Gigabit Ethernet over Category 5 unshielded twisted pair cable

Evaluating electrical characteristics of 1000BASE-T Physical Layer Devices

Master Thesis Project

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Abstract

The 1000BASE-T Gigabit Ethernet standard offers an easy upgrade path for today's 10BASE-T and 100BASE-TX networks. Most office networks uses these two standards and therefore 1000BASE-T is designed to be able to use the same Category 5 unshielded twisted pair (UTP) cabling system. By transmitting and receiving 5-level symbols on all four twisted wire pairs simultaneously the transfer rate of 1000 Mbps is reached. Two bits are encoded into one symbol and four symbols are transmitted simultaneously, one on each wire pair. The 1000BASE-T physical layer device has to be able to deal with the characteristics of the UTP cable. For example the UTP cable introduces crosstalk due to induced currents between the wire pairs and also echo due to impedance mismatches between the cable and the device.

To ensure that the 1000BASE-T physical layer devices are compliant with the IEEE 802.3ab Gigabit Ethernet standard their electrical characteristics have to be evaluated. The IEEE 802.3ab standard provides a set of tests that are required to prove IEEE compliancy. This report provides a detailed description of all the tests needed, including test setups, test equipment and post processing code needed for the transmitter tests.

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1.0 Introduction

The purpose of this report is to give a complete set of tests to determine if a 1000BASE-T physical layer device is IEEE compliant or not. To be able to successfully market and sell Ethernet products they have to be IEEE compliant. A document, which describes the tests performed and proves the results is usually requested by the customers. The following report provides a complete set of tests that will prove a device IEEE compliant or not.

The development of the test suite was done at Lucent Technologies Inc. Microelectronics group in Milpitas, CA, USA and will be used when testing their 1000BASE-T products. All test required are described in the IEEE 802.3ab standard for 1000BASE-T physical layer devices. The standard is used as a guide when developing the tests because detailed information about all the tests are not always provided.

The report starts with an introduction to Ethernet networking and is followed by a more detailed section about design principles and design challenges for 1000BASE-T. Chapter 3 then provides the test suite and the test methods.

2.0 Theory

2.1 Ethernet Development

The Ethernet protocol is based on the experiences from a 3 Mbps experimental network developed by Xerox in 1976. In 1980 Xerox proposed an Ethernet standard together with Intel and DEC. They proposed a network with a 10 Mbps baseband transmission rate over a shared media. This resulted in the first generation Ethernet later known as 10BASE5.

2.2 Transmission Methods

There are two commonly used basic transmission methods for transmitting a digital signal over a cable - baseband and broadband.
In baseband systems the stream of digital pulses is encoded and then directly transmitted onto the cable. This means that the frequency spectrum of the pulse stream can be wide extending from zero to some high value, depending on the pulse rate. Shared use of a media can then be accomplished by time division multiplexing.
In broadband systems the stream of digital pulses is modulated onto a sinusoidal carrier signal and then transmitted onto the cable.
For all modern Ethernet systems, baseband transmission is used.

2.3 The CSMA/CD principle

The Ethernet protocol operates according to the CSMA/CD (carrier-sense, multiple-access/collision-detect) principle. *Carrier Sense* means that all the stations connected to a common media must always listen to the network. If a signal is present the network is busy, if not it is idle. *Multiple Access* allows any station to start transmitting if the network is idle. *Collision Detect* requires that all the stations have the ability to detect colliding bit-streams. This can happen if two or more stations start transmitting at the same time. The network itself consists only of a passive media and there is no central network controller. All the stations listens to the network traffic all the time and are responsible for controlling their own transmissions and receptions.

2.4 The Ethernet Standards

The Ethernet protocol became an official IEEE standard in 1985. Over the years there has been many additions to the first 10 Mbps coaxial-bus-based network. The Ethernet standard has progressed to star-configured networks that now supports 10 Mbps, 100 Mbps and also 1000 Mbps. The additions are all described in the IEEE 802.3 Ethernet standard. The medias used are not coaxial cables anymore. The two most commonly used medias today are fiber optic cables and unshielded twisted pair (UTP) cables.
From the first generation coax-based systems the Ethernet development went down several different paths but the first real mass-market success came with the 10BASE-T standard in 1990. The 10BASE-T standard describes a 10 Mbps network that became successful due to its use of multiport repeaters (HUB's) and structured telephone wiring. 10BASE-T uses twisted pair telephone-cables between the HUB and the workstations. A typical office installation uses the same wiring practice as telephone wiring.

The next widely used standard came with the 100BASE-TX in 1995. The 100BASE-TX standard is also known as Fast Ethernet with a speed ten times the one for 10BASE-T. The foundation for Fast Ethernet remains the same as for 10BASE-T with its use of multiport HUB's and structured cabling. The telephone cables used for 10BASE-T will not support the higher transmission rate used by Fast Ethernet. This is due to too high signal degradation in the cable and also due to the level of electromagnetic radiation emitted during transmission. The level exceeds the limit allowed by both American and European regulations. Instead of telephone cable a UTP cable has to be used. There are several different categories of UTP cable available:

- **Category 1 and Category 2.** Cables used for telephone service.
- **Category 3.** Specified for use up to 16 Mbps. Typically used for voice and data transmission rates up to 10 Mbps.
- **Category 5.** Specified for use up to 100 Mbps. The most commonly used network cable today.

There are also a few new categories of UTP cable on the market – Category 6 supports frequencies up to 200 MHz and Category 7 that supports frequencies up to 600 MHz. None of the new categories are yet included or used by any Ethernet standard. 100BASE-T networks uses Category 5 cable or shorter known as CAT 5 cable.

Further development has led to the latest addition to the Ethernet family of standards, Gigabit Ethernet over copper and optical fiber. The standard was approved in 1998. Gigabit Ethernet provides the transmission rate to bring Ethernet into a new high-speed era and it is based on the same key principles as the old 10BASE-T standard: multiport repeaters and structured wiring with dedicated cable to each network station. The Gigabit Ethernet standard includes a few different media types listed in table 2.1

Media Type	**Maximum Cable Length**
1000BASE-T, CAT 5 UTP copper link	100 m
1000BASE-SX short wavelength, 62.5 µm multimode fiber optic link	275 m
1000BASE-SX short wavelength, 50 µm multimode fiber optic link	550 m
1000BASE-LX long wavelength, 62.5 µm multimode fiber optic link	550 m
1000BASE-LX long wavelength, 50 µm multimode fiber optic link	550 m
1000BASE-LX long wavelength, 10 µm single-mode fiber optic link	5000 m

Table 2.1 – The Gigabit Ethernet standards

The primary long-distance Gigabit Ethernet is the 1000BASE-LX single-mode fiber (SMF). For fiber transmissions two different wavelengths are used. SX stands for short wavelength and uses 850 nm. LX means long wavelength and uses 1300 nm. All the different Gigabit standards are built around the same model, called the IEEE 802.3 CSMA/CD LAN model shown in figure 2.1.

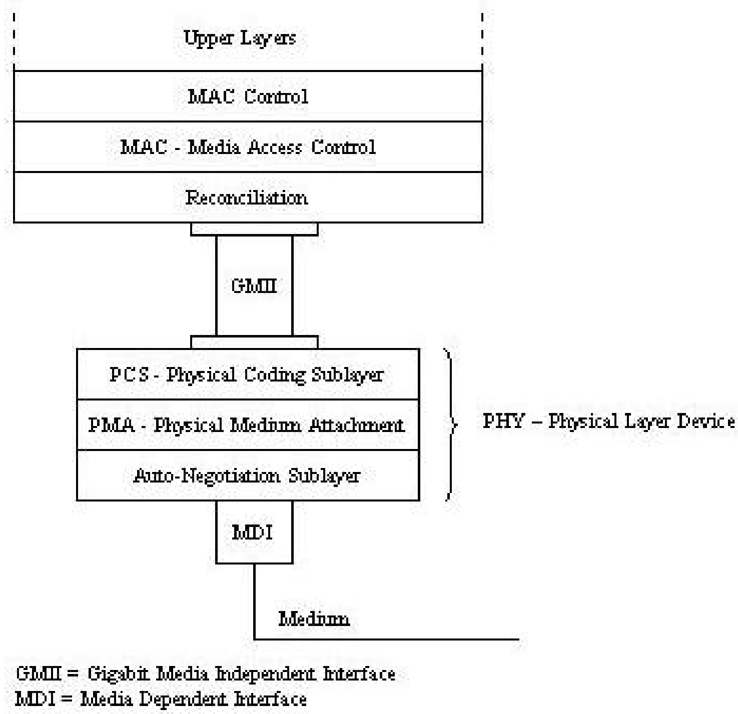

Figure 2.1 - IEEE 802.3 CSMA/CD LAN model

The difference between the standards lies in the use of different medias. But the only thing that needs to be adapted to the media in the LAN model is the physical layer (PHY). The MAC and the rest of the upper layers are not dependent on the used media. The MAC layer connects to the physical layer through the GMII bus. The GMII bus is a 125 MHz digital bus also independent of the media. The physical layer transmits the data received from the MAC onto the media after converting it to a suitable format depending on the media used. The PHY also receives data from the media that needs to be converted to the digital GMII-format and transmitted to the MAC. This report focuses on the 1000BASE-T PHY that can be used for distances up to 100 m using Category 5 or better UTP cables.

2.5 The 1000BASE-T Gigabit Ethernet Standard

The purpose of this standard is to provide an upgrade path from 100BASE-TX networks. The 1000BASE-T standard requires a 4-pair Category 5 unshielded twisted pair cable. 1000BASE-T supports 1000 Mbps operation over up to 100 m of this kind of cable. This cable is the most widely used indoors cable and upgrading from 100BASE-TX to 1000BASE-T can be done without installing new network cables. This is the biggest advantage for 1000BASE-T compared to the fiber optic versions of Gigabit Ethernet. The disadvantage is of course the short range but for most office networks 100 m is more than sufficient. IEEE approved the 1000BASE-T standard in June 1999.

2.6 1000BASE-T Gigabit Ethernet - Design Principles

Almost all office networks today run at 10 Mbps or 100 Mbps over standard CAT 5 UTP cable. The networks are designed according to the star principle with one dedicated cable from the HUB or SWITCH to each workstation. The cable consists of four pairs of twisted wires. For 10 Mbps and 100 Mbps traffic using 10BASE-T or 100BASE-TX only two of these pairs are used. The signals are transmitted differentially. Therefore a pair of wires is required to transfer a signal. One pair is used for transmitting data and one pair for receiving data. The connection consists in other words of two simplex links to form one full-duplex link. This is where 1000BASE-T differs from 10BASE-T and 100BASE-TX. Instead of using two simplex links, 1000BASE-T sends encoded signals simultaneously in both directions on the same wire pair. 1000BASE-T also uses all four pairs of wires available in the cable. The 1000 Mbps data rate is reached by a transmission rate of 250 Mbps at each wire pair. Figure 2.2 describes the link topology of 1000BASE-T.

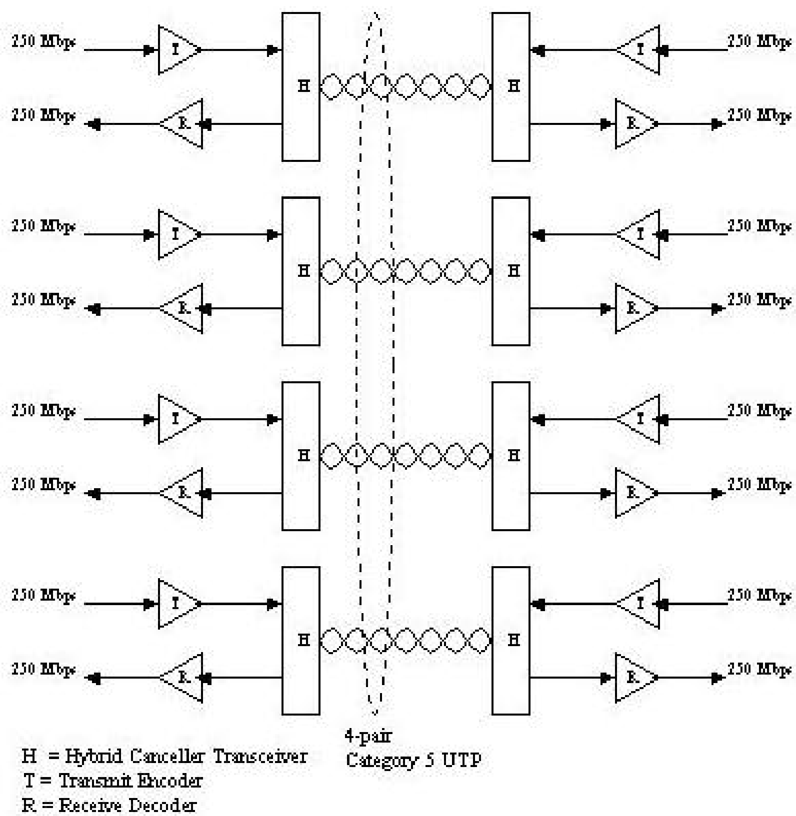

Figure 2.2 -1000BASE-T Link Topology

The actual transmitted signal on each wire pair is a 5-level {+2, +1, 0, -1, -2} pulse modulated symbol (PAM5). Four symbols, transmitted simultaneously on the four pairs of wire, forms a code-group (4D-PAM5) that represents an 8-bit frame octet. This means that every symbol corresponds to two bits of data. The 4D-PAM5 coding allows the 1000 Mbps data rate to be achieved with a symbol rate of only 125 Msymbols/s per wire pair. This matches the speed of the GMII bus that delivers eight bits of data at a rate of 125 MHz. All the eight bits can therefore be transferred using only one 4D-PAM5 symbol. The encoding of the outgoing data and also the decoding of the incoming data takes place in physical coding sublayer (PCS). The PCS layer

also performs scrambling of the data to randomize the symbol sequence. This is done to minimize the spectral lines in the transmitted signal and thereby reducing the electromagnetic radiation during transmission. There are separate scramblers for the *master* and the *slave* and this makes the two opposite traveling symbol streams more or less uncorrelated which aids symbol recovery at the receiving end.
Whenever two physical layer devices are connected one is chosen to be *master* and one is chosen to be *slave*. Transmission from the *master* is then timed by its local clock and the *slave* is timed by the clock it recovers from the received symbol stream. For this reason a continuous stream of Idle symbols is sent whenever there is no regular transmission in progress. This keeps the two connected PHY's synchronized at all times. The Idle symbols are selected from a subset of the PAM5 symbols, only {+2, 0, -2} are allowed. The process when the master and the slave is chosen is called *Auto-Negotiation.* During *Auto-Negotiation* a few other tasks are also performed.

- The link is ensured to be operational. For instance, if the cable is to long the signal degradation will make it impossible to transfer data without losses. This is not acceptable and under these circumstances *Auto-Negotiation* will fail.
- The speed of the connection is negotiated. Most physical layer devices are able to operate at multiple speeds such as 10/100/1000 Mbps.
- It is decided whether the link will operate in full-duplex mode (simultaneous bi-directional traffic) or half-duplex mode (one way traffic). All physical layer devices might not be able to handle full-duplex traffic.

The physical medium attachment layer (PMA) consists of four independent transceivers. The signal being received on one pair is the sum of the just-sent signal and the signal transmitted from the other end of the link. The transceiver implements a special receive function where the inverse of the transmitted signal is added to the composite signal from the wire pair. The PMA also implements a few other functions to aid the performance of the physical layer device. These functions include signal equalization, *echo* cancellation and *crosstalk* cancellation. They are described, and their need is explained in the next section.

2.7 1000BASE-T Gigabit Ethernet - Design Challenges

The media used for 1000BASE-T is a simple unshielded twisted pair cable. The cable consists of four pairs of copper wires twisted together inside an insulating tube. When an electrical signal travels along an imperfect conductor it looses power. This loss, or attenuation, is a function of the conductor length and the signal frequency. The loss increases with the length of the cable. It also becomes greater with an increasing frequency. The ”frequency-loss” is due to the skin effect. The skin effect states that AC currents tend to ride along the skin of a conductor. This skin becomes thinner with increasing frequency and a thinner skin results in a higher loss. The attenuation of the cable limits the cable length. If the length exceeds some number, depending on the cable type, the signal is so week it can simply not be detected. In this case the Category 5 UTP cable limits the length to 100 m for 1000BASE-T Gigabit Ethernet. As stated above, the UTP cable consists of four twisted pairs of wires. These four pairs are bundled closely together inside a tube of insulating material. When wires are bundled this close together another problem appears. Time-varying currents in one wire tend to induce time-varying currents in nearby wires, see figure 2.3. This is called *crosstalk.*

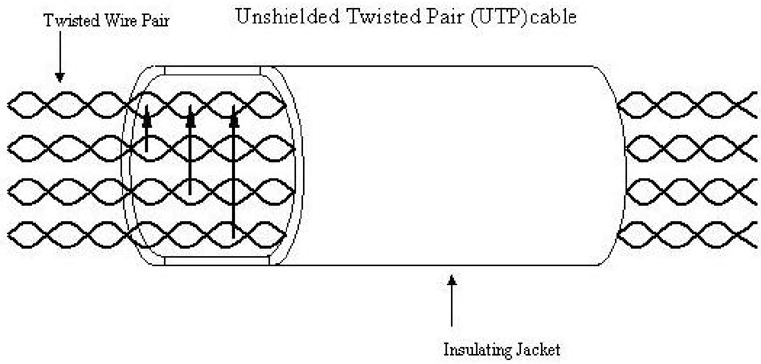

Figure 2.3 - Crosstalk in UTP cables

Because the presence of four wire pairs there is for every wire pair three other wire pairs that will induce currents. The induced currents result in noise at the receiver. Crosstalk is divided into three groups, Near-end crosstalk (NEXT), Far-end crosstalk (FEXT) and Alien crosstalk.

NEXT is when a local transmitter affects a local receiver. NEXT is pretty easily cancelled because the symbols causing the crosstalk are available in the local PHY. For each of the four transmitters in a 1000BASE-T PHY three NEXT cancellers are needed. This is because there are three other wire pairs present that induce noise. The NEXT canceller has to be adaptive because the magnitude of the crosstalk is depending on quality of the specific cable the PHY is connected to.

FEXT is when a remote transmitter affects a local receiver. The FEXT is caused by three of the remote transmitters and the symbols they are transmitting are not known. But by observing the incoming signal on all the local receivers the FEXT can be modeled and canceled. This is of course much more complicated than canceling NEXT but still possible.

Alien crosstalk is noise induced by other cables close to the UTP cable. For instance, data cables and voice grade cables usually run close to each other. Sometimes even in a tight bundle. This causes noise coupled between the different cables. The noise is coupled almost equally onto the four pairs and can therefore be detected. By using cross-coupled noise cancellers, correlated noise can be eliminated.

When a circuit is connected to a cable it “sees” the characteristic impedance of that cable. For the UTP cable the characteristic impedance is 100 Ω. The maximum power transfer theorem states that the maximum power of a signal is transferred from a source to its load when the source and load impedances are matched. In this case the source is the one of the PHY transmitters and the load is one of the twisted pairs in the UTP cable. The UTP has a characteristic impedance of 100 Ω and therefore the output impedance of the transmitter should have the same value. When the impedances are perfectly matched all the power of the signal is transferred onto the cable. However, there are always at least a slight mismatch between the cable’s characteristic impedance and the transmitter output impedance. When there is a mismatch between the impedances all the power of the signal is not transferred onto the cable. The portion not transferred is reflected back to the source. The reflected signal is also called *echo* because it is reflected back to the transmitting PHY. The reflected signal becomes interference at the local transmitter. The ratio of the reflected voltage and the incident voltage is called the reflection coefficient. When providing data for the reflection problem it is often given using the term Return Loss. Return Loss is the

magnitude of the reflection coefficient expressed in decibels. Echo can be canceled using a similar technique as for NEXT. The just transmitted symbols causing the reflection are always known. All the four transmitters emit signals that get reflected back to the every corresponding receiver. To eliminate the echo all transmitter-receiver pairs are equipped with an echo canceller. The echo is in the same way as crosstalk dependent on the specific cable used. Therefore the echo cancellers also need the ability to adapt to the cable environment.
Symbols are transmitted and received with a speed of 125MHz. This means that a new symbol is emitted every 8 ns. This short period can cause coherent symbols to interfere with each other. This is due to the rise/fall-time of the transmitters and the attenuation characteristics of the cable. Inter-symbol interference can be taken care of by using adaptive equalizers, a technique already used in 100BASE-T applications.

Echo, near-end crosstalk (NEXT), far-end crosstalk, alien crosstalk and inter-symbol interference all create noise at the receivers interfering with the actual signal. Figure 2.4 describes the noise environment for a 1000BASE-T channel.

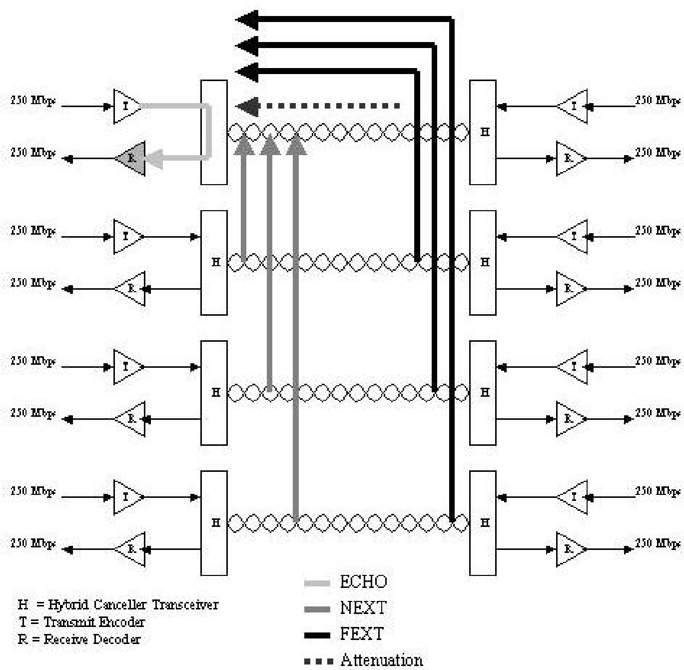

Figure 2.4 - 1000BASE-T noise environment

The noise components can be canceled using digital adaptive filters. The problem is that if all noise components are to be canceled it requires a large number of adaptive filters. Some of the noise components might not be that important to remove simply because they are small. The echo canceller, the equalizer and the NEXT cancellers are however needed to ensure that the required bit-error-rate is achieved. If these three functions are implemented it results in five adaptive filters for each receiver, one for the equalizer, one for the echo canceller and three for the NEXT canceller. NEXT consists of three components, one from each one of the other cable pairs. Five filters for each one of the four receivers results in a total of twenty adaptive filters (and a lot of chip real estate) for every physical layer device.

3.0 Evaluation and Testing

The IEEE 802.3 Gigabit Ethernet standard does not only describe the basic design principles. It also provides detailed specifications of signal shapes and signal levels etc. The purpose of this high level of detail is to ensure that all IEEE compliant devices will be able to interoperate properly regardless of its brand name. When designing networks, equipment from different manufacturers can be mixed together as long as they are IEEE compliant.

In the standard there is a sub-clause defining the electrical characteristics of the PHY. The sub-clause further describes how to determine these characteristics. The characteristics of cabling and connectors are also specified. It is important to understand the difference between production testing and device characterization. In production, only the basic functionality of the devices and a few important electrical characteristics are tested. The tests are performed on Automatic Test Equipment (ATE's) and are limited to a very short period of time. When millions of devices have to be tested only a few seconds can be spent on every device.

This chapter describes the electrical characterization performed in the design lab. Only a small number of devices sampled from different production batches are characterized. A wide range of electrical characteristics are closely examined and their dependence on environmental conditions such as temperature and supply voltage are recorded.

3.1 Transmitter Electrical Specifications – Test Modes

For testing purposes the standard states that the PHY must provide a set of four test-modes. The output signal from the transmitter during normal transmission can be very hard to observe. A sequence of pseudo-random unknown symbols changing every 8 ns makes testing very hard, if not impossible. The four test-modes that are provided force the PHY to transmit known sequences of data.

Test-mode 1 transmits the following sequence of data symbols from all four transmitters: {{**+2** followed by 127 **0** symbols}, {**-2** followed by 127 **0** symbols}, {**+1** followed by 127 **0** symbols}, {**-1** followed by 127 **0** symbols}, {128 **+2** symbols, 128 **–2** symbols, 128 **+2** symbols, 128 **–2** symbols}, {1024 **0** symbols}}. The sequence is repeated continually without breaks between the repetitions. Figure 3.1 shows an example of the test-mode 1 waveform.

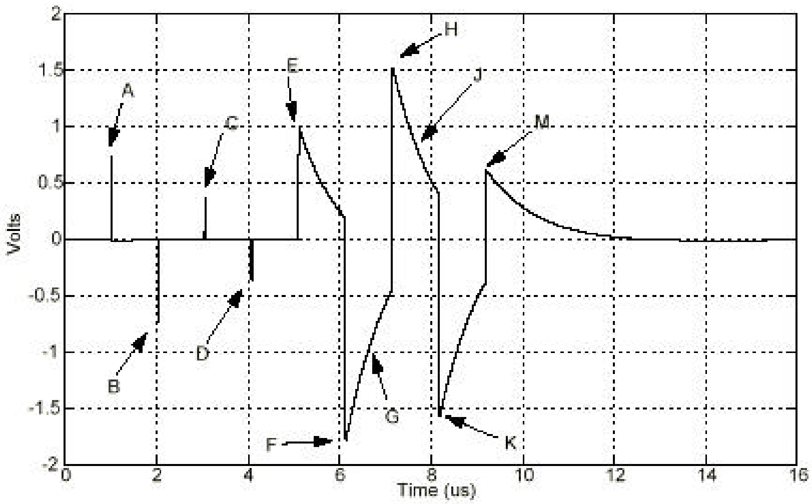

Figure 3.1 - Example of transmitter test-mode 1 waveform (1 cycle)

When in test-mode 2, the PHY transmits the symbol sequence {**+2**, **-2**} repeatedly on all four transmitters. Test-mode 2 is timed by the local (125.00 MHz ±0.01%) master clock – master timing mode.

When in test-mode 3, the PHY transmits the same symbol sequence as for test-mode 2. But instead of using the local clock, test-mode 3 is timed by the recovered (125.00 MHz ±1%) clock – slave timing mode. A typical transmitter output for transmitter test-modes 2 and 3 is shown in figure 3.2.

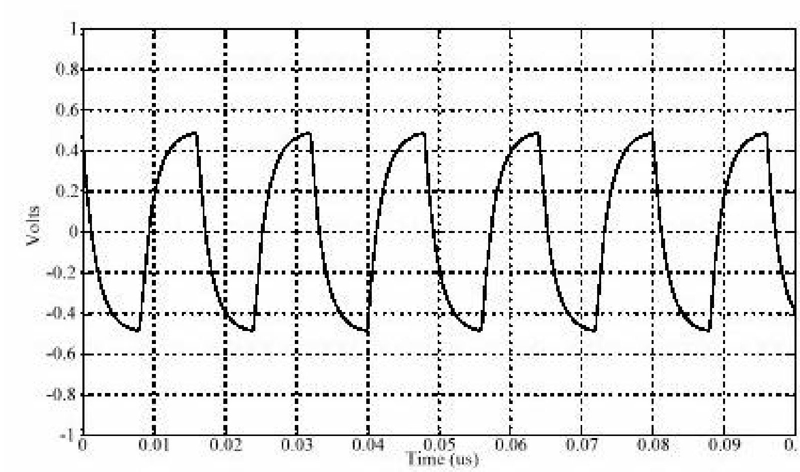

Figure 3.2 – Example of transmitter test-modes 2 and 3 waveform

The symbol sequence transmitted when the PHY is in test-mode 4 is generated by the following procedure.

- An 11-bit-length shift register, as shown in figure 3.3, is used to generate the bit-sequences defined by the scrambler generator polynomial $g = 1 + x^9 + x^{11}$.

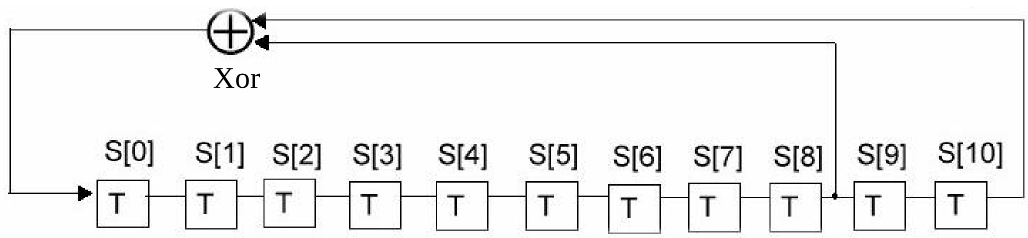

Figure 3.3 – Shift-register used when generating test-mode 4

The bits in the shift register is named S[10:0]. At each symbol period (8 ns) the shift register is advanced by one bit and one new bit is generated and inserted into S[0]. Bits S[8] and S[10] are exclusive OR'd together to generate the next S[0].

- The bit sequences x0, x1, x2 are generated from combinations of the bits in the shift register.

x0 = S[0]

x1 = S[1] & S[4]

x2 = S[2] & S[4]

where & is logical AND

- The transmitted symbol sequence is generated by the bit sequences x0, x1, x2 according to table 3.1.

x2	**x1**	**x0**	**symbol**
0	0	0	0
0	0	1	+1
0	1	0	+2
0	1	1	-1
1	0	0	0
1	0	1	+1
1	1	0	-2
1	1	1	-1

Table 3.1 – Transmitter test-mode 4 symbol mapping

The symbol sequence is transmitted simultaneously on all four transmitters. A typical transmitter test-mode 4 output is shown in figure 3.4.

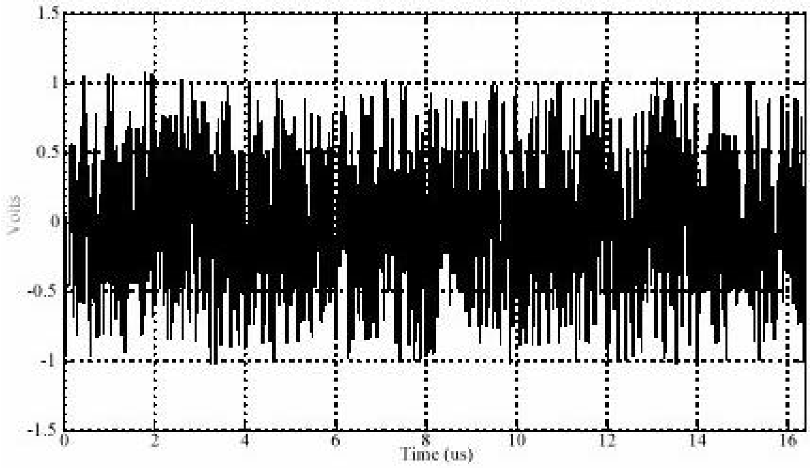

Figure 3.4 – Example of Transmitter test-mode 4 waveform (1 cycle)

3.2 Transmitter Electrical Specifications – Test Setups

The IEEE standard specifies a set of four test fixtures that shall be used when testing the transmitter electrical specification. The standard states that these four test fixtures or their functional equivalents must be used when testing the transmitter. Figure 3.5, 3.6, 3.7 and 3.8 shows the fixtures as they are given in the standard.

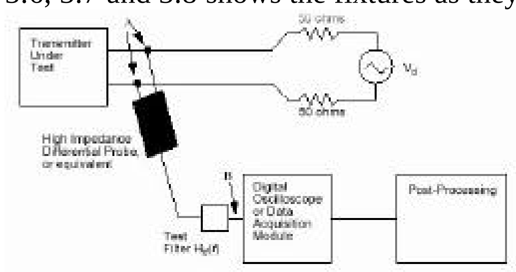

Figure 3.5 – IEEE Transmitter test fixture 1

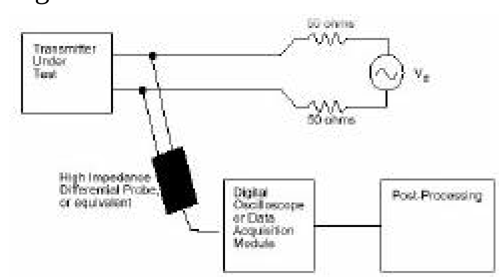

Figure 3.6 – IEEE Transmitter test fixture 2

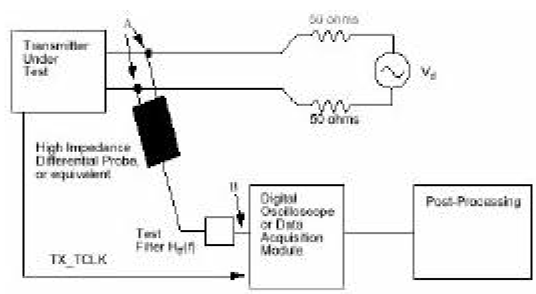

Figure 3.7 – IEEE Transmitter test fixture 3

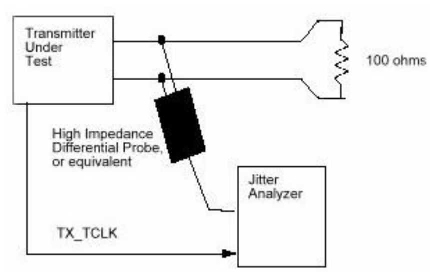

Figure 3.8 – IEEE Transmitter test fixture 4

In test fixture 1 through 3 the transmitters is directly connected a 100 Ω differential signal generator. The signal generator transmits a sine wave with specified frequency and amplitude according to table 3.2 below. The sine wave is called V_d or the disturbing signal. An oscilloscope is monitoring the output from the transmitter using a high impedance differential probe. The test filter H_{tf} (f) in fixture 1 and 3 can be implemented as an analogue filter as indicated in figure 3.5 and 3.7 or as a digital filter in the post processing block. The test filter has the continuous time transfer function:

$$H_{tf}(f) = jf / (jf - 2 * 10^6) \quad \text{f in Hz and}$$

j denotes the square root of –1

If the filter is implemented as a digital filter in the post processing block it shall have the discrete time equivalent transfer function.

Test Fixture	V_d Amplitude	V_d Frequency	Test Filter
1	1.4 V peak-to-peak	31.25 MHz	Yes
2	1.4 V peak-to-peak	31.25 MHz	No
3	2.7 V peak-to-peak	20.83 MHz	Yes

Table 3.2 – Test fixture 1 through 3 setup

The purpose of the disturbing signal is to simulate the presence of a remote transmitter. 1000BASE-T uses bi-directional transmission but when testing the device only one of the signals is of interest. If a remote transmitter is connected it will be impossible to observe just one of the signals. But transmitter still has to be tested under the influence of an incoming signal to make sure it will operate properly under these conditions. Therefore, a well-defined signal is used to simulate the remote transmitter. The oscilloscope sees the sum of the transmitter output and the disturbing sine wave. The disturbing signal then has to be removed before the transmitter output can be evaluated, this is the main purpose of the post processing block. Instead of removing a complex 1000BASE-T signal the post processing block only has to remove a simple sine wave. The signal TX_TCLK (also known as CLK125) in fixture 3 and 4 is the transmit clock that times the symbol transmission.

In test fixture 4 the transmitter is directly connected to a 100 Ω resistive load. The oscilloscope is, as before, monitoring the transmitter output through a high impedance differential probe.

During the development of the evaluation procedures a few modifications have been made to the test fixtures. There are two major versions of the test fixtures.

The first version, referred to as the Lucent setup, is almost identical to the original IEEE fixtures. Figure 3.9 shows a detailed view of the Lucent setup for fixture 1 through 3.

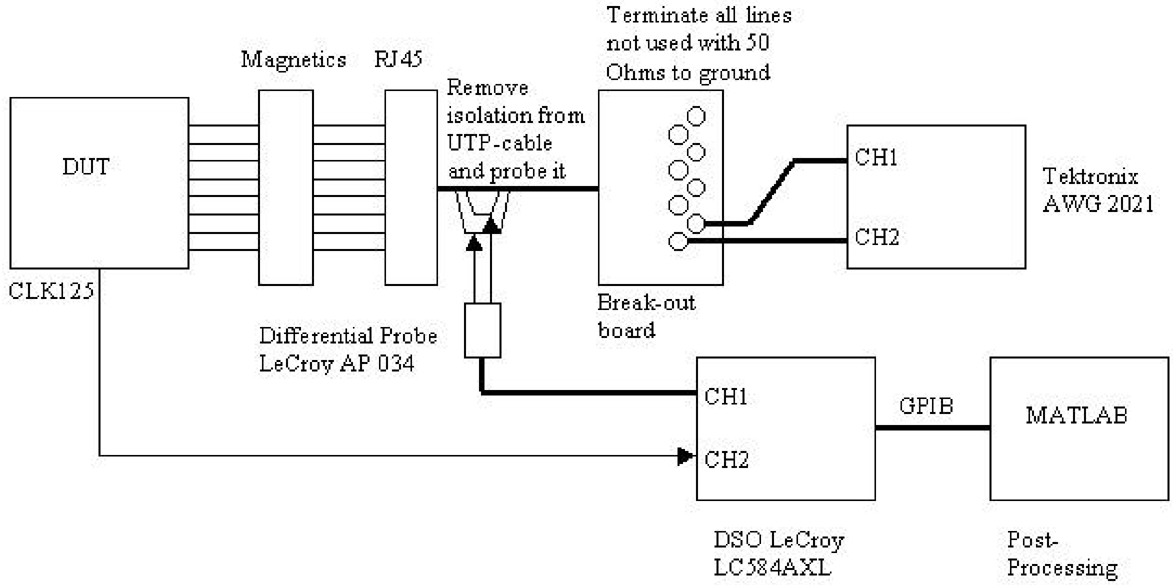

Figure 3.9 – Lucent version of test fixture 1 through 3

There is one new component introduced in this setup compared to the original IEEE setup. A break-out board is inserted between the device under test (DUT) and the disturbing signal generator. The board connects one RJ45 connector to eight SMA connectors. The only function of the break-out board is to make it possible to easily connect any two of the eight wires in the UTP cable to the disturbing signal generator. Because all the transmitter tests have to be done for all four transmitters one by one the disturbing signal has to be applied to the corresponding cable pair. The DUT output is connected to the break-out board with a short CAT 5 UTP patch cable. Close to the RJ45 a piece of isolation is removed from the cable to enable probing of the cable pairs. The two SMA's corresponding to the transmitter currently under test is connected to the disturbing signal generator. The other six connectors are terminated with 50 Ω to ground. To monitor the signal a high impedance differential probe is connected to the UTP cable where the isolation was removed. The rest of the instruments used are:

- Digital storage oscilloscope (DSO), LeCroy LC584AXL
- High impedance differential probe, LeCroy AP 034
- Disturbing signal generator, Tektronix AWG2021, Arbitrary Waveform Generator

The second setup is developed by the Inter-Operability Lab (IOL) at the University of New Hampshire. The IOL is an independent testing lab where manufacturers of network equipment can get their test results verified. The main purpose of the IOL is to perform inter-operability test between different brands of network equipment. All major manufacturers are members of the lab and they are all providing equipment of their own to be tested for compatibility with other brands.

The IOL setup introduces yet another component. The new device is a passive three-port component called power-splitter. The three ports are named 1, 2 and S. Like its name implies, the power splitter divides the power of the input at port S evenly between port 1 and port 2. Inputs to port 1 and port 2 are averaged to produce one output at port S. The key feature of the power splitters is that ports 1 and 2 are isolated. The IOL setup uses this feature to apply the disturbing signal to the DUT while only a small part of it reaches the oscilloscope, see figure 3.10.

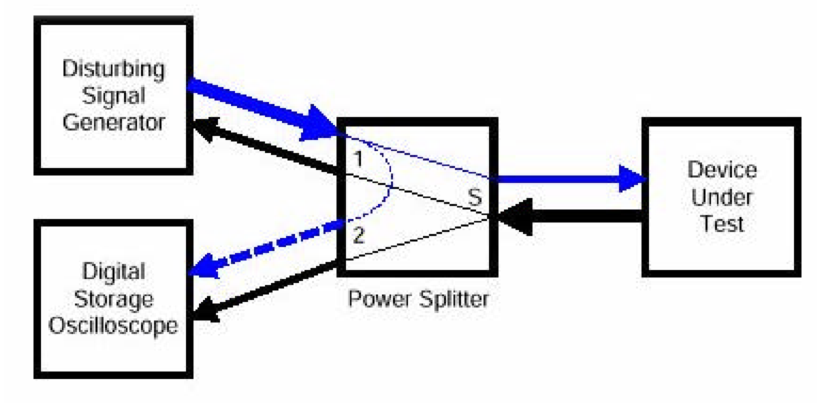

Figure 3.10 – Power splitter operation

The part that reaches the oscilloscope is the remains left after passing the power splitter twice (2 * 3 dB) and reflecting against the DUT. A 1000BASE-T compliant PHY has a return loss of at least 16 dB, which means that the total isolation is at least 6 + 16 = 22 dB. The isolation between port 1 and port 2 exceeds 22 dB. A total of two power splitters are needed, one for each wire in the cable pair. A detailed view of the IOL setup is shown in figure 3.11.

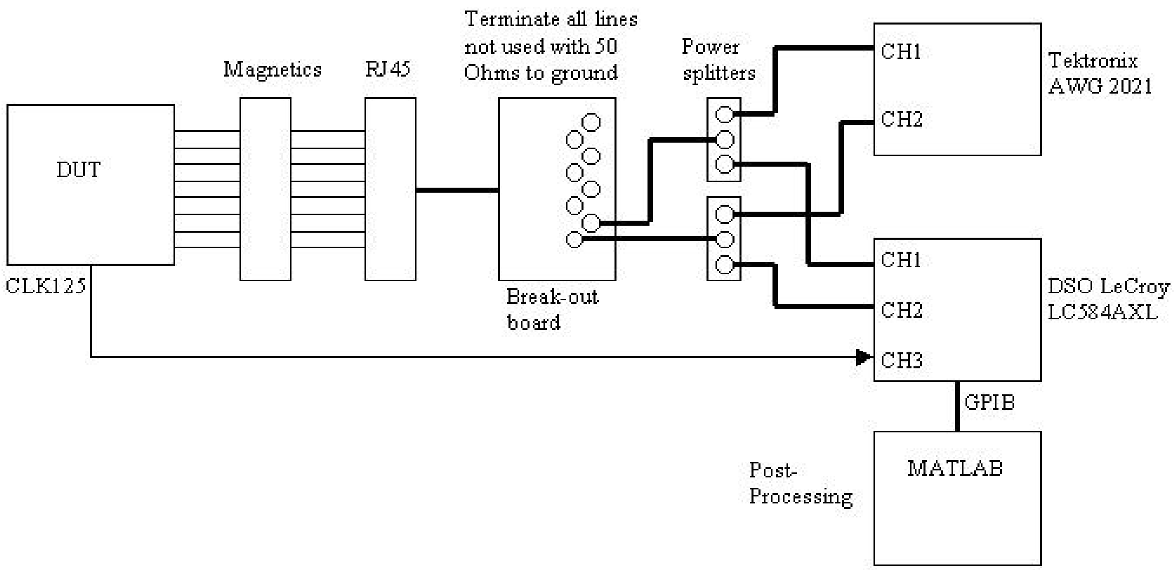

Figure 3.11 - IOL version of test fixture 1 through 3

Because only a small portion of the disturbing signal reaches the scope, the vertical range of the signal that reaches the scope is reduced. The signal from the DUT is approximately 2 V peak-to-peak. Using the Lucent setup for test fixture 3 this results in a 4.7 V peak-to-peak signal reaching the scope (V_d = 2.7 V peak-to-peak). But when using the IOL setup the disturbing signal is almost eliminated. Here, only the DUT 2 V peak-to-peak signal reaches the oscilloscope. Both setups uses a digital storage oscilloscope to capture the signal. Digital scope has a limited number of vertical recording levels. When reducing the vertical range of the captured signal the vertical resolution of the captured signal is increased because the oscilloscope always uses the same number of levels to display the signal. For a smaller signal the difference between the levels becomes smaller. The increased vertical resolution results in a smaller quantization error on the captured signal.
The use of power splitters also eliminates the need for a differential probe. Instead of having to probe the cable the signal is now transmitted directly to the oscilloscope through the power splitter. When probing the UTP cable in the Lucent setup some noise are introduced because the wire have to be stripped to give access to the wires.

The power splitters have two characteristics that need to be considered to improve the accuracy of the measurements. The power splitters have a high-pass characteristic. That is, they work as a high-pass filter. The cut-off frequency can be determined and the effect of the filtering can be compensated for in the post processing block. The insertion loss of the power splitters can also be determined and compensated for.

Test fixture 4 is simpler than the other three. This setup is not using the disturbing signal generator. The DUT is simply terminated by 100 Ω. There is a UNH version of test fixure 4 as well, shown in figure 3.12. As before the IOL version eliminates the differential probe and thereby also some of the noise components.

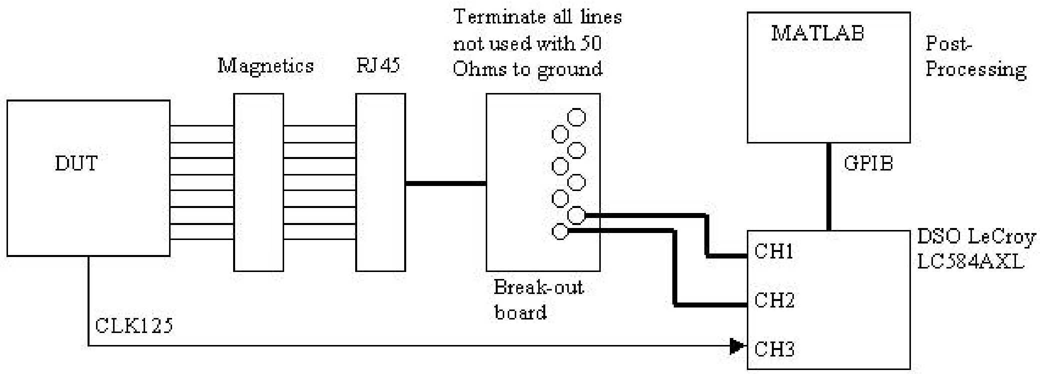

Figure 3.12 - IOL version of test fixture 4

The conclusion is that the IOL setups are better than the IEEE versions. They reduce noise and increase accuracy of the tests. The drawback is that these setups make the post processing block more complex because the effects of the power splitter have to be compensated for.
From here on only the IOL version of test fixtures are used and they are referred to as test fixture 1, 2, 3 and 4.

3.3 Transmitter Electrical Specifications – Post Processing

The post processing block is implemented in Matlab on a PC. The captured signal is downloaded to the computer via GPIB.
The main task of the post processing block is to remove the remains of the disturbing signal when it is needed. Only a small portion of the disturbing signal reaches the oscilloscope as described in preceding chapter. Figure 3.13 shows an example of a test mode 1 waveform with the remains of the disturbing signal included.

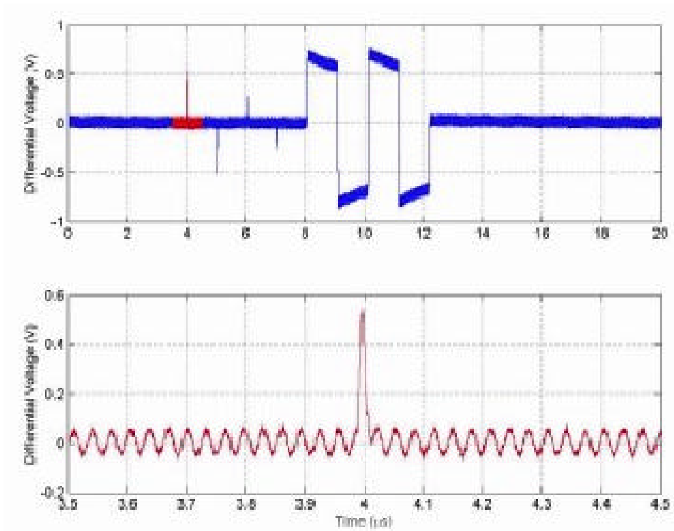

Figure 3.13 - Observed transmitter test mode 1 waveform before post processing with zoom-in on the first peak.

The disturbing signal is removed by subtracting the best-fit sine wave at the disturbing signal frequency. The frequency can be measured before the signal is captured, which leaves amplitude and phase as the only uncertainties.
The post processing block also compensates for the insertion loss and low-frequency response of the power splitters. The insertion loss is determined to be approximately 3.2 dB from 1 to 150 MHz. The captured waveform is multiplied with a scale factor 1.44 (= $10^{3.2/20}$) to cancel the effect of power splitter insertion loss. The low-frequency response of the power splitters is modeled as a first order high-pass filter with a cut of frequency of 18.5 kHz. The inverse function of this filter is applied to the captured signal to restore the low frequency components.
The post processing block also performs a few simpler tasks like extracting voltage levels at certain points of the test-signals etc.

3.4 Electrical Specification Tests

This chapter describes the tests of the electrical specifications as defined by the IEEE 802.3ab standard.

3.4.1 Peak differential output voltage and level accuracy

The purpose of this test is to verify the correct transmitter output levels.

Test setup:

- This test uses transmitter test fixture 1.
- The DUT transmits the transmitter test mode 1 symbol sequence.

The test is performed by recording the voltage levels at points A, B, C and D in the test mode 1 waveform. A, B, C and D are defined as the maximum/minimum value of the peaks as indicated in figure 3.1. The test is done for all four cable-pairs. For enhanced accuracy the peak voltage levels can be recorded multiple times and then averaged to produce a result.

Specification:

- The absolute values of the peak of the waveform at points A and B shall fall within the range of 0.67 V to 0.82V.
- The absolute values of the peak of the waveform at points A and B shall differ by less than 1%.
- The absolute values of the peak of the waveform at points C and D shall differ by less than 2% from 0.5 times the average of the absolute values of the peaks of the waveform at points A and B.

3.4.2 Maximum output droop

When the transmitter is forced to keep the signal at a constant high level the signal tend to slowly fall back to the zero level. This phenomenon is called droop. The purpose of this test is to verify that signal does not decay to fast.

Test setup:

- This test uses transmitter test fixture 2

- The DUT transmits the transmitter test mode 1 symbol sequence.

The test is performed by recording the voltage levels at points F, G, H and J in the test mode 1 waveform. Point F is defined as the point where the waveform reaches its minimum value at the location indicated in figure 3.1. Point G is defined as the point exactly 500ns after point F. Point H is defined as the point where the waveform reaches its maximum value at the location indicated in figure 3.1. Point J is defined as the point exactly 500ns after point H. The test is done for all four cable-pairs. For enhanced accuracy the voltage levels can be recorded multiple times and then averaged to produce a result.

Specification:

- The magnitude of the negative peak value of the waveform at point G shall be greater than 73.1% of the magnitude of the negative peak value of the waveform at point F.
- The magnitude of the peak value of the waveform at point J shall be greater than 73.1% of the magnitude of the peak value of the waveform at point H.

3.4.3 Differential output templates

The purpose of this test is to verify that the transmit output fits into the transmit template.

Test setup:

- This test uses transmitter test fixture 1.
- The DUT transmits the transmitter test mode 1 symbol sequence.

This test is performed by comparing the waveform around points A, B, C, D, F and H to the time domain templates in figure 3.13 and 3.14. The test is done for all four cable-pairs.

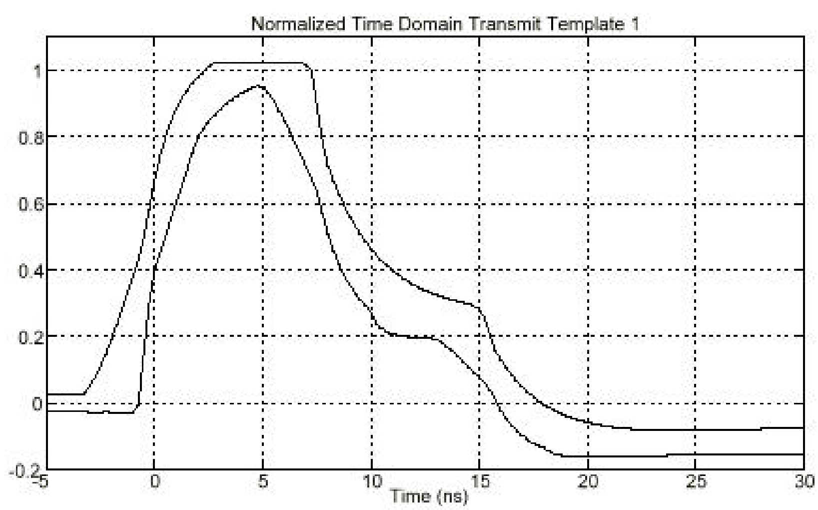

Figure 3.13 – Transmit template 1

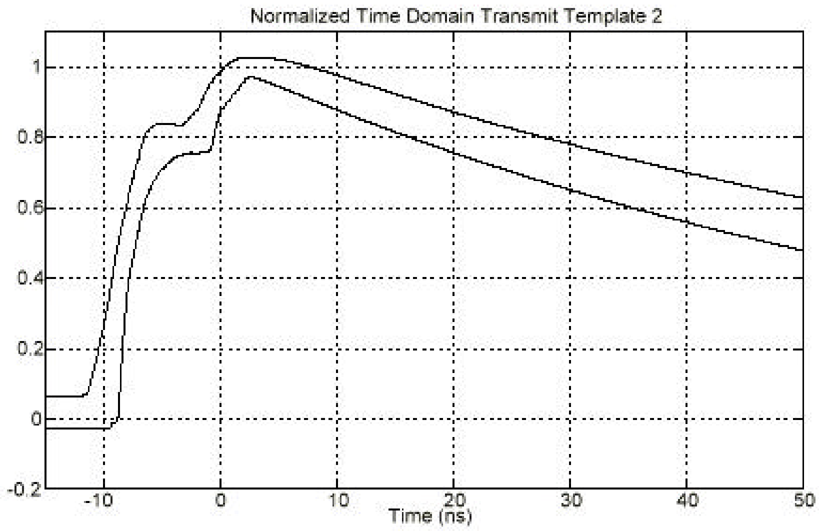

Figure 3.14 – Transmit template 2

The waveforms around A, B, C, and D are compared to template 1. The waveforms around F and H are compared to template 2. The location of points A, B, C, D, F and H is defined in figure 3.1. Before the waveforms are compared to the templates they are normalized.

- The waveform around point A is normalized to the peak voltage at point A.
- The waveform around point B is normalized to the negative of the peak voltage at point A.
- The waveform around point C is normalized to 0.5 times the peak voltage at point A.
- The waveform around point D is normalized to the negative of 0.5 times the peak voltage at point A.
- The waveform around point F is normalized to the peak voltage at point F.
- The waveform around point H is normalized to the peak voltage at point H.

Specification: After normalization the waveforms shall fit within their corresponding template. The waveforms may be shifted in time to fit the template.

3.4.4 Transmitter distortion

The purpose of this test is to verify that the transmitter peak distortion is below the specified value of 10 mV.

Test setup:

- This test uses transmitter test fixture 3.
- The DUT transmits the transmitter test mode 4 symbol sequence.

The output from the DUT is sampled with the rate given by the symbol clock, CLK125. The sampled signal is then compared to an ideal signal created in the post processing block.

Note that this test is not yet operational for two reasons.
First, the IEEE specification of transmitter distortion is very vague. It is not clear how to interpret this part of the standard. The definition of peak distortion is given only in form of a Matlab-function, which is currently not working for unknown reasons. The distortion Matlab-function is listed in Appendix C.
Second, due to the nature of the test mode signal used for the distortion test the sine wave fitting function in the post processing block is very unstable. For the transmitter tests described above the test mode 1 symbol sequence is used. This symbol sequence leaves parts of the signal completely flat where the sine wave easily can be detected. The test mode 4 waveform used for this test does not leave any part of the signal flat. The current version of the post processing software lacks the ability to detect the disturbing signal when the DUT is transmitting the test mode 4 signal sequence.

Specification:

The transmitter peak distortion shall be less than 10 mV.

3.4.5 Transmitter timing jitter

Timing jitter is defined as the period deviation from an ideal signal. For instance, for 1000BASE-T signal the ideal symbol period is 8 ns and the timing jitter here states how much the real signal period differs from the ideal period. The jitter is measured at the zero crossings of the signal.
The purpose of this test is to verify that the jitter introduced by the transmitter when in Master or Slave mode does not exceed the specification.

Test setup:

- This test uses transmitter test fixture 4.
- The DUT transmits the transmitter test mode 2 symbol sequence when testing Master jitter.
- The DUT transmits the transmitter test mode 3 symbol sequence when testing Slave jitter.

The peak-to-peak jitter of the transmitter output relative to the CLK125 signal is referred to as J_{txout}. This is the jitter introduced by the transmitter only. The clock signal also introduces jitter but by measuring the jitter relative to CLK125 the clock jitter is not included. However, the CLK125 jitter is also calculated. For the Master the CLK125 is defined as the peak-to-peak jitter of CLK125 relative an ideal reference. For the Slave the CLK125 jitter is defined as the peak-to-peak jitter of CLK125 relative to the Master CLK125.
Note that when taking the Slave jitter measurement the DUT has to be connected to a 1000BASE-T compliant device. This is because the clock signal is recovered from the incoming symbol sequence when DUT is in Slave mode. The connection has to be made with the worst-case test cable described in Appendix B.
Two test filters are used by the post processing block for the jitter calculations. They are defined as:

$H_{jf1}(f) = jf / (jf + 5000)$ f in Hz and j denotes the square root of -1

and

$H_{jf2}(f) = jf / (jf + 32000)$ f in Hz and j denotes the square root of -1

Specification:

- The Master CLK125 jitter shall be less than 1.4 ns.
- When the Master CLK125 signal is filtered by H_{jf1}, the resulting timing jitter plus the Master J_{txout} shall be less than 0.3 ns.
- The Slave CLK125 jitter shall be less than 1.4 ns.
- When the Slave CLK125 signal is filtered by H_{jf2}, the resulting timing jitter plus the Slave J_{txout} shall be no more than 0.4 ns greater than the corresponding simultaneously measured Master jitter.

3.4.6 Common-mode noise rejection

The purpose of this test is to verify the DUT's resistance against common-mode noise. Common-mode noise is generally the result when the cabling system is subjected to electromagnetic fields. This test uses a capacitive cable clamp to inject common mode signals into the cabling system.

Test setup:

This test setup introduces two new components. They are both custom made for 1000BASE-T testing.
The first one is the capacitive cable clamp mentioned above. The cable clamp is described in Annex 40B in the IEEE 802.3ab standard. In short, it consists of an inner conductor, an outer conductor and an isolating layer in between. The inner conductor is a copper pipe where the CAT5 UTP test cable is pulled through. The outer conductor is an aluminum bar with two BNC connectors attached to it. The center connector of the BNC is connected to the copper pipe. The isolating layer between the two conductors is a circular layer of high-density polyethylene.
The second new component is the test cable. The test cable is a worst case UTP cable and it is described in Appendix B. The test setup for the common-mode noise rejection test is described in figure 3.15.

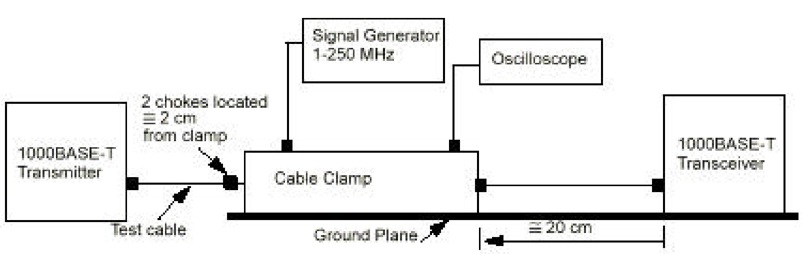

Figure 3.15 – Common-mode noise rejection test setup

The test cable between two 1000BASE-T PHY's with the cable inserted into the cable clamp. A signal generator is connected to one end of the cable clamp and an oscilloscope to the other end. The output from the signal generator is set to sweep from 1 MHz to 250 MHz with an amplitude adjusted to 1.0 V_{rms} on the oscilloscope.

Specification:

The DUT shall be able to receive data when the signal generator frequency is varied between 1 MHz and 250 MHz.

3.4.7 Alien crosstalk noise rejection

Test Setup:

A noise source consisting of a 100BASE-TX compliant transmitter sending idle symbols is connected through a resistive net to any one of the four cable pairs as indicated in figure 3.16. The level of the noise signal should be approximately 25 mV peak-to-peak. The receive DUT is connected to a 1000BASE-T transmitter with the test cable described in Appendix B.

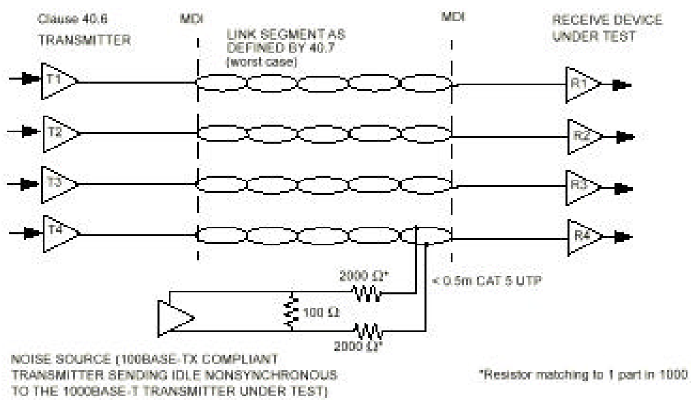

Figure 3.16 – Alien crosstalk noise rejection test setup

Specification:

When the noise source is connected to any one of the four cable pairs, the frame error rate shall be less than 10^{-7} for 125 octet frames.

3.4.8 Return loss

The differential impedance of a 1000BASE-T compliant device is ideally 100 Ω. The differential impedance is measured across the transmitter output pair. The impedance has to be 100 Ω to match the characteristic impedance of the UTP cable. If the impedances are not matched the transmitted signal will cause reflections. The impedance can of course not be exactly 100 Ω and therefore the standard allows a small amount of reflections. Return loss is a measure of how much of the power of the signal that gets reflected.

Test Setup:

One of the output pairs of the DUT is connected to the reflection port of a RF Network Analyzer (for example, HP 8347A). The reflection port is a single-ended 50 Ω port so the connection is made through a balun, which couples the 100 Ω differential DUT output to the network analyzer.

Specification:

The return loss shall be at least 16dB for frequencies between 1.0 MHz and 40 MHz and least

$$10 - 20 * \log (f/50) \text{ dB}$$

for frequencies between 40 MHz and 100 MHz. The return loss must be maintained when the DUT is connected to cabling with a characteristic impedance of 100 Ω ± 15%.

3.5 Performance Testing

To approximate the bit error rate two devices are connected with the worst-case test cable. By letting them pass traffic for a longer period of time (10-20 hours) and counting the number of missing data-packets the bit error rate can be approximated. The bit error rate test is performed with a wide range of data patterns a data loads. The standard states that the packet error rate shall be less than 10^{-7} for 125 octet packets.

Interoperability tests are usually performed too. This means that the device tested against other PHY brands available. It is interesting to know if the autonegotiation works properly and how the bit error rate is affected.

Further, the power dissipation is also measured. The power dissipation is measured during a few different circumstances. While the devices is passing different loads of traffic, while passing idle symbols, half duplex and full duplex traffic etc.

4.0 Conclusions

By using the tests described in this report it can be determined if a physical layer device is IEEE compliant or not. The test suite is based on the IEEE 802.3ab standard where all the tests are described. Some of the tests are slightly modified compared to the standard, mainly to increase the accuracy of the tests. The standard is a theoretical document, which should be used as a guide when developing the tests and that is why some of the tests can be a bit different.

The main problem when testing 1000BASE-T devices is the transmitter tests. The problem lies in removing the disturbing signal from the test-signals. Matlab is used to search for the best fitting sine-wave but due to noise and the nature of the test-signals this operation often fails. For the distortion test the sine fitting function never works. This is because the signal used when testing distortion, the test mode 4 symbol sequence. To get the distortion test to be operational the removal procedure of the disturbing signal has to be modified. Preferably the characteristics of the disturbing signal should be known before it is applied to the device under test. By turning the output of the device off both the amplitude and the frequency can be measured in Matlab by capturing only the disturbing signal. The phase or delay will on the other hand be different from capture to capture because the signal generator and the device are not using synchronized clocks. If they could be synchronized the phase to could be measured before the test is done. Then all the characteristics of the disturbing signals are known and it can be removed immediately without having to detect it first. Another approach might be to use a different algorithm for detecting the disturbing sine-wave. The current version of the post processing software uses the Matlab function fminsearch also known as fmins. For instance, there is an algorithm called MUSIC that can be used for detecting a sine wave in noise. This algorithm may work better. Or by using ML-estimation a filter can be designed to remove the disturbing sine-wave.

The Matlab code included in this report might have to be modified to work properly if a different set of equipment than described here is used.

References

IEEE Standard 802.3ab – 1999

"Gigabit Ethernet Networking" by David G Cunningham and William G. Lane, Macmillan Technology Series 1999.

"Gigabit Ethernet, PMA Test Suite" InterOperability Lab, University of New Hampshire.

"1000BASE-T Technology Overview, Part 1: Design Challenges" by Adam Healey, University of New Hampshire.

Appendix A - Equipment List

- Oscilloscope, LeCroy LC584AXL.
- Differential probe, LeCroy AP 034.
- Arbitrary waveform generator, Tektronix AWG 2021.
- RF Network Analyzer, HP 8347A
- 2 x Power splitter/combiner, Mini-Circuits ZSF-2-1W.
- Break-out board, 1 RJ45 to 8 SMA.
- PC with GPIB interface. MATLAB and LeCroy ScopeExplorer software.
- Cable clamp
- Worst-case test cable

Appendix B – Worst-case test cable

The test cable is constructed by combining 100 and 120 Ω cable segments according to table B.1. The test cable creates a poor signal to echo ratio link that is used for a few of the tests described in this report.

Cable segment	Length (m)	Characteristic impedance (at frequencies > 1 MHz)	Attenuation (per 100 m at 31.25 MHz)
1	1.20	120 ± 5 Ω	7.8 to 8.8 dB
2	x	100 ± 5 Ω	10.8 to 11.8 dB
3	1.48	120 ± 5 Ω	7.8 to 8.8 dB
4	y	100 ± 5 Ω	10.8 to 11.8 dB

Table B.1 – Test cable segment specifications

- x is chosen so that the total delay of cable segments 1, 2 and 3, averaged across all pairs, is equal to 570 ns at 31.25 MHz. If this would cause the total attenuation of cable segments 1, 2 and 3, averaged across all pairs, to exceed:

  $2.1f^{0.529} + 0.4/f$ (dB) Equation B.1

  Then x is chosen so that equation B1 is not exceeded at any frequency.
- y is chosen so that the total attenuation of cable segments 1, 2, 3 and 4, averaged across all pairs, does not violate equation B1 at any frequency (y may be 0).

Appendix C – MATLAB-code for transmitter test post processing

In this appendix the MATLAB functions used for post processing the transmitter test waveforms are listed.

peakandlevel.m: Used for the Peak differential output voltage and level accuracy test. Extracts points A, B, C and D from the test mode 1 waveform. Then calculates and displays the peak voltage and level accuracy. Input to this function is a capture of the test mode 1 waveform using test fixture 1.

droop.m: Used for the maximum output droop test. Extracts points F, G, H and J and calculates the maximum droop. Input to this function is a capture of the test mode 1 waveform using test fixture 2.

templateA.m: Used to compare peak A of the test mode 1 waveform with the template. Plots the peak and the template borders. Input to this function is a capture of the test mode 1 waveform using test fixture 1. Template testing for peak B, C, D, F and H works the same way.

templateAavg.m: Works the same way as templateA.m except that this function uses a number of captures of the test mode 1 waveform to create a averaged waveform.

shift.m: Used after running a templatetest function. This function enables shifting the peak waveform in the template.

downsample2_1.m: Reduces the sample rate of a captured waveform to half of the original sample rate.

distortion.m: The function given by IEEE as a definition of transmitter distortion.

%peakandlevel.m - Peak differential output voltage and level accuracy test.

```
%
%Uses: sinefit.m
%
%Revision history:
%v1.0 - 05/24/00
%
%---------------------------------------------
%Created by Matt Nilsson - Lucent Technologies
%---------------------------------------------

clear
samplerate=8e9;     % Scope samplerate
timediv=1e-6;       % Scope tmie/div

% Input data file
dataFile=input('Data file name: ','s');
fid=fopen(dataFile,'r');
sampledData=fscanf(fid,'%f');
fclose(fid);
sampledData=sampledData.';

% Create testfilter and filter sampled data
[L,K] = butter(1,2e6/4e9,'high');
filteredData = filter(L,K,sampledData);

% Using the first division on the scope to find sinewave.
% NOTE: For this reason position the testmode waveform
% to the right of the first timediv.
sineData=filteredData(1:(samplerate*timediv));

% Set MATLAB options
options=foptions;
options(1)=0;
options(2)=1e-8;
options(3)=1e-8;
options(14)=2000;
gradfun=zeros(0);

phase=0;

%First attempt to find the disturbing sinewave.
P=fmins('sinefit',[.9 phase 31.25],options,gradfun,sineData,samplerate);

% If failed, try again with new phase border condition.
while P(1)<.5
  phase=phase+.5;
  P=fmins('sinefit',[.9 phase 31.25],options,gradfun,sineData,samplerate);
end
```

```
% Remove sinewave
processedData=filteredData - ...
    P(1)*sin(2*pi*(P(3)*1e6*[0:length(sampledData)-1]/samplerate + P(2)*1e-
9*samplerate));

% Display final amplitude, phase, frequency of detected sinewave
P

% Find testmode1 points A, B, C and D
A=processedData(1:(samplerate*timediv*2));
[A,Aindex]=max(A);

B=processedData((samplerate*timediv):(samplerate*timediv*3));
[B,Bindex]=min(B);
Bindex=Bindex+(samplerate*timediv-1);

C=processedData((samplerate*timediv*2):(samplerate*timediv*4));
[C,Cindex]=max(C);
Cindex=Cindex+(samplerate*timediv*2-1);

D=processedData((samplerate*timediv*3):(samplerate*timediv*5));
[D,Dindex]=min(D);
Dindex=Dindex+(samplerate*timediv*3-1);

% Display peak voltage
A
B

% Calculate level accuracy
ABdiff=(abs(abs(A)-abs(B))/max(A,B))*100

Cdiff=(abs(abs(C)-.25*abs(abs(A)+abs(B)))/(.25*abs(abs(A)+abs(B))))*100

Ddiff=(abs(abs(D)-.25*abs(abs(A)+abs(B)))/(.25*abs(abs(A)+abs(B))))*100
```

```
%droop.m - Droop test
%
%Uses: sinefit.m
%
%Revision history:
%v1.0 - 05/24/00
%
%---------------------------------------------
%Created by Matt Nilsson - Lucent Technologies
%---------------------------------------------

clear
samplerate=8e9;        % Scope samplerate
timediv=1e-6;          % Scope time/div

% Input data file
dataFile=input('Data file name: ','s');
fid=fopen(dataFile,'r');
sampledData=fscanf(fid,'%f');
fclose(fid);
sampledData=sampledData.';

% Using the first division on the scope to find sinewave.
% NOTE: For this reason position the testmode waveform
% to the right of the first timediv.
sineData=sampledData(1:(samplerate*timediv));

% Set MATLAB options
options=foptions;
options(1)=0;
options(2)=1e-8;
options(3)=1e-8;
options(14)=2000;
gradfun=zeros(0);

phase=0;

%First attempt to find the disturbing sinewave.
P=fmins('sinefit',[.9 phase 31.25],options,gradfun,sineData,samplerate);

% If failed, try again with new phase border condition.
while P(1)<.5
  phase=phase+.5;
  P=fmins('sinefit',[.9 phase 31.25],options,gradfun,sineData,samplerate);
end

% Display final amplitude, phase, frequency of detected sinewave
P
```

```
% Remove sinewave
processedData=sampledData - ...
    P(1)*sin(2*pi*(P(3)*1e6*[0:length(sampledData)-1]/samplerate + P(2)*1e-
9*samplerate));

% Find droop measurement points
F=processedData((samplerate*timediv*5):(samplerate*timediv*7));
[F,Findex]=min(F);
Findex=Findex+(samplerate*timediv*5-1);

H=processedData((samplerate*timediv*6):(samplerate*timediv*8));
[H,Hindex]=max(H);
Hindex=Hindex+(samplerate*timediv*6-1);

Gindex=Findex+(samplerate*500e-9);
G=processedData(Gindex);

Jindex=Hindex+(samplerate*500e-9);
J=processedData(Jindex);

% Calculate droop
FnG=100*abs(G)/abs(F)

HnJ=100*abs(J)/abs(H)
```

```
%templateA.m - Template test, peak A
%
%Uses: sinefit.m, downsample2_1.m, template1.m
%
%Revision history:
%v1.0 - 05/24/00
%
%--------------------------------------------
%Created by Matt Nilsson - Lucent Technologies
%--------------------------------------------

clear;
clf;
template1;                  % Load templatefile
samplerate=8e9;       % Scope samplerate
timediv=1e-6;          % Scope time/div

% Input data file
dataFile=input('Data file name: ','s')
fid=fopen(dataFile,'r');
sampledData=fscanf(fid,'%f');
fclose(fid);
sampledData=sampledData.';

% Create testfilter and filter sampled data
[L,K] = butter(1,2e6/4e9,'high');
filteredData = filter(L,K,sampledData);

% Using the first division on the scope to find sinewave.
% NOTE: For this reason position the testmode waveform
% to the right of the first timediv.
sineData=filteredData(1:(samplerate*timediv));

% Set MATLAB options
options=foptions;
options(1)=0;
options(2)=1e-8;
options(3)=1e-8;
options(14)=2000;
gradfun=zeros(0);

phase=0;

%First attempt to find the disturbing sinewave.
P=fmins('sinefit',[.9 phase 31.25],options,gradfun,sineData,samplerate);

% If failed, try again with new phase border condition.
while P(1)<.5
  phase=phase+0.5;
```

```
 P=fmins('sinefit',[.9 phase 31.25],options,gradfun,sineData,samplerate);
end

% Display final amplitude, phase, frequency of detected sinewave
P

% Remove sinewave
processedData=filteredData - ...
    P(1)*sin(2*pi*(P(3)*1e6*[0:length(sampledData)-1]/samplerate + P(2)*1e-
9*samplerate));

% Find peak A
A=processedData(1:(samplerate*timediv*2));

% Adjust samplerate to match template
A=downsample2_1(A);

% Match peak of waveform and peak of template
[Amax,Aindex]=max(A);
peak=A((Aindex-40):(Aindex+100));

% Normalize
peak = peak./Amax;

% Plot template and peak A
plot(peak,'black');
hold;
top = template1(:,2);
bot = template1(:,3);
plot(top,'red');
plot(bot,'red');
```

```
%templateAavg.m - Averaging template test, peak A
%
%Uses: sinefit.m, downsample2_1.m, template1.m
%
%Revision history:
%v1.0 - 05/31/00
%
%--------------------------------------------
%Created by Matt Nilsson - Lucent Technologies
%--------------------------------------------

clear;
clf;
template1;                    % load templatefile
samplerate=8e9;     % scope samplerate
timediv=1e-6;       % scope time/div

%create testfilter
[L,K] = butter(1,2e6/4e9,'high');

%set MATLAB options
options=foptions;
options(1)=0;
options(2)=1e-8;
options(3)=1e-8;
options(14)=2000;
gradfun=zeros(0);

result_matrix=0;
dataFile=input('Data file name: ','s');
numberoffiles=input('Number of files:');

for i=1:numberoffiles

  %put filename together and read file
  filenumber=num2str(i);
  filename=strcat(dataFile,filenumber);
  filename=strcat(filename,'.txt');
  fid=fopen(filename,'r');
  sampledData=fscanf(fid,'%f');
  fclose(fid);
  sampledData=sampledData.';

  %filter sampled data
  filteredData = filter(L,K,sampledData);

  % Using the first division on the scope to find sinewave.
  % NOTE: For this reason position the testmode waveform
  % to the right of the first timediv.
```

```
  sineData=filteredData(1:(samplerate*timediv));

  phase=0;

  %First attempt to find the disturbing sinewave.
  P=fmins('sinefit',[.9 phase 31.25],options,gradfun,sineData,samplerate);

  % If failed, try again with new phase border condition.
  while P(1)<.5
    phase=phase+0.5;
    P=fmins('sinefit',[.9 phase 31.25],options,gradfun,sineData,samplerate);
  end

  % Display final amplitude, phase, frequency of detected sinewave
  P

  % Remove sinewave
  processedData=filteredData - ...
    P(1)*sin(2*pi*(P(3)*1e6*[0:length(sampledData)-1]/samplerate + P(2)*1e-
9*samplerate));

  % Find peak A
  A=processedData(1:(samplerate*timediv*2));

  % Adjust samplerate to match template
  A=downsample2_1(A);

  % Match peak of waveform an peak of template
  [Amax,Aindex]=max(A);
        peak=A((Aindex-40):(Aindex+100));

  result_matrix=result_matrix+peak;

end

% Average
A=result_matrix./numberoffiles;

% Normalize
[Amax,Aindex]=max(A);
peak = A./Amax;

% Plot template and peak A
plot(peak,'black');
hold;
top = template1(:,2);
bot = template1(:,3);
plot(top,'red');
plot(bot,'red');
```

```
%shift.m - Shifting waveform left/right, use only after running templatetests
%
%Revision history:
%v1.0 - 05/24/00
%
%---------------------------------------------
%Created by Matt Nilsson - Lucent Technologies
%---------------------------------------------

clf;
offset=input('Steps to shift peak:');

if offset<0
   addon=ones(abs(offset),1);
   top_addon=top(1).*addon;
   bot_addon=bot(1).*addon;
   top=cat(1,top_addon,top);
   bot=cat(1,bot_addon,bot);
end

if offset>0
   peak_addon=zeros(1,offset);
   peak=cat(2,peak_addon,peak);
end

plot(peak,'black');
hold;
plot(top,'red');
plot(bot,'red');
```

```
% sinefit.m
% Function for fitting sine wave
% Provided by IEEE
function err=sinefit(parameters,data,symbolRate)


err=sum((data- ...
    parameters(1)*sin(2*pi*(parameters(3)*1e6*[0:(length(data)-1)]/symbolRate +
parameters(2)*1e-9*symbolRate))).^2);
```

```
%downsample2_1.m - Removing every second sample
%
%Revision history:
%v1.0 - 05/24/00
%
%---------------------------------------------
%Created by Matt Nilsson - Lucent Technologies
%---------------------------------------------


function [halfsample] = downsample2_1(fullsample)
for i = 1:(length(fullsample)/2)
   halfsample(i) = fullsample(2*i);
end
```

```
%distortion.m - Distortion Specification Post Processing
%

% Initialize Variables
clear
symbolRate=125e6;                        % symbol rate
dataFile=input('Data file name: ','s')

% Generate test pattern symbol sequence

scramblerSequence=ones(1,2047);
for i=12:2047
  scramblerSequence(i)=mod(scramblerSequence(i-11) + scramblerSequence(i-9),2);
end

for i=1:2047
  temp=scramblerSequence(mod(i-1,2047)+1) + ...
      2*mod(scramblerSequence(mod(i-2,2047)+1) + scramblerSequence(mod(i-
5,2047)+1),2) + ...
      4*mod(scramblerSequence(mod(i-3,2047)+1) + scramblerSequence(mod(i-
5,2047)+1),2);
  switch temp
    case 0,
      testPattern(i)=0;
    case 1,
      testPattern(i)=1;
    case 2,
      testPattern(i)=2;
    case 3,
      testPattern(i)=-1;
    case 4,
      testPattern(i)=0;
    case 5,
      testPattern(i)=1;
    case 6,
      testPattern(i)=-2;
    case 7,
      testPattern(i)=-1;
  end
end



% Input data file
fid=fopen(dataFile,'r');
sampledData=fscanf(fid,'%f');
fclose(fid);
sampledData=sampledData.';
```

```
if (length(sampledData) < 2047)
  error('Must have 2047 consecutive samples for processing');
elseif (length(sampledData) > 2047)
  fprintf(1,'\n Warning - only using first 2047 samples in data file');
  sampledData=sampledData(1:2047);
end


% Fit a sine wave to the data and temporarily remove it to yield processed data

options=foptions;
options(1)=0;
options(2)=1e-8;
options(3)=1e-8;
options(14)=2000;
gradfun=zeros(0);
P=fmins('sinefit',[2.0 0 125/6.],options,gradfun,sampledData,symbolRate);

P

processedData=sampledData - ...
    P(1)*sin(2*pi*(P(3)*1e6*[0:2046]/symbolRate + P(2)*1e-9*symbolRate));



% LMS Canceller

numberCoeff=70;  % Number of coefficients in canceller
coefficients=zeros(1,numberCoeff);
delayLine=testPattern;

% Align data in delayLine to sampled data pattern
temp=xcorr(processedData,delayLine);
index=find(abs(temp)==max(abs(temp)));
index=mod(mod(length(processedData) - index(1),2047)+numberCoeff-10,2047);
delayLine=[delayLine((end-index):end) delayLine(1:(end-index-1))];


% Compute coefficients that minimize squared error in cyclic block

for i=1:2047
  X(i,:)=delayLine(mod([0:(numberCoeff-1)]+i-1,2047)+1);
end
coefficients=(inv(X.' * X)*(processedData*X).').';



% Canceller
for i=1:2047
```

```
  err(i)=processedData(i) - sum(delayLine(1+mod((i-1):(i+numberCoeff-
2),2047)).*coefficients);
end

% Add back temporarily removed sine wave

err=err+P(1)*sin(2*pi*(P(3)*1e6*[0:2046]./symbolRate + P(2)*1e-9*symbolRate));


% Re-fit sine wave and do a final removal

options=foptions;
options(1)=0;
options(2)=1e-12;
options(3)=1e-12;
options(14)=10000;
gradfun=zeros(0);
P=fmins('sinefit',[2.0 0 125/6.],options,gradfun,err,symbolRate);

P

processedData=sampledData - ...
    P(1)*sin(2*pi*(P(3)*1e6*[0:2046]/symbolRate + P(2)*1e-9*symbolRate));


% Compute coefficients that minimize squared error in cyclic block

coefficients=(inv(X.' * X)*(processedData*X).').';



% Canceller
for i=1:2047
  err(i)=processedData(i) - sum(delayLine(1+mod((i-1):(i+numberCoeff-
2),2047)).*coefficients);
end

% SNR Calculation
signal=0.5;
noise=mean(err.^2);

SNR=10*log10(signal./noise);

% Output Peak Distortion

peakDistortion=max(abs(err))


% Function for fitting sine wave
function err=sinefit(parameters,data,symbolRate)
```

```
err=sum((data- ...
    parameters(1)*sin(2*pi*(parameters(3)*1e6*[0:(length(data)-1)]/symbolRate +
parameters(2)*1e-9*symbolRate))).^2);
```