SpaceWire Test and Development with STAR-System and the SpaceWire PCIe Mk2

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***Abstract*—Although SpaceWire [1] is fast approaching its 20th anniversary, the requirements for equipment to test and develop new SpaceWire devices and networks continues to evolve and push the capabilities of commercial technology.**

STAR-Dundee has developed a new PCI Express product, the SpaceWire PCIe Mk2, to take advantage of the higher data rates offered in newer generations of the PCIe standard. The device features three SpaceWire ports capable of operating at 400 Mbit/s link speeds, and a PCIe Gen-3 interface that enables transmitting and receiving from/to software at the maximum rate on all links concurrently.

This high throughput is achieved through improvements to the STAR-System software suite [2], which also includes other new features to support the latest requirements for SpaceWire test and development. As well as new graphical applications providing functionality such as the ability to operate as a Remote Memory Access Protocol (RMAP) [3] initiator, support for ARM targets and the Python scripting language is also included.

This paper describes the advancements present in the SpaceWire PCIe Mk2 board and the STAR-System software suite, which simplify test and development activities while also providing higher throughput and lower latency transmission and reception of data.

Keywords—SpaceWire, Test and Development, SpaceWire PCIe Mk2, STAR-System

I. Introduction

The requirements for SpaceWire test and development products continue to evolve as the functionality offered by commercial technology changes. Back in 2002, a SpaceWire PCI board with ports operating at 200 Mbit/s, offering a maximum throughput of 800 Mbit/s to a 32-bit x86 Windows XP PC and accessed via a C API (Application Programming Interface), was a perfectly good solution for testing new SpaceWire developments.

In 2022, 400 Mbit/s SpaceWire links are sometimes required, while PCIe Gen-3 offers the capability to transfer data to and from all three of the SpaceWire ports on STAR-Dundee's new PCIe board, the SpaceWire PCIe Mk2, at the full 400 Mbit/s data rate on each port, giving a total throughput in excess of 1.8 Gbit/s. The host computers have also evolved, and STAR-Dundee's latest STAR-System software suite supports both Windows and Linux on 32-bit and 64-bit x86 machines, with ARM targets also supported on Linux.

The C programming language continues to be popular but newer scripting languages such as Python simplify the implementation of test scripts, while in some scenarios graphical applications to perform common tasks can potentially eliminate the need for any development using an API. The latest version of STAR-System, version 5.01, includes C, C++ and Python APIs plus several new graphical applications to perform tasks such as configuring deterministic triggering behaviour and acting as an RMAP initiator.

This paper describes the many benefits of the SpaceWire PCIe Mk2 combined with the STAR-System software suite, including the high performance it offers for SpaceWire test and development.

II. The SpaceWire PCIe Mk2

The SpaceWire PCIe Mk2 board was developed to replace the SpaceWire PCIe (Mk1) board, which was initially released in 2012. Like its predecessor, the PCIe Mk2 has three SpaceWire ports, which can be used to transmit and receive data from/to software at high speed, and it can act as either an interface or a router. A photograph of the SpaceWire PCIe Mk2 is shown in Figure 1.

Unlike its predecessor, the SpaceWire ports on the PCIe Mk2 can operate at link speeds of up to 400 Mbit/s and there are two external SMB trigger interfaces which can be configured as input or output triggers. There is also extensive fault protection to meet most FMEA (Failure Mode and Effects Analysis) compliance requirements. This protection covers the input power voltages from the host PC, the overvoltage of any of the point of load converters on the board, the output voltage on the SpaceWire ports, and the trigger output voltage. The SpaceWire ports are cold-sparing so that the PCIe Mk2 board can be powered down without adversely affecting any system it is connected to by a SpaceWire link, while the SpaceWire LVDS (Low-Voltage Differential Signalling) transmitters can be tri-stated.

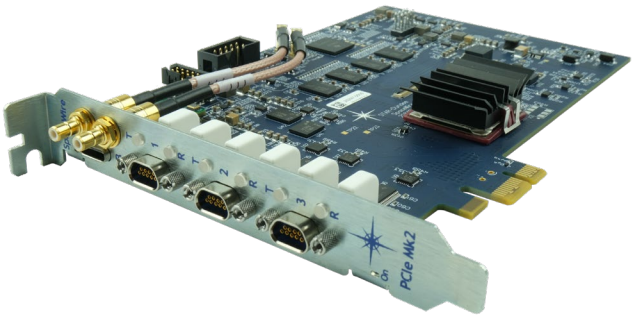

Fig. 1. SpaceWire PCIe Mk2

The PCIe interface to the host PC is a Gen-3, ×1 lane which is compatible with Gen-1, Gen-2, Gen-3 and Gen-4 PCIe slots of ×1, ×4, ×8 and ×16 widths, making it incredibly flexible. This interface also provides the data rates required to support all three SpaceWire ports transmitting and receiving data concurrently.

III. STAR-System

The software provided with the SpaceWire PCIe Mk2 hardware is the STAR-System software suite which supports all STAR-Dundee's SpaceWire and SpaceFibre interface and router devices released since 2011, including the original SpaceWire PCIe (Mk1). This helps to ensure backwards compatibility between the two products, with the same software interfaces provided to access both the Mk1 and Mk2 PCIe boards, and STAR-Dundee's other products.

The latest release of STAR-System, version 5.01, has been updated to include support for the SpaceWire PCIe Mk2 while continuing to support all previous devices. A new driver for the device, designed to also support higher speed SpaceFibre [4] devices, offers very high performance. Several new features have also been added, with the inclusion of a new API to support CCSDS Space Packet Protocols [5] along with a version of the APIs for the Python scripting language, which can be a powerful means to script tests, for example.

Support has recently been added to the Linux release of STAR-System for ARMv6, ARMv7 and ARMv8 targets, in addition to the previously supported i386 and x86-64 targets, as more development and testing is conducted using ARM processors. The latest release has also been successfully tested on Windows 11 and support has been added for the latest Linux kernel at the time of release, v5.16.9.

There have been many improvements to the graphical applications included with STAR-System. These provide functionality commonly required during test and development, not only to transmit and receive packets but also to inject errors and access the triggering functionality, for example. The latest updates include a new application that can act as an RMAP initiator and the addition of graphs to the Source and Sink applications which can transmit and receive packets at very high rates. The screenshot in Figure 2 shows three Sink windows receiving packets in a triple loopback test at the theoretical maximum data rate for a 400 Mbit/s link of around 304 Mbit/s per port, graphing those rates for each port.

As previously mentioned, STAR-System and the PCIe Mk2 are capable of much more than simply transmitting and receiving packets. An Error Injection application can be used to inject different types of errors on the link, while corresponding API functionality can transmit these errors in sequence with data characters to ensure an error occurs at a defined point in a packet. Packet timestamps can be added to received packets so that the start and end time of each packet can be recorded at sub-microsecond resolution.

In addition to the external trigger interfaces on the front of the device, the PCIe Mk2 includes further triggering capability which can be accessed from the STAR-System Triggering API or the associated graphical application. This triggering capability can be used to trigger an action to be performed when an event occurs. The event may be a signal on one of the external trigger interfaces, or it may be a packet being received or an error occurring on the link. The action may be to transmit a packet or time-code or to signal to on one of the trigger interfaces. Several different events and actions are supported, including counters which can be used to ensure an action occurs at a specific time. These actions and events can then be combined to provide deterministic behaviour, even when using a non-deterministic operating system, with the hardware responsible for determining when an action should take place.

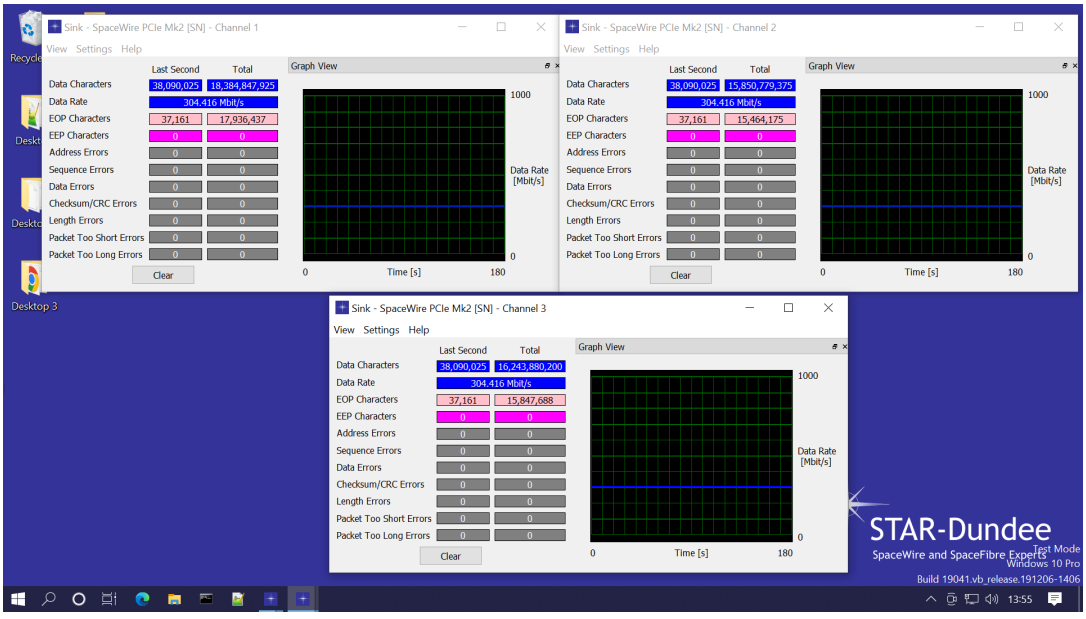

Fig. 2. STAR-System Sink Showing Triple Loopback Results

IV. Performance

Even when not using the triggering functionality, the PCIe Mk2 and STAR-System have been designed to offer extremely high performance when combined. This not only includes providing high throughput and low latency, but also ensuring CPU usage on the host PC transmitting and receiving packets is kept low, to allow further processing of the data being transmitted and received to be performed.

STAR-System includes several tools to test the performance of a product and/or the devices that they are connected to, including the Source and Sink applications mentioned earlier. The STAR-System Performance Tester application, however, provides the most comprehensive performance testing, allowing throughput and latency tests to be performed and the results output to a text file for graphing in a spreadsheet.

To measure the performance of the PCIe Mk2, several tests were performed using the Performance Tester on a relatively low-cost test PC with the following specifications:

- ASUS PRIME H310i PLUS R2.0 Motherboard
- Intel Core i5 Six Core Processor i5-9600 (3.1GHz) 9MB Cache
- 8 GB Corsair VENGEANCE DDR4 2400MHz
- 240 GB ADATA SU630 SSD

This PC is dual-bootable, allowing tests to be performed on 64-bit versions of both Windows 10 and Linux. The results of the tests were consistent between the two platforms as STAR-System has been designed to be efficient on each.

The most basic test is a throughput test with the device in loopback, where a SpaceWire cable is connected between two ports of the PCIe Mk2. The Performance Tester allows such a test to be repeated for a range of different packet sizes and the chart in Figure 3 shows the data rate and CPU usage for packet sizes between 1 and 100 bytes along the x-axis.

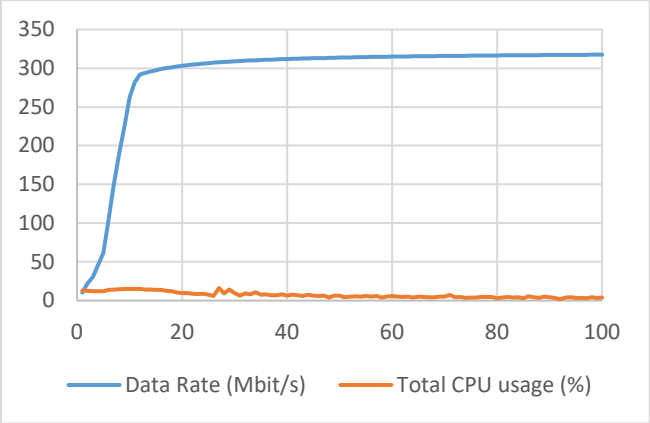

Fig. 3. Single Loopback Test on Windows

For this test, the Windows operating system was used, and the link speed was set to 400 Mbit/s to test the fastest possible data rate with the board. On a 400 Mbit/s link, the theoretical maximum for an infinite length packet is 320 Mbit/s due to SpaceWire's use of 10 bits to encode each byte of data. End of Packet markers also reduce the maximum data rate which can be achieved when sending packets, and the chart shows that STAR-System and the PCIe Mk2 achieve a data rate close to the theoretical maximum for packet sizes of 12 bytes and above. CPU usage is also below 15% for most of the test, ensuring that it's possible to do more than just transmit and receive data but also process the received data with the available CPU time.

Figure 4 shows the results of a similar test, but this time on the Linux operating system and using all three ports of the PCIe Mk2. Ports 1 and 3 are connected with a SpaceWire cable, while a loopback cable is connected to port 2. This allows all three SpaceWire ports to be exercised concurrently with packets flowing in both directions on each port. Due to the additional overhead of flow control tokens, which are sent in the opposite direction to the data, the theoretical maximum on each port operating at 400 Mbit/s is reduced from 320 Mbit/s to around 304 Mbit/s, giving a total theoretical maximum of around 912 Mbit/s.

With this test, it takes slightly longer to approach the theoretical maximum, but does so for packet sizes greater than 50 bytes in length. Note that as packets are flowing in both directions on each port, the total throughput for transmitting and receiving combined is twice what is shown in the chart, resulting in a total throughput exceeding 1.8 Gbit/s. As with the single loopback test, the triple loopback test does not make full use of the CPU with usage around 40% for the smallest packets and dropping to less than 20% for 100-byte packets. This should give plenty of capacity to process packets without affecting throughput.

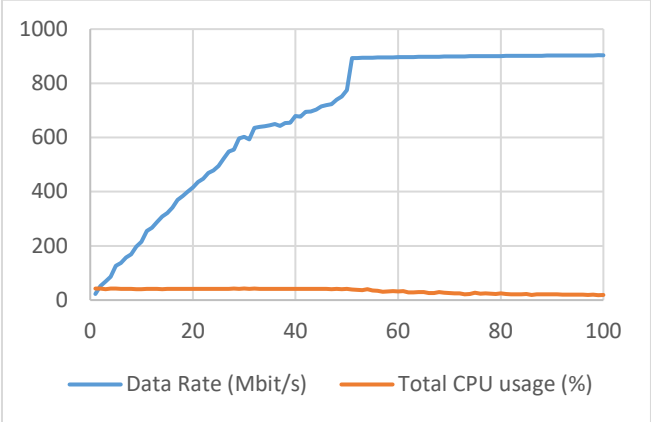

Fig. 4. Triple Loopback Test on Linux

The Performance Tester's latency test was also used to measure the average time to transmit and receive a packet. The chart in Figure 5 shows the average time in microseconds to transmit a packet from software out of one port of the SpaceWire PCIe Mk2 and receive it on another port of the PCIe Mk2 into software. This average latency is therefore the average round-trip time for a single packet. The test was performed under the Windows operating system on the same PC as the other tests, once again using packet sizes from 1 to 100 bytes and a link speed of 400 Mbit/s.

The chart shows that there is very little overhead introduced by software or the PCIe Mk2 to the round-trip time. The difference in latency between a packet of 1 byte in length and one of 100 bytes in length is around 2 or 3 microseconds, which can be attributed to the additional time it takes for the larger packet to travel over the SpaceWire link. The overhead introduced by STAR-System and the PCIe Mk2 is therefore around 48 microseconds.

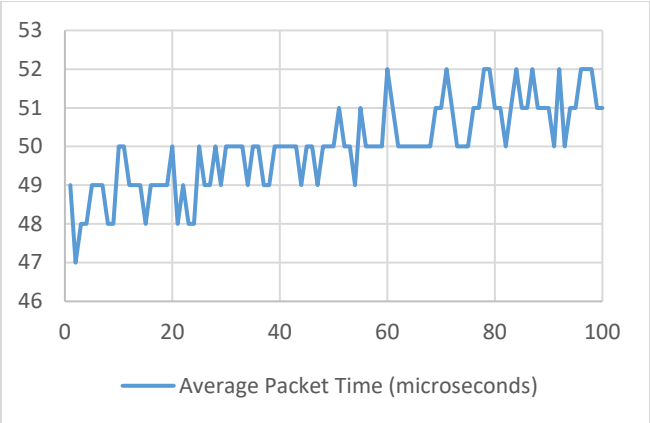

Fig. 5. Latency Test on Windows

However, it should be remembered that this is a worst-case scenario. STAR-System and the PCIe Mk2 are designed to be incredibly efficient when transmitting and receiving multiple packets, so this overhead will not apply to each individual packet. Instead, it's likely that the total overhead for groups of packets will be similar, with only the additional time required to cross the SpaceWire link added.

V. Conclusions

The SpaceWire PCIe Mk2 is the fastest SpaceWire product developed so far by STAR-Dundee. Its Gen-3 PCIe interface, support for 400 Mbit/s SpaceWire link speeds and integrated software and hardware design, permits total throughput exceeding 1.8 Gbit/s. This is achieved with relatively low CPU usage, allowing the generation of data to be transmitted and the processing of data received to be conducted in parallel.

The STAR-System software suite includes many of the APIs required for this generation and processing including individual APIs for commonly used protocols such as RMAP and the CCSDS Space Packet Protocol. Graphical applications provide the capability to perform many of these tasks without any programming, while a Python API and optional LabVIEW support [6] can be used to quickly script tests.

This is all achieved while maintaining backwards compatibility with the original SpaceWire PCIe board and with the same interface provided with other STAR-Dundee interface and router devices. This makes migrating from another product to the PCIe Mk2 a very simple exercise.

Through the use of a common interface and devices which support field upgrading, STAR-Dundee's products can also evolve to include new features or to support new targets as the commercial computing environment changes. Version 5.01 of STAR-System has support for the latest versions of Windows and Linux, with ARM support included in the Linux release. New features continue to be developed for both STAR-System and the PCIe Mk2 and are made available through STAR-Dundee's website to existing users, ensuring the PCIe Mk2, and the Mk1 version of the product, will continue to provide the capabilities required for SpaceWire test and development for many years to come.

The SpaceWire PCIe Mk2 is already in production and began shipping to users in September of 2022.

Acknowledgements

STAR-Dundee would like to acknowledge the feedback provided by the users of its products, which act as requirements for improvements to existing products and features of new products.

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