AN ETHERNET BASED AIRBORNE DATA ACQUISITION SYSTEM

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ABSTRACT

There is growing interest in the airborne instrumentation community to adopt commercial standards to obtain scalable data rates, standards based interoperability, and utilization of Commercial Off The Shelf (COTS) products to reduce system costs. However, there has been few such data acquisition systems developed to date. L-3 Telemetry East has developed a prototype called the Network Data Acquisition System (NetDAS), which is based on the 10/100 Base-T Ethernet standard, TCP/UDP/IP network protocols and an industrial Ethernet switch. NetDAS has added network capability to the legacy MPC-800 telemetry system by replacing the existing formatter module with a formatter/controller based on a COTS CPU module and a custom designed bridge module. NetDAS has demonstrated transmission bit rates as high as 20 Mbps from a single unit using UDP/IP and an Ethernet switch. The NetDAS system has also demonstrated scalable and distributed architecture.

KEYWORDS

Airborne Telemetry, Network Data Acquisition System, Ethernet, COTS

INTRODUCTION

The NexGenBus program recognized that new applications in airborne telemetry require modern airborne data acquisition systems to handle much higher data rates than previous systems [1]. Video recording, for example, often requires bandwidth as high as several megabits per second. This is near the capacity of legacy busses, such as CAIS[2], which was designed to run at 5 Mbps. To handle multiple channels of high bit rate acquisition, building a system from multiple sub-systems becomes necessary. However, such a design suffers from high cost due to redundancy of functional units and high complexity of the system. This clumsy arrangement of units does not offer satisfactory solutions to future growth of testing requirements [1].

Legacy products based on proprietary busses use non-standard and often proprietary protocols, with no common form-factors and interconnections. Building these systems using custom designs afforded great space savings and provided the capability to build the exact features that were required/desired into the design. However, it dramatically increased the cost due to the increased engineering effort for design and development. It also hindered the ability to stay current with new standards, requirements or technology changes, as any of these would add to a new development effort.

The CAIS bus standard lacks the bandwidth or the open-systems standards that will be required to support network-based data acquisition systems of the future. It has only a small number of supporting vendors and has not resulted in significant price reduction of the units.

On the other hand, the commercial industry has made great strides in standards based high-speed interconnections. One example is Ethernet. Since its inception in 1976, it has been gradually accepted as a worldwide Local Area Network (LAN) standard. In 1991, 10 Base-T (10 Mbps using Category 5 cable) Ethernet was standardized. In 1995 100 Base-T (100Mbps using Category 5 cable) Fast Ethernet was released and in 1998-1999, Gigabit Ethernet. To date, the 10/100 Base-T Ethernet has become a mature technology supported by many Commercial Off The Shelf (COTS) hardware and software products available at low price. Recent advances in Gigabit Ethernet and 10 Gigabit Ethernet offers a migration path for even higher bit rate transfers.

There is growing interest in the airborne instrumentation community to adopt commercial standards to obtain scalable data rates, standards based interoperability, and utilization of COTS hardware and software to reduce system costs. However, there have been few data acquisition systems developed based on low cost COTS and commercial data transfer protocols. This paper presents the NetDAS prototype system developed by L-3 communications Telemetry East which uses commercial 10/100 Base-T Ethernet, has a scalable architecture, uses COTS hardware and software, and has successfully migrated from a centralized to a distributed system architecture.

SYSTEM OVERVIEW

The NetDAS system was migrated from the L-3 TE MPC-800 product line, which was a small form factor data acquisition telemetry system [3]. A legacy MPC-800 system consists of a master module and optional multiple slave modules. The master module includes a formatter which controls the data acquisition of the system, and various data acquisition cards stacked up on a proprietary MPC bus. The control of the data acquisition by the formatter is based on a simple command-response bus protocol. This was extended to multiple slaves through a daisy-chained 10-wire interface, which can transmit data up to 5 Mbps. The overview of the system is shown in Figure 1.

The migration to a network based system was primarily accomplished by replacing the existing formatter module with a formatter/controller module based on an off-the-shelf credit card sized CPU and a "bridge" module that used an FPGA to interface the existing MPC bus to the processor bus (Figure 2). The processor used was a Motorola PowerPC 860 that had 8MB Flash and 16MB DRAM and ran at 50 MHz. The Bridge module was based on a Xilinx VirtexII 500 FPGA, with an embedded formatter and a processor-to-MPC Bus Bridge. The module was controlled by multitasking embedded software running under a commercial Real Time Operating System (RTOS). The software provides system control, configuration and status monitoring functions.

A 10/100Base-T Ethernet interface was implemented in the controller and bridge module to replace the simple command-response based 10-wire interconnection interface. With no centralized formatter in the NetDAS system, the local formatter in each bridge module mastered the data acquisition in each unit. Multicast or unicast Ethernet commands from a control station in the network were used to control the bridge module. This control station was an Ethernet enabled laptop PC, but could be replaced by a remote control unit in the future. This architecture separated the command flow (control station) path from the data transfer path. Acquired data could be transmitted to and aggregated at any device within the network, whereas in the legacy system, the data was always aggregated at the centralized formatter. Thus the system architecture was migrated from a centralized system to a distributed system. In our prototype design, the sampled data was transmitted to an Ethernet-to-PCM converter, where the packetized data was converted to a legacy PCM stream, for recording or Telemetry. The PCM stream was then fed into a bitsync and decommutator for data analysis and display.

All units in the NetDAS system were connected through a COTS industrial Ethernet store-and-forward switch. This data acquisition subnet was optionally connected to company wide LAN through a gateway. In this configuration, remote set-up and control could be controlled from a desktop or easily done with a wireless computer. The overview of the NetDAS system is illustrated in Figure 3.

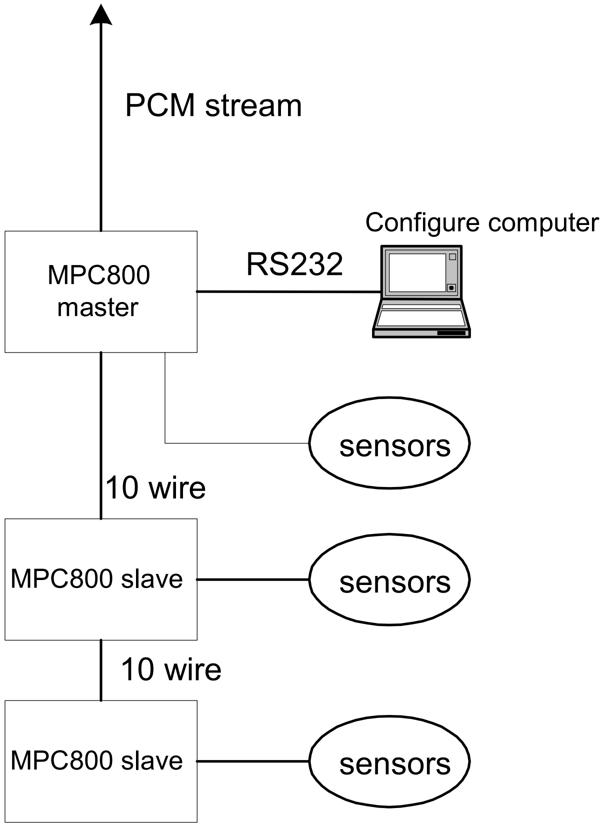

Figure 1: Architecture of the legacy MPC-800 telemetry system

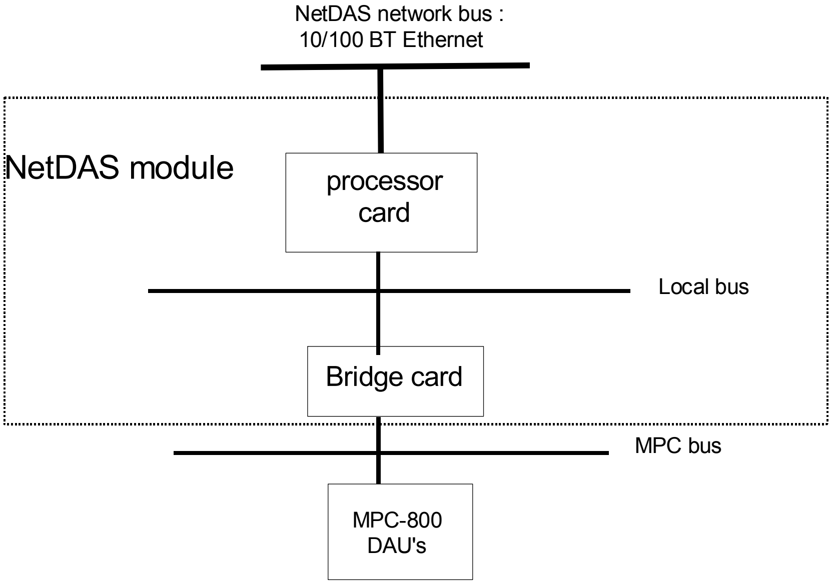

Figure 2 NetDAS module

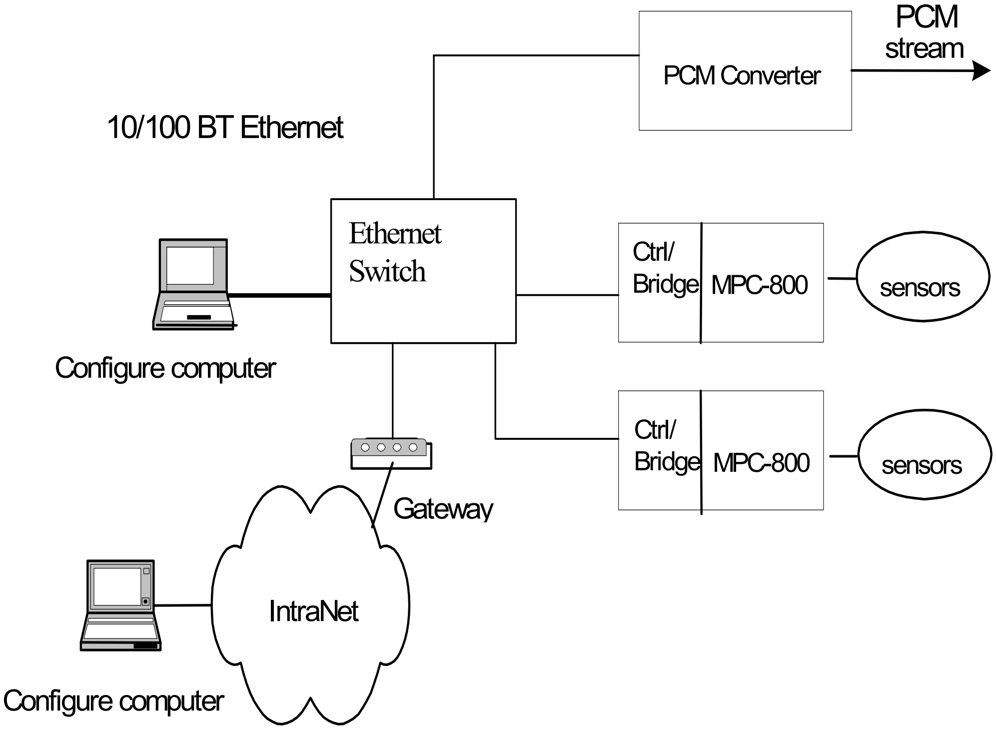

Figure 3: Architecture of the NetDAS Telemetry System

DATA TRANSFER

Data acquired in a NetDAS module was transmitted to a destination (data sink) designated by a configuration computer prior to system operation. The data transfer was through UDP/IP protocol [4,5]. UDP was chosen instead of TCP because it was more suitable for the real-time data delivery for most of our telemetry applications. Although TCP [6] is connection oriented and provides higher transmission integrity, its shift window algorithm requires large buffers and this introduces uncertainty in message latency, which is undesirable for real-time data transfer where timely delivery is of high priority. UDP on the other hand is connectionless and therefore does not require a shift window or acknowledgements, which enables the latency of the messages to be more deterministic. Another advantage of UDP over TCP is its smaller overhead, which means higher bandwidth utilization. For a 1K-byte data packet, for example, the overhead for UDP over IP/Ethernet is about 5.9%, whereas for TCP it is about 8.2%.

The maximum size for a UDP packet is 64K bytes. However, in the data link layer, the packet size is subject to the limitation of MTU (Maximum Transmission Unit) of the link, which is 1500-bytes for Ethernet. To avoid undesirable IP fragmentation, we designed the data packet size to be the size of one minor frame, which ranged from 512 to 1024 bytes in our prototype system.

The format of the data packets conformed to the "source data format" defined in **CCSDS 102.0-B-5** [7]. The primary header for each packet was only 6 bytes. It is capable of encapsulating various lengths of data in each packet and grouping various packets into larger major packets.

The throughput of a NetDAS unit was tested for a point-to-point data transfer using back-to-back UDP sent through a 100 Base-T interface. The test was repeated for different data payload sizes, varying from 128 bytes to 1024 bytes, as summarized in Table 1. At first, the data transfer was through a commercial UDP/IP stack, which was compatible to a Berkeley Software Distribution (BSD) network stack. It demonstrated a linear increase in throughput with an increase of data payload size. For data payload of 128 bytes, the average throughput was 1.17 Mbps excluding overhead, and increased to 8.46 Mbps when the packet payload was increased to 1024 bytes (Table 1).

Further analysis showed that the latency in the network stack was significant. For example, the average duration for sending a UDP packet with a 256 byte payload was 896 µs. Only 100 µs was consumed by the Ethernet driver to do the actual sending. The majority of the rest was consumed in the network stack. To further verify the finding, we developed a zero-copy stack, which eliminated the copy of data from the software application to the Ethernet driver and optimized the algorithm for the generation of Ethernet packets and UDP/IP header. The result tripled the data throughput for all data payload sizes. The comparison of the results for the commercial stack and the optimized stack is listed in Table 1.

Data payload size (bytes)	Maximum Throughput obtained using commercial driver (Mbits/sec)	Maximum throughput obtained using custom designed driver (Mbits/sec)
128	1.17	3.10
256	2.25	7.64
512	4.14	13.43
1024	8.46	21.72

Table 1: Test results of maximum throughput using commercial and custom designed UDP/IP stacks

PCM GENERATION

An Ethernet to PCM converter was developed to convert the packetized Ethernet acquisition data into a PCM stream. The PCM converter consisted of a COTS PC/104 system and a custom designed PCM Converter. The PCM Converter design was based on a Xilinx FPGA. It accepted acquisition data from the ISA bus of the PC/104 system and converted the data into a continuous PCM stream. The PCM Converter ran at a fixed bit rate set by the configuration computer. The functions of the software application included data buffering, command and configuration handling, and an embedded web server for status reporting.

SYSTEM CONFIGURATION AND CONTROL

System configuration and control was done through an Ethernet enabled laptop PC residing in the same sub-network. The configuration and control commands were transmitted using the UDP protocol. UDP was chosen for this function mainly because of its support of broadcast and multicast transmission, which is important for certain commands such as simultaneous sampling. Since UDP does not guarantee delivery, a communication protocol based on a sequence number (provided by the sender for each out-going command) and acknowledgement message (provided by the command receiver) was implemented in the application to provide delivery confirmation over UDP.

The end-to-end system was initially tested in a minimal system configuration, which included a configuration PC, a network enabled data acquisition unit, a PCM converter and a PCM bitsync/decommutator and display. The depth of the format was 64 bytes with no sub format and ran at 256Kbps. Two analog channels controlled by a variable voltage, two strain gauge channels and two digital channels controlled by switches were demonstrated. The sampled data was successfully transmitted to and displayed by the bitsync/decommutator.

DISCUSSION

The following is a discussion of the choices made by L3 in the design of the NetDAS system. Because this is a prototype and is still evolving, some design choices may be changed, added upon or deleted depending on the results from testing, customer's and government input.

1. Bus Selection

L3 has selected 10/100Base-T Ethernet as the network bus for the NetDAS system. L3 has found that 100Mbps transfer rate is sufficient for most of our field applications. The use of Ethernet was justified by the availability of low cost interface devices and COTS industrial switches. For higher bit rate transmission and for the backbone bus for avionic instrumentation, the Next Generation Instrumentation Bus Team (NexGenBus) of the Naval Air Warfare Center has performed intensive research. They have suggested the Fibre Channel Avionic Environment (FC-AE) as the leading candidate for a next generation avionic bus [8]. The major advantage of FC-AE over Gigabit

Ethernet is its support of time synchronization, guaranteed delivery in the link layer, and the better standardization of cables. However, FC-AE is not widely available nor as widely accepted as Gigabit Ethernet has become, especially in the commercial sector. The NetDAS prototype leaves the next, higher bandwidth layer interconnects, undefined. It is expected that small (few ports) Industrial Temperature range Gigabit Ethernet switches are on the threshold of being commercially available. When they are, they will offer a strong argument against FC-AE.

Some disadvantages of Ethernet, such as no assurance in quality of service and no time synchronization mechanism, can be overcome by selecting suitable higher-level protocols. Sending acknowledgments for UDP packets can increase the reliability in data delivery. Precision Timing Protocols (PTP) [9] can provide time synchronization within the subnet to the sub microsecond level, which will be discussed later in this paper.

Should the FC-AE bus be adopted as the backbone bus of our system in the future, an Ethernet-to-FC-AE bridge can provide the connection of the NetDAS Ethernet to FC-AE bus.

2. Interoperability and Scalability

Interoperability was attained by the use of Ethernet, which is well defined and understood. The combination of Ethernet and Fast Ethernet allows scalability by supporting 10 Base-T on the low end and up to multiple 100 Base-T inputs to data “sinks” on the high end. Store and Forward switches allow many acquisition units to send data to sinks by buffering. Ultimately, the limit is the number of Fast Ethernet connections to the sinks, data rates of each link, and the number of ports of the switches. Switches can be cascaded, acting as concentrators, but their aggregate bandwidths must be monitored. “Load Balancing” is unlikely after the system is assembled and must therefore be determined apriori. A sink could ultimately be used to form a bridge to another network standard. For example, a sink could have multiple Fast Ethernet links with a Fibre Channel link to another network. Figure 4 illustrates an example of the Tree Network Topology of the future system.

3. Time Synchronization

The initial NetDAS system only included one data acquisition unit. Should multiple data acquisition units be in the system, clock synchronization between units is necessary. Among several available network time synchronization protocols, PTP (IEEE 1588) protocol [9] offers excellent accuracy in a closed network. This protocol defines a means of a Master Clock and a Slave Clock to exchange timestamp messages. To increase timestamp accuracy by minimizing software effects, this timestamp can be obtained with the assistance of dedicated hardware without intrusive modification of the interface. In Ethernet, an ideal solution is to sniff packets at the MII interface of the PHY Integrated Circuit and record the timestamp in registers. With careful design, very accurate time synchronization can be achieved. Recent publications have shown that standard deviation of clock offset was below 50 ns level in a network with repeaters. When switches were used, this number was approximately 100 ns [10].

We plan to implement PTP protocol in the prototype system. The design of the NetDAS bridge card allows MII interface signal be captured by the on-board FPGA. The time synchronization accuracy will be measured and published in the future.

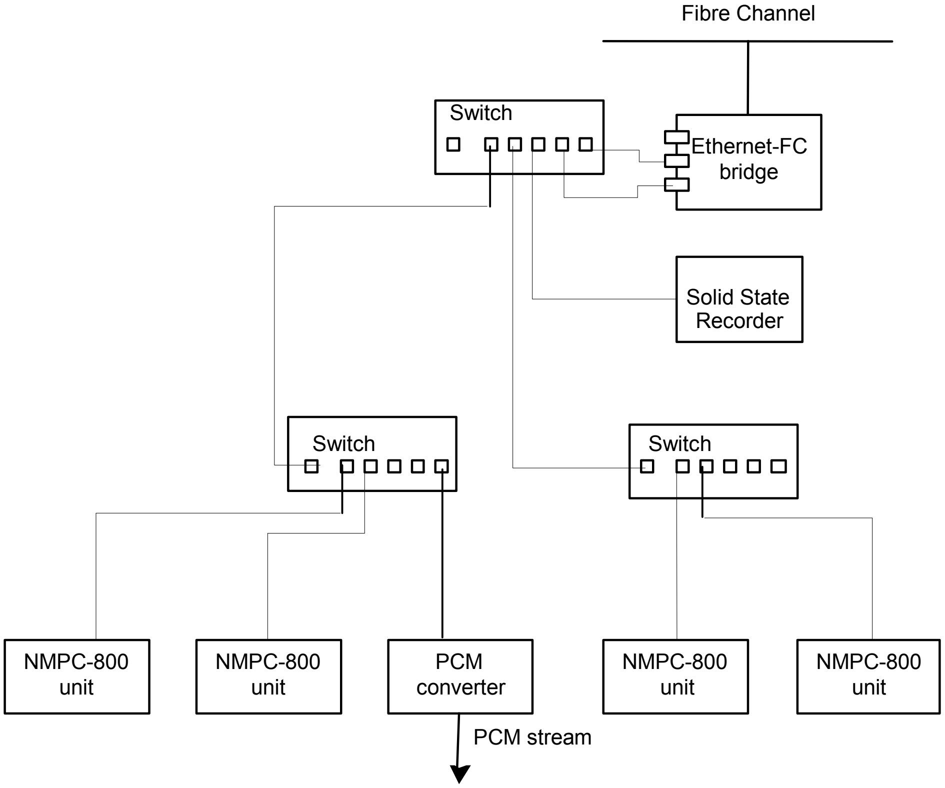

Figure 4: Scalable Network Topology of the NetDAS system

CONCLUSION

A legacy proprietary bus based data acquisition system has been successfully migrated into a networked based data acquisition system. The NetDAS prototype demonstrated high bit rate data transfer, COTS interoperability and architecture scalability. Starting with a traditional sensor, this analog data was formatted and then packetized. The packetized data was sent through an Ethernet switch to a PCM converter and finally to a data display. Thus an end-to-end network based data acquisition system has been successfully implemented and demonstrated.

The 10/100 Base-T Ethernet throughput is largely effected by processor speed, packet size and stack implementation. The selection of a commercial protocol stack must be carefully chosen to keep overhead to a minimum and to prevent unpredictable message latency. By making simple modifications to the UDP/IP stack the demonstrated data rate throughput was tripled in the NetDAS prototype.

By implementing an Ethernet to PCM converter the ability to use legacy systems (PCM data systems or TM) can be preserved.

When implementing multiple network based data acquisition units accurate time synchronization between units will be required. A strong candidate for synchronizing nodes within a network based data acquisition system is with the use of PTP IEEE1588.

REFERENCES

[1] Next Generation Instrumentation Bus Team, Test Report for Fibre Channel NGB-00-DOC-7, 2000
[2] CAIS Joint Program Office, CAIS Bus Interface Standard, Sep. 1999
[3] Edward Grozalis and Jiwang Dai, White Paper for A Network-Based Data Acquisition System, Dec. 2002 (unpublished)
[4] Information Sciences Institute, Internet Protocol (RFC 791), Sep. 1981
[5] Information Sciences Institute, User Datagram Protocol (RFC 768), 1980
[6] Information Sciences Institute , Transmission Control Protocol (RFC 793), 1981
[7] Consultative Committee for Space Data Systems(CCSDS), Recommendation for Space Data System Standards – Packet Telemetry (CCSDS 102.0-B-5), Nov. 2000
[8] Next Generation Instrumentation Bus Team , A study to Determine the Viability of Commercial Busses for Use as a Test Vehicle Instrumentation Bus (NGB-98-DOC-1), Dec. 3, 1998
[9]IEEE, IEEE 1588 Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, Sep. 2002
[10] John C. Edison, Michael C. Fischer and Joe White: IEEE-1588 Standard For a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, Proceedings of the 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, Dec. 3-5, 2002

ACKNOWLEDGEMENTS

The authors are thankful to Mr. Robert Hearne, for his development of the PCM converter. They also appreciate the enlightening comments and views given by the JDANS working group.