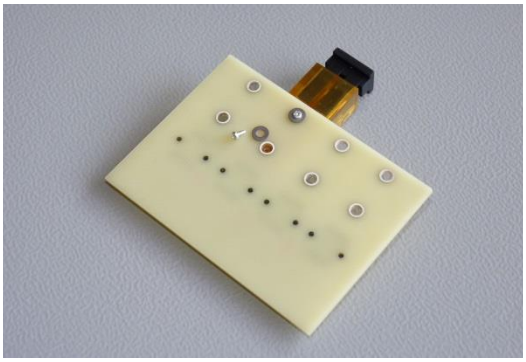
The assembly sequence of the VTRx module on its host board and references to relevant CAD files are shown in Figure 6 below.



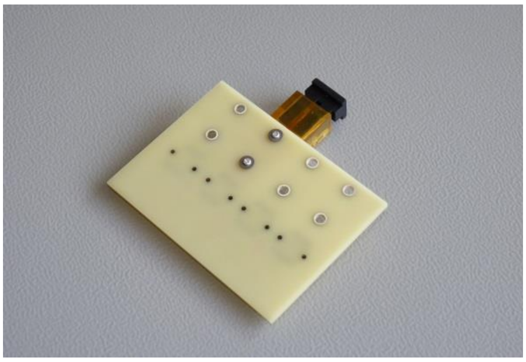
Starting Point: PCB symbols from CERN Cadence library[1] and SFP+ edge connector[2]



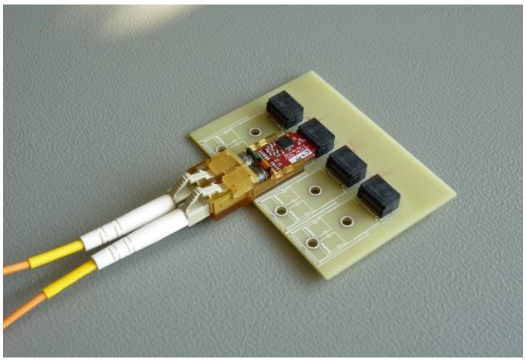
Step 1: plug VTXx into edge connector and locate guide posts on the VTXx in the holes in the PCB



Step 2: Fasten screw[3]



Step 3: Fasten screw



Step 4: Insert optical connectors

Figure 6: VTRx assembly steps on host board

Figure 7 and Figure 8 show the recommended location of the front panel and the position of the guideposts with respect to the SFP connector of the multi-mode VTRx/VTTx and single-mode VTRx modules, respectively. In both cases, if multiple VTRx/VTTx modules are used on the same board, the recommended spacing between the modules is 15 mm.

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[1] VTRx and VTTx are part of the cnmech and cnconnector libraries, help file is available [16] and/or contact the authors for access to the part details for use outside CERN.

[2] One example is Tyco Electronics part number 1888247-1

[3] M1.4 Micro Self Tapping screws Pan head; available in lengths of 3, 4, 5, or 6 mm depending on thickness of host PCB. Vendor: NEWSTAR FASTENINGS, Summit House, London Rd, RG12 2AQ BRACKNELL, GB

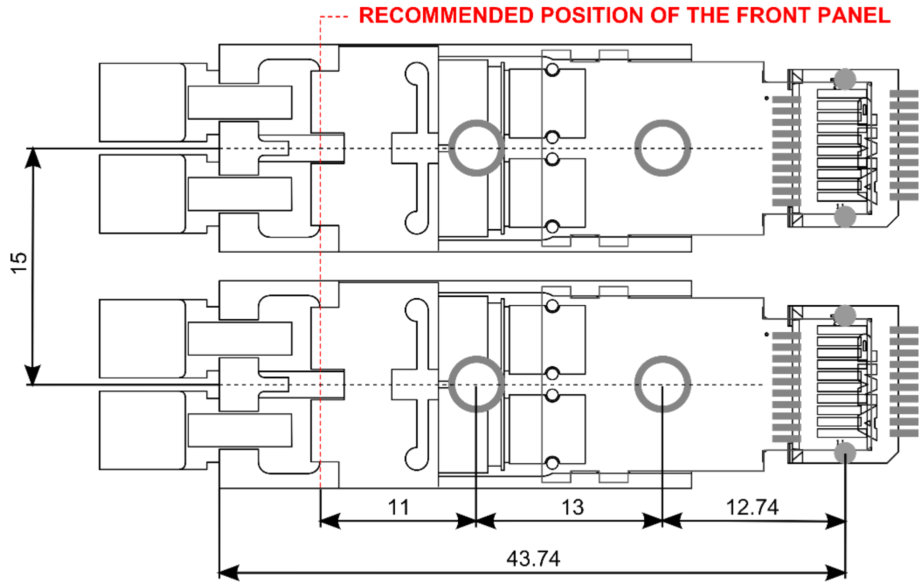

Figure 7 Mechanical drawing of the multi-mode VTRx/VTTx showing the location of the front panel with respect to the guideposts and the SFP connector on the host board. All dimensions are in millimetres.

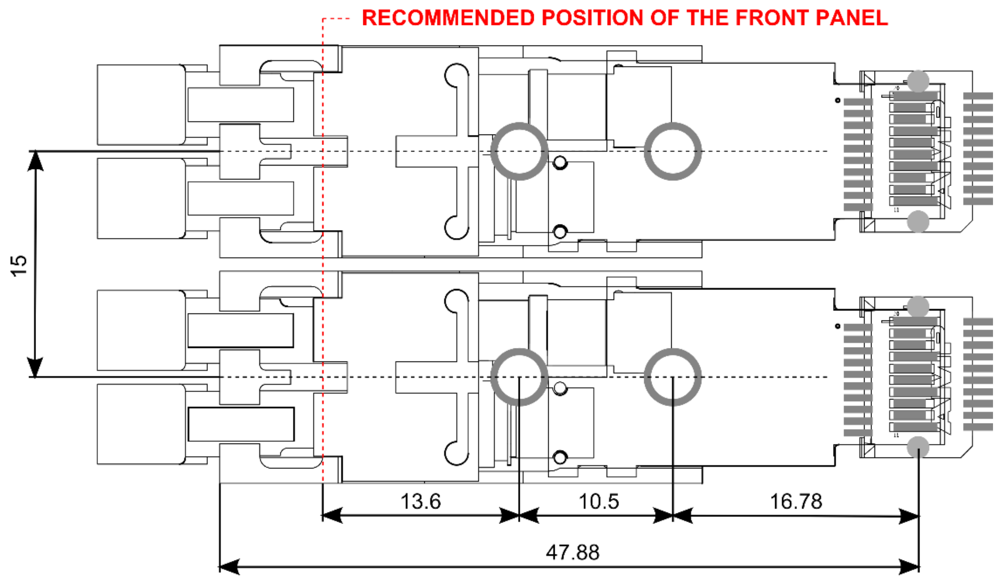

Figure 8 Mechanical drawing of the single-mode VTRx showing the location of the front panel with respect to the guideposts and the SFP connector on the host board. All dimensions are in millimetres.

4.2 Electrical connectivity

The electrical connectivity of the VTRx and VTTx modules is described in Table 5 and in

Table 6 respectively, while the connector electrical footprints are illustrated in Figure 9**.**

Attention: VccR=VccT=2.5V ±5% The VTRx and VTTx modules are thus electrically incompatible with standard SFP+ modules. The typical power consumption using the default power-on reset values of the various module variants are listed hereafter:

- Single-mode VTRx : 210mA (525mW);
- Multi-mode VTRx : 140mA (350mW) ;
- Multi-mode VTTx : 200mA (500mW).

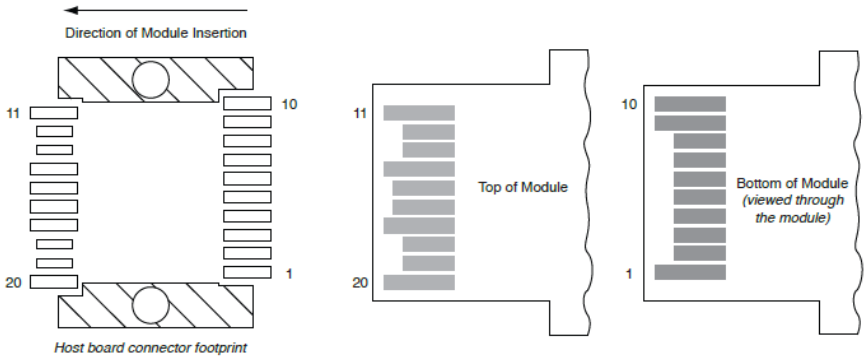

Figure 9: Connector footprints of host board connector (left) and VTRx/VTTx card-edge (centre and right) showing the pin numbering convention.

Table 5: VTRx module electrical connectivity

Pin #	Signal Name	Comment
1	V_{EE}T	
2	n/c	
3	Tx_Disable	TX output is on when 0V applied (internal pull-up)
4	SDA	To be pulled up to +1.5V on host board
5	SCL	
6	Mod_ABS	Connected to GND internally
7	n/c	
8	RSSI	Mirrored photo current. Requires an external pull-up resistor.
9	n/c	
10	V_{EE}R	
11	V_{EE}R	
12	RD+	These two pins are inverted w.r.t. standard SFP+
13	RD-	
14	V_{EE}R	
15	V_{CC}R	
16	V_{CC}T	
17	V_{EE}T	
18	TD+	Inverted in the case of SM variants
19	TD-	
20	V_{EE}T	

Table 6: VTTX module electrical connectivity

Pin #	Signal Name	Comment
1	$V_{EE}T$	
2	n/c	
3	Tx_Disable	TX output is on when 0V applied (internal pull-up)
4	SDA	To be pulled up to +1.5V on host board, controls laser driver connected to TD+ and TD-
5	SCL	
6	Mod_ABS	Connected to GND internally
7	SCK2	To be pulled up to +1.5V on host board, controls laser driver connected to TD2+ and TD2-
8	n/c	
9	SDA2	To be pulled up to +1.5V on host board, controls laser driver connected to TD2+ and TD2-
10	$V_{EE}T$	
11	$V_{EE}T$	
12	TD2+	Inputs for LD2
13	TD2-	
14	$V_{EE}T$	
15	$V_{CC}T2$	
16	$V_{CC}T$	
17	$V_{EE}T$	
18	TD+	Inputs for LD1
19	TD-	
20	$V_{EE}T$	

Figure 10 and Figure 11 show the typical application configuration of the VTRx and VTTx, respectively. The high-speed connections between the SERDES and the VTRx/VTTx are implemented using AC coupled differential lines. The DC blocking capacitors are installed on the VTRx/VTTx module.

For normal operation, the laser driver(s) is (are) pre-configured with default laser bias and modulation settings. Applications required to alter these settings can use the I2C control interface to access the laser driver control registers. In case of the VTTx the second laser driver is accessible through an independent control interface (SDA2/SCL2). The I2C data and clock lines should be pulled up to 1.5V on host board. To enable the transmitter(s) the TX_DISABLE input must be connected to ground ($V_{ee}T$).

The VTRx module can provide information about the average optical power of the received light. The RSSI output (pin #8) is a current sink that draws a current equivalent to the generated photo current. To use this feature the user must connect the RSSI output of the module to $V_{cc}R$ using an appropriately sized resistor, R1 (e.g. R1=1 kOhm). The resulting voltage on the RSSI pin is $V_{RSSI}=V_{cc}R-I_{avg}*R1$, where I_{avg} is the mirrored photo current. For correct operation the voltage on the resistor should not exceed 2.5V. In case of a voltage sensor with a limited measuring range a voltage divider can be created by connecting RSSI output also to ground with an additional resistor, R2. The resulting voltage on the RSSI pin then becomes $V_{RSSI} = R2/(R1+R2) * (V_{cc}R – I_{avg} * R1)$. For example, with a measurement range of 0 – 1.2 V and $V_{cc}R$ = 2.5V suitable resistor values are R1 = 4.8 kOhm and R2 = 2.3 kOhm. These two configurations are shown in Figure 10, with the required R1 and the optional R2 (grey).

The 2.5V module supply voltages ($V_{cc}T$/ $V_{cc}T2$ and $V_{cc}R$) must be properly decoupled on the host board using an LC filter network as shown in Figure 10 and Figure 11. The recommended value of L is between 1uH and 4.7uH. Note that ferrite bead inductors must be avoided if the module is used inside a strong magnetic field. Air-core inductors can be used provided their DC resistance does not exceed 0.6 ohm. Moreover, this inductor can be safely ignored if the module is powered by CERN's radiation tolerant DC/DC converter module (FEASTMP) [17], which already includes an LC filter at its output.

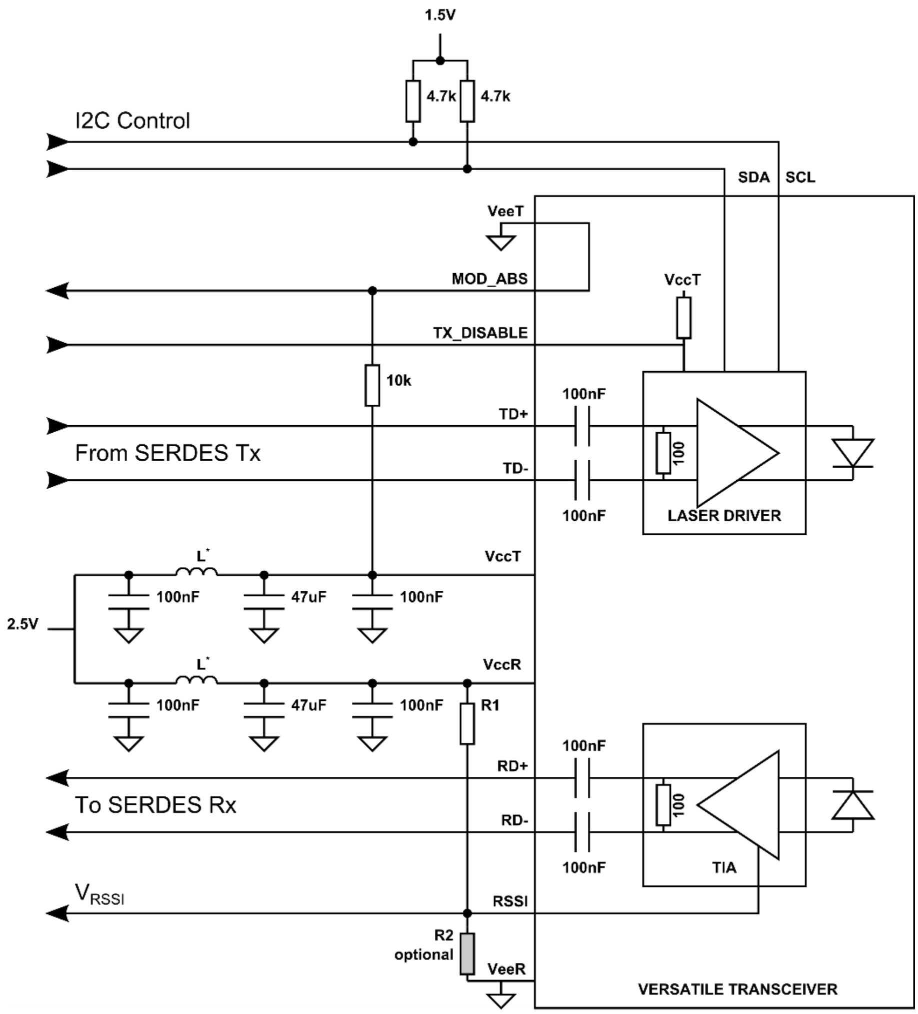

Figure 10 Typical application configuration of the VTRx.

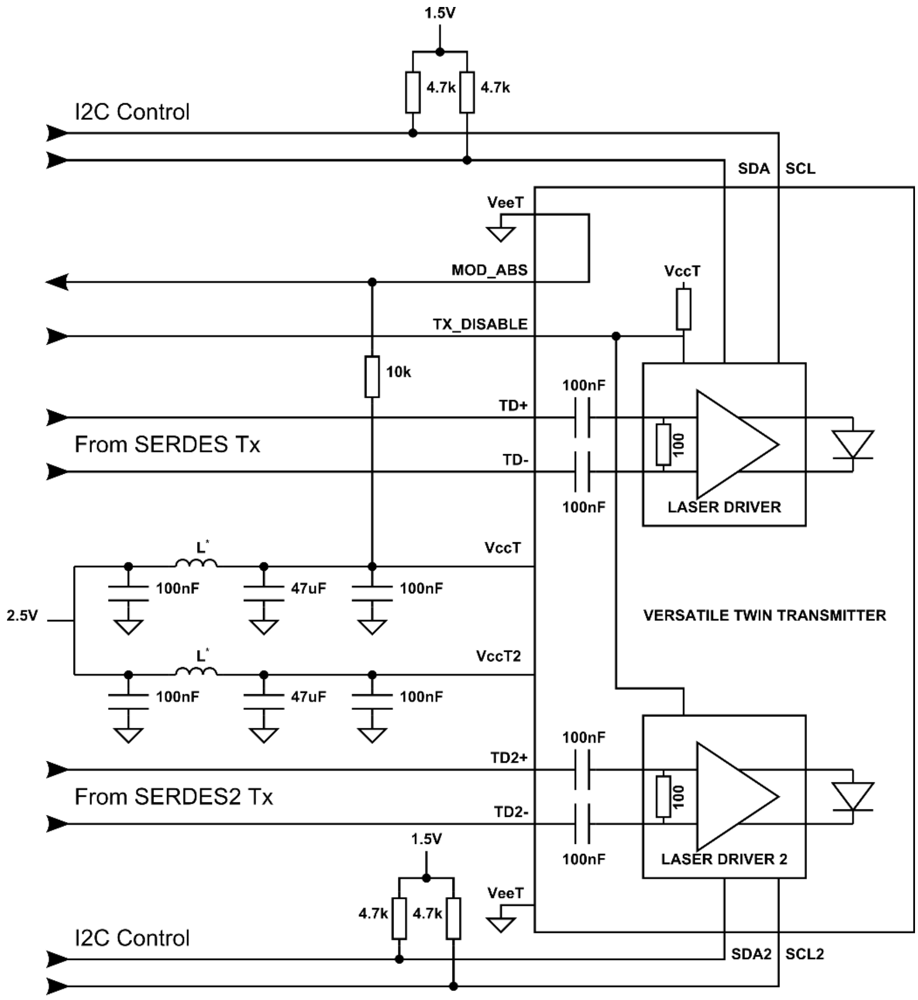

Figure 11 Typical application configuration of the VTTx.

4.3 VTRx and VTTx I2C control connections

In the simplest configuration where one VTRx is connected to one GBTX to establish a bi-directional link, the I2C connection shown in Figure 12 should be used. The I2C control information is passed from the upstream controller via the optical serial data channel to the GBTX, which translates it to a series of I2C, commands that are sent from the GBTX to the VTRx to control the GBLD (labelled LDD in figure).

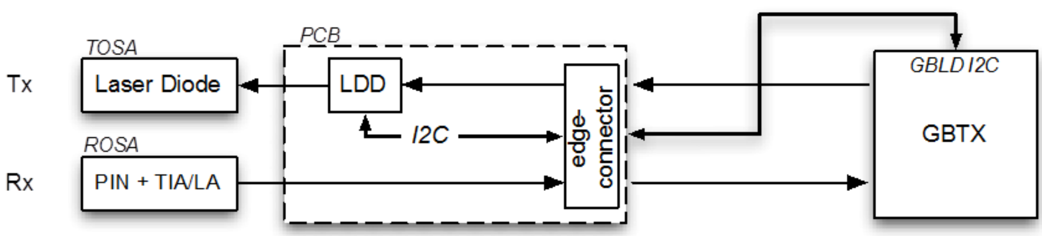

Figure 12: Dedicated I2C connection between GBTX chip and VTRx module.

In order to control a VTTx, the control information must be passed first to a GBTX with attached GBT-SCA that act as system controller. There are then two methods for communicating with the VTTx in order to control the two on-board GBLD chips: passing via the GBTX attached to a particular VTTx channel as in Figure 13; or directly attaching the VTTx to a GBT-SCA I2C port as shown in Figure 14. In the latter case the I2C address space available on the VTTx is such that only one VTTx can be present on each I2C port. In contrast, the former case allows up to 16 GBTX chips and their 8 attendant VTTx modules to share one I2C port.

In all cases, the two I2C control lines (SCL and SDA) require external pull-up resistors to 1.5 V for correct functioning of the VTRx and/or VTTx modules.

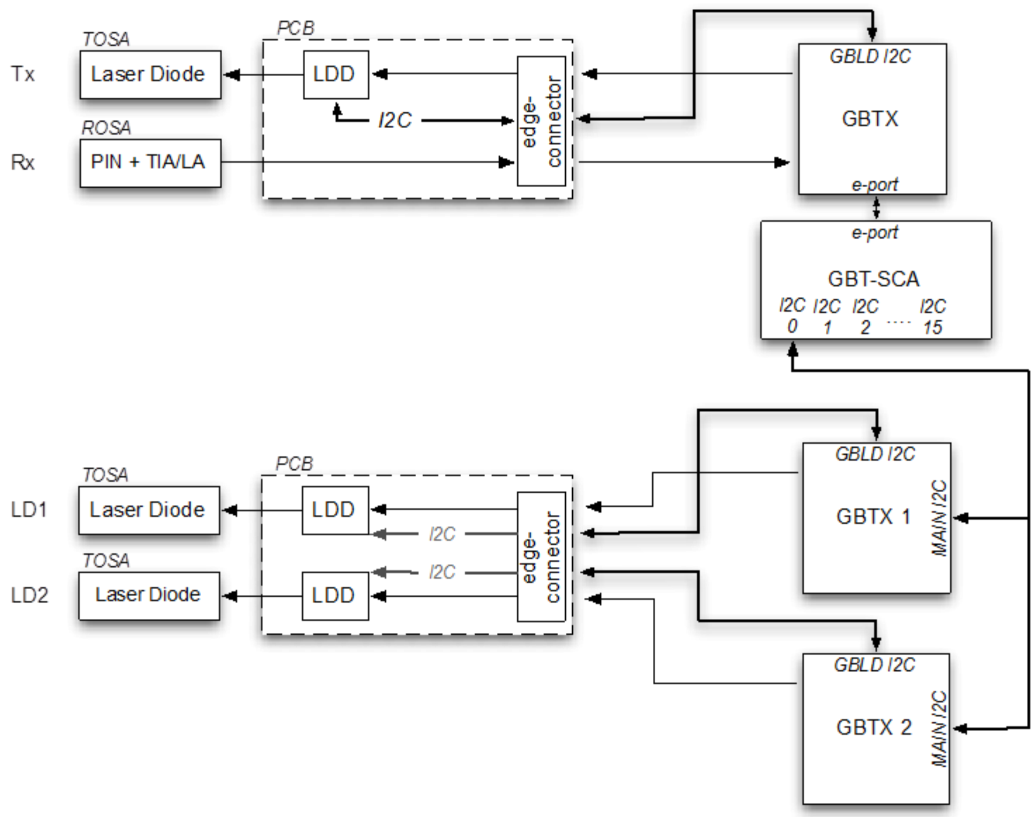

Figure 13: Use of dedicated I2C connection between GBTX chip and VTTx module to configure VTTx via the I2C connection between GBT-SCA and GBTX.

At power-on or after reset, the laser driver channels are activated by default to the following values:

- MM transmitters: IBIAS=6mA and IMOD=6mA
- SM transmitters: IBIAS=40mA and IMOD=20mA

This will ensure proper link start-up even with heavily irradiated laser transmitters close to their end-of-life. In the MM case, these settings correspond to optimal operation of the links in most conditions. In the SM case, it is recommended to decrease the IBIAS setting after power-on in order to reach more optimal operating conditions.

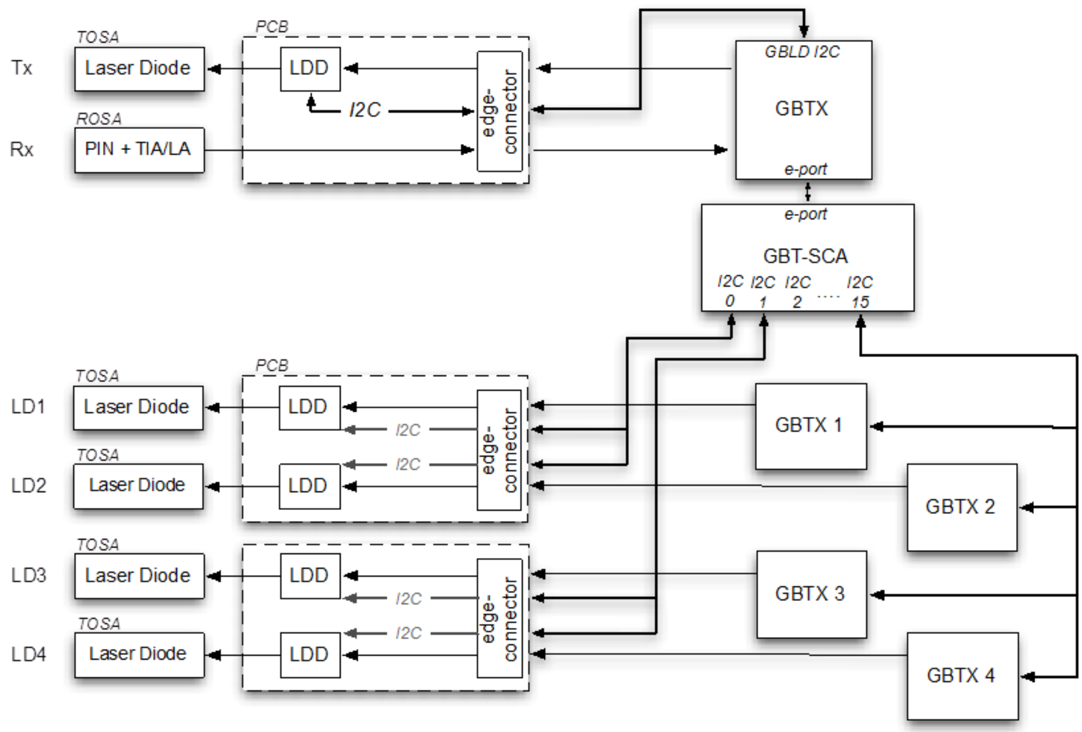

Figure 14: Use of generic I2C connection between GBT-SCA chip and VTTx module to configure VTTx modules and GBTX chips.

5 Implementing the Versatile Link

All Versatile Link implementations have only one component in common: the VTRx or VTTx module described in section 4 above. All other components are selected by the experiments themselves to best fit their backend electronics and their environmental, historical and topological constraints. Implementations by various detectors may thus differ from one another. It is the responsibility of the experiments to ensure compliance with the system-level specifications or to adapt them accordingly, as discussed in sections 3 and 0.

In order to demonstrate Versatile Link feasibility, several passive and backend components were characterized and shown to be compatible with the VTRx/VTTx modules and to meet the system requirements. In the following subsections, we list a set of recommended components allowing operation of the Versatile Link with good margins. This list is by no means exhaustive as other solutions may exist or may have emerged since the evaluations mentioned here took place. It may however serve as a useful starting point, especially for experiments that do not wish to invest heavily into qualifying opto-electronic components.

5.1 Passive components

5.1.1 Fibres

To meet the Versatile Link specification, multimode fibre should be of grade OM3 or above and have an attenuation of less than 4dB/km. One of the many fibre types that can be recommended for use outside the radiation area is the Corning Clearcurve™ OM3 MM fibre.

Singlemode fibre should have an attenuation of less than 0.4dB/km. One of the many fibre types meeting the Versatile Link specifications outside the radiation area is the Corning SMF-28e SM fibre.

Both Clearcurve™ and SMF-28e fibre have been found to feature good radiation resistance. However, the radiation resistance of optical fibres is strongly dependent on the concentration of dopants and impurities contained in the glass core and cladding. It will thus vary for different fibre types and will change from preform to preform. For this reason, experiments envisaging using standard fibre inside their detectors should be ready to qualify all preforms being ordered, if they need radiation resistance. Alternatively, they can order radiation resistant fibre for their exposed routes. The following three radiation resistant fibres have been tested and found to be compliant with the Versatile Link specification:

- DrakaElite Super RadHard GI-MM fibre (not fully OM3 compliant, but acceptable for short distances)
- DrakaElite Super RadHard SM fibre
- Fujikura RRSMFB (Radiation Resistant Single-Mode) fibre

Useful publications from the Versatile Link team are:[18],[19], [20], [21],[22] [23]and [24].

5.1.2 Cables

The choice of optical cable is driven by the detector-specific routes, the fibre count and the foreseen installation procedure. The same requirements as for standard electrical cables apply, plus specific ones for bend radius, torsion, pull strength and crush/impact resistance.

The cable design is considered to be so system specific that no vendor recommendation was issued by the Versatile Link development team. Cable selection and qualification is thus left in the hands of the experiments.

5.1.3 Connectors

Two connector types are likely to be used in the Versatile Link, for both SM and MM variants:

- LC single channel connector
- MT-based multi-channel connector

The LC connector is required to connect to the VTRx and is recommended for all other single channel breakpoints. Both SM and MM LC connector types should be flat polished (with superior or ultra polish grade).

The MT-based connector will most likely be used at intermediate breakpoints and at the backend. A modularity of 12 or 24 channels is recommended, even though densities up to 72 channels have been reported. The MT ferrule forms the basis of nearly all dense multi-channel connectors available on the market today, and is usually embedded in push-pull shells of type MPO or MTP. SM MT ferrules should be angle-polished, while MM-MT ferrules should be flat-polished (in both cases with superior or ultra polish grade).

Both LC and MT-based connector types have been successfully used by LHC experiments in the past and have recently been re-validated by the Versatile Link team, confirming their excellent robustness, radiation resistance and durability. They are available from a large number of suppliers worldwide, and should best be specified together with the cables, becoming part of pre-terminated assemblies.

A **word of caution** may be useful at this point for users concerned with magnetic components: both LC and MT connector types use stainless steel springs, and the MT relies on steel guide pins for alignment. The connectors are thus magnetic components and will be subject to forces in field gradient regions of the detector. Non-magnetic connector versions were developed in the past for some LHC detectors (based on bronze-beryllium springs and ceramic guide pins), but not for the Versatile Link project. It is up to the experiments to decide if they wish to impose non-magnetic connectors for their system and to launch the corresponding customization effort, if deemed necessary.

5.2 Backend components

Several commercial transceiver modules were thoroughly evaluated in the framework of the Versatile Link project [25]. The tests performed included:

- Transmitter Tests: Optical Modulation Amplitude, Extinction Ratio, Eye Opening, Rise Time, Fall Time, Total Jitter, and Deterministic Jitter.
- Receiver Tests: Total Jitter, Deterministic Jitter, and Receiver Sensitivity.
- On some devices, crosstalk and temperature dependence measurements were also performed

The recommendations below date back to 2012 or earlier and only reflect the market situation at that time. The recommended devices fully meet the Versatile Link specifications, unless otherwise noted.

5.2.1 SFP+ single channel transceivers

- MM SFP+ Backend Transceiver: Avago AFBR 703SDZ (non-conformities 1 and 2)
- SM SFP+ Backend Transceiver: Finisar FTLX1471D3BCL

Non- conformity 1: The minimum Tx OMA of part AFBR 703SDZ is specified as -4.3dBm (Versatile Link requires −3.2dBm min). This penalty of 1.1dB in the downstream MM Versatile Link power budget can easily be accommodated: the MM_Tx_VRx margin decreases to 3.1dB, which is still above the 3dB recommended value.

Non- conformity 2: Avago has announced discontinuation of the AFBR 703SDZ component. The replacement part AFBR 703SMZ, although very similar to the SDZ model, was not tested by the Versatile Link team.

5.2.2 Multi-channel MM arrays

- Avago MiniPod Receiver AFBR-82UxxxZ
- Avago MiniPod Transmitter AFBR-81UxxxZ (non- conformity 3)
- Samtec FireFly Receiver ECUO-R12-14-XXX-0-X-1-X-XX
- Samtec FireFly Transmitter ECUO-T12-14-XXX-0-X-1-X-XX (non-conformity 3)

Non- conformity 3: The Tx OMA specification of -5.6dBm is dependent upon the performance of the module's optical interface, which may represent up to 2 dB insertion loss. This is 2.4dB below the Versatile Link requirement of -3.2dBm. See discussion below.

The Avago minipod, micropod (AFBR-77D1SZ, AFBR-78D1SZ) and CXP (AFBR-83PDZ) modules are all based on the same optical engines. They are thus likely to feature similar performance levels. The Avago minipod and Samtec FireFly devices are recommended here due to their good balance between size, ruggedness and ease of integration on-board. Experiments with specific constraints may however consider using the smaller mid-board micropod or the larger board-edge CXP module.

At evaluation time, the listed array devices clearly outperformed all their competitors and were thus selected as reference backend array modules despite the fact that their transmitter OMA specification is very conservative and falls below the required -3.2dBm value. All tested transmitter modules had OMA levels well above their specification and well within Versatile Link requirements. Nevertheless, these multi-channel components should not be selected for large systems without carefully reviewing the downstream power-budget (see column MM_Tx_VRx of Table 3). Four possible mitigation strategies can be envisaged:

i. For systems with asymmetric bandwidth requirements, one can envisage using at the backend fully compliant single channel SFP+ transceiver modules for the downstream links and receiver arrays for the upstream links.
ii. If the required VTRx radiation resistance is much smaller than assumed in the Versatile Link specification (2.5dB penalty at 5e14n/cm^2), the VRx radiation penalty specification could be relaxed, hence regaining margin to accommodate the low Tx OMA specification. For instance, a Tx OMA of -5.6dBm and a Rx radiation penalty of 1.3dB would lead to an acceptable margin of 3dB.
iii. A high power transmitter module grade could be defined with the vendor, guaranteeing sufficient OMA. For instance, specifying with the vendor a special part with a min Tx OMA of -4.4dBm instead of -5.6dBm would result in an acceptable 3dB overall power margin.
iv. If the system is relatively small and if the backend modules are easily accessible and replaceable, one can envisage taking the risk of having to swap modules should the power

limits be reached. Note however that these modules are 12-channel arrays, and that a full module would need to be replaced even if only one single channel fails to meet the power budget.

5.2.3 Multi-channel SM arrays

SM QSFP+ and 12-channel receiver modules have been identified, but were not fully characterized for compliance with the Versatile Link. Experiments envisaging using such components are encouraged to contact the Versatile Link team.

5.3 Quality assurance

The fact that only the Versatile Transceiver VTRx or VTTx module is imposed by the Versatile Link project gives a lot of flexibility to experiments to shape their optical system according to their own requirements. However, this freedom comes at a price: Quality assurance and control.

The following QA steps are recommended when implementing a Versatile Link-based system:

- Optical system review, once all components in the chain have been identified. The purpose of such a review is to check the specifications of all components, ensure compatibility with Versatile Link specifications, and confirm the power budget and margin.
- Optical system demonstrator based on all selected components. This step complements the paper system review and demonstrates components availability and system feasibility by building a full chain.
- Radiation resistance qualification, if applicable. This step demonstrates that the selected fibre, cable and connectors are resistant to the required radiation dose.
- Production readiness review. This review is necessary to assess prices, schedule and resources available to follow up production.
- Preproduction qualification of passive and backend components (for large systems). This check ensures that the delivered preproduction batch meets specifications, and allows fine-tuning logistics and quality control processes before starting production.
- Production quality control. This step checks the production batches on a sample basis and ensures stability of the production quality.

The Versatile Link team is available to assist experiments in any of these steps, if desired.

5.4 Handling and storage

Electrostatic discharge (ESD) can damage or destroy electronic and optoelectronic components. Protection against ESD is essential while handling all active optoelectronic Versatile Link components. Use proper precautions such as a combination of conductive table-mat and wrist-strap, and conductive floor-mat and heel-strap.

Always clean optical connectors before inserting them into the VTRx receptacle and always protect the VTRx optical interface with its dust cap when not in use. In case the VTRx receptacle needs to be cleaned, use only low-pressure nitrogen or dry optical-grade cleaning gas; do not use cleaning studs which may push dirt deeper onto the optical facet of the device.

Do not bend optical fibre or cables with a radius of less than 10x their diameter, and in any case do not use bend radii smaller than 25mm to avoid inducing transmission losses in the fibre (unless using bend-insensitive fibre).

Store Versatile Link components in dry conditions. Store active components in dry, ESD-free conditions. For medium to long-term storage, use sealed antistatic bags.

5.5 Operating the VTRx in the cold (-30°C < T < 0 °C)

The spectral response of the GaAs photo-diode used in the multi-mode VTRx ROSA is shown in Figure 15. In a multi-mode Versatile Link system, the optical wavelength of the transmitter overlaps with the flat part of the responsivity curve at room temperature. However, at lower operating temperatures, the curve will shift towards shorter wavelengths resulting in some drop of the responsivity within the specified operating range. According to the Versatile Link back-end specification, the wavelength of the transmitted optical signal falls between 840 and 860 nm. Taking into account the temperature induced responsivity drop within this window, the VTRx will meet the receiver specifications from 0 °C to 60 °C.

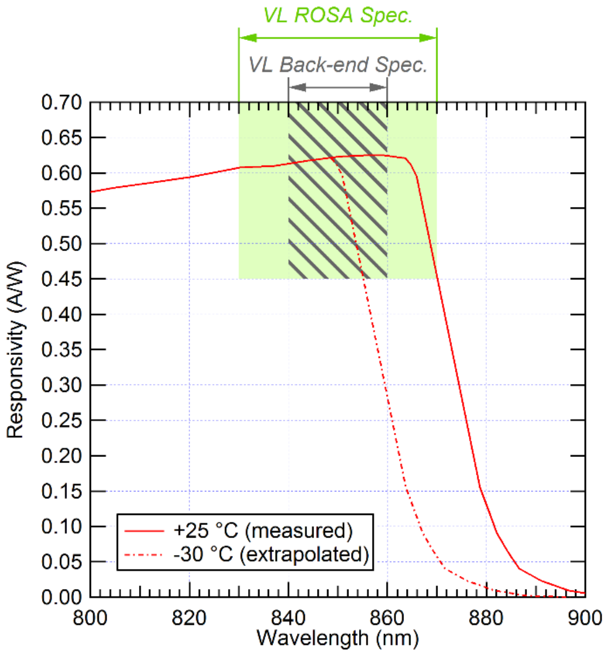

Figure 15: Spectral response of the photo-diode used in the multi-mode VTRx ROSA. The responsivity measured at room temperature is shown together with the extrapolated responsivity at -30 °C.

For front-ends operating between -30 °C and 0 °C the worst-case downlink penalty can be as much as 3dB if the transmitter emits at 860 nm. Users can mitigate this problem by adopting one of the following solutions:

- Build extra margin in downlink budget by either using a back-end transceiver with higher TX OMA, or by reallocating the radiation penalty if the radiation induced degradation is not a concern.
- Screen back-end transceivers to avoid parts that emit at wavelengths beyond 850 nm.

6 Application example

In 2012, the LHCb experiment asked to perform a Versatile Link transmission test over 400m of OM4 fibre.

The test was performed with a MM VTRx module, 400m of Corning Clear Curve OM4 fibre, two connectorized breakpoints and an SFP+ MM Avago Transceiver AFBR 703SDZ. The results concluded that transmission at 4.8Gbps over 400m of OM4 fibre is feasible with practically no penalty, see Figure 16 below.

In parallel to the experimental demonstration, the Versatile Link power budget was re-calculated for 400m of Corning Clear Curve fibre (with a loss of 2.3dB/km instead of 4dB/km), three breakpoints (at 0.75dB per point instead of 0.5dB) and an Avago SFP+ backend transmitter OMA of -4.3dBm (instead of -3.2dBm). The revised power budget is shown in Table 7, with the original Versatile Link specs referenced in the cells with a grey background.

It is interesting to note that despite the excellent experimental results obtained on one prototype link, the power budget (which is a worst case calculation) is tight. This indicates that in a large system such as LHCb, some channels will statistically come close to operation failure during their lifetime unless mitigation actions are taken. In the downstream direction (Tx_VRx), replacing the SFP+ transceiver with a denser and more recent Avago minipod or micropod transmitter array (with a minimum OMA of -5.6dBm) will decrease the margin even further. In the upstream direction (VTx_Rx), configuring the minipod or micropod receiver in reduced bandwidth mode (5Gpbs) may recover some of the lost margin.

In such a situation, it is up to the experiment to assess the risk of implementing the system as is, and/or to take mitigation actions if possible (see section 5.2.2 above).

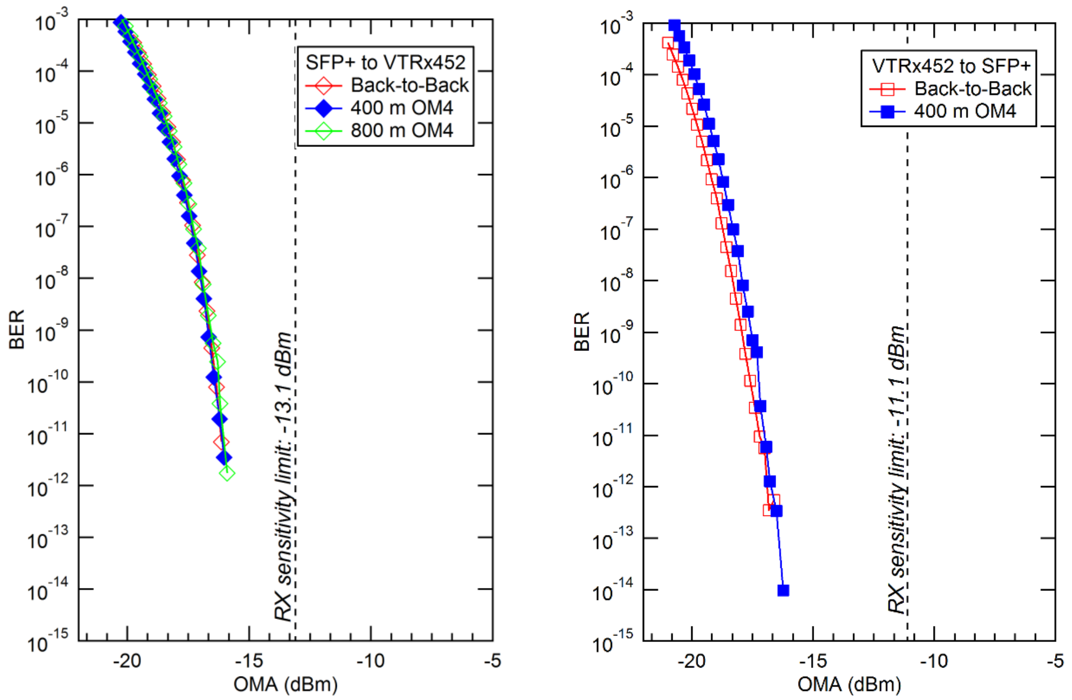

Figure 16: Bit Error Rate plots of 400m long Versatile Link in the downstream (left) and upstream (right) directions

Table 7: Versatile Link power budget (in grey background cells) compared to a possible link of 400m for LHCb (see text for details)

	MM_VTx_Rx	VTx_Rx LHCb	MM_Tx_VRx	Tx_VRx LHCb
Min. Tx OMA	-5.2 dBm	-5.2 dBm	-3.2 dBm	-4.3 dBm
Max Rx sensitivity	-11.1 dBm	-11.1 dBm	-13.1 dBm	-13.1 dBm
Power budget	**5.9 dB**	**5.9 dB**	**9.9 dB**	**8.8 dB**
Fibre attenuation	0.6 dB	0.95 dB	0.6 dB	0.95 dB
Insertion loss	1.5 dB	2.25 dB	1.5 dB	2.25 dB
Link penalties	1.0 dB	1.3 dB	1.0 dB	0.8 dB
Tx rad. penalty	0 dB	0 dB	-	-
Rx rad. penalty	-	-	2.5 dB	2.5 dB
Fibre rad. penalty	0.1 dB	0.1 dB	0.1 dB	0.1 dB
Margin	**2.7 dB**	**1.3 dB**	**4.2 dB**	**2.2 dB**

7 Evaluation samples

VTRx and VTTx evaluation samples are available from CERN in small quantities for prototyping purposes. To facilitate initial debugging and integration into test systems, an FPGA Mezzanine Card (FMC) has been developed hosting one VTRx and one VTTx module (Figure 17). This VTRx-FMC mezzanine can be plugged into any host board featuring an FMC-HPC-compliant port, such as for instance the Gigabit Link Interface Board (GLIB) [26], the FMC Carrier 7 board (FC7) or other widely available Virtex-6 or Kintex-7 boards. Firmware is also available for some of these platforms. Interested users are encouraged to contact the Versatile Link team for additional information.

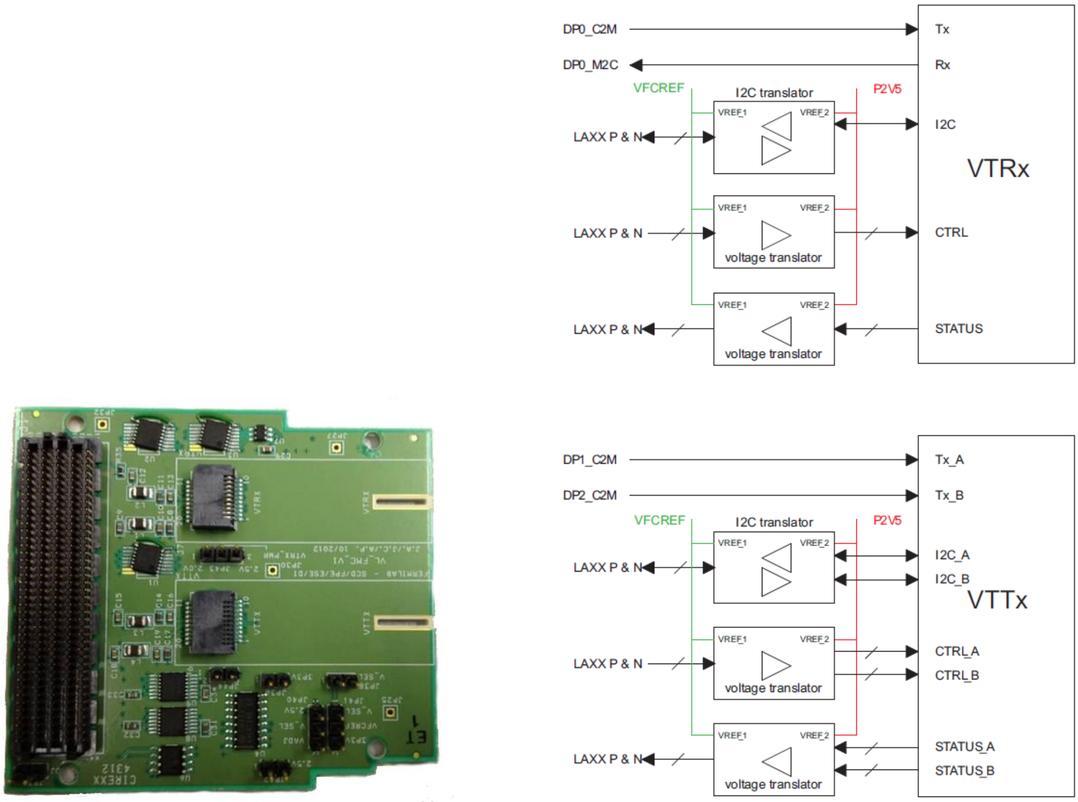

Figure 17: VTRx FMC picture (with two slots, one for VTRx and one for VTTx) and block diagrams

8 Documentation

The Versatile Link project documentation can be downloaded from the public page of the collaboration workspace:

https://espace.cern.ch/project-versatile-link/public/default.aspx

The public documents folder contains:

- The project proposal and its amendments
- A selected set of project overview presentations
- All material published in peer reviewed journals (and referenced below)
- A link to the project specification repository (including the latest version of this document)

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