



Solutions for SPI protocol testing and debugging in embedded system.

There are many reasons to use serial protocols in embedded system: simplicity, low pin count and the ability to setup a kind of network of simple devices to implement a complex functionality. Focusing on the Serial Peripheral Interface (SPI), this paper explores the reasons to test and debug a SPI port. It then describes and compares the tools available on the market to do so, from general purpose oscilloscopes to specialised PC-based SPI exercisers and analyzers.

Serial buses are everywhere in embedded design.

Among the existing protocols, SPI and I²C have established themselves as **de facto** standard. They are well suited for low-cost and (not always so) low-speed communication between ICs, between microprocessors and between microprocessors and peripherals. EEPROMs, real-time clocks (RTCs), ADCs, DACs, thermal management devices and LCD controllers are such peripherals. Table 1 briefly compares these two protocols.

| | SPI | I ² C |
|----------------------------------|---------------------------------|---|
| Clock frequency | free (n x MHz, 10n x MHz, ...) | 10 kHz, 100 kHz, 400 kHz, 1 MHz and 3.4 MHz |
| Number of wires | 4 | 2 |
| Duplex | Full duplex | Half duplex |
| Multi-master | Yes ¹ | Yes |
| Multi-slave | Yes | Yes |
| Built-in slave addressing | No | Yes |
| Access length defined | No | Yes |
| Flow control | No | Yes |

Table 1 : SPI and I²C compared

SPI and I²C compete well at different levels for the usage mentioned above, but we can say that SPI is better suited than I²C for 'data stream' applications that make use its full duplex capability, as opposed to reading and writing addressed locations in a slave device. As example of a 'data stream' application, we can think of transfers between a microprocessor and a DSP or sending data samples to a DAC.

Strictly speaking, there are many 'SPI protocols'. Designing a port with a protocol similar to SPI might seem quite straightforward. After all, it is all 'just' about producing a reference clock signal to generate and sample data onto 2 separate lines for in and out, let them play simultaneously and select the slave with a third slave select ('chip enable') line...

Well, if you think to it, there are so many variations from the protocol first established by Motorola (4 wires, byte-by-byte scheme). To get an idea of the possible combinations, just consider the following issues:

- ▶ Will the protocol use a continuous clock or will the clock be active only when data are sampled and generated?
- ▶ For non-continuous clock, what is the clock line default level?
- ▶ Will the protocol allow any data length on the serial lines or be restricted to burst access of, say, 8 bits?
- ▶ Which clock edge will be used to sample the incoming data? Rising or falling?

¹ Multi-master is possible but is not defined by the SPI standard and not often done. It may require additional signals.



- ▶ Same question for data generation: rising or falling clock edge?
- ▶ What is the polarity of the slave select lines?

Clock rates, clock phase, clock continuity, sampling and toggling edges, signals polarities: actually, none of these parameters is really known in advance when using a 'SPI' device, or, rather, a 'SPI-like protocol device'².

This may be one of the reasons why SPI is nowadays so ubiquitous: in its principle, SPI is quite simple, with nothing is defined or preordained by an authority committee. Aside, because it is the peripheral protocol used for many popular processors from Motorola, then Freescale Semiconductor, such as the MPC8260 (communication processor) and microcontrollers such as the M68HC11 well there is a chance that you'll run into it one or other of these days. So you need to be SPI-savvy!

| Manufacturer | Device Types |
|--------------------------------|---|
| Analog Devices | DSP, ADC, digital Pot., codec |
| Atmel | CPU, EEPROM, digital Pot. |
| Cirrus Logic | ADC, DAC, codec |
| EPSON | RTC |
| Fairchild | EEPROM |
| Freescale Semiconductor | DSP, MCU |
| Infineon | Pressure Sensor |
| Intel | CAN Controller |
| Linear Technology | ADC, DAC, Temperature Sensor + Voltage Monitor |
| Macronix | FLASH |
| Maxim | ADC, DAC, UART, Analog Switches |
| Microchip | Micro controller, EEPROM, ADC, CAN controller |
| National Semiconductor | LCD Controller, dig. temperature sensor, USB Controller |
| SanDisk | FLASH, MultiMediaCard |
| Texas Instruments | DSP, ADC, DAC |
| Zilog | MCU |

Table 2 : Non-exhaustive list of SPI devices manufacturers

Why would you want to 'debug' a standard protocol?

After all, if SPI has been around for all this time, it is very unlikely that current implementations would cause any trouble? All an engineer would have to do is to connect a network of SPI-compliant devices and let them play, right?

Actually, there are many cases where you would like to check what is going on at the protocol level. Here are some reasons:

| SPI Debug / Test Case | Description |
|--|--|
| CASE 1: Don't debug SPI, debug through SPI | A SPI functional port is used as an access port to gain visibility on an embedded system by analyzing the traffic exchanged between the devices on a SPI network and by stimulating the embedded system through its SPI interconnection. |
| CASE 2: Command or higher level of the stack built on SPI | The SPI port is analyzed and stimulated to test and debug the protocol stack built on top of the SPI signalling. |

² In comparison, I²C has remained more 'pure' over the years.



| SPI Debug / Test Case | Description |
|---|---|
| CASE 3: Detect which SPI protocol is used | The SPI port is debugged to check its parameters and how it derives from the standard 'pure' SPI interface. |
| CASE 4: Debug and test your own design of a SPI controller | A SPI port can be part of a custom design on CPLD, FPGA, ASIC or SoC. Like any design, this requires debug and test, which can be performed with SPI-oriented test and debug tools. |

Table 3 : Overview of SPI test and debug cases

CASE 1: Don't debug SPI, debug through SPI

Organising testing and debugging of an embedded system requires choosing several input and output ports used to access and observe the behaviour of the system.

JTAG scheme

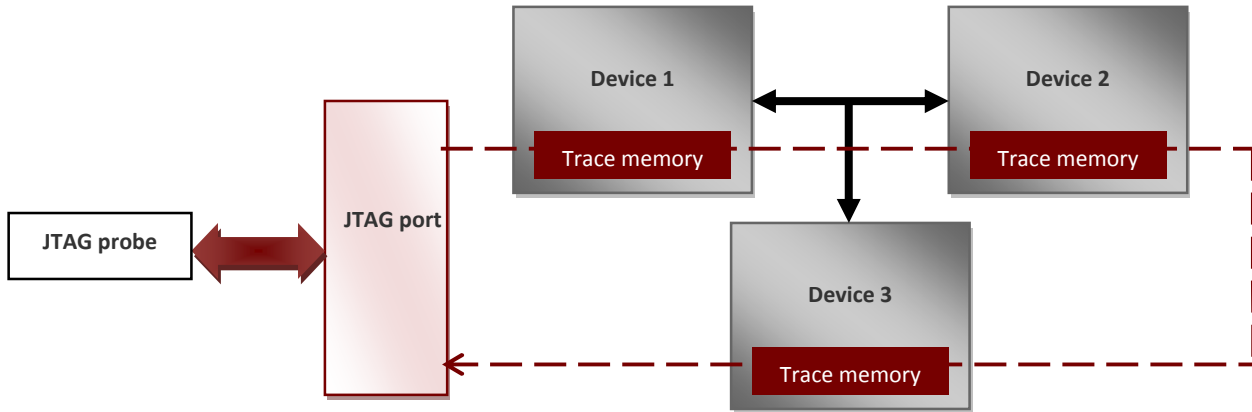


Figure 1: System debug done by collecting trace data from system memories through JTAG port

JTAG often comes in mind first, because it is used by emulators for software tracing. In many cases, it can be used to collect data from embedded memories and other chips like CPLDs and FPGAs. However, while efficient for very specific uses (like single processor software debug) a debug port like this offers a very low speed communication and can only be used like a 'side door' to access a whole system and collect previously stored trace data. Using JTAG to bring stimuli to a system and using the same JTAG port to collect results from the same system is a viable debug and test scheme as long as memory (for tracing storage) and speed are not an issue.

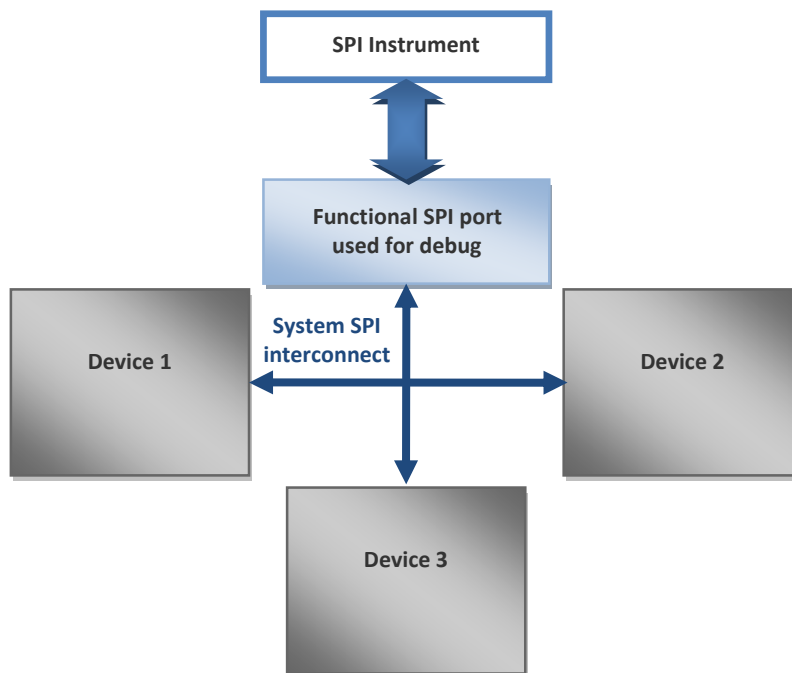
SPI scheme: intercept functional SPI traffic by placing an instrument on the bus

Suppose that your embedded system is composed of a network of devices like processors, peripherals, programmable devices (CPLD / FPGA) that use SPI protocol to communicate with each other.

Intercepting and interpreting the SPI traffic exchanged on this network will bring valuable and 'real-time' information about the system, allowing you to actually *observe* the system. With careful trigger generation and/or data sorting, you can narrow your search for troublesome bugs. Moreover, if you can play arbitrary sequences or *replay recorded sequences* onto the SPI bus whenever you like, you'll be able to stimulate the system very precisely, at a very low level.



Figure 2: System debug through the functional SPI interconnect



Low-level stimulation and analysis is useful for embedded system test and debug

Processor-centric embedded systems offer a great deal of flexibility for test and debug, since (almost) everything is controlled from the embedded microcontroller and it is very easy to segment and write software to test any part of the system. It is very commonly thought that the embedded microcontroller is the only access point to the system for stimulation (through its serial ports and GPIO, for instance) and analysis (through simple register access, for instance).

However, even for such systems, low-level stimulation and analysis can reveal extremely useful. Tracking down embedded systems bugs is of course about debug the software, but it is also all about having good ways to observe any given peripheral, co-processor or external device. Many debug strategies exist, but in the end, insuring that a whole system will function correctly starts by checking the behaviour of each of its individual component parts independently.

Bringing stimuli directly to the I/O port of a given device allows early testing of device and hence, early validation of parts of the whole system functionality. This is especially useful during the design process, when not everything is available yet... There is often a vital need to emulate non-existing parts of a system to interact with parts that are available, observing resultant responses to specific stimuli. When you can carefully test each component of a system before assembling them together, you'll reduce the incidence of - or increase the likelihood of finding - later-occurring bugs.

Similarly, intercepting and observing traffic at the functional interfaces of the embedded system components and correlating them with any running software ran by the processor would increase your productivity. If you observe a system from more than one single access point, you'll increase the visibility you get from it. If you get a high visibility of the system, there is an excellent probability that you'll speed up the debug process.

Because SPI is very common as functional interface, and because it can reach quite interesting streaming speeds, using SPI as an access port to your system can definitely help test (stimulate) and debug it.



CASE 2: Debug command or higher level of the stack built on SPI

Standard SPI only defines the signal level, not how data is organized. Unlike I²C, SPI does not define any device addressing. It does not define any flow control, nor any command³... All you have is a few data and control lines and you are free to add any protocol layer to this.

This basically means that implementing a SPI system requires designing a protocol stack – simple or complex, this is up to you... As such, this development must be tested and debugged anyway. This is also a test and debug case where there is a need to plug yourself onto the SPI bus to analyze and exercise it.

CASE 3: Detect which SPI protocol is used

SPI variants are numerous. When something goes wrong with an interconnect of SPI devices, you must first check which SPI configuration is used (SPI mode, clock, ...) and even, if the device 'so-called' SPI protocol really complies with what you think.

CASE 4: Debug and test your own design of a SPI controller

What if you designed a SPI master or slave yourself? Whether you need an I/O port for a CPLD, FPGA, ASIC or SoC, a SPI port has got many advantages:

- ▶ If performance requirements allow it, a serial interface is better than parallel memory-like interfaces for general purpose or register access because it spares costly pins.
- ▶ It allows arbitrary clock frequencies, up to several 10th of MHz (even more, if you do a careful routing on the board).
- ▶ It is 'self-contained' on 4 (or less) wires: clock, slave select and data lines.

Given its relatively low complexity and because any additional protocol layer will likely be custom (since nothing is defined with the SPI standard), you'll probably end up designing instead of integrating a ready-to-use IP. During and after the development of your own SPI interface, it will be necessary to test and debug it... This is another case where you'll need the proper tools and environment.

What is available for SPI debug and test?

Let's take a look at the solutions currently available for SPI test and debug. Table 4 provides an overview of the existing techniques and tools.

| Device / tool | Purpose |
|--|---|
| Oscilloscope and Logic Analyzers with SPI protocol analysis support | Probing and analyzing SPI port at signal level and provide visualisation and decoding support. Analyze only. |
| Processor with a SPI interface | Provide a 'software' access point onto the SPI interconnect. Stimulate and Analyze. |
| Arbitrary digital pattern generator | Stimulate SPI interconnect at signal level. Stimulate only. |
| PC-based SPI analyzer | Probing and analyzing SPI port at signal level and provide visualisation and decoding support. Analyze only. |
| PC-based SPI exerciser | Stimulate SPI interconnect at signal level – act as a master onto the SPI interconnect. Stimulate only. |
| Combined PC-based SPI exerciser / analyzer | Combination of the 2 tools above: Stimulate and Analyze. |

Table 4: Overview of existing techniques for SPI debug and test

³ Actually, the original SPI protocol defined serial data grouped by bytes, but there are many devices today that use other arbitrary – and even variable-length bit grouping.



Oscilloscope and Logic Analyzers with SPI protocol support.

This can appear to be the most obvious solution for any engineer having experience with hardware design. Scopes and logic analyzers will let you visualize and record information at signal level from the SPI port and provide enough triggering capabilities to track virtually anything from your SPI traffic.

Many oscilloscope and logic analyzer vendors provide specific protocol support (generally: SPI, I²C, CAN and so on...) - software add-ons for your scope or logic analyzer. Once you have triggered something from the SPI traffic, these software add-ons work on the sampled data to provide you with protocol-specific information to help visualise and decode it.

With many scopes, you'll be able to see the SPI signals superimposed with the decoding of the protocol according to the settings you would have defined (see Figure 3). This enhances your readability of what is going on at the protocol level. If you want to analyze data on your PC, you'll be able to download what you sampled as a file through the scope PC interface (GPIB, USB, Ethernet, ...) and most often, data will be presented as 'SPI decoded data'.

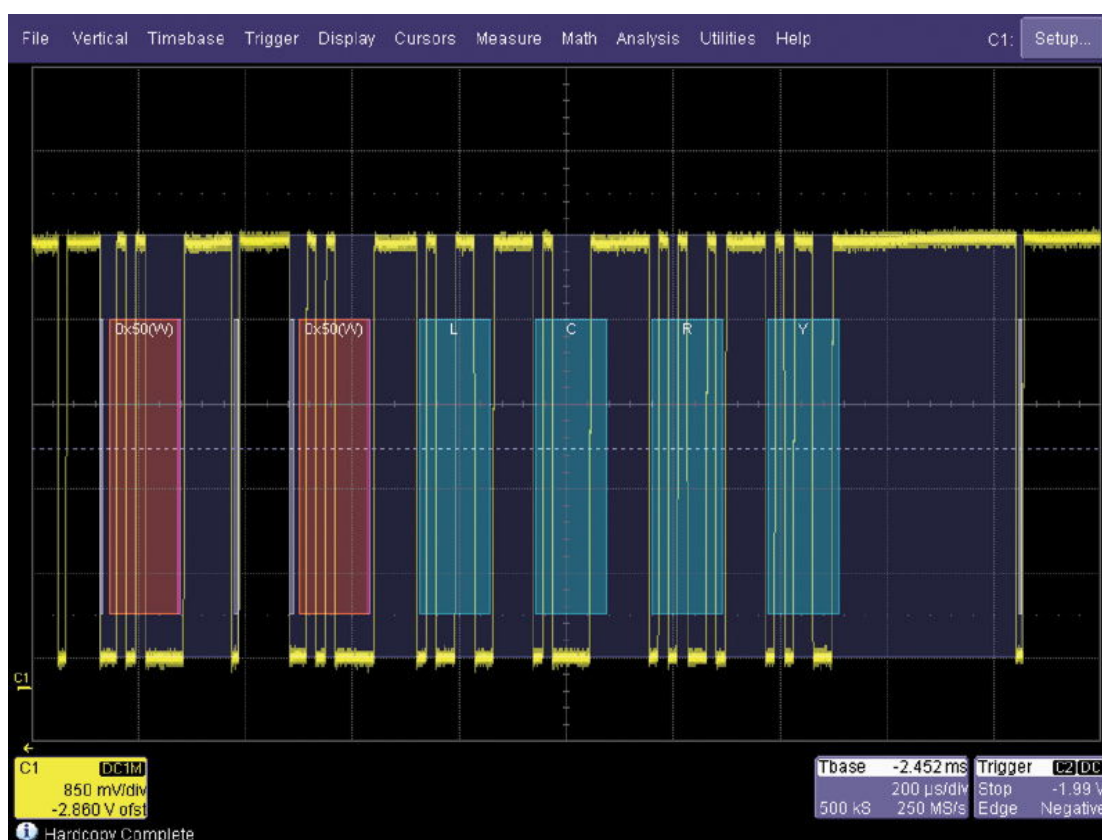


Figure 3: Example of protocol visualisation enhancement in oscilloscope

Processor with SPI interface

This approach is in fact about using the system resources for self-testing and self-debugging. In this case, the engineer uses embedded software specifically developed for testing and debugging. To get an insight of what is going on in the embedded system, you must define a program that will send adequate stimuli to the SPI bus and use the software itself to read back results stored in the embedded system memory mapped registers or any other storage location. Because this technique only indirectly accesses the SPI bus, it requires a great deal of interpretation. It might be your preferred choice if you are skilled with software development and reluctant to dig into the hardware at signal level.

Actually, this approach may be considered as a 'first-line test and debug strategy' and must be used if possible before implementing any other more invading technique. It is very useful to check if the system



'does what it must do'... and is often the way you'll detect that there is a problem with it, when the results that you receive are not as you expected. According to the problem, you'll need to investigate and perhaps go at a much lower-level, for which you'll need other complementary techniques than just using the embedded system processor as single debug resource.

However, please bear in mind that using a processor for SPI stimulation won't always allow you to send *any* stimulus at clock cycle resolution: by their very nature, it is sometimes very tricky to have a processor produce digital stimuli with a cycle-accurate timing. Moreover, due to software execution latencies, you won't always be able to stimulate the SPI interface at maximum speed, which may be desirable if you wish to characterise your SPI interface.

Arbitrary digital pattern generator

Arbitrary digital pattern generators are sometimes referred to as digital I/O and have the ability to produce arbitrary digital stimuli. As opposed to the previous 'processor' solution, this is a very low-level solution which operates at signal level. Basically, it consists in defining how each of your port signal lines will toggle.

Good digital pattern generator should provide efficient ways to define your pattern, like a programming interface, that would allow you to emulate the SPI protocol.

Digital pattern generator efficiently complement any analysis tool, since they provide a very low-level way to send stimuli to your embedded system and hence, lots of control about what is *exactly* sent onto the SPI interconnect. Arbitrary pattern generator allows overcoming the limitations of the use of a processor (see above) for stimuli generation.

PC-based SPI analyzer, SPI exerciser and combined PC-based SPI analyzer/exerciser

PC-based instruments are connected to a PC through one of its ports (USB, PCI, Ethernet...) and run proprietary software to control the instrument and process the data generated for the instrument or collected from it.

PC-based SPI analyzer and PC-based SPI exerciser are categories of devices specialised for SPI analysis and SPI stimulation. Schematically:

- ▶ PC-based SPI analyzers sample the embedded system SPI traffic and sends it to the PC memory. Good PC-based analyzers provide SPI protocol decoding support, and tools for data visualisation on the PC, like a waveform viewer.
- ▶ PC-based SPI exercisers let act as a master on the SPI bus directly from the PC. It configures the used SPI port (clock characteristics, number of slaves, single access length ...), offers interfaces from the PC to define the data to be sent onto the SPI interconnect, and stimulate the SPI interconnect according to the defined timing and other protocol characteristics.
- ▶ Combined SPI Exerciser/Analyzer devices are also available.

In comparison with more classical instruments, PC-based SPI tools offer the following advantages:

- ▶ **Interfaces:** good PC-based SPI tools benefit from the flexibility of the PC and present multiple interfaces like GUI and other programming interfaces (for example: C/C++ or scripting interface). Having programming interfaces to control a SPI instrument is especially valuable because you don't leave your PC environment for low-level SPI test and debug. It offers a great deal of flexibility for test automation and data processing and, with careful programming, to develop a fully integrated test and debug solution that couples both software debug (software execution with the embedded processor) and low-level hardware debug, through the embedded system SPI port. Data generation is greatly simplified too, since the SPI exerciser can be coupled to any software or simulation used as a stimulus source.
- ▶ **Memory:** when lots of data must be analyzed or when a tool must generate long data runs (e.g. stream samples to a DAC, a DSP or a CODEC), PC memory is largely available and inexpensive.



- ▶ **Compactness:** during embedded system development, more expensive and encumbering equipment like logic analyzers are not always conveniently available since they are most often shared between multiple engineers. It is also very handy to be able to place a single small device next to your laptop in the design room...
- ▶ **Price:** PC instruments cost far less than their bench-top general purpose equivalents because the specialized hardware and performance are limited to specific minimum characteristics, yet they benefit from the PC's standard (and already available) memory and data processing power.

Productivity matters

The right solution for debugging and testing SPI must make the most of your time during test and debug – in other words, help you validate your embedded system faster and help you find and correct bugs faster.

Embedded system development involves a wide variety of skills and very often a team of software and hardware engineers with their own specialties and own habits. Being really productive during test and debug does not necessarily mean choosing the most powerful oscilloscope because it has got the highest sampling rate. In many cases, you'll end up with costly equipment that engineers won't use because it is not available or because it does not really fit the test and debug case or because the engineers *are not familiar with it*.

Embedded system development *is difficult* because it mixes so much potential software and hardware issues. Even an embedded software developer can end up checking the system at signal level *because it impacts the software he is writing*.

PC-based instruments offer a good match for embedded system designer who are not used to playing with oscilloscope or logic analyzers or any other bench-top instrument located in the lab.

- ▶ They usually provide a familiar programming interface, in C/C++, Visual Basic or any other standard programming language.
- ▶ They offer a good continuity between the design environment and the test and debug environment.
- ▶ They can better interact with software debug, since performed from the same, familiar PC environment.
- ▶ They usually focus on specific tasks ("SPI debug").
- ▶ They are priced so that each engineer can afford one on his/her desk, next to his/her laptop. So, the embedded software engineer won't need to go to the lab, export his files or wait for a scope or a LA to be unoccupied to start debugging at low level.
- ▶ Combined SPI exerciser / analyzer offer multiple functions and many options that fit **both** embedded system **stimulation** AND embedded system **analysis**.

Testing and debugging times are increasingly important in the total design process, because of the growing complexity of embedded systems. Efficient test and debug strategy heavily depends on the skills and intelligence of the engineers who perform it. If your engineer is a software specialist, he'll do wonders with a PC. PC instruments will just allow him/her keep on using its favourite PC environment, even for low-level tasks like SPI test and debug.

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