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# ETHERNET/IP RACE TRACK: PERFORMANCE METRICS & TESTING FOR YOUR INDUSTRIAL NETWORK INTERFACE

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## KEYWORDS

Industrial Ethernet, Performance Metrics, Performance Tests, EtherNet/IP

## ABSTRACT

Networking has become a reality on the industrial floor. Most devices in the industrial environment are networked in order to reduce the cost of installation and maintenance and improve interoperability. Proprietary hardware and protocols were traditionally used for these networks, but in the last few years more companies have been switching over to networks based on Ethernet and TCP/IP.

The information technology (IT) world has used Ethernet and TCP/IP for decades, and has developed many tests for the performance of network devices. These performance tests may not be applicable to industrial equipment, since they are primarily designed for testing how fast a device forwards packets from one port to another (i.e. hubs, switches, and routers). Industrial equipment users are more concerned with how fast they can turn on a relay, control a valve, or read the status of a machine.

The Intelligent Systems Division (ISD) at the National Institute of Standards and Technology (NIST) is working with the Open DeviceNet Vendors Association (ODVA) to develop performance metrics and tests for EtherNet/IP (Ethernet / Industrial Protocol) devices. These metrics and tests will be designed to give the user an idea of how fast their signals will be processed by a particular device. Instead of testing networking infrastructure devices like the IT world does, these tests will be designed primarily for the end point devices, such as programmable logic controllers (PLCs), distributed control systems (DCSs), distributed input/output (I/O) devices, sensors, and actuators. The tests will also not be designed to provide information about how the device performs at all levels of the networking protocol, but instead will give the overall performance of the device for the user to compare two similar products.

Although the IT specific metrics and tests do not directly relate to industrial Ethernet, it is possible to borrow from their experience and develop performance tests for EtherNet/IP. ISD and ODVA are using a small set of definitions from the Internet Engineering Task Force (IETF) Request For Comment (RFC) documents number 1242 and 2544. These documents define the benchmarking terminology and methodology for network interconnection devices. Most networking equipment is tested against these RFCs, which will give us the benefit of a large amount of already developed software and hardware to start with. Network analysis tools are readily available, and allow the user to develop application-oriented software in order to perform specific tests. We hope to use the available features and capabilities of commercial equipment to develop metrics and tests for EtherNet/IP devices. ISD's long-term goal for this project is to extend these metrics and tests beyond EtherNet/IP to create standard metrics and tests for all industrial Ethernet protocols.

# 1 BACKGROUND

Industrial computers have been around for decades. These have ranged from the large rack computers of the 1970's to the state-of-the-art, system-on-a-chip computers of today. Along the way, networks have been introduced to connect multiple computers together to work cooperatively in the industrial environment.

By far, the largest implementation of industrial networking is serial communications based on the RS-232 family (RS-232, RS-422, and RS-485). These have been, and are still being, used in the industrial environment for many different purposes. The RS-232 family is very robust and most computers come with a serial interface that can be used to test and troubleshoot problems with the network.

Other than RS-232 serial communications, industrial networks have been dominated by proprietary network protocols. Some of these networks are based on layering industrial networking protocols over standard hardware, while others required special hardware as well. Examples of industrial networks with specialized hardware include[1]: Profibus, Modbus, DeviceNet, Foundation Fieldbus, and Data Highway.

Engineers have found it useful to implement Ethernet networks in their office environment, and with the spread of inexpensive Ethernet hardware and software, they are now incorporating Ethernet into their industrial devices. This allows the engineer to incorporate the industrial side of the plant with the administrative side easier, adding functionality to the industrial equipment that was not available in the past. Many of the previously designed networks based on specialized hardware have added Ethernet versions of their networks: ProfiNet, Modbus/TCP, EtherNet/IP, Foundation Fieldbus HSE, etc.

## 1.1 ETHERNET/IP

EtherNet/IP was developed by ODVA and released as a specification in June of 2001. It allows simple I/O devices like sensors/actuators or complex control devices like robots, PLCs, welders, and process controllers to exchange time-critical application information [1]. The EtherNet/IP standard takes the

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[1] Commercial equipment and software referred to in this document are identified for informational purposes only, and does not imply recommendation of or endorsement by the National Institute of Standards and Technology, nor does it imply that the products so identified are the best available for the purpose.

Control and Information Protocol (CIP) developed for DeviceNet and ControlNet and layers it over an Ethernet based network. A picture of how this looks in the Open Systems Interconnect (OSI) 7-layer reference model is shown in Figure 1. The CIP protocol also extends above the Application layer into what is typically called the User layer, but is not displayed here.

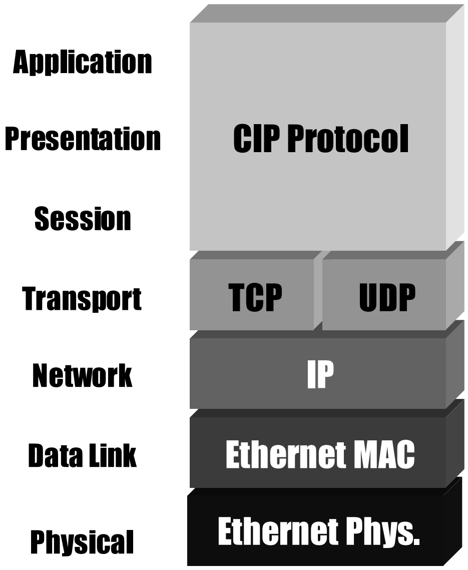


**FIGURE 1 - ETHERNET/IP DISPLAYED IN OSI 7-LAYER MODEL**

EtherNet/IP defines the ability for a device to talk over what they term an explicit or implicit connection from one device to another. Explicit connections are primarily for initialization or configuration data for a device and use the Transmission Control Protocol over the Internet Protocol (TCP/IP), while implicit connections are strictly for I/O data and use the User Datagram Protocol over the Internet Protocol (UDP/IP). When talking about I/O connections, EtherNet/IP uses the names Originator and Target to describe a producer-consumer model of data exchange. One device, like a sensor, produces data and other devices, like PLCs or smart actuators, consume that data. Note that more than one device can consume the data at the same time. A more detailed description can be found in the EtherNet/IP specification [1].

EtherNet/IP devices typically produce or consume data based on a value called the Requested Packet Interval (RPI). Producer devices will send out a packet of data at time intervals based on the RPI, whereas consumer devices will listen for a packet of data at that RPI. Both devices agree during the connection initialization phase on the RPI for both devices to use. Some EtherNet/IP devices use condition-based communication, but these devices will not be discussed in this paper.

## 2 CONFORMANCE & PERFORMANCE TESTING: WHY BOTHER?

### 2.1 PURPOSE OF CONFORMANCE TESTING

Conformance testing establishes that a device meets the specifications that it was designed to meet. Conformance testing, in many cases, requires the manufacturer to send their device to a laboratory that establishes that the device meets a specific set of requirements. For example, most if not all extension cords or plug-strips carry the mark of Underwriters Laboratory (UL). This lab was established to make sure electrical equipment would not cause harm to people. Many people don't think anything about these marks, but these are important tests performed on the hardware before it can be sold.

Networking equipment also requires conformance testing. The Institute for Electronics and Electrical Engineers (IEEE) maintains Ethernet as standard number 802. Any networking device that claims to use Ethernet should be conformance tested against the IEEE 802 standard. This conformance testing is for both hardware and software, checking to make sure that the correct electrical signals go over the wire and that software can correctly interface to the network driver. As long as the user has the driver correctly configured, any Ethernet network interface card can be used on any Ethernet network. While this may be true, it does not guarantee that all Ethernet network interface cards or devices will communicate properly.

The same situation exists with industrial Ethernet as well. A device that uses Modbus/TCP will typically not be able to communicate with a device that speaks EtherNet/IP unless specially configured. This may seem obvious, but they might both be labeled as industrial Ethernet devices. Network bridges are specifically designed to connect multiple networks and convert the data transmitted on one network to be re-transmitted on another network using its native protocol.

ODVA requires all devices given the special *EtherNet/IP* mark to be conformance tested by an ODVA approved laboratory. This ensures that when a user buys a product with the EtherNet/IP label attached, they can be assured that the device will interface to their software properly, use the correct voltages on the wire, and connect using the same type of plug. This allows the user to tailor their system design to their needs without being tied into a particular vendor's solution.

## 2.2 PURPOSE OF PERFORMANCE TESTING

Performance testing basically tells you how well something will work under certain circumstances; how hard a device is, how fast it is, how strong it is, how long it will last, how much it can do, etc. Performance testing has not been typically applied to industrial computer equipment, but that is changing.

When industrial networks used special hardware, they could be specifically designed for certain performance characteristics. The networks were limited in speed, limited in length, and designed around a particular network architecture. Ethernet, until recently, was not considered a viable choice for industrial networking due primarily to its determinism limitations.

Ethernet, as it was originally designed, was based on a half-duplex, trunk network with all devices talking and listening over one pair of wires. There were many features built-in to the IEEE 802 standard to handle collisions when multiple devices try to talk on the wire at the same time, which made the standard overly complex for the industrial environment. Ethernet has progressed considerably since its original design, however. Most implementations of Ethernet are now based on full-duplex, hierarchical tree networks, where multiple devices can use the network at the same time without slowing down the overall network speed. Devices transmit and receive on two pairs of wires and are directly attached to network switches on their own separate wire. By eliminating the collision problem and recommending network architectures, industrial vendors have now found that Ethernet is viable as an industrial network and they are designing equipment using it.

While Ethernet may be moving to the plant floor, many users are still concerned with its potential problems, especially when compared to other industrial networks. Industrial devices and controllers are much more sensitive to data delivery times than administrative computers. If a web page or database access takes 100 ms longer than usual, most people will not be able to notice. But, if a nuclear or chemical process controller doesn't receive the data it needs in that same 100 ms time period, process abnormalities or major damage may occur.

## 2.3 CONFORMANCE VS. PERFORMANCE TESTING

In order for devices to bear the mark of *EtherNet/IP*, they must go through conformance testing. This establishes that the device meets the EtherNet/IP specification. Most of these devices are tested for their performance characteristics by the vendor, but the devices do not obtain any formal performance testing. This makes it difficult for a user to compare devices other than by reading the vendor's specifications. It is difficult to compare one device to another since many times they will not list the same information using the same metrics.

As an analogy, all internal combustion automobiles can be described by the same basic specifications. Their standard engine specifications of horsepower, torque, compression ratio, displacement, etc. are published and provide some information about the performance of the vehicle. However, there is no way to compare the fuel economy of a vehicle without running performance tests on the entire vehicle. All internal combustion engines have the same basic function, but they all function slightly differently.

Because of this, the Environmental Protection Agency (EPA) requires every new automobile model to be performance tested to determine the basic fuel economy of the vehicle as a whole. These tests are well established and are the same for all vehicles. A sports car goes through the same test as an economy car and a minivan. These tests only measure the performance of the vehicle at a few places (i.e. city and highway), but they give the user a general picture of the relative efficiency of the vehicle. Also, the numbers that are produced from these tests always contain a warning like, "Actual results may vary." Vehicle owners have learned over time that they may not get exactly the numbers produced by the EPA's tests, but the tests give the owner a way to compare multiple vehicles.

By developing a set of common performance tests for EtherNet/IP, users will be able to compare multiple devices without having to know the internal details of each device. Many devices look the same and perform the same basic functionality, but may have widely varying performance characteristics. A user may not be able to easily determine the difference between a network switch from multiple vendors, or even multiple products from the same vendor. Users are inundated with data sheets for products that may look similar, or they may include difficult language intended to make their product sound better by including industry jargon or acronyms. Network switches are an example. Many different companies sell network switches, but not all network switches are the same. A low cost switch from the local computer store may be suitable for home use, but that may not be sufficient for the industrial plant floor. Also, major network equipment vendors may quote higher-end products that may be overkill for the industrial user's specific application. By having some common set of performance metrics and tests that are well established and consistent between all products, a user can compare multiple devices and group them into different levels of products based on their performance characteristics.

# 3 NIST INDUSTRIAL NETWORKING PERFORMANCE TESTBED

## 3.1 "STANDARD" PERFORMANCE METRICS

The Internet Engineering Task-Force (IETF) maintains many of the "standards" for networking technology. These are maintained as documents called Request For Comment (RFC) documents. They are posted for a time giving people around the world a chance to make comments on the technology as draft documents, eventually, being published as full RFCs. Many of the common technologies like the Internet Protocol (IP), Transmission Control Protocol (TCP), and User Datagram Protocol (UDP) are not standards maintained by an organization like IEEE, but actually RFCs maintained by the IETF.

There are multiple RFCs for testing networking equipment performance. Two in particular are RFC 1242 – "Benchmarking Terminology for Network Interconnection Devices" – and RFC 2544 – "Benchmarking Methodology for Network Interconnect Devices" [2,3]. Most, if not all, networking infrastructure equipment (i.e. switches, routers, hubs, bridges) is tested against these two RFCs as well as others. In order to test industrial equipment, NIST and ODVA are trying to work with these RFCs and develop them into tests for industrial equipment.

These RFCs cannot be directly applied to industrial networked equipment, since they were primarily developed for what are called pass-through devices. Pass-through devices are devices that take data in one port and pass them out again through another port on the same device. Hubs and switches are examples of pass-through devices. Most industrial equipment that we will be concerned with are called end-point devices. End point devices, like computers, sensors, and actuators, produce or consume network data packets. The hardest part of this work has been to create tests that can use common methodology as defined by the RFCs, but are still relevant to the industrial equipment under test.

NIST and ODVA have borrowed four definitions in particular from RFC 1244 that will provide us with a common set of terminology to describe both the tests and results. Those terms are:

- **Throughput** – The maximum continuous traffic rate that a device can handle without dropping a single packet (Frames/sec @ a given frame size).
- **Overload Behavior** – A description of the action of a device in an overload state. (This is qualitative.)
    - Overload states exist when the device's internal resources either receives too much information to process or bad information and the device goes into a state other than its normal run mode.
    - Describe what the device does when its resources are exhausted.
    - Describe what the response is to the system management in an overload state.
    - Describe how well a device recovers from an overload state.
- **Latency** – The time interval between a message being sent to a device and a corresponding event occurring.

- **Jitter** – The difference between the minimum and maximum time for a particular series of events. We have included standard deviation in this measurement as well.

We have also added two modifications to the Latency term.

- **Response Latency** – The closed-loop latency of a device to process a command and respond to it.
- **Action Latency** – The closed-loop latency of a device to process a command a return a desired output (e.g. analog/digital output signal).

## 3.2 TESTBED DESCRIPTION

NIST has put together a basic set of equipment that we are using to develop performance tests for EtherNet/IP networks. The testbed equipment includes an industrial PLC with multiple network interfaces and a distributed Input/Output system with a 24 Volt Digital I/O module and 0-10 Volt Analog I/O module. We also have a network analyzer and traffic generator with six 10/100 ports capable of making timing measurements with accuracies of 100 ns and producing 1000 independent network streams at beyond wire-rate. As a network infrastructure device, we have a managed network switch that allows us to setup multiple virtual LANs and control the address buffers. A laptop computer controls the equipment in the testbed and stores the data collected. All of the EtherNet/IP devices in the testbed have been conformance tested. A diagram of the performance testbed is shown in Figure 2.

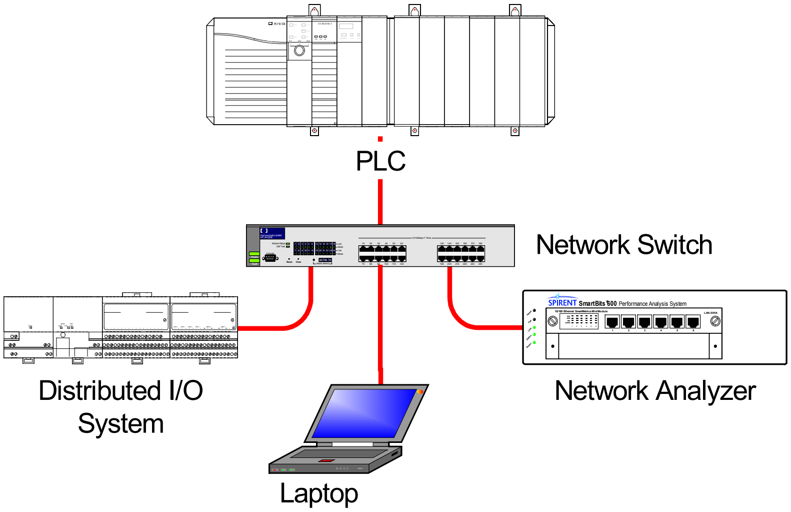


**FIGURE 2 - ETHERNET/IP PERFORMANCE TESTBED LAYOUT**

## 3.3 TESTING DESCRIPTION

Since most EtherNet/IP devices use an RPI value for their communications, it is important to determine what effect that RPI value has on the performance of a particular device. Also, since RPI is time based and most devices use their internal clock for determining the time, it is necessary to measure the performance of the devices internal clock. In order to test the performance aspects of a devices RPI value, a device will be tested to determine the maximum amount of data it can either produce or consume at a particular RPI value. This produces a 2D matrix of RPI values vs. maximum data capacity. Pseudo-code for the testing procedure is shown below.

**Testing Procedure Pseudo-Code**

```
-  Setup RPI and Connection Size for the test
-  Establish connection with the device under test (DUT)
-  Communicate with the DUT for some time
-  Check for packet loss
-  Calculate statistics (min, max, average, standard deviation, etc.)
-  If packet loss, increase RPI value (decrease frequency) and continue
-  Else, report RPI and statistics
```

While this pseudo-code looks very simple, looks can be deceiving. Producer and consumer devices behave quite differently, and require vastly different programs in order to accomplish the test. While testing a producer device, the test equipment can be a passive participant. Producer devices, once setup, usually transmit their data indefinitely allowing the test equipment to listen to the packets coming from the DUT and make calculations based on those packets. Consumer devices are expecting to receive packets at a certain rate, which means that the test equipment has to become an active participant. The test equipment must maintain a steady flow of data not only to ensure that the DUT reacts properly, but also to ensure that minimal errors are introduced into the test that would affect the results.

In addition to the timing requirements of the data, there are also problems in determining packet loss for a consumer device. Since EtherNet/IP packets include a sequence number in the I/O data stream, it is easy to determine whether packets from a producer device were dropped or even received out of order. This is not the case with consumer devices. While the test equipment will be sending out a sequence number with the data, it is not an easy process to determine whether packets are being lost or whether packets were received out of sequence. The consumer device has to be intelligent enough to send back a message with some indication of the packets received.

# 4 ETHERNET/IP PERFORMANCE (EIPPERF) SOFTWARE

## 4.1 CURRENT VERSION (VERSION 0.6)

The EIPPerf software, being developed by NIST, is intended to investigate the performance characteristics of an EtherNet/IP device. The first step has been to use the basic testing procedure described above and develop it into fully functioning software. The current version has been designed to interpret packets coming from multiple producer devices that were previously recorded.

NIST was involved in the EtherNet/IP Interoperability Plug-Fest held at the General Motors Technology Center in Warren, MI in March 2003. Many companies that develop products for EtherNet/IP were involved, and data was recorded during the Plug-Fest for later analysis. The data was recorded during a large-scale integration test involving all of the products being attached to a common network and operating simultaneously. The test equipment was setup to listen to the network and store all the packets received. Twenty-six data sets containing over 120 Mbytes of data were recorded. In order to process the data from the Plug-Fest, the EIPPerf software was designed to:

- Read the pre-recorded data sets
- Breakdown the packet headers
- Sort the packets based on source, destination, and EtherNet/IP connection ID, and
- Calculate some statistical values for the packets

Some of the data collected is shown below in Figure 3. The first two charts show the same device in two different data sets as the RPI values were changed. The other two charts show different devices at different times during the data collection. A picture of the software window is shown in Figure 4.

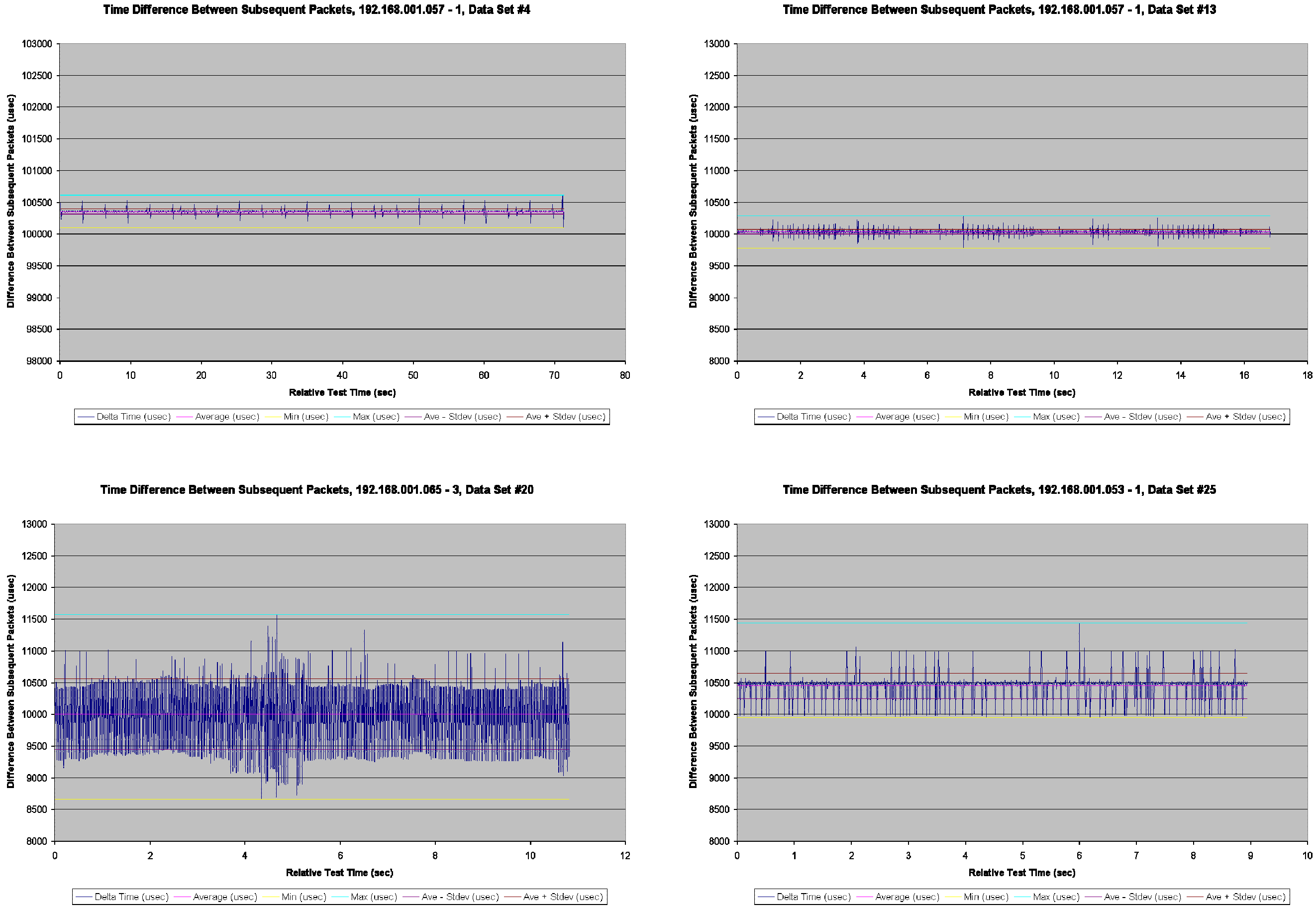
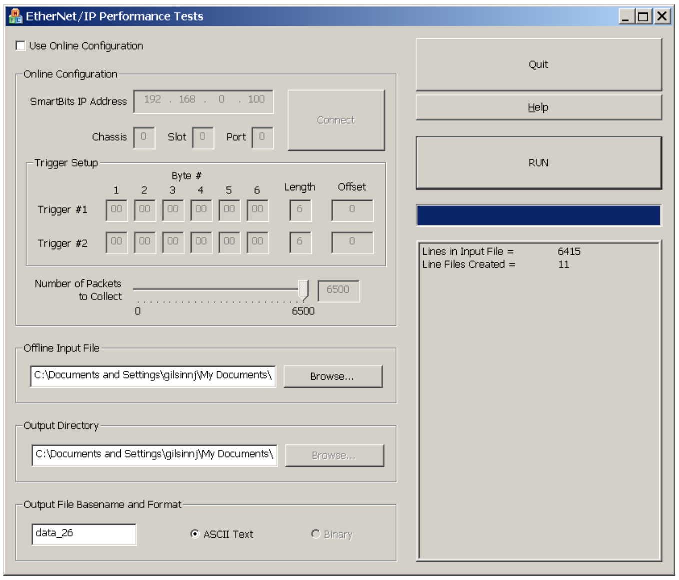


FIGURE 3 - SELECTED CHARTS FROM ETHERNET/IP PLUG-FEST DATA

## 4.2 NEAR-TERM REVISION (VERSION 1.0)

Now that the basic code to breakdown EtherNet/IP packets, sort them, and calculate statistical values from them has been finished, it is possible to move on to more difficult parts of the testing procedure. Version 1.0 of the software will incorporate real-time data recording and near real-time data analysis. As described above, the current version of the software only reads pre-recorded data to analyze. The new software will read real-time data from a network and analyze it in near real-time. It is not possible to perform the data analysis in real-time, since some of the statistical values calculated need access to the entire data set before being calculated (e.g. standard deviation).



EtherNet/IP Performance Tests

☐ Use Online Configuration

Online Configuration

SmartBits IP Address 192 . 168 . 0 . 100

Chassis 0 Slot 0 Port 0

Trigger Setup

| | Byte # 1 | 2 | 3 | 4 | 5 | 6 | Length | Offset |
|---|---|---|---|---|---|---|---|---|
| Trigger #1 | 00 | 00 | 00 | 00 | 00 | 00 | 6 | 0 |
| Trigger #2 | 00 | 00 | 00 | 00 | 00 | 00 | 6 | 0 |

Number of Packets to Collect 6500 (0 – 6500)

Offline Input File: C:\Documents and Settings\gilsinnj\My Documents\

Output Directory: C:\Documents and Settings\gilsinnj\My Documents\

Output File Basename and Format: data_26 ● ASCII Text ○ Binary

```
Lines in Input File =        6415
Line Files Created =         11
```

FIGURE 4 - EIPPERF SOFTWARE

# 5 FUTURE WORK

## 5.1 IMPROVEMENTS TO SOFTWARE & ADDITONAL TESTS

As stated above, version 1.0 of the software will incorporate real-time data recording and near real-time data analysis. This will allow the test to be fully automated, although the data analysis may still require post-processing to produce charts displaying the data. Later versions of the software will include consumer devices into the test procedure as well as additional performance tests.

The initial test procedure is very limited in scope. This was intentional in order to get some initial results that were relevant to many devices. The initial test procedure will need to be expanded upon in order to develop a more fully functioning and well-rounded set of performance tests. This will involve studying the RFCs more carefully and looking into additional sources to determine where more tests are appropriate. Also, the test procedure does not involve exposing the devices to background traffic. The system is installed on a separate network with no extraneous traffic applied to the system. A set of expected background traffic will need to be defined and then test procedures will be developed to determine the effect of that traffic on the performance of the devices and the system as a whole.

## 5.2 LONG-TERM GOALS

The long-term goal of this NIST project is to help develop performance metrics and tests for all industrial Ethernet standards. Our collaboration with ODVA allows us to remain narrowly focused for the moment, developing a set of metrics and tests strictly for EtherNet/IP. Once this set of tests and metrics are developed and proven, NIST hopes to migrate these to other industrial Ethernet standards. While the exact software and hardware designs will not transfer from one network standard to another, the basic metrics and testing methodology should be consistent.

# 6 REFERENCES & ADDITIONAL INFORMATION

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