High-Speed, Real-Time Recording Systems

Fourth Edition

Recording Systems
Talon Recorders
Application

Appendix A: High-Speed A/D Converters
Appendix B: Switched Serial Fabrics

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Preface

In today’s world of high-speed A/D converters operating in the gigahertz range, real-time signal recording has become a challenging task that requires specialized hardware and intelligent application software. When designing a real-time recorder capable of streaming sustained data to disk at rates of up to 5 GB/sec and higher, the system developer has to consider the limitations presented by the recorder’s operating and file systems, the limitations of disk drive technology, the hardware interfaces, and the RAID controller technology.

Fortunately for the application developer, serial fabrics have emerged to provide the high-speed interfaces required to move this data; disk drive and RAID HBAs (Host-Bus Adapters) are now exploiting serial interfaces; finally, the emergence of SSD (Solid-State Drive) technology provides a performance level previously unattainable in real-time recording systems. Developing software that can take advantage of these new technologies presents a challenge that can be met by understanding some key concepts required to build a high-speed, real-time recording system.

In this handbook, we will look at some of these techniques and will discuss some of the features that are widely desired in such a system, including the use of a non-proprietary file system, the use of a client-server architecture, and the presence of a user-friendly API (Application Programming Interface). Finally, we will highlight the latest Pentek Talon® High-Speed Recording and Playback Systems and an application based on one of them.

For more information on complementary subjects, the reader is referred to these Pentek Handbooks:

Critical Techniques for High-Speed A/D Converters in Real-Time Systems
High-Speed Switched Serial Fabrics Improve System Design
Putting FPGAs to Work in Software Radio Systems
Putting VPX and OpenVPX to Work
Software-Defined Radio
Introduction

- Desired sustained data transfers up to 5 GB/sec and beyond
- Limitations to such transfers are presented by the:
  - Operating system
  - File system
  - Disk drive technology
  - Hardware interfaces
  - RAID controller technology
- Serial fabrics and RAID HBAs provide the high-speed interfaces to move this data
- Solid-State Drives provide performance levels previously unattainable

Real-Time Recording

- Real-Time recording captures every sample provided by the front end without loss
- Desire to move data faster today than could be done yesterday
- The commercial server PC market provides an excellent choice as a recording platform
- CPU technology is constantly advancing in architecture and processing speed
- Memory interfaces can stream data at 10 GB/sec
- Serial fabrics provide PCI Express capable of data rates of 8 GB/sec

When designing a real-time recording system capable of streaming sustained data to disk at rates of up to 5 GB/sec and beyond, the system developer has to consider the limitations presented by the recorder’s operating and file systems, the limitations of disk drive technology, the hardware interfaces, and the RAID controller technology.

The high-speed A/D converters we review in Appendix A that operate at sampling frequencies in excess of 100 MHz, present real-time signal recording with a challenging task that requires specialized hardware and intelligent application software.

Fortunately for the application developer, the serial fabrics we present in Appendix B provide the high-speed interfaces required to move this data.

The disk drive and RAID HBAs (Host-Bus Adapters) we will discuss in this chapter also exploit serial interfaces; finally, the emergence of solid-state drive technology provides a performance level previously unattainable in real-time recording systems.

Developing software that can take advantage of these new technologies presents a challenge that can be met by understanding some key concepts required to build a real-time recording system.

In order for a recording system to be considered “real-time”, it must capture every sample of data provided by the front end with absolutely no loss. This must happen consistently to create confidence that the system will perform in the most mission-critical situations.

When choosing a platform to develop the recording system, it is important to consider the constant requirement to move data faster today than could be done yesterday. With this in mind, the commercial server PC market provides an excellent platform choice as it benefits from the consumer-driven requirement to move, process and store greater and greater amounts of data every day.

Within the server PC, microprocessor technology is constantly advancing in both processing speed and in architecture. Memory interfaces are capable of streaming data at rates of 10 GB/sec and higher. Serial fabrics have provided PCI Express Gen. 2 with x16 interfaces capable of maximum data rates of 8 GB/sec. Finally, SATA II provides disk storage rates of 3 Gb/sec to a single drive.

The latest Intel processors are approaching 4 GHz clock rates with hex and octal cores, while memory continues to get smaller, cheaper and faster. This provides us with a solid foundation to build on, one that we can grow with, as new high-speed digitizers are introduced.
Once the foundation of our recorder is established, it is essential to provide a front-end I/O device that is capable of streaming data in real-time. As shown in the above figure, this front-end device typically consists of one or more high-speed A/D converters or digital interfaces that acquire data at a constant rate, and a set of DMA engines that move data off the device. In a real-time system, these DMA engines are the most critical feature of the I/O device, since their design dictates how well this hardware can stream the data and maintain its real-time performance requirement.

While the DMA engines are responsible for moving data off the device, it is the PCI Express engine, inherent within the device, that provides the path to the server PC’s system memory. It is here that the data is buffered and made available to the storage device. The server PC’s PCIe interface is the path from the I/O device to the system’s memory. It is essential that our I/O device provides a sufficiently fast PCIe interface with the bandwidth required to maintain the data rates of the front-end.

It is also essential that the I/O device has the ability to stream data continuously with no software intervention, allowing the hardware to be solely responsible for the data movement. The latest high-performance I/O devices provide intelligent DMA chaining that allows the system developer to custom-tailor the data flow to maximize performance and assure the system meets the real-time requirements.

The DMA engine should allow the user to chain large buffers of data and should provide many chains in a link list. If this is provided, it is the application developer’s responsibility to create a large circular buffer, consisting of many chains, each of considerable size. Buffering this data in such a way, allows the system to absorb any momentary latency hits, which can be caused by a number of external factors.

Buffered data must be sent to disk at data rates that match those of the front-end I/O device. Utilizing off-the-shelf high-performance RAID HBAs, allows the developer to take advantage of the inherent features and functionality provided, including selectable RAID-level control and automated disk recovery facilities. The challenge in selecting the best RAID controller lies in finding one that reliably meets the sustained streaming read/write requirements of the system.
A hard-disk drive (HDD or hard drive or hard disk) is a non-volatile, random access digital data storage device. It features rotating rigid platters on a motor-driven spindle within a protective enclosure. Data is magnetically read from and written to the platter by read/write heads that float on a film of air above the platters.

Hard-disk drives have decreased in cost and physical size over the years while dramatically increasing in capacity. Hard-disk drives have been the dominant device for data storage in general-purpose computers since the early 1960s. They have maintained this position because advances in their recording density have kept pace with storage requirements. Today’s HDDs operate on high-speed serial interfaces, such as SATA (Serial ATA).

The factors that limit the time to access the data on a hard-disk drive are mostly related to the mechanical nature of the rotating disks and moving heads. Seek time is a measure of how long it takes the drive head assembly to travel to the track of the disk that contains data. Rotational latency is incurred because the desired disk sector may not be directly under the head when data transfer is requested. These two delays are on the order of milliseconds each.

When developing a recording system, it is important to recognize the non-linearity of the HDD.

Since the density of an HDD remains constant through the disk and the rotation speed remains constant, the read and write rates of a disk fall as HDD accesses move from the outer edge of the disk to the inner edge. This is due to the fact that the circumference of the outer edge of a disk is longer than the circumference of the inner edge. Since the disk rotates at the same speed for either edge and the density is the same, the disk will provide many more bytes per second on the outer edge than the inner edge.

Since disks present their logical addressing from the outer edge to the inner edge, disk read and write rates fall as a disk fills up. This can be seen in the above screen plot. RAIDs* built on several HDDs, provide a similar non-linearity in their data rates. Because of this, it is imperative that the system developer either provide enough drives in the RAID to meet the maximum data-rate requirement for the entire volume, or limit the size of the drive volume to the percentage of disk space that will meet the system’s data-rate requirement.

* RAID, acronym for Redundant Array of Independent Disks, is a storage technology that provides increased reliability and functions through redundancy.
As we said previously, RAID arrays built on several HDDs display a similar non-linearity in data rates.

For example, let’s consider the case of designing a recording system that would maintain 500 MB/sec data transfer rates. The drive volume should be formatted to use about 50% of the available disk capacity. This is done simply by formatting the drive to the appropriate size within the operating system.

It is important to leave a sufficient amount of overhead, when selecting the formatted disk amount. In this case, while the system may keep up with the 500 MB/sec requirement for almost seventy percent of the drive volume, fifty percent is a much safer number, provided it supplies enough storage for the application.

There are other critical factors to consider to assure real-time performance when designing a recording system. When dealing with non-real-time operating systems like Windows and Linux, it is important to minimize the operating system’s impact on the recording application. The amount of processor intervention in the recording software can be minimized by dedicating the data transfers to the DMA controllers and simply leaving the processor to manage the data flow. The developer should also elevate the priorities of real-time tasks within the application and keep background tasks at lower priorities to avoid impacting the recorder’s performance.

A Solid-State Drive (SSD) is a data storage device that uses solid-state memory to store data with the intention of providing access in the same manner as a traditional HDD. SSDs are distinguished from traditional HDDs, which are electromechanical devices containing spinning disks and movable read/write heads. Instead, SSDs use microchips which retain data in non-volatile memory chips and contain no moving parts.

Compared to HDDs, SSDs are typically less susceptible to shock and vibration, are silent, have much lower access time and latency, do not display data rate non-linearity, and typically support a limited number of writes over the life of the device. SSDs use the same interface as hard disk drives, thus easily replacing them in most applications.

Most SSDs use NAND-based flash memory, which retains memory even without power. SSDs using volatile random-access memory (RAM) also exist for situations which require even faster access, but do not necessarily need data persistence after power loss, or use external power or batteries to maintain the data after power is removed.

A hybrid drive combines the features of an HDD and an SSD into one unit, containing a large HDD, with a smaller SSD cache to improve performance of frequently accessed files. These are not suitable for data-intensive work, nor do they offer the other advantages of SSDs.
When designing a real-time recorder, it is important to provide the user a control interface that is intuitive and easy to use. The easiest way to achieve this is through a GUI (Graphical User Interface). A GUI enables the user to control the recorder by pushing virtual buttons with a mouse or via a touch screen. The GUI should allow the user to not only control the recorder, but should also provide facilities to manage the data files, utilities to monitor and analyze the signals being recorded, and should provide constant status information to the user.

The GUI should have the ability to run either locally on the recorder or remotely on an independent PC or other device. Being able to run on a remote device allows the user the ability to put the recorder in an environment that may not be appropriate for the operator. This allows the recorder to be close to the sensor or antenna source, placing the A/D or digital I/O interface near the signal of interest.

The best way to provide both local and remote control of the recorder is through a client-server architecture. This architecture provides a socket-based communication link between the client GUI and the server recording application, separating the real-time portion of the recorder (the Server) from the non-real-time portion (the Client). The client can then connect to the server, whether the client sits on the server PC itself or on a PC that is connected to the server over Ethernet.

By sending messages to the server, the client GUI can control all aspects of the recorder. This includes the ability to start and stop recordings, to set up front-end hardware parameters, to monitor incoming-signal information and to request status information from the server. The interface for this messaging structure should be defined in an API (Application Programming Interface). While the API is used by the GUI to communicate with the server, it can also be provided to the user in a format that allows the recorder to be integrated into a larger system.

(More on the next page)
User API

By providing a user API, the recorder becomes more than a stand-alone system; it serves as a user development platform as well. This allows different types of users the flexibility they may desire, while providing the out-of-the-box experience of a system all-in-one product.

In order to define an API that can be easily integrated into a larger application, it is important to define the API routines in a simple and straightforward manner. These routines should abstract the user from the details of the message building, the socket interface and other intricacies of the recording architecture. Error checking should be included in the recording server, allowing the user to receive error codes in response to failed messages.

The API should not only contain routines that control the interface, but should also contain routines that obtain general status information, perform built-in-test facilities and allow the user to view snapshots of the data prior to and during recording. Combining these facilities, provides the user with the ability to create a well-featured recorder application as part of a bigger system.

Other Design Considerations

One of the problems engineers often have to deal with after recording data in the field, is the issue of off-loading the mission data to a system that will perform the analysis, post-processing and archiving. This process should be made simple and quick, minimizing the down-time that field engineers have during the offload process. There are several strategies to consider here.

The use of a non-proprietary file system, such as NTFS, to record data provides the ability to avoid the offload process required by systems that use a proprietary file system. In this situation, the user can instantly access recordings as standard files on the recording device itself. By providing the disk storage as hot-swappable SATA drives, field engineers can simply swap out disks filled with mission data for fresh ones and transport only the data disks to their analysis system. By adding a RAID controller to the analysis system, similar to the one designed into the recorder, data can instantly be accessed on the analysis machine, avoiding the offload process completely. Additionally, the recorder is instantly available to collect new data as soon as the disk swap is made, allowing for almost no downtime in the field.

Data files that are provided to the analysis system must contain critical information related to the recording event itself. This can be accomplished by adding a small header to the beginning of each data file. The parameters stored in this header should be well-defined and contain all of the critical information about the recording. The parameters should include time-stamping, I/O module settings, and general information about the recording session itself. Additionally, user-settable fields should be reserved, allowing the user to add other information to the file header.

The information stored in the file header should be usable by system analysis and signal visualization tools. Integrating these tools into the recorder, provides a robust product: one that allows field engineers the ability to verify their signal integrity prior to, during, and after a recording session.

Summary

When creating a real-time recorder, it is important to consider all of the qualities inherent in a high-performance, user-friendly system. The use of a high-performance PC allows us to take advantage of the latest technology, while the use of a non-proprietary file system provides us with the convenience of immediate access to the data files. A GUI provides an easy-to-use control panel, while the availability of a user API enables the integration of the recorder into a larger system application.

By building this platform on a well-defined client-server architecture, the developer can provide both of these facilities to the user. Integrating this with a high-performance front-end I/O module and the latest technology offered by the PC market, assures that the system will provide a satisfying experience with excellent reliability.
Talon High-Speed Recording Systems: Flexible and Deployable Solutions

High-Speed Recording Systems

Talon® High-Speed Recording Systems eliminate the time and risk associated with new technology system development. With increasing pressure in both the defense and commercial arenas to get to the market first, today’s system engineers are looking for more complete off-the-shelf system offerings.

Out of the box, these systems arrive complete with a full-featured virtual operator control panel ready for immediate data recording and/or playback operation.

Because they consist of modular COTS board-level products and the flexible Pentek SystemFlow® software, they are easily scalable to larger multichannel data acquisition and recording applications requiring aggregate recording rates of up to 5.0 GB/sec.

Ready-to-Run Recording Systems

Depending on model, the Pentek offerings are fully integrated systems featuring a range of A/D and D/A resources or digital I/O with high-speed disk arrays.

These systems are built on a Windows workstation and they can easily satisfy a broad spectrum of recording needs. Furthermore, users can install postprocessing and analysis tools to operate on the recorded data which is stored in the familiar NTFS format.

Recording Systems Form Factors

Pentek’s High-Speed Recording Systems are available as Lab Systems, Portable Systems, Rugged, and Extreme Systems.

RTV and RTS Lab Systems are housed in a 19-in. rack-mountable chassis in a PC server configuration. They are designed for commercial applications in a lab or office environment.

RTR Portable Systems are available in a small briefcase-sized enclosures with integral LCD display and keyboard. They, too, provide a PC server configuration and are designed for harsh environment field applications where size and weight is of paramount importance.

RTR Rugged Rackmount Systems are housed in a 19-in. rugged rack-mountable chassis. They are built to survive shock and vibration and they target operation in harsh environments and remote locations that may be unsuitable for humans.

RTX Extreme Systems are available in a rackmount chassis designed to military specs. They are designed to operate under extreme environmental conditions using forced-air or conduction-cooling to draw heat from system components.
Client/Server Architecture

As shown above, the SystemFlow® architecture provides for easy communication between the recording system Client PC on the left and the Server on the right.

Client/Server Communication

Client and Server communicate through a standard socket connection. This arrangement enables the Server to provide real-time recording and playback functions that can be controlled from a local or a remote Client. It also allows Client and Server to run on different operating systems.

Function Libraries

The function libraries and tools for controlling the recording and playback functions include the Application Programming Interface, the Graphical User Interface and the integrated Signal Viewer.

SystemFlow API

The SystemFlow API allows developers to configure and customize the system interfaces and operation. Source code is supplied for all client API functions. A well-defined set of plug-ins allows the user to extend server API functions.

SystemFlow GUI

The SystemFlow architecture features a Windows-based GUI that provides a simple means to configure and control the system. Custom configurations can be stored as profiles and later loaded when needed, allowing the user to select preconfigured settings with a single click.

SystemFlow Signal Viewer

SystemFlow also includes signal viewing and analysis tools that allow the user to monitor the signal prior to, during, and after a recording session. These tools include a virtual oscilloscope, a spectrum analyzer and a spectrogram display. More information on System Flow and the Signal Viewer is provided on the next two pages.

NTFS File System

The NTFS file management system provides immediate access to the recorded data, thereby eliminating time-consuming data-conversion processes required with proprietary file management systems. It also eliminates the need for custom hardware and software platforms where the recorded data may need to be physically transported for conversion.
The Pentek SystemFlow Recording Software for Analog Recorders provides a rich set of function libraries and tools for controlling all Pentek analog high-speed real-time recording systems. SystemFlow software allows developers to configure and customize system interfaces and behavior.

The **Recorder Interface** shows a system block diagram and includes configuration, record, playback and status screens, each with intuitive controls and indicators. The user can easily move between screens to set configuration parameters, control and monitor a recording, play back a recorded signal and monitor board temperatures and voltage levels.

The **Hardware Configuration** screen provides a simple and intuitive means for setting up the system parameters. The configuration screen shown here, allows user entries for input source, center frequency, decimation, as well as gate and trigger information. All parameters contain limit-checking and integrated help to provide an easier-to-use out-of-the-box experience.

The SystemFlow **Signal Viewer** includes a virtual oscilloscope, a spectrum analyzer and a spectrogram display for signal monitoring in both the time and frequency domains. It is extremely useful for previewing live inputs prior to recording and for monitoring signals as they are being recorded to help ensure successful recording sessions. The viewer can also be used to inspect and analyze the recorded files after the recording is complete.

Advanced signal analysis capabilities include automatic calculators for signal amplitude and frequency, second and third harmonic components, THD (total harmonic distortion) and SINAD (signal to noise and distortion). With time and frequency zoom, panning modes and dual annotated cursors to mark and measure points of interest, the Signal Viewer can often eliminate the need for a separate oscilloscope or spectrum analyzer in the field.
Pentek SystemFlow Recording Software for Digital Recorders

The SystemFlow Main Interface for Digital Recorders shows a block diagram of the system and provides the user with a control interface for the recording system. It includes Configuration, Record, Playback, and Status screens, each with intuitive controls and indicators. The user can easily move between screens to set configuration parameters, control and monitor a recording, and play back a recorded stream.

The Configure screen presents operational system parameters including temperature and voltages. Parameters are entered for each input or output channel specifying UDP or TCP protocol, client or server connection, the IP address and port number. All parameters contain limit-checking and integrated help to provide an easier-to-use out-of-the-box experience.

The Record screen allows you to browse a folder and enter a file name for the recording. The length of the recording for each channel can be specified in megabytes or in seconds. Intuitive buttons for Record, Pause and Stop simplify operation. Status indicators for each channel display the mode, the number of recorded bytes, and the average data rate. A Data Loss indicator alerts the user to any problem, such as a disk-full condition.

By checking the Master Record boxes, any combination of channels in the lower screen can be grouped for synchronous recording via the upper Master Record screen. The recording time can be specified, and monitoring functions inform the operator of recording progress.
Shown in this diagram is the dataflow during a typical recording session.

The Pentek Transceiver Board may contain a 2-channel 200 MHz A/D for digitizing two input analog channels. The digitized outputs are downconverted by the two DDCs (Digital Downconverters) and moved on to the PC system memory via the PCI Express interface. Both the DDCs and the PCIe interface are implemented in the board’s FPGA.

Data then moves from the system memory to the Recording System RAID Controller and is then recorded to disk via the SATA interface. DMA controllers conduct all data transfers, bypassing the CPU for guaranteed real-time operation.
During a playback session, data stored on disk moves through the SATA interface of the Playback System RAID Controller. From there, data is passed to the PC system memory through the PCIe interface and then to the Pentek Transceiver board through its PCIe interface, all via hardware DMA controllers for real-time operation.

This board also contains DUCs (Digital Upconverters) which upconvert the data to the original IF frequency bands. Two 800 MHz D/As convert the data to analog form and provide signals that are identical to the analog signals that were originally recorded.

These can be further analyzed with any Windows-compatible analysis software.
The Talon **RTV 2601** is a turnkey multiband recording and playback system used for recording and reproducing signals with bandwidths up to 80 MHz. The RTV 2601 uses a 16-bit, 200 MHz A/D converter to provide real-time sustained recording rates to disk of up to 400 MB/sec. The A/D is complemented with a 16-bit 800 MHz D/A that provides the ability to reproduce signals captured in the field.

The RTV 2601 comes in a 4U 19 in. rackmount package that is 22.75 in. deep. Signal I/O is provided in the rear of the unit, while the hot-swappable data drives are available at the front. Air is pulled through the system from front to back allowing it to operate at ambient temperatures from 5 to 35 deg C.

The RTV 2601 includes a programmable digital downconverter so users can configure the system to capture signals with frequencies as low as 300 kHz and as high as 700 MHz. Corresponding signal bandwidths range from a few kilohertz to 80 MHz. A digital upconverter and D/A produce an analog output matching the recorded IF signal frequency.

The system includes a built-in sample clock synthesizer programmable to any desired frequency from 10 MHz to 200 MHz. This clock synthesizer can be locked to an external 10 MHz reference clock and has excellent phase noise characteristics. Alternately, the user can supply an external sample clock to drive the A/D and D/A converters. The RTV 2601 also supports external triggering, allowing users to trigger a recording or playback on an external signal.

The **RTV 2601** includes the Pentek SystemFlow recording software. SystemFlow features a Windows-based GUI (Graphical User Interface) that provides a simple means to configure and control the recorder. As an option, a GPS or IRIG receiver card can be supplied with the system for accurate time stamping of recorded data.
The Talon RTV 2602 Serial FPDP Value Recorder is designed to provide a low-cost solution to users looking to capture and play back multiple Serial FPDP streams. It can record up to four Serial FPDP channels to the built-in 4 TB RAID consisting of cost-effective, enterprise-class HDD storage. It is a complete turnkey recording system, ideal for capturing any type of streaming sources. These include live transfers from sensors or data from other computers and is fully compatible with the VITA 17.1 specification.

The RTV 2602 comes in a 4U 19 in. rack-mount package that is 22.75 in. deep. Signal I/O is provided in the rear of the unit, while the hot-swappable data drives are available in the front. Air is pulled through the system from front to back to allow operation at ambient temperatures from 5° to 35° C.

The RTV 2606 can be populated with up to four SFP connectors supporting Serial FPDP over copper, single-mode, or multi-mode fiber, to accommodate all popular Serial FPDP interfaces. It is capable of both receiving and transmitting data over these links and supports real-time data storage to disk.

Programmable modes include flow control in both receive and transmit directions, CRC support, and copy/loop modes. The system is capable of handling 1.0625, 2.125, 2.5, 3.125 and 4.25 GBaup link rates. Up to four channels can be recorded simultaneously with an aggregate recording rate of up to 400 MB/sec.

As an option, a GPS or IRIG receiver card can be supplied with the system providing accurate time stamping of recorded data. Additionally, the GPS receiver delivers GPS position information that can be recorded along with the input signals.

The RTV 2602 includes the Pentek SystemFlow recording software which features a Windows-based GUI.
The Talon RTR 2726A is a turnkey, multiband recording and playback system that allows the user to record and reproduce high-bandwidth signals with lightweight, portable and rugged packages. This model provides aggregate recording rates of up to 3.2 GB/sec and is ideal for the user who requires both portability and solid performance in a compact recording system.

The RTR 2726A is supplied in a small footprint portable package measuring only 16.0” W x 6.9” D x 13.0” H and weighing just less than 30 pounds.

With measurements similar to small briefcases, this portable workstation includes Intel Core i7 processors, high-resolution 17” LCD monitors, and up to 15.3 TB of SSD storage.

A/D sampling rate, DDC decimation and bandwidth, D/A sampling rate and DUC interpolation are among the GUI-selectable system parameters, that provide fully-programmable systems capable of recording and reproducing a wide range of signals.

Included with this system is Pentek’s SystemFlow recording software. Built on a Windows 7 Professional workstation with high performance Intel Core i7 processor, the system allows the user to install post-processing and analysis tools to operate on the recorded data. They record data to the native NTFS file system, providing immediate access to the data. Custom configurations can be stored as profiles and later loaded when needed, so users can select preconfigured settings with a single click.

Versions of the RTR 2726A are also available as a Rackmount Lab unit (Model RTS 2706), Rugged Rackmount (Model RTR 2746), and Extreme Rackmount (Model RTX 2766).
The Talon **RTR 2750** is a turnkey recording system that provides phase-coherent recording of 16 independent input channels. Each input channel includes a 250 MHz 16-bit A/D and an FPGA-based digital down-converter with programmable decimations from 2 to 65536, thereby providing the ability to capture RF signals with bandwidths up to 100 MHz.

With options for AC- or DC-coupled input channels, RF signals up to 700 MHz in frequency can be sampled and streamed to disk in real-time at sustained aggregate recording rates up to 8 GB/sec in a 4U rackmount solution.

Designed to operate under conditions of vibration and extended operating temperatures, the **RTR 2750** is ideal for military, airborne and field applications that require a rugged system. The hot-swappable solid state storage drives provide the highest level of performance under harsh conditions and allow for quick removal of mission-critical data.

A/D sampling rates, DDC decimations and trigger settings are among the selectable system parameters, providing a system that is simple to configure and operate. An optional GPS time and position stamping facility allows the user to timestamp each acquisition as well as track the location of a system in motion.

For users who wish to create a custom user interface or to integrate the Talon recording system into a larger application, a C-callable API is also provided as part of SystemFlow. Source code and examples are supplied to allow for a quick and simple integration effort.

Data can be off-loaded through gigabit Ethernet ports or USB 3.0 ports. Additionally, data can be copied to optical disk, using the 8X double layer DVD±R/RW drive.
The Talon RTS 2707 is a turnkey, multiband recording and playback system for recording and reproducing high-bandwidth signals. The RTS 2707 uses 12-bit, 500 MHz A/D converters and provides aggregate recording rates up to 1.6 GB/sec.

The RTS 2707 uses Pentek’s high-powered Virtex-6-based Cobalt modules, that provide flexibility in channel count, with optional digital downconversion capabilities. Optional 16-bit, 800 MHz D/A converters with digital upconversion allow real-time reproduction of recorded signals.

A/D sampling rates, DDC decimations and bandwidths, D/A sampling rates and DUC interpolations are among the GUI-selectable system parameters, providing a fully-programmable system capable of recording and reproducing a wide range of signals. Optional GPS time and position stamping allows the user to record this critical signal information.

The RTS 2707 includes the SystemFlow Recording Software. SystemFlow features a Windows-based GUI that provides a simple means to configure and control the recorder.

The RTS 2707 is configured in a 4U 19” rackmountable chassis, with hot-swappable data drives, front panel USB ports and I/O connectors on the rear panel. Systems are scalable to accommodate multiple chassis to increase channel counts and aggregate data rates.

Multiple RAID levels, including 0, 1, 5, 6, 10 and 50, provide a choice for the required level of redundancy. The hot-swappable HDDs provide storage capacities of up to 100 TB in a single 6U chassis.

Versions of the RTS 2707 are available as Rugged Portable (Model RTR 2727), Rugged Rackmount (Model RTR 2747), and Extreme Rackmount (Model RTX 2767).
The Talon RTR 2748 is a turnkey recording and playback system that allows users to record and reproduce signals with bandwidths up to 500 MHz. The RTR 2748 can be configured as a one- or two-channel system to provide real-time aggregate recording and playback rates up to 4.0 GB/sec to an array of solid-state drives.

The RTR 2748 uses Pentek’s high-powered Virtex-6-based Cobalt boards that provide the data streaming engine for the high-speed A/D converters. A built-in synchronization module is provided to allow for multi-channel phase-coherent operation. GPS time and position stamping is optionally available.

The RTR 2748 includes the SystemFlow Recording Software. SystemFlow features a Windows-based GUI that provides a simple means to configure and control the system. Custom configurations can be stored as profiles and later loaded when needed, allowing the user to select preconfigured settings with a single click.

Built on a Windows 7 Professional workstation, the RTR 2748 allows the user to install post-processing and analysis tools to operate on the recorded data. The RTR 2748 records data to the native NTFS file system that provides immediate access to the recorded data.

Data can be off-loaded via gigabit Ethernet ports, or USB 2.0 and USB 3.0 ports. Additionally, data can be copied to optical disk, using the 8X double layer DVD±R/RW drive.

Because SSDs operate reliably under conditions of shock and vibration, the RTR 2748 performs well in ground, shipborne and airborne environments. The drives can be easily removed or exchanged during a mission to retrieve the data.

Versions of the RTR 2748 are also available as a Rugged Portable (Model RTR 2728), and Extreme Rackmount (Model RTX 2768).
The Talon RTX 2769 is a turnkey system that is built to operate under harsh conditions. Designed to withstand high vibration and operating temperatures, the RTX 2769 is intended for military, airborne and UAV applications requiring a rugged system.

Aimed at recording high-bandwidth signals, the RTX 2769 uses 12-bit, 3.6 GHz A/D converters. It can be configured as a one- or two-channel system and can record sampled data, packed as 8-bit- or 16-bit-wide consecutive samples (12-bit digitized samples residing in the 12 MSBs of the 16-bit word). A high-speed RAID array provides an aggregate streaming recording rate to disk of 4.8 GB/sec.

The RTX 2769 uses Pentek’s high-powered Virtex-7-based Onyx boards that provide the data streaming engine for the high-speed A/D converters. Channel and packing modes as well as gate and trigger settings are among the selectable system parameters, providing complete control over this ultra wideband recording system.

Built on a Windows 7 Professional workstation, the RTX 2769 allows the user to install post-processing and analysis tools to operate on the recorded data. The RTX 2769 records data to the native NTFS file system that provides immediate access to the recorded data.

The Talon RTX 2769 uses a shock- and vibration-isolated inner chassis and solid-state drives to assure reliability under harsh conditions. Developed by Pentek to enhance the operation of Extreme recorders, up to four front-panel removable QuickPac™ drive canisters are provided, each containing up to eight SSDs. Fastened with four thumbscrews, each drive canister can hold up to 7.6 TB of data storage and allows for quick and easy removal of mission-critical data with a minimum of down time.

 Versions of the RTX 2769 are available as a Rugged Portable (Model RTR 2729A), and Rugged Rackmount (Model RTR 2749).
The Talon RTS 2620 combines the power of a Pentek Talon Recording System with those of an RF tuner and RF upconverter hardware plus Pentek's Sentinel Intelligent Signal Scanner. The RTS 2620 provides SIGINT engineers the ability to scan the 6 GHz spectrum for signals of interest and monitor or record bandwidths up to 40 MHz wide once a signal band of interest is detected.

A spectral scan facility allows the user to sweep the spectrum at 30 GHz/sec, while threshold detection allows the system to automatically lock onto and record signal bands. Scan results are displayed in a waterfall plot and can also be recorded to allow users to look back at some earlier spectral activity.

Once a signal of interest is detected, the real-time recorder can capture and store hundreds of terabytes of data to disk, allowing users to store days worth of data. The optional RF upconverter reproduces signals captured at RF frequencies up to 6 GHz.

The Pentek Model 78621 Cobalt board transceiver serves as the engine of the RTS 2620 and is coupled with a 6 GHz tuner to provide excellent dynamic range across the entire spectrum. The 200 MHz 16-bit A/D board provides 86 dB of spurious-free dynamic range and 74 dB of SNR.

The Virtex-6-based DDC with selectable decimations of up to 64 k provides exceptional processing gain while allowing users to zoom into signals of varying bandwidths. All system components are integrated into a rackmount chassis that ranges in size from 3U to 6U depending on storage requirements. Front panel removable HDDs, configured as a RAID are hot-swappable and configurable.

An optional GPS receiver and built-in PLLs allow all devices in the RF chain to be locked in phase and correlated to GPS time. GPS position information can optionally be recorded, allowing the recorder’s position to be tracked while acquiring RF signals.
Pentek’s Sentinel™ recorders add intelligent signal monitoring and detection for Talon real-time recording systems. The intuitive GUI allows users to monitor the entire spectrum or select a region of interest, while a selectable resolution bandwidth allows the user to trade sweep rate for a finer resolution and better dynamic range. Scan settings can be saved as profiles to allow for quick setup in the field.

RF energy in each band of the scan is detected and presented in a waterfall display. Any RF band can be selected for real-time monitoring or recording. In addition to manually selecting a band for recording, a recording can be automatically started by configuring signal strength threshold levels to trigger it.

The Sentinel hardware resources are controlled through enhancements to Talon’s SystemFlow software package that includes a Virtual Oscilloscope, Virtual Spectrum Analyzer and Spectrogram displays, providing a complete suite of analysis tools to complement the Sentinel hardware resources.

As shown in the figure above, an RF Scanner GUI allows complete control of the system through a single interface. Start and stop frequencies of a scan can be set by the user as well as the resolution bandwidth. All user parameters can be saved as profiles for easy setup in the field.

Frequency slices from the waterfall display can be selected and monitored, allowing the user to zoom into bands of interest. Threshold triggering levels can be set to record signals that exceed a specified energy. Recordings can also be manually started and stopped.

The Signal Viewer includes a virtual oscilloscope and spectrum analyzer for signal monitoring in both the time and frequency domains. It is extremely useful for previewing live inputs prior to recording, and for monitoring signals as they are being recorded.
The Talon RTS 2715 is a turnkey rackmount lab recording system for storing one or two 10-gigabit Ethernet (10GbE) streams. It is ideal for capturing any type of streaming sources including live transfers from sensors or data from other computers and supports both TCP and UDP protocols. Using highly-optimized disk storage technology, the system achieves aggregate recording rates up to 1.6 GB/sec.

Two rear panel SFP+LC connectors for 850 nm multi-mode or single-mode fibre cables, or CX4 connectors for copper twinax cables accommodate all popular 10 GbE interfaces. Optional GPS time and position stamping accurately identifies each record in the file header.

The RTS 2715 includes the SystemFlow Recording Software. SystemFlow features a Windows-based GUI (Graphical User Interface) that provides a simple and intuitive means to configure and control the system. Custom configurations can be stored as profiles and later loaded as needed, allowing the user to select preconfigured settings with a single click.

Built on a server-class Windows 7 Professional workstation, the RTS 2715 allows the user to install post-processing and analysis tools to operate on the recorded data. The RTS 2715 records data to the native NTFS file system, providing immediate access to the data.

The RTS 2715 is configured in a 4U or 5U 19” rack-mountable chassis, with hot-swap data drives, front panel USB ports and I/O connectors on the rear panel. Systems are scalable to accommodate multiple chassis to increase channel counts and aggregate data rates.

Versions of the RTS 2715 are also available as Rugged Rackmount (Model RTR 2755), and Extreme Rackmount (Model RTX 2775).
The Talon RTR 2736A is a complete turnkey recording system designed to operate under conditions of shock and vibration. It records and plays back multiple serial FPDP data streams in a rugged, lightweight portable package. It is ideal for capturing any type of streaming sources including live transfers from sensors or data from other computers and is fully compatible with the VITA 17.1 specification. Using highly-optimized disk storage technology, this system achieves aggregate recording rates up to 3.2 GB/sec.

The system can be populated with up to eight SFP connectors supporting Serial FPDP over copper, single-mode, or multi-mode fiber, to accommodate all popular serial FPDP interfaces. It is capable of receiving and transmitting data over these links and supports real-time data storage to disk. The system is capable of handling 1.0625, 2.125, 2.5, 3.125 and 4.25 GBaud link rates supporting data transfer rates of up to 420 MB/sec per serial FPDP link.

The system includes the SystemFlow Recording Software. SystemFlow features a Windows-based GUI that provides a simple and intuitive means to configure and control the system. Custom configurations can be stored as profiles and later loaded as needed, allowing the user to select preconfigured settings with a single click.

The RTR 2736A is configured in portable, lightweight chassis with hot-swap SSDs, front panel USB ports and I/O connections on the side panel. It is built in extremely rugged, 100% aluminum alloy unit, reinforced with shock absorbing rubber corners and impact-resistant protective glass. Using vibration- and shock-resistant SSDs, the system is designed to operate reliably as a portable field system in harsh environments.

Versions of the RTR 2736A are also available as a Rackmount Lab unit (Model RTS 2716), Rugged Rackmount (Model RTR 2756), and Extreme Rackmount (Model RTX 2776).
The Talon RTX 2778 is a turnkey record and playback system that is built to operate under harsh conditions. Designed to withstand high vibration and operating temperatures, the RTX 2778 is intended for military, airborne and UAV applications requiring a rugged system.

The RTX 2778 records and plays back digital data using the Pentek Model 78610 LVDS digital I/O board. Using highly optimized disk storage technology, the system achieves aggregate recording rates of up to 1.0 GB/sec.

The RTX 2778 utilizes a 32-bit LVDS interface that can be clocked at speeds up to 250 MHz. It includes Data Valid and Suspend signals and provides the ability to turn these signals on and off as well as control their polarity.

The RTX 2778 includes the SystemFlow Recording Software. SystemFlow features a Windows-based GUI (Graphical User Interface) that provides a simple means to configure and control the system.

Built on a Windows 7 Professional workstation, the RTX 2778 allows the user to install post-processing and analysis tools to operate on the recorded data. The RTX 2778 records data to the native NTFS file system, providing immediate access to the recorded data.

The Talon RTX 2778 uses a shock- and vibration-isolated inner chassis and solid-state drives to assure reliability under harsh conditions. Developed by Pentek to enhance the operation of Extreme recorders, up to four front-panel removable QuickPac™ drive canisters are provided, each containing up to eight SSDs. Fastened with four thumbscrews, each drive canister can hold up to 7.6 TB of data storage and allows for quick and easy removal of mission-critical data with a minimum of down time.

Versions of the RTX 2778 are also available as a Rackmount Lab unit (Model RTS 2718), Rugged Portable (Model RTR 2738), and Rugged Rackmount (Model RTR 2758).
Utilizing the Talon RTS 2706 Configurable Recording System discussed previously, this system provides the ability to scan three RF channels synchronously and record the digitized signals to disk.

In addition to the RTS 2706, this system includes three commercially available rackmount RF tuners and a KVM switch. An Ethernet hub is included to allow the RTS 2706 to control the tuners through their Ethernet interface. Each tuner’s RJ45 Ethernet port is wired to the Ethernet hub which, in turn, is wired to one of the Ethernet ports of the RTS 2706.

The KVM switch is wired directly to one of the USB ports of the RTS 2706. This connection allows for the RTS 2706 to be controlled from a keyboard and mouse attached to the KVM switch. An LCD display can also be attached to this switch for viewing the signals before, during and after the recording.

The three RF tuners are set up to have their IF outputs connected to the three input channels of the RTS 2706 recorder. The recorder is equipped with the Cobalt Model 78621 PCIe 3-Channel 200 MHz A/D with factory-installed 3-Channel DDC in the Virtex-6 FPGA. The DDCs offer a decimation range of 2x to 65,536x providing a wide range to satisfy most applications.

The 10 MHz reference clock is distributed to the A/Ds of the 78621 and also to RF Tuner #1 which, in turn, supplies it to RF Tuners #2 and #3. In addition, the RF LO and the IF LO are distributed from RF Tuner #1 to the others. This arrangement achieves phase-synchronous scanning to meet the specification of this application.

The 10 MHz reference clock is generated by the GPS board which is located in one of the PCIe slots of the RTS 2706 recorder. A GPS antenna is supplied with the system and provides for accurate position and time-stamping of each recording.
The Pentek SystemFlow recording software supplied with this system provides all the features discussed previously. In addition, controls for a scanning facility are included. The screen shot shown here allows the user to define the start and stop frequencies of the scan, the frequency bin size, dwell time, and other scan parameters that may be important to a particular scan.

A typical example of a three-channel phase-synchronous scan is shown above.

This system has been successfully built, tested and delivered by Pentek as Model RTS 2706-013.
## High Speed A/D Converter Markets

- Commercial Wireless
- Military Communications
- Radar
- Sonar
- Telemetry
- Beamforming
- Direction Finding
- Wireless Networks
- Control Systems
- Signals Intelligence
- Medical Imaging
- Military Countermeasures
- Nuclear Instrumentation
- Structural Analysis

**Figure 29**

Markets for high-speed A/D converters are significant in size and many are growing rapidly. New markets emerge regularly based on A/D technology advances, lower costs, and the general trend of replacing older mechanical and analog systems with DSP (digital signal processing) systems.

DSP offers significant advantages for handling signal complexity, communications security, improved accuracy and reliability, reduced size, weight and power.

Commercial users of high-speed A/Ds include wireless mobile communication systems, airline radar systems, air traffic control towers, ship communications, and wireless networks for home, office and public facilities.

Industrial uses include medical imaging systems and process control systems for manufacturing.

Government systems account for many of the high-end applications such as phased-array military radar, communications countermeasure systems, global military radio networks, unmanned aerial vehicles and intelligence gathering systems.

## New Monolithic A/D Technology

- Smaller geometry, lower core voltages and power dissipation
- Much higher sample rates and bit accuracy
- Wideband input circuitry optimized for direct IF sampling
  - IF (intermediate frequency) signals are usually greater than Fs
  - Differential, transformer coupled inputs minimize noise
- High Performance Integrated S&H (sample-and-hold)
  - Higher immunity to clock waveform symmetry and level
- Improved multi-stage flash conversion techniques
- Digital sample code generation and error correction
  - Devices can be calibrated and trimmed during production
- Improved thermal tracking of DC offset, gain, and linearity
- Improved power supply noise rejection and immunity

**Figure 30**

Because of the complexity of these market segments, wideband A/D converters have made significant advances in recent years.

This is due partly to silicon process improvements and also to many applications that require direct sampling of IF signals well above 100 MHz.

One of the most important advances is the sample-and-hold (or track-and-hold) circuitry at the front end.

Just as important, are new sample clock interfaces and drivers.

At these speeds, you need state-of-the-art flash and multistage flash conversion techniques.

New techniques in digital error code correction and thermal compensation circuitry help eliminate errors in bit accuracy, linearity and gain.

Lastly, these new devices are more immune to power supply and system noise.
Monolithic A/Ds for Fs Greater than 100 MHz and Bits Greater than Eight

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Part No.</th>
<th>Sample Freq.</th>
<th>Channels</th>
<th>Bits</th>
<th>Input BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas Instr.</td>
<td>ADC12D1800</td>
<td>3,600 MHz</td>
<td>1</td>
<td>12</td>
<td>1,750 MHz</td>
</tr>
<tr>
<td>Linear Tech.</td>
<td>LTC2380-16</td>
<td>2,000 MHz</td>
<td>1</td>
<td>16</td>
<td>34 MHz</td>
</tr>
<tr>
<td>Atmel</td>
<td>AT84AS008</td>
<td>2,000 MHz</td>
<td>1</td>
<td>10</td>
<td>3,000 MHz</td>
</tr>
<tr>
<td>Texas Instr.</td>
<td>ADC12D1800</td>
<td>1,800 MHz</td>
<td>2</td>
<td>12</td>
<td>2,800 MHz</td>
</tr>
<tr>
<td>Linear Tech.</td>
<td>LTC2379-18</td>
<td>1,600 MHz</td>
<td>1</td>
<td>18</td>
<td>34 MHz</td>
</tr>
<tr>
<td>Maxim</td>
<td>MAX108</td>
<td>1,500 MHz</td>
<td>1</td>
<td>8</td>
<td>2,200 MHz</td>
</tr>
<tr>
<td>Texas Instr.</td>
<td>ADC08D1000</td>
<td>1,000 MHz</td>
<td>2</td>
<td>8</td>
<td>1,700 MHz</td>
</tr>
<tr>
<td>Atmel</td>
<td>AT84AD001B</td>
<td>1,000 MHz</td>
<td>2</td>
<td>8</td>
<td>1,500 MHz</td>
</tr>
<tr>
<td>Maxim</td>
<td>MAX101A</td>
<td>500 MHz</td>
<td>1</td>
<td>8</td>
<td>1,200 MHz</td>
</tr>
<tr>
<td>Atmel</td>
<td>AT84AD004</td>
<td>500 MHz</td>
<td>2</td>
<td>8</td>
<td>1,000 MHz</td>
</tr>
<tr>
<td>Texas Instr.</td>
<td>ADS54J69</td>
<td>500 MHz</td>
<td>2</td>
<td>16</td>
<td>1,200 MHz</td>
</tr>
<tr>
<td>Texas Instr.</td>
<td>ADS5463</td>
<td>500 MHz</td>
<td>1</td>
<td>12</td>
<td>750 MHz</td>
</tr>
<tr>
<td>Texas Instr.</td>
<td>ADS5474</td>
<td>400 MHz</td>
<td>1</td>
<td>14</td>
<td>750 MHz</td>
</tr>
<tr>
<td>Texas Instr.</td>
<td>ADS42LB69</td>
<td>250 MHz</td>
<td>2</td>
<td>16</td>
<td>900 MHz</td>
</tr>
<tr>
<td>Analog Dev.</td>
<td>AD9480</td>
<td>250 MHz</td>
<td>1</td>
<td>8</td>
<td>400 MHz</td>
</tr>
<tr>
<td>Texas Instr.</td>
<td>ADS5485</td>
<td>200 MHz</td>
<td>1</td>
<td>16</td>
<td>300 MHz</td>
</tr>
<tr>
<td>Analog Dev.</td>
<td>AD9430</td>
<td>215 MHz</td>
<td>1</td>
<td>12</td>
<td>700 MHz</td>
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<tr>
<td>Analog Dev.</td>
<td>AD9410</td>
<td>210 MHz</td>
<td>1</td>
<td>10</td>
<td>500 MHz</td>
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<tr>
<td>Analog Dev.</td>
<td>AD9054</td>
<td>200 MHz</td>
<td>1</td>
<td>8</td>
<td>350 MHz</td>
</tr>
<tr>
<td>Linear Tech.</td>
<td>LTC2255</td>
<td>125 MHz</td>
<td>1</td>
<td>14</td>
<td>300 MHz</td>
</tr>
</tbody>
</table>

Figure 31

Shown in the table above in order of decreasing sampling frequency, are some representative examples of commercially available, monolithic A/D converters with sampling rates greater than 100 MHz and resolution of at least 8 bits.

All these devices are potential candidates for board-level products for embedded systems, such as those made by Pentek.

We have listed the input bandwidth in this table to highlight the importance of these A/Ds in direct IF sampling applications, also known as undersampling.

In the next section, we’ll discuss in some detail the principles and rules of sampling.
Appendix A: High-Speed A/D Converters

Direct Baseband RF Signal Acquisition

- Antenna signals are usually in the microvolt range
- RF amplifier boosts signal to full scale input voltage of the A/D - usually 0 to +10 dBm
- RF amplifier often includes a tuned bandpass filter centered on the signal of interest
- No analog frequency translation before the A/D
- Appropriate for HF signal frequencies (3 - 30 MHz)

In the case where the antenna signal frequency is too high to be digitized directly by the A/D converter, it has to be translated down using an analog mixer and local oscillator.

The top diagram shows a simplified representation of this analog translation to baseband with a low pass filter following the mixer.

The bottom diagram shows the translation to an intermediate frequency or IF — this is quite common. In this case, the filter is a bandpass filter centered at the IF frequency.

So far, we’ve discussed three types of front-end circuitry:

1) Direct sampling with no translation
2) Analog translation to baseband
3) Analog translation to IF

But how do we design the filters in each case?

Let’s go back to review some fundamental sampling theory.

Most receiver systems start with a signal originating from an antenna that’s often in the microvolt level, so it must first be amplified by an RF amplifier stage.

The amplifier is usually a tuned RF circuit which only passes the frequency band of interest, providing signal gain within that band and rejecting noise and unwanted signals in adjacent frequency bands.

If the RF input signal is at a low enough frequency, it can be digitized directly by an A/D converter, and no analog translation is necessary.

For example, you can usually perform direct baseband sampling on HF signals with no translation required, since the frequency content is below 30 MHz.
Filtering Helps Avoid Noise and Aliasing

- In all systems, the A/D input must be filtered for two important reasons:
  - Eliminate out of band noise
  - Eliminate aliasing
- Nyquist sampling theorem requires the input signal bandwidth must be less than one-half the sampling rate of the A/D converter
- Some systems (like an IF stage) provide inherent bandlimiting before the A/D
- Fundamental Sampling Modes
  - Baseband Wideband Sampling
  - Baseband Pre-select Sampling
  - Undersampling

Filters ahead of the A/D are needed primarily for two reasons: to eliminate out-of-band noise and to eliminate out-of-band signals that can cause aliasing.

Nyquist tells us that whenever you sample a signal with an A/D, the bandwidth of that signal must be less than half the sampling frequency of the A/D.

Filters help us guarantee that this rule is met. Sometimes the bandwidth is already limited by the signal source, like the output of an IF stage that takes advantage of the IF filter bandwidth. But each case has to be analyzed individually.

The design of the filter is also critically linked to the sampling mode. Here we’ve listed three fundamental sampling modes:

1) Baseband **Wideband** sampling
2) Baseband **Pre-select** sampling
3) **Undersampling**, which is also sometimes called subsampling

To help you get a feel for the filter requirements of each mode, we present a convenient tool for analyzing the effects of sampling in the frequency domain.

Fan-fold Paper Model to Visualize Sampling

This simple technique has been very useful to our customers and our own applications engineers to help them understand what happens during sampling.

Imagine that we have a stack of the old fan-fold computer printer paper but with transparent sheets.

Now, we assign the frequency axis along the bottom edge of this paper, scaled so that multiples of the sampling frequency line up with the backward folds of the paper, as shown.

Using that frequency scale, we plot out the spectrum of the signal we want to sample with amplitude plotted on the vertical axis.
Fan-fold Paper Model to Visualize Sampling

- Now collapse the stack of transparent fan-fold paper and look through all the sheets.
- This represents how sampling “folds” the entire RF input spectrum into a single page from 0 to Fs/2.
- Once aliasing occurs, there is no way to undo it.

![Diagram](image1)

Now, let’s collapse the stack of transparent paper flat together and hold the stack up to a light so we can see through all the sheets.

We are now looking at the frequency plot of the sampled signal at the output of the A/D converter.

Notice that we’ve lost a lot of information because we can’t tell which sheet a particular signal is on. And, unfortunately, after sampling that information is lost forever.

We’ve also contaminated any particular signal with signals from other sheets which have folded on top of it.

Not only that, we’ve also folded the noise from all the sheets so they pile up in the region between DC and the half sampling rate, potentially ruining the signal to noise ratio.

How do we avoid this mess in each of the three sampling modes?

Baseband Sampling of Wideband Signals

- For baseband signals over a wide frequency range, use a low pass filter with cutoff frequency, Fc, less than Fs/2, where Fs is the A/D sample rate.
- After sampling, only the baseband signal is captured, eliminating folding of aliased signals and noise.

![Diagram](image2)

For the baseband **wideband** sampling mode, where we want to look at everything from DC up to a frequency below the half sampling rate, we can install a low pass filter with a cutoff frequency, Fc, located below Fs/2.

The frequency response of the filter is shown in green.

Now, all of the out-of-band signals and noise on the pages above Fs/2 are eliminated so that when the folding occurs, it doesn’t corrupt the baseband signal.
For the baseband preselect sampling mode, we need to use a bandpass filter with the frequency response shown in green.

We get the same benefits as the previous case for out-of-band signals and noise above Fs/2, but more importantly, we can keep large adjacent signals like the one shown, from getting to the A/D converter.

The reason for this is that if the large unwanted signal gets through to the A/D converter, it uses up its dynamic range.

For applications where there are known, strong unwanted signals, this technique can be extremely useful in improving the signal-to-noise ratio of the smaller signal of interest.

The third sampling mode, called undersampling or subsampling, is ideal for many systems that use an analog RF translator front end. These receivers usually deliver IF outputs, often at 21.4 or 70 MHz, with bandwidths ranging from a few kilohertz to tens of MHz—depending on the receiver.

If we wanted to perform baseband sampling on a 70 MHz signal, we would have to choose a sampling rate of well over 140 MHz. This may require an A/D that adds significant cost and power to the system.

However, because the IF signal is inherently bandlimited, we can take advantage of the folding caused by sampling and use a lower frequency A/D.

This is a little tricky since you have to carefully choose the sampling frequency and filtering according to the signal frequency and bandwidth.

Let’s see how.
The fan-fold paper really comes in handy here.

First, design a bandpass filter that rejects unwanted signals and noise.

This is often fully satisfied by the standard IF filter in the RF translator, but you do have to check this.

Sharper filters add cost and maintenance but they do let you get away with a lower sampling rate as we’ll see in the next figure.

Second (top of next column), choose a sampling frequency so that the passband of the filter, along with its skirts, falls entirely on a single page of fan fold paper.

There are many possible solutions to each case, so you have to pick the one that works best. You may have to go back and forth a few times to readjust the filter and sampling rate to get the best scheme.

Here are some tradeoffs to consider:

With a higher sampling rate, the pages are wider and the filter becomes less complex. Also, there is a lower noise density folded into the 0 to Fs/2 band after sampling.

At higher sampling rates, however, the A/D is more expensive and the number of bits of accuracy drops off.

You also need to be sure that the A/D has a good wideband input stage to handle the IF signal with minimum distortion.

Equally important is the aperture uncertainty or phase jitter of the sample-and-hold amplifier, which is usually part of the A/D.

To make this job easier, many A/D converters are now specifically characterized to operate in undersampling applications.
Appendix A: High-Speed A/D Converters

Undersampling Performs Frequency Translation

- Signal of interest folds into the 0 to Fs/2 region
- Undersampling performs an automatic frequency translation
- Translated image may be reversed in frequency depending on which side of the “fold” the input falls

Guidelines for Sampling and Undersampling

- Use the fan fold paper to validate your sampling plan for the characteristics of your input signal
- Carefully evaluate A/D specifications for operation in the undersampling mode
- Ensure low-noise, wideband circuitry in the front end ahead of the A/D
- Transforming coupling often is superior to an amplifier for IF or RF input signals
- Eliminate as many out-of-band signals and noise as possible, since they will fold
- Ensure the the sample clock is clean with low phase noise and jitter

The effect of undersampling, as you probably expected by now, is that the IF signal is folded down to the first page. This is really an automatic frequency translation, performed for free by the sampling process.

For the signals on every odd numbered sheet, the effect is a frequency translation by a multiple of Fs. For the signals on even numbered sheets, there is a reversal of the frequency axis on that sheet, followed by a translation by an odd multiple of Fs/2. Again, this is much easier to follow by visualizing the fan-fold model.

This undersampling technique is extremely popular in software radio systems which almost always follow the A/D converter with a DDC (digital downconverter).

Regardless of where the undersampling folding process translated the signal of interest, the DDC can translate it down to 0 Hz as a complex baseband signal. Once the complex signal is at baseband, the reversal of the frequency axis is easily undone by simply changing the sign of the Q component.

There are usually several different sample clock frequencies that will work for undersampling. While the fan-fold paper model can show all of the correct frequency plans, the best choice will usually be determined by several other important practical considerations shown above.

Some A/D converters are specifically characterized for undersampling applications, while others are designed only for baseband sampling. Make sure to verify the specifications.

Noise and distortion of the input signal must be minimized so these components don’t fold into the sampled signal. Special care must be taken to preserve the purity of the sample clock signal.

Undersampling can be an extremely valuable tool for software radio applications, since it can eliminate at least one additional stage of analog frequency translation and simplify system design.

Undersampling allows you to use an A/D converter with a lower sampling rate, which usually means more bits of resolution and better dynamic range. This lower sample rate also reduces the cost and complexity of the next stage of digital signal processing, recording, storage, or transmission.
Switched Serial Gigabit Interfaces - Why?

- Too many different I/O technologies per system
  - FPDP, PCI, VME, Ethernet, RS-232, FibreChannel, SCSI, PMC, IP, 1553, LVDS, ATM, etc.
- Bus backplanes are major data bottlenecks
  - All boards must share a common bus, one at a time!
- Parallel switched fabrics are expensive
  - RACEWay was controlled by one vendor
- Cabling increases system cost and complicates maintenance
  - Cables and connectors can be a major factor in MTBF
- Software upgrades are difficult for specialized interfaces
  - Performance goals require software tuning of signal paths
- Need a better solution for moving data!
  - Fast, flexible, open, and inexpensive

The VMEbus still serves as the dominant bus structure for high-performance real-time embedded systems. As requirements grew following its introduction, VME acquired new interfaces such as VSB, RACEway, RACE++, VME64 et al. that provided improved performance.

All these different I/O technologies caused new problems with backplanes creating data bottlenecks and interfaces controlled by one vendor. System costs increased due to cabling, maintenance and software upgrades. A better solution for moving data was needed and it had to be fast, flexible, and inexpensive.

The answer turned out to be Switched Serial Gigabit Interfaces.

High-Speed Switched Serial Interfaces

- Gigabit links send data over a pair of wires using differential signaling
- Sequential 1s and 0s are sent over the pair of wires at a fixed bit rate
  - Popular serial rates: 10 MHz, 100 MHz, 1 GHz, 2.5 GHz, 3.125 GHz, etc.
- The clock, data, and data word framing are encoded into the serial bits stream, typically using 8b/10b coding:
  - 10 bits of serial transmission are required to deliver 8 bits of data
  - Extra 2 bits maintain synchronization, framing and DC line balance
- SERDES - Serializer / Deserializer
  - Serializer: Encodes clock, frame, and 8 bits of data into a 10-bit stream
  - Deserializer: Decodes clock, frame and 8 bits of data from a 10-bit stream
  - Usually combined into one device for full duplex operation

A switched serial fabric system connects devices together to support multiple simultaneous data transfers, usually implemented with a crossbar switch. Using differential signaling, data is sent over a pair of wires at a fixed bit rate such as 100 MHz, 1 GHz, 2.5 GHz, 3.125 GHz, etc.

The clock, data, and data word framing are encoded into the serial stream, usually with 8b/10b coding. Ten bits of serial transmission deliver eight bits of data. The extra two bits maintain synchronization, framing and DC line balance.

The Serializer shown above encodes clock, frame, and eight bits of data into a 10-bit stream. The Deserializer decodes the 10-bit stream into clock, frame, and eight bits of data. These two functions are usually combined into one device for full duplex operation, known as the SERDES (SERializer/DESerializer).
Appendix B: Switched Serial Fabrics

Gigabit Serial Data Rates

Gigabit Serial Transfer Rates Depend On:
- Serial clock frequency (serial bit rate)
- Number of bit “lanes” ganged together (e.g. 4X = 4 bit lanes)
- Physical layer encoding overhead, e.g. 8b/10b: 80% efficiency
- Peak Rate (MB/sec) = (Serial Rate x Lanes x 80%) / (8 bits per byte)
  = (Serial Rate x Lanes) / 10

<table>
<thead>
<tr>
<th>Bit Clock</th>
<th>1X</th>
<th>4X</th>
<th>8X</th>
<th>16X</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 GHz</td>
<td>100 MB/sec</td>
<td>400 MB/sec</td>
<td>800 MB/sec</td>
<td>1.6 GB/sec</td>
</tr>
<tr>
<td>2.5 GHz</td>
<td>250 MB/sec</td>
<td>1.0 GB/sec</td>
<td>2.0 GB/sec</td>
<td>4.0 GB/sec</td>
</tr>
<tr>
<td>3.125 GHz</td>
<td>312 MB/sec</td>
<td>1.25 GB/sec</td>
<td>2.5 GB/sec</td>
<td>5.0 GB/sec</td>
</tr>
<tr>
<td>5.0 GHz</td>
<td>500 MB/sec</td>
<td>2.0 GB/sec</td>
<td>4.0 GB/sec</td>
<td>8.0 GB/sec</td>
</tr>
<tr>
<td>10.0 GHz</td>
<td>1.0 GHz/sec</td>
<td>4.0 GHz/sec</td>
<td>8.0 GB/sec</td>
<td>16.0 GB/sec</td>
</tr>
</tbody>
</table>

Figure 46

The raw speed of serial fabrics is governed by three factors:

The serial bit clock frequency; the channel coding efficiency; and the number of lanes or parallel bit streams ganged together in the interface.

The table above shows the peak transfer rates for each lane width with 1, 2.5, 3.125, 5.0 and 10 GHz bit clocks. Since there are 8 bits per byte, the peak rate expressed in MB/sec becomes the serial rate expressed in GHz, times the number of lanes, divided by 10.

For example, for PCI Express Gen. 2.0 that uses 8b/10b coding (80% efficiency) with eight-bit lanes or x8, the peak transfer rate in each direction is the serial bit clock of (5.0 GHz * 8 lanes) / 10 = 4.0 GB/sec.

PCI Express Gen. 3.0 uses an 8.0 GHz bit clock and changes the coding from 8b/10b to 128b/130b thereby improving the coding efficiency from 80% to 98.46%. Using the same example as before, the peak transfer rate for Gen.3 is almost 8.0 GB/sec (7.877 GB/sec to be exact).

Of course, there is some additional overhead in the packet protocols, some of which are presented next.

Popular Gigabit Serial Protocols

Xilinx offers a simple link layer protocol IP core engine called Aurora that interfaces with the RocketIO gigabit serial physical layer interfaces available in the Virtex-II Pro family.

Altera supports its Stratix GX Multi-Gigabit Transceivers with the SerialLite link layer protocol as well as full implementations of switched fabric IP cores.

The nice thing about this strategy is that you can design and build FPGA-based hardware products that adapt to different fabrics, depending on the protocol IP core you install.

VITA 49 is a radio transport protocol for SDR (Software Defined Radio) architectures that enables interoperability between diverse SDR components from different vendors

PCI Express is Intel’s initiative for connectivity between processors and boards in personal computers and workstations. It’s been used extensively to improve performance of graphics boards in Windows computers.

RapidIO is a packet-switched fabric targeted for embedded computer component vendors and system integrators. It addresses the needs of real-time computing at several levels.
Appendix B: Switched Serial Fabrics

Dedicated Point-to-Point Serial Links

- Dedicated Hardwired Connections
  - Paths are based on particular application requirements
  - Paths set up during system integration with cables or fixed wiring
  - Applications: Aurora, VITA 49, PCI Express, Serial RapidIO

The first type of serial links is the dedicated point-to-point link. As its name implies, it utilizes dedicated hardware connections and its paths are based on the requirements of the particular application. The paths are set up during system integration and utilize cables or fixed wiring.

Applications that utilize dedicated point-to-point serial links include those that are running Aurora, VITA 49, PCI Express and RapidIO.

Manually-Switched Point-to-Point Links

- Software Configurable “Protocol Transparent” Switch
  - Switch paths are changed in hardware “manually” by a control processor
  - Paths can be changed during initialization and during runtime
  - Switch is transparent to the serial protocol
  - Switch supports virtually all gigabit serial links
  - Applications: Aurora, VITA 49, PCI Express, Serial RapidIO
  - Switching Scheme for Pentek 4207

Next in line are manually-switched point-to-point serial links. Think of them as “protocol transparent” switches that are software configurable. In this case the switch paths are changed in the hardware “manually” by a control processor that directs the traffic. They can be changed during system initialization and during runtime.

This switch supports virtually all gigabit serial links and it’s transparent to the serial protocol. It can be used in applications running Aurora, VITA 49, PCI Express and Serial RapidIO.
Appendix B: Switched Serial Fabrics

Memory-Mapped Serial Links

- One system processor establishes memory map for all devices
  - This function is known as the “root complex”
- Switches or bridges implement defined memory mapped connections
- Supports multiple “initiators” and multiple “targets”
- Arbitration is done through token passing
- Does not provide automatic re-routing
- Example: PCI Express

Memory-mapped serial links are based on a memory map that’s established by a system processor.

The defined memory-mapped connections are implemented with hardware switches or bridges.

This type of link supports multiple “initiators” and multiple “targets”. Arbitration is done through token passing and automatic rerouting is not supported.

A protocol example that uses this link is PCI Express.

Packet-Switched Serial Links

- Switched “fabric” protocol uses data packets that include:
  - Header information to identify source, destination, packet type, data size, time stamp, sequence number, and priority
  - Data “payload”
  - Footer information for checksum and end of packet marker
- Intelligent switch evaluates packet header to determine routing
- Automatic re-routing through alternate switch paths avoid conflicts
- Packets and Switch are unique and dedicated to a particular protocol
- Supports multiple processors
- Example: Serial RapidIO

Packet-switched serial links utilize a switched fabric protocol that uses data packets. Each data packet includes:

- A header that provides information to identify the source, destination, packet type, data size, time stamp, sequence number and priority
- The data “payload” which contains the actual data
- A footer with checksum and end of packet marker information

This intelligent switch evaluates packet header information to determine the routing. Automatic rerouting through alternate paths avoids conflicts. The packets and the switch support multiple processors. They are unique and dedicated to a particular protocol.

Applications running Serial RapidIO can utilize this packet-switched fabric.
## Appendix B: Switched Serial Fabrics

### Comparison of Serial Links

<table>
<thead>
<tr>
<th></th>
<th>Dedicated Point-to-Point</th>
<th>Manually Switched Point-to-Point</th>
<th>Memory Mapped Fabric</th>
<th>Packet Switched Fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software Reconfigurable Paths</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Self-Routing Packets</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Automatic Path Re-Routing</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Packet Overhead Required</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
<td>High</td>
</tr>
<tr>
<td>Payload Data Efficiency</td>
<td>High</td>
<td>High</td>
<td>Med</td>
<td>Low</td>
</tr>
<tr>
<td>Software Driver Complexity</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
<td>High</td>
</tr>
<tr>
<td>FPGA Interface Complexity</td>
<td>Low</td>
<td>Low</td>
<td>Med</td>
<td>High</td>
</tr>
<tr>
<td>Protocol Transparent</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Protocols Supported</td>
<td>Aurora VITA 49 PCIe Srio</td>
<td>Aurora VITA 49 PCIe Srio</td>
<td>PCIe</td>
<td>Srio</td>
</tr>
</tbody>
</table>

*Figure 52*

This table provides a side-by-side comparison of the four types of serial links we discussed in the previous pages and summarizes their main properties and supported protocols. It can help the system designer narrow down the available links and protocols when evaluating the requirements of a proposed high-speed embedded system.
Appendix B: Switched Serial Fabrics

PCI Express Interface

Introduced by Intel in 2004, PCIe (PCI Express) is a bidirectional serial link capable of high-bandwidth data transfers. Designed to replace the more limited PCI expansion bus, PCI Express supports enhanced features such as power management, hot-swappable devices, and has the ability to handle both host-directed and peer-to-peer data transfers. PCI Express can also emulate network environments by sending data between two points without routing it back and forth through the host chip.

Enabling greater bandwidth and performance, PCI Express helps simplify board design and is scalable for future increases in processor speeds and advances in high-performance computing and embedded systems.

Upgraded in 2007, PCI Express 2.0 doubled the data transfer rate over its predecessor for a transfer rate of up to 4.0 GB/sec for an x8 PCIe channel. Providing backwards compatibility with version 1.0, PCIe 2.0 provides scalable performance, higher bandwidth, lower overhead and lower latency data transfers.

PCI Express 3.0 upgrades the encoding scheme to 128b/130b from the previous 8b/10b, reducing the overhead to approximately 1.54% ((130-128)/130), as opposed to the 20% of PCIe 2.0. PCIe 3.0 doubles PCIe 2.0 peak transfer rate from 4.0 GB/sec to 8.0 GB/sec for an x8 PCIe channel.

Conceptually, the PCIe bus can be thought of as a ‘high-speed serial replacement’ of the older parallel PCI/PCI-X bus. At the software level, PCIe preserves compatibility with PCI: a PCIe device can be configured and used in legacy applications and operating systems which have no direct knowledge of PCIe’s newer features. In terms of bus protocol, PCIe communication utilizes point-to-point switched serial links.

If you bought a desktop PC with Windows OS in the last few of years, it most likely came with a PCIe graphics card.

This development led to the rapid acceptance of PCIe at the consumer level, as the only bus that could accommodate increasingly faster graphics speeds. The high-bandwidth PCIe interface and fast dedicated graphics board memory made the better PC graphics possible.

Inside a PCI Express PC

Looking inside a desktop PCIe PC we see the familiar motherboard, part of which is shown in the above photograph. At the top of the photo, we see the familiar PCI connectors where you’d find most of the legacy PCI expansion cards, such as 100BaseT Ethernet or sound.

Next to these PCI connectors are two small x1 PCIe connectors and at the bottom of the photograph we see a PCIe x16 connector. This is where the video card would plug in.

A PCIe card will fit into a slot of its physical size or bigger. It will not fit into a smaller PCIe slot. Some slots use open-ended sockets to permit physically longer cards and will negotiate the best available electrical connection. The number of lanes actually connected to a slot may also be less than the number supported by the physical slot size. An example is an x8 slot that actually only runs at x1; these slots will allow any x1, x2, x4 or x8 card to be used, though only running at the x1 speed. The advantage gained is that a larger range of PCIe cards can still be used without requiring the motherboard hardware to support the full transfer rate, thereby keeping design and implementation costs down.
Serial ATA (SATA or Serial Advanced Technology Attachment) is a computer bus interface for connecting host bus adapters to mass storage devices such as hard disk or optical drives. Serial ATA was designed to replace the older ATA standard (also known as EIDE), offering several advantages over the older parallel ATA interface: reduced cable-bulk and cost (7 conductors versus 40), native hot swapping, faster data transfer through higher signalling rates, and more efficient transfer through an optional I/O queuing protocol.

SATA host-adapters and devices communicate via a high-speed serial cable over two pairs of conductors. In contrast, parallel ATA (the redesignation for the legacy ATA specifications) used a 16-bit wide data bus with many additional support and control signals, all operating at much lower frequency. To ensure backward compatibility with legacy ATA software and applications, SATA uses the same basic ATA command-set as legacy ATA devices.

As of 2010, SATA has replaced parallel ATA in most shipping consumer desktop and laptop computers, and is expected to eventually replace it in embedded applications where space and cost are important factors.