



Magnetics Guide

Application Note

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Vitesse
Corporate Headquarters
741 Calle Plano
Camarillo, California 93012
United States

www.vitesse.com

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Revision History

Revision	Date	Description
Rev 1.0	April 1, 2006	First release
Rev 1.1	July 31, 2006	EMC test results for VSC8601/8641 family added. 8-core 3-wire CMC on PHY side added.
Rev 1.2	October 30, 2007	12-port (2x6) Power-over-Ethernet (PoE) magnetic modules added.
Rev 2.0	June 9, 2012	Updated text regarding CMC on the PHY side. Simplified EMC Test Data.

1 Introduction

This application note provides a designer with the basic knowledge of magnetic modules as well as some test data. The proper understanding of features of the magnetic module to be used with Vitesse PHY and integrated Switch/PHY devices is very important to ensure the best Electro-Magnetic Compatibility (EMC) and IEEE conformance of the finished product.

1.1 Audience

The target audiences for this document are hardware design engineers and managers using magnetics with Vitesse Gigabit Ethernet PHYs.

1.2 References

Some important references are:

- IEEE 802.3-2004 - CSMA/CD Access Method and Physical Layer Specification
- FCC - Part 15: Radio Frequency Devices

1.3 Terms and Abbreviations

Table 1. Terms and Abbreviations

Term	Explanation
CAT5	Category 5 (copper cable)
CSMA/CD	Carrier Sense Multiple Access / Collision Detection
CMC	Common-Mode Choke
DSP	Digital Signal Processing
EMC	Electro-Magnetic Compatibility
EVB	Evaluation Board
FCC	Federal Communication Committee
IEEE	Institute of Electrical and Electronics Engineers
PCB	Printed Circuit Board
PHY	Physical Layer Device
PoE	Power-over-Ethernet
PMA	Physical Medium Attachment
RF	Radio Frequency
SFP	Small Form-factor Pluggable (module)

2 Magnetics Role in Ethernet Systems

While not explicitly required by IEEE 802.3-2004, magnetics are the most commonly used method of meeting the requirements of the 10/100/1000BASE-T PMA electrical interface. However, there is no one standard configuration that meets all objectives for all designs at the lowest cost. Magnetics offer a straightforward solution to many functions of this interface, including electrical isolation, signal balancing, common-mode rejection, impedance matching, and EMC improvement. The following is a brief description of each of these areas.

2.1 Electrical Isolation

For human safety, the IEEE specification requires a 10/100/1000BASE-T port to be able to withstand 1,500 VAC at 50 Hz to 60 Hz for 1 minute between ports or from each port to the chassis ground. Transformers can easily and inexpensively meet this isolation requirement and are commonly used for this purpose.

2.2 Signal Balancing / Common-Mode Rejection

Each 10/100/1000BASE-T network cable consists of four sets of twisted pairs connected in a balanced configuration. While there are various circuit topologies that can provide the necessary balanced operation without magnetics, transformers simply and easily provide the balanced connection to each pair of a cable and can also provide a very effective rejection of common-mode signals.

The common-mode rejection of a transformer functions in both of the signal directions of a port. This common-mode rejection attenuates common-mode signals coming both from the cable to the PHY and also from the PHY (and its surrounding system) to the cable. This common mode attenuation is beneficial for the following reasons:

- Reduction of the common-mode signals picked up by the cable from its environment improves the signal-to-noise ratio of the system. This allows the PHY DSP to more easily recover the data signal and achieve the desired bit error rate. This is also known as electromagnetic immunity.
- The noise from the board circuits can couple to the sensitive signal traces going from the PHY to the magnetics, but due to the nature of this noise, most of it will couple equally to both differential signals, thus creating common-mode noise. This noise will be attenuated by the magnetics and improves the EMC performance. Because 10/100/1000BASE-T uses unshielded twisted pair cables, the cables radiate any common-mode noise that is coupled through the magnetics and onto the cables.

3 EMC Improvement

All high-speed digital devices create and use radio frequency (RF) energy. If this energy is allowed to escape into the device's environment it can become a source of electromagnetic interference.

The PHY devices are high-speed mixed-design (digital and analog) devices but their EMC can be significantly improved if a few important guidelines are met.

It is necessary to carefully design the systems to minimize the amount of RF energy reaching the 10/100/1000BASE-T ports, since this energy can be easily radiated from the unshielded CAT5 cables. Designers use multiple techniques to control RF emissions. While there is no single technique or component guaranteeing a successful EMC design, generally the measures involved fall into one of the two categories: **minimization** and **containment**.

3.1 Electro-Magnetic Interference Minimization

Minimization involves addressing the parasitic RF energy sources causing EMC problems. If this energy is minimized, there will be less need for additional minimization measures. It is not the purpose of this Application Note to cover all aspects of EMC improvement but it is important to list some of the major rules used to minimize the energy emitted from interference sources. These rules are as follows:

- Use the slowest practical rise and fall times on digital signals, especially clocks. These edges can often be slowed sufficiently by inserting a series resistor of a few tens of Ohms close to the signal source.
- Keep high-speed digital lines, especially clocks, as short as possible. Route them over unbroken ground or power planes. This will help to avoid turning these signal lines into efficient antenna.
- Avoid routing high-speed lines near lines going off-board. This is especially important for the 10/100/1000BASE-T signals. Capacitive and inductive coupling between traces can couple RF energy onto the off-board lines and into any cables connected to them.
- When high-speed lines on a circuit board must cross over off-board lines, ensure they do so at right angles. Where the lines must run parallel to one another, maximize the spacing between them and minimize the length of the parallel section. This will help to reduce the coupling between the lines.

For integrated Switch/PHY devices (e.g. SparX family) all the logic is integrated into a single device, and there are no external busses connected that can generate noise. This significantly improves the EMC performance of the systems.

3.2 Electro-Magnetic Interference Containment

Containment measures serve to prevent RF energy from escaping into the environment. The three basic techniques of containment are power filtering, signal filtering, and shielding.

3.2.1 Power Filtering

Power filtering means that all the high-speed digital and high-power analog modules are provided with local decoupling capacitors and, where necessary, either series resistors or ferrite beads are provided for the power rails. This way the noise generated locally is filtered 'on the spot' and not spread all over the entire board to

eventually escape into environment. Since high value capacitors are efficient at low frequencies and vice versa, each power rail should have a combination of high capacitance and low capacitance ones.

3.2.2 Signal Filtering

Signal filtering involves passing signals that must exit a chassis through frequency-selective circuits that attenuate the RF energy sufficiently well to meet EMC requirements. There is often a tradeoff between providing adequate attenuation of the interference energy and maintaining the integrity of the desired signal. This is where the distinction between common-mode and differential signals becomes advantageous. In 10/100/1000BASE-T systems, differential signals are used to convey the data in each port. Fortunately, most of the interference energy present on these same ports is in the form of a common-mode signal. Magnetic devices such as transformers with common-mode chokes do an excellent job of strongly attenuating common-mode signals while passing differential signals nearly unchanged.

3.2.3 Shielding

Shielding makes use of the fact that no electromagnetic field can pass through a perfect electrical conductor. If a source of RF energy can be completely enclosed within an unbroken conducting container, then none of that energy will exist outside of the container. If there are holes, seams, connectors, etc. passing through the container, or if the container is made of a poorly conducting material, then energy can escape and create interference.

Various shielding methods are used in system design. The primary method is to enclose the circuitry within a conductive housing or chassis. This can be made of either metal or plastic that has been treated to have a conductive surface. Individual pieces of the chassis must be in good conductive contact with one another. Conductive gasket material, multi-fingered leaf springs, and closely spaced screws are some of the techniques often used to ensure good conduction between chassis sections.

Another way of shielding is local shielding of noisy traces or busses inside the PCB; it is done by placing them in the inner layers and surrounding with copper planes, usually ground and power ones. For clock bearing traces, the positive side effect of this isolation measure is that it also keeps these signals clean from the induced noise causing clock jitter.

For integrated Switch/PHY devices (e.g. SparX family) all the logic is build into a single device, and there are no external busses and clock lines connected that can generate noise. As a result, these systems can often be made using an inexpensive 2-layer PCB and a plastic housing without shielding.

4 Magnetics Guide

4.1 Magnetic Types

Several different magnetic types are available, all conforming IEEE requirements. Only those containing a common-mode choke (CMC) are described in the document.

They can be split into two groups:

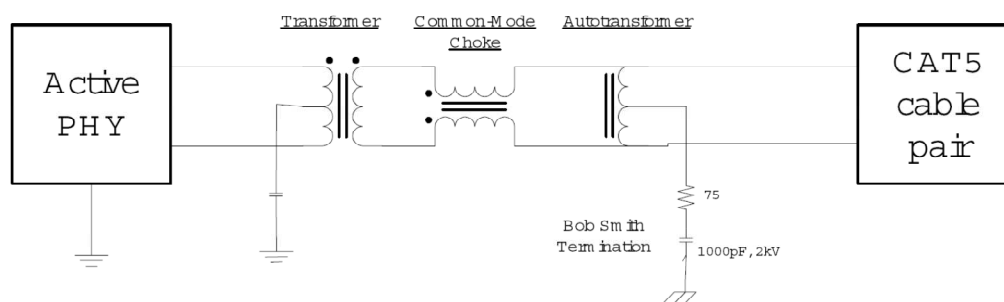
1. 12-core magnetics that consist of transformer, a common mode choke, and an autotransformer,
2. 8-core magnetics that consist of a transformer and a common mode choke.

Their advantages and disadvantages are described below.

4.1.1 12-Core Magnetics

A 12-core magnetic module (see 0) consists of a transformer, CMC, and an autotransformer (i.e. 3 separate magnetic cores) for each of the 4 twisted pairs in the cable.

Figure 1. 12-core magnetic (only one pair shown)



The purpose of the transformer with ratio of '1:1' is to create galvanic isolation between the cable and the system. The PHY side center tap of the transformer should connect through a capacitor to ground.

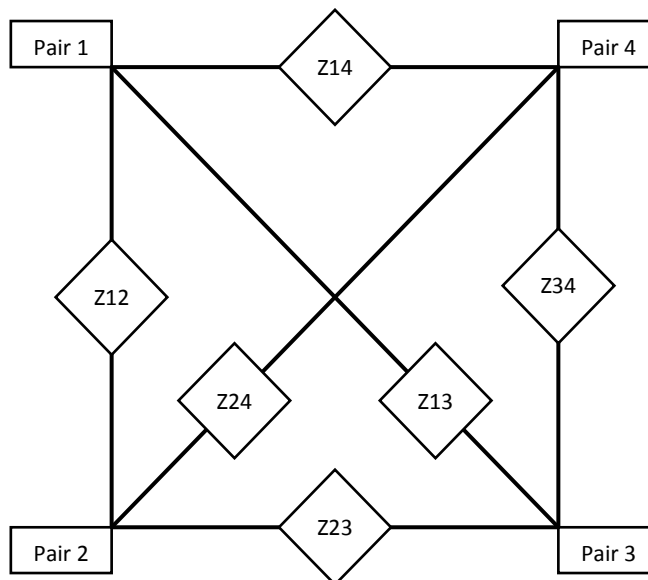
The purpose of CMC is to attenuate common-mode noise in the twisted pair: both noise coming from the system itself, where the CMC decreases the electromagnetic emission (i.e. doing the signal filtering for the entire customer's system as described above), and noise coming from the outside, where the CMC improves the electromagnetic immunity.

The autotransformer presents high impedance to the differential signal in the twisted pair, thus as though not existing for it, but very low impedance to the common-mode currents flowing to a circuit referred to as a Bob Smith termination.

4.1.2 Bob Smith Termination

Robert W. (Bob) Smith's patented idea proposes the way to reduce the common mode currents on a multi-pair system (e.g. CAT5 network cable). It is based on the fact that the pair-to-pair relationships of a CAT5 cable form transmission lines in themselves (see Figure 2). Due to the approximate symmetry in the construction of the CAT5 cable, each pair has the same relation with any other pair.

Figure 2. Intrinsic characteristic impedance between each pair of the four pairs



Providing those pair-to-pair transmission lines with termination matching their characteristic impedance in order to absorb the reflected wave and prevent standing wave from occurring significantly lowers parasitic interference radiation.

The high voltage capacitor between the common point of all the four resistors and the Chassis ground is not a part of Bob Smith termination but helps in filtering the noise residue managing to leak out through the transformer.

4.1.3 8-Core Magnetics

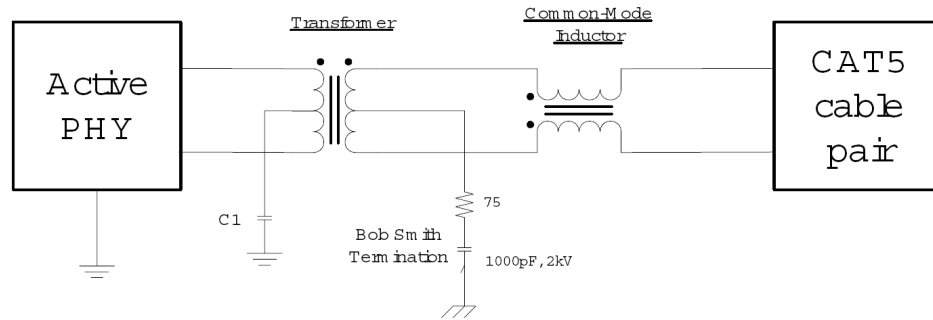
The 8-core magnetic only has a transformer and a CMC placed on either the cable side (see Figure 3) or the PHY side (see 0 and Figure 5) of the transformer.

Placing the CMC on the cable side has the following advantages:

- It also attenuates any common-mode noise that is generated by either the center taps noise of the transformer,
- Or by the transformer windings imbalance,
- Filters the noise in the systems where the Chassis ground is connected to the digital ground (quite popular case on computer motherboards) and, even being connected to Earth ground through the power supply circuit, is still noisy enough to inject noise through the high voltage capacitor (in this case removing the capacitor might be better EMC-wise).

The disadvantage, though, is that the Bob Smith termination becomes less effective for common mode noise due to the high impedance inserted between the cable and the impedance-matching resistor. The 12-core version and the 8-core version with CMC on PHY side do not have this disadvantage but require really quiet Chassis ground.

Figure 3. 8-core magnetic with CMC on cable side (only one pair shown)



Using an 8-core magnetic with the classic 2-wire CMC on the PHY side (see 0) is also not ideal due to the possible noise coupling from the ground plane to the cable through the transformer's center tap capacitor.

In addition, based on a limited tests conducted with transformers having CMC on the PHY side, the margin within the template has been somewhat reduced. We therefore recommend that future designs not to use this transformer configuration, (that is with CMC on the PHY side).

For older designs where this configuration has been used successfully, and passed all system level applicable standard tests, they may continue using these transformers.

Figure 4. 8-core magnetic with classic 2-wire CMC on PHY side (only one pair shown)

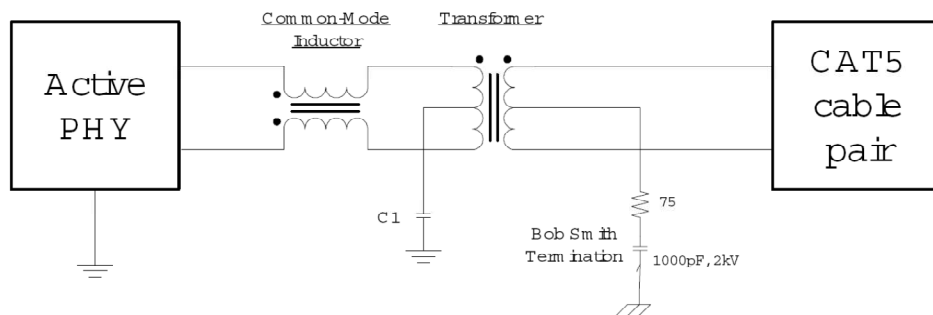
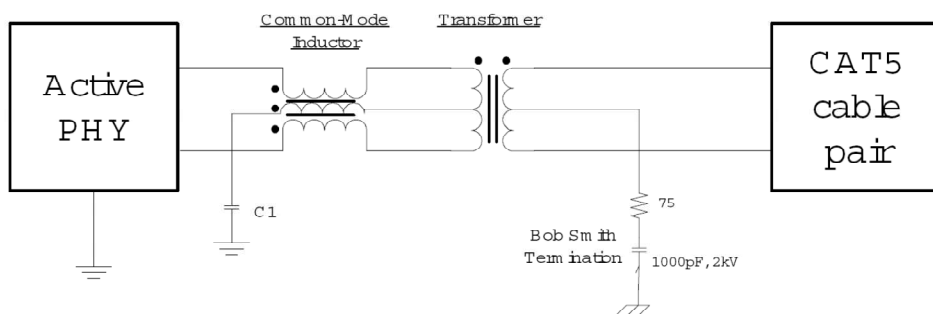


Figure 5. Modern 8-core magnetic with 3-wire CMC on PHY side (only one pair shown)



4.1.4 **8-Core versus 12-Core**

Generally speaking, there is no universal advice what is 'the best' but, instead, the right magnetic selection should be done depending on conditions in every specific case.

The 8-core magnetics are cheaper, thus more attractive, but riskier in many cases and cautiously recommended to skilled. The 12-core ones make the design process much easier without demanding extreme experience in the layout art, especially if the Ethernet module is a part of a system with a big digital section generating a lot of interference noise.

4.1.5 **Other Factors**

Although the schematic representation of different magnetic modules looks alike, there might be a lot of difference in their electrical and EMC performance. The coupling between the signals on each side of the transformer and common-mode chokes can couple noise and thereby reduce the effect of the common mode chokes.

4.2 **Integrated or Discrete?**

To minimize the component count and the product size, some manufacturers deliver magnetic modules, where the magnetic block is build into the RJ45-type connector block. As any compromise, this has both advantages and disadvantages.

Advantages:

- Lower component count -> lower production (assembly) cost,
- Potentially better EMC shielding of the sensitive cable side signals by the metal shield,
- Smaller footprint than separate magnetics and a connector.

Disadvantages:

- Harder to rework if a magnetic/connector is failing during production test -> Higher production cost,
- Due to the space limitations, the magnetics cores are smaller and closer to each other thus degrading crosstalk and EMC characteristics, increasing non-linear distortion and losses.

Especially the electromagnetic emission performance can be either better or worse, depending on the product they are used in. The integrated magnetic/connector modules have a metal shield placed around the whole part; it effectively screens the part from any noise that is present inside the system box. However, due to the small size of the magnetic part of the module, there is a high risk that the noise is coupled between the cable side and the PHY side of the magnetics, thereby limiting the common-mode choke effect. The sizes of the magnetic cores used in the magnetic/connector combinations are also normally smaller than those used in separate magnetics, and the performance is thereby lower.

Using separate magnetics and connectors has an advantage of lower coupling between the different parts inside the magnetics, and this results in better common-mode filtering. The disadvantage is that, once the signals have been filtered by the magnetics, they are routed to the connector on the PCB, and if the box contains a lot on noisy logic, this can couple to these lines and create EMC problems.

The designer needs to balance these advantages and disadvantages against each other when deciding what to use in his board design but much more often the best EMC performance is reached by using 12-core discrete magnetics.

5 Test Data

5.1 EMC Test Data

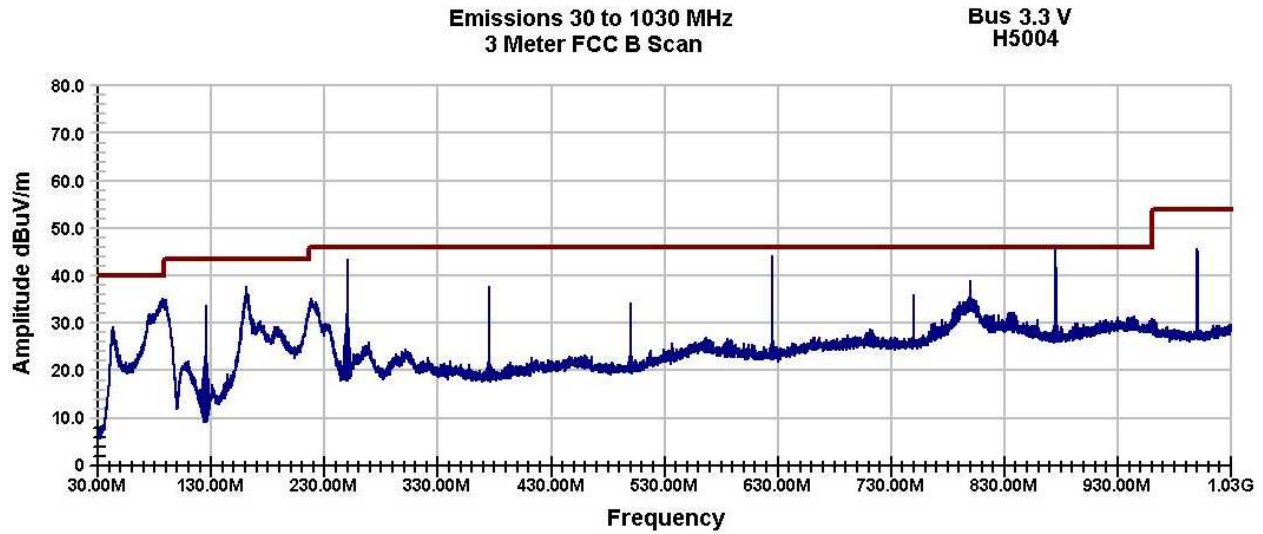
The table below summarizes the different magnetics and magnetic/connector combinations that have been tested with the SparX customer evaluation boards (EVBs).

Experiment has been conducted with and without a closed metal chassis and, as no noisy circuits exist on the SparX-G8 (VSC7388) and SparX-G5 (VSC7385) EVBs, the EMC results did not differ significantly.

Table 2. EMC Test Data

Vendor	Part Number	Configuration	Test Setup	EMC Class (FCC, Part 15)	Margin	Comment
Pulse	H5008	Single, 12-core	SparX-G8 Managed EVB	B	9.2dB	Without chassis
Pulse	H5009	Single, 8-core	SparX-G8 Managed EVB	B	1.3dB	Without chassis
Pulse	H5007	Single, 12-core	VSC8641/VSC8601 EMC Board	B	2.1dB	Without chassis
Pulse	H5004	Single, 8-core	VSC8641/VSC8601 EMC Board	B	1.0dB	Without chassis
Pulse	LF9207A	Single, 12-core	SparX-G8 Managed EVB	B	2.0dB	Without chassis

Figure 6. EMC Emissions – VSC8601/8641 PHY Family



5.2 IEEE Return Loss Data

The IEEE standard defines the minimum Return Loss parameter value in dB for the reference impedance of 100 Ω as follows:

Table 3. IEEE Minimum Return Loss for Reference Impedance of 100 Ω

Return Loss, dB	Frequency, MHz
15	1-20
$15 - 10 * \log_{10} (f / 20)$, where f is the frequency in MHz	20-100

Below are the Return Loss values measured for different PHYs and transformers used.

Figure 7. Return Loss Values Measured

