Building a Robust 10GBASE-T Solution

The industry demands a robust, low-cost 10 GbE interconnect that functions properly in the presence of unanticipated noise sources such as mobile radios. Intel is pleased to introduce the industry’s first integrated MACPHY using the 5th Channel and anticipates broad adoption of 10GBASE-T as demand for high performance networking expands.

ABSTRACT
10BASE-T Ethernet, twisted pair cabling is and has been the most ubiquitous media type for wired LAN communications. With all the advantages of low cost, simple-to-use cabling, installations of 10GBASE-T are running at one thousand times (1000x) the data rate of 10BASE-T. As data rates increased internal noise on the cable began to be addressed. At 10GBASE-T data rates, cable configuration and signal processing techniques were not enough to handle external sources of Radio Frequency Interference (RFI).

Using a dedicated 5th Channel receiver, signal processing, and Fast Retrain algorithms, external RFI is eliminated in nearly all cases, making the 10GBASE-T LAN essentially noise-proof in the data center environment.

Ethernet on Twisted-pair Cabling
Since the early days of 10BASE-T Ethernet, twisted pair cabling has been the most ubiquitous media type for wired LAN communications and is found in every data center universally. The industry has enjoyed the advantages of this low cost, simple-to-use cabling for three generations, and is now deploying 10GBASE-T at one thousand times (1000x) the data rate of 10BASE-T.

Some Things Haven’t Changed
The interconnect basics have remained the same, particularly the simplicity of the user experience. 10GBASE-T maintains the structured cabling deployment model with twisted-pair wiring, use of RJ45 connectors, field-terminated patch panels, 100 meters of reach, and autonegotiation for backwards compatibility to the lower speeds of Ethernet, including 1000BASE-T and 100BASE-TX. However, the 10x performance rate of 10GBASE-T does create some unique challenges.

The Evolution of Cabling
As the industry has evolved from lower-rate Ethernet to higher rates, it has required the further use of the available bandwidth of twisted-pair copper cabling. Each generation of Ethernet PHY uses both more efficient signaling and improved signal processing to mitigate the limitations found in twisted-pair cabling at higher transmission frequencies.

The cabling specifications have also seen enhancements as the bandwidth requirement increased for each generation of Ethernet. While the original 10BASE-T ran on two-pair Cat 3 cabling, 100BASE-TX (Fast Ethernet) saw the need for two-pair Cat 5 cable. 1000BASE-T evolved to using all four pairs of Cat 5e cabling and implemented bi-directional signaling, requiring both echo and near-end crosstalk (NEXT) cancellation on each pair. 10GBASE-T pushes the interconnect a bit harder, requiring Cat 6A or better cabling and additional complex signal processing technologies to ensure a reach...
Key Differences in 10GBASE-T

The 10x performance improvement of 10GBASE-T has come from two key differences. 10GBASE-T has the symbol rate of 800 Mega-symbols per second (Msps). That is up from 125 Msps in Gigabit Ethernet, a factor of 6.4x. The bits/symbol ratio has also increased from two bits in 1000BASE-T to 3.25 bits, a factor of 1.6. The frequency range used has also increased from ~80 MHz to <500 MHz. The increased signaling spectrum of 10GBASE-T means that it is potentially more vulnerable to electromagnetic interference. (See spectrum table below.)

Cable and Noise Environment

Cable environment and noise sources are similar to 1000BASE-T, but more difficult to eliminate due to the higher data rate as shown in Figure 1.

As shown in Figure 2, the 10GBASE-T receiver needs to cancel the following:
- Echo: The transmit signal on the receiver
- NEXT: Crosstalk from adjacent Tx pairs
- FEXT: Crosstalk from link partner Tx pairs
- ISI: Inter-symbol Interference between signals in time
- LDPC: Forward Error Correction decoding
- ANEXT: Crosstalk from neighboring cables

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**10GBASE-T Signal Spectrum**

<table>
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<tr>
<th>Signaling Characteristic</th>
<th>1000BASE-T</th>
<th>10GBASE-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mega-symbols per second (Msps)</td>
<td>125 Msps</td>
<td>800 Msps</td>
</tr>
<tr>
<td>Bits/Symbol</td>
<td>2 bits</td>
<td>3.25 Bits</td>
</tr>
<tr>
<td>Signal Spectrum</td>
<td>&lt;80 MHz</td>
<td>&lt;500 MHz</td>
</tr>
</tbody>
</table>

**Figure 1.** Noise Sources and the 10 Gbps Signal

**Figure 2.** Noise Cancellation Effect
The Design of Cat 6A to Mitigate Noise Sources from Adjacent Cables

Noise coupled onto the cables up to the Nyquist frequency of 400 MHz will be in-band noise that interferes with the data. Alien crosstalk (ANEXT) of any source can impact link quality.

One particular source of ANEXT was factored into the architecture of 10GBASE-T. At the lower symbol rate of 1000BASE-T, there was little need to consider noise radiating from one cable to its neighbor. Since 10GBASE-T increases the symbol rate from 125 Msps to 800 Msps, noise radiated from neighboring cables became a potential source of interference. This drove the development of Cat 6A with specific ANEXT requirements. These requirements included increasing the twist and diameter of the cable; and Cat 6A cable includes a separator for controlling the pair positions within the cable. The IEEE 802.3an* standard also provided an ANEXT mitigation technique called "power back off" (PBO). PBO ensures that short-link transmitters transmit at a lower power level, as short links have much less signal attenuation.

A New Challenge: External Radio Frequency Interference (RFI)

For all the attention given to noise sources within the cabling, there was little consideration in the development of the 10GBASE-T standard for external radio frequency interference (RFI), which can be part of the environment.

The increase in the symbol rate of 10GBASE-T by a factor of 6.4x extends the signal spectrum from ~80 MHz in 1000BASE-T to close to 500 MHz in 10GBASE-T. This increases the window of vulnerability to external noise interference. (See table below.)

Out-of-Band Noise Signals

Out-of-band noise is the noise contained in frequencies outside the frequency range of the 10GBASE-T signal. They can be above the bandwidth range of 10GBASE-T, such as cell phone interference. For 10GBASE-T, signals above 500 MHz can be filtered out using simple on-chip filters.

In-Band Noise Signals

Many noise sources that were well out of band for 1000BASE-T are in-band for 10GBASE-T. Radio transmitters such as HAM radio and walkie-talkies can operate in these frequencies creating the potential for interference. Signals from these sources can couple onto unshielded cables such as unshielded twisted-pair (UTP) as a common mode (CM) signal. A small fraction of the CM noise is converted to a differential mode signal. This in-band, uncorrelated differential signal would be seen as noise to the Ethernet receiver; alien noise that cannot be easily cancelled. The most common offenders are radio transmitters that operate at ~150 MHz and 450 MHz regions.

Ideally, a 10GBASE-T PHY could detect the in-band RF interference and cancel it. After all, robust 10GBASE-T performance is achieved by using sophisticated digital signal processing (DSP) techniques that cancel many inherent noise sources, such as echo, Near End Crosstalk (NEXT) and Far End Crosstalk (FEXT). The challenge is to isolate any RFI source and devise a technique to cancel this additional source of noise. It is instructive to review the mechanism by which RFI is coupled into a 10GBASE-T PHY, and how RFI induces errors on a link.

### Radio Frequency Interference Sources

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-Band</td>
<td>&lt;=500 MHz</td>
<td>Walkie-Talkie, HAM, Marine radios</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stationary Sources: TV, FM Radio: weak</td>
</tr>
<tr>
<td>Out of Band</td>
<td>&gt;~500 MHz</td>
<td>Cell Phones, Wi-Fi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>More radios ...</td>
</tr>
</tbody>
</table>
How Errors Are Introduced Via External Electromagnetic Interference

10GBASE-T specifies a balanced cabling system, where all links are fully differential. In the ideal system, the intended data transmission is fully differential, and any noise unintentionally coupled onto the twisted pairs is fully common mode. The common mode noise signals are easily rejected by the coupling transformers and differential input amplifiers of the PHY devices. In practice, however, some of the common mode noise signal can be converted into differential mode, for example, in the transformers or even in the cable itself. Once the noise has made the jump into the differential domain it is difficult to distinguish from the intended data signal. As a result, external electromagnetic interference can introduce errors into a 10GBASE-T transmission channel, resulting in a loss of link if the RFI source is not quickly identified and filtered out.

Cat 6A cabling is constructed using twisted pairs that have the benefit of rejecting ambient electromagnetic fields that appear to the wire pair as common mode energy. However, the rejection of these RF common mode signals offered by the twist is not complete; cabling does experience some common-to-differential mode conversion. Any differential noise would be seen by an Ethernet system as alien noise.

RFI Noise Cancellation Mechanisms

New and effective mechanisms have been developed to address these external noise sources. These RFI cancellation mechanisms provide the necessary immunity to external RFI sources. This DSP-based cancellation process includes a number of innovations that enable a robust 10GBASE-T link.

The Intel® Ethernet Converged Network Adapter X540 has dedicated EMI hardware for detecting and cancelling RFI noise. The RFI cancellation system exploits the information readily available within a 10GBASE-T PHY to provide immunity to external RFI sources.

The Intel X540 controller implements a 5th channel receiver dedicated to the common mode signal specifically designed for RFI/EMI detection. The 5th channel, along with a powerful cable diagnostic algorithm that accurately measures all of the time dimension sequences within the group of four channels, greatly improves reliability and signal integrity.

The basis of the Intel® X540 RFI architecture is to quickly identify and isolate the interfering signal. An image of the noise signal is created and used by the PHY to cancel or “subtract” it from the intended data signal.

The DSP techniques used within the Intel® Ethernet Converged Network Adapter X540 provide robustness in the presence of RF interference. The RFI noise cancelling mechanism provides direct information to the PHY about the source of interference. The DSP then can directly compensate for this noise source, providing robust operation both in compliance testing, as well as in enterprise applications.

Fast Retrain

The 5th channel mechanism solves a large majority of RFI events. A second mechanism available in the Intel® Ethernet Controller X540 is the Fast Retrain. Several years after the 10GBASE-T standard was completed, the IEEE adopted Fast Retrain as part of the 802.3az (Energy Efficient Ethernet) project. Fast Retrain is used as a fallback mechanism if the RFI cancelling function does not adequately cancel the RFI noise in the channel.

When a Fast Retrain event is triggered, the 10GBASE-T PHY will go through a subset of the training states that is used during a normal PHY startup sequence. This Fast Retrain sequence lasts ~30 ms as opposed to the normal two second PHY startup sequence. There is no limit on the number of successful Fast Retrain attempts. In the event that the nature of the interference source is so strong that the Fast Retrain mechanism cannot converge, the 10GBASE-T PHY should initiate a full startup sequence (as called for in IEEE 802.3an).

Support for the Fast Retrain mechanism is advertised via the standard autonegotiation-based register set. Fast Retrain can be enabled/disabled via the control interface (MDIO).

Practical Testing Setup:
- System w/LOM Port
- Bi-directional Traffic
- System w/Adapter Card Port
The Test Results
The test results below show impressive improvement between the 5th channel being disabled and enabled.

With the 5th channel disabled and the 10 V/m field strength, using the Fast Retrain mechanism alone, there are no link drops but there are 91 Fast Retrains. With the 5th channel enabled, there are no link drops and the number of retraining drops from 91 to eight retraining. As the field strength approaches 5 V/m the number of retraining drops to zero (0).

<table>
<thead>
<tr>
<th>Field Strength</th>
<th>5th Channel Enabled?</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 V/m</td>
<td>No</td>
<td>No link drop</td>
</tr>
<tr>
<td></td>
<td></td>
<td>91 Fast Retrains</td>
</tr>
<tr>
<td>10 V/m</td>
<td>Yes</td>
<td>No link drop</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 Fast Retrains</td>
</tr>
<tr>
<td>8.5 V/m</td>
<td>Yes</td>
<td>No link drop</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Fast Retrains</td>
</tr>
<tr>
<td>5 V/m</td>
<td>Yes</td>
<td>No link drop</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0 Fast Retrains</td>
</tr>
</tbody>
</table>

Practical Testing Configurations

- iPhone 4*, AT&T Wireless*
- HTC Incredible*, Verizon Wireless*
- HTC 7*, T-Mobile*
- Blackberry 8900*, AT&T Wireless

Cell Tower in Close Proximity to Building with Repeaters Inside Used for All Tests

Motorola XPR 6580* 800 MHz/900 MHz Radio

Motorola Talkabout MR350R* 462-467 MHz FRS
Conclusion

Industry progress has gone a long way towards removing RFI as a barrier to reliable 10GBASE-T performance. In the adjacent table, each generation of improvement is outlined.

Twisted pair cabling is the low-cost interconnect of choice and still the dominant interconnect within the data center. The industry demands a robust, low-cost 10 GbE interconnect that continues to function as intended, even in the presence of unanticipated noise sources. Intel is pleased to introduce the industry’s first integrated MAC/PHY using the 5th Channel and anticipates broad adoption of 10GBASE-T as demand for high performance networking expands in servers and as 10GBASE-T becomes integrated as the LAN on Motherboard (LOM).

### Progression of Reduction of RFI Effects

<table>
<thead>
<tr>
<th>Generation</th>
<th>Behavior</th>
</tr>
</thead>
</table>
| 2008       | • Drops link or has very high BER, cannot recover while noise present  
• CISPR 24 tests run with shielded cable |
| 2009       | • Drops link but can adjust, regain link, and continue to operate |
| 2010       | • Maintains link, but has a high BER period while adjusting to noise  
• Adjustment may take ~10-100 msec (specification issue)  
• Noise frequency is remembered so that subsequent events of same interferer will not cause errors |
| 2012       | • Completely immune to most RFI sources  
• Worst case adaptation = few nanoseconds (that is, would be noted as a single bit error)  
• No danger of link drop. |

For more information on 10GBASE-T products, visit [www.intel.com/go/ethernet](http://www.intel.com/go/ethernet)

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