Advances in Antenna Measurement Instrumentation and Systems

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***Abstract*— Since the early days of antenna pattern recorders, advances in instrumentation and computers have enabled measurement systems to become highly automated and much more capable providing higher productivity, more efficient use of test facilities, and reduced data acquisition time.**

Recently, measurement speeds of microwave receivers and vector network analyzers have advanced considerably. To take full advantage of these speed improvements, the measurement system architecture must be carefully considered. A comparison of several system architectures is given, along with discussion of key concepts and parameters that affect system timing, and a general method of calculating overall test time.

A summary table illustrates that small timing differences due to instrumentation and system architecture can have a significant impact on overall test time.

Further advances in system throughput are being explored using techniques such as simultaneous multi-frequency measurements in conjunction with a narrowband or wide band Receiver. A brief description of these techniques and initial proof of concept results are included.

Keywords-automated system, measurement speed, measurement time, timing, productivity

I. INTRODUCTION

As automated antenna measurement system architectures have evolved, workstations have primarily controlled instrumentation using industry standard protocols such as GPIB and Ethernet. However, both have constraints that may limit the speed of an antenna measurement system [1]. To overcome these limitations, hybrid architectures have been developed that include hardware triggering and parallel digital interfaces. Typically GPIB or Ethernet is used to set up instruments prior to an acquisition, and the other interfaces are used to accomplish real-time signaling between instruments and high speed data transfer. The methods used to implement this concept vary, and the total amount of time required to test an antenna can be quite different depending on the system architecture and the capabilities of the instrumentation.

II. DATA ACQUISITION OVERVIEW

For an automated antenna measurement system, measurements are typically made on an evenly spaced position grid. Data is collected while the scan axis is moving, and the step axis is moved between scans. In recent developments [1], the measurement grid is not evenly spaced and/or multiple axes move simultaneously, but the acquisition process is similar. Position Triggers must be generated on the desired measurement grid to indicate when measurements are to be made. Other instruments, such as a Receiver, respond to these triggers to initiate a measurement that later becomes a point on a plot. Position Triggers occurring at 1 degree spacing are illustrated below in Figure 1.

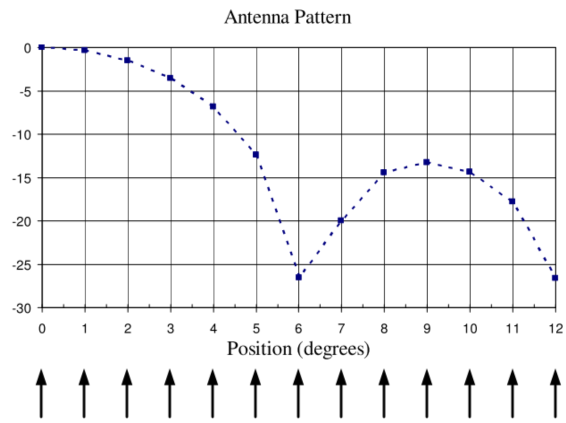

Figure 1. Position Triggers on Scan Axis

For the simplest case, the Receiver may make only one measurement as a result of each position trigger. However, for multi-channel, multi-frequency tests, many measurements may be performed as a result of a single position trigger. Using an RF multiplexer, channels must be sequentially selected and the Receiver must make a separate measurement for each one. For multi-frequency measurements, signal sources must be triggered to change frequencies and the system must wait for the RF output of the signal source to settle to the new frequency. The Receiver must make one or more measurements per frequency. The number of measurements required can multiply quickly, and system timing, including data transfer, becomes critical to overall measurement time.

III. SYSTEM ARCHITECTURES

To discuss various types of system architectures, it is useful to divide the instrumentation into four subsystems:

- Transmit subsystem – Provides the stimulus for the test, typically a transmit signal source
- Receive subsystem – measures the RF response of the system
- Position Control subsystem – controls motion of axes, provides position triggering and position measurement data

- Data Acquisition and Analysis – primary user interface, configures instruments, collects the measured data, runs analyses, and provides output plots or analysis results

These four subsystems are shown in Figure 2 along with the trigger signals and data paths typically required for one type of system architecture.

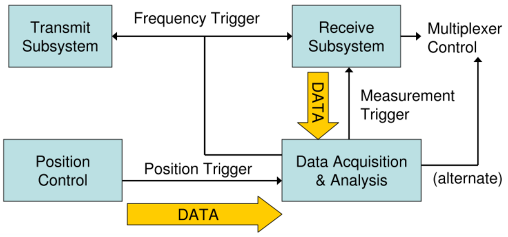

Figure 2. Typical System

This architecture shows a central Data Acquisition and Analysis subsystem that communicates with all of the other subsystems, receiving and generating trigger signals and collecting the data as required. The Multiplexer control may be performed by the Receive Subsystem or the Data Acquisition Subsystem, depending on the capabilities of the specific instrumentation. The Position Trigger indicates the need to make measurements, the Measurement Trigger signals the Receive Subsystem to take 1 or more channels of data, and the Frequency Trigger causes the Transmit and Receive Subsystems to step to the next frequency in the list.

This system architecture may be implemented in several different ways. In older systems, the GPIB interface may be used for everything, including triggering and reading data from the devices. All of these transactions are funneled through a single shared interface and all activity is sequential. The timing overhead associated with this can be significant, resulting in errors and/or long measurement times.

As an example, note that any fixed or variable delays in the position detection and triggering process result in data skewing that can produce errors in the Scan Axis proportional to its speed. Figure 3 illustrates the data flow necessary for the Workstation to detect a Position Trigger, and then trigger the Receiver using GPIB. This approach can result in milliseconds of time delays. For a scan axis moving at 3 RPM, 6 milliseconds of delay can result in a 0.1 degree error.

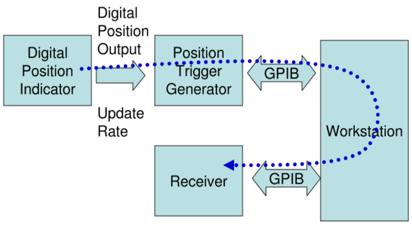

Figure 3. Position Triggering using GPIB

For multi-channel and multi-frequency measurements, the multiplexer and frequency switching processes must also be performed between Receiver measurements. Detecting the proper time, and triggering the appropriate device using only GPIB or Ethernet, results in a slow measurement system.

To create a faster measurement system, two primary features are needed to supplement GPIB or Ethernet: (1) Data Buffering, (2) Hardware Triggering.

Data buffering may be centralized or distributed. In a centralized architecture, data buffering is provided by the Data Acquisition and Analysis subsystem (see Figure 4), and the data paths from subsystems must be high speed. For example, the MI-2097 Automated Antenna Measurement System by MI Technologies uses high speed parallel digital interfaces from instruments to the Data Acquisition Coprocessor (DAC), and the DAC provides the buffering function.

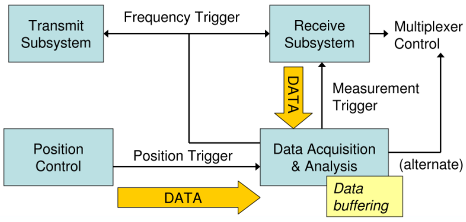

Figure 4. Centralized Data Buffering

In a distributed data buffering architecture (see Figure 5), buffering is included in each subsystem that provides measured data, and the high speed parallel interfaces can be eliminated. Each instrument collects a measurement point when triggered and stores it in a buffer. Hardware triggers determine when measurements are made, but the data is not required to be transferred immediately for each measurement. Several measurements can be completed before being transferred in blocks to the Data Acquisition and Analysis subsystem. To use this approach, buffering is required in the Receive subsystem and may also be required in the Position Control subsystem if real-time position measurements are required. (Note that if position triggers are generated precisely enough, real-time position measurements may not be required.)

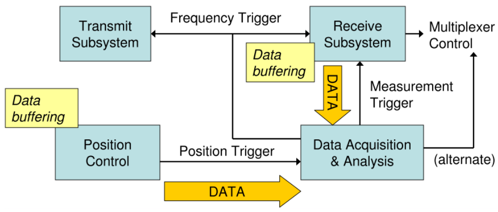

Figure 5. Distributed Data Buffering

With distributed data buffering, the Data Acquisition and Analysis subsystem can collect large blocks of data from each instrument under less stringent time constraints than with a centralized architecture. Ethernet is well-suited for this task and may already be implemented in the system as the standard interface to configure instrumentation. In this case, the high speed interfaces required for data transfer are simply eliminated.

Hardware triggering, typically implemented using a digital signal through a coaxial cable, may also be centralized or distributed. Centralized triggering requires a real-time control device, such as the DAC, that can receive and generate triggers to control the measurement sequence. Distributed triggering requires no central device. Triggers are generated in one instrument and transmitted directly to another. Distributed triggering can only be implemented to the extent the appropriate trigger and response mechanisms are built into the instrumentation.

Some systems based on vector network analyzers (VNA's) use a fully or partially distributed triggering system. Many VNAs accept an external hardware trigger to initiate a measurement sequence that can consist of single or multiple frequencies. A simple system can be designed by connecting the Position Trigger output of the Position Control subsystem to the trigger input of the VNA. The system workstation can then read data from the VNA.

More complex VNA-based systems may require remote mixing, remote sources, multiple channels, and data buffering. Although the VNA may have multiple input channels, multiplexers are frequently used instead to reduce the number of RF cables in the system [1]. VNA's do not typically control multiplexers directly, so an external device, such as the MI-788 Networked Acquisition Controller (NAC) by MI Technologies may be used to control the data acquisition sequence instead. The NAC can synchronize the control of multiplexers with the VNA measurement sequence, control frequency switching for remote sources, and generate or accept Position Triggers. The system is now implemented as a centralized triggering system, which provides the fastest acquisition time with the most flexibility for a VNA-Based System.

One way of implementing a fully distributed triggering system is to build additional capability into the Receiver. The Receiver must accept a Position Trigger as an input, control the multiplexers directly, and issue the Frequency Trigger to the signal sources when needed. With these capabilities, no centralized control device is needed unless additional capabilities are required (such as an interface to a beam steering controller). A distributed triggering solution can be less expensive by reducing the number of instruments required.

Hardware triggering requires additional cables in the system to interconnect the instruments. A Trigger Bus has been developed to simplify system cabling, improve signal integrity, and reduce cost. A single Trigger Bus cable containing 4 differential signals is connected to each instrument in the system, and each is programmed to drive or receive signals over the Trigger Bus. The resulting system architecture shown in Figure 6 supports both distributed triggering and distributed buffering.

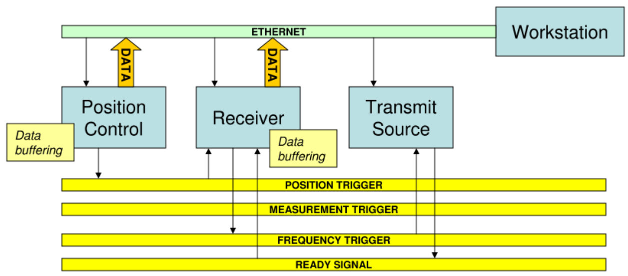

Figure 6. System Architecture with Trigger Bus

Many data acquisition needs are fully supported with this architecture without the need for a separate real-time data acquisition controller. The Workstation sets up each instrument for the acquisition, the instruments communicate the real-time signals through the Trigger Bus and buffer measured data, and the Workstation efficiently reads the buffered data over Ethernet without the real-time constraints of other architectures. If additional capability is needed, the Trigger Bus architecture is flexible enough to support it.

IV. System Timing Concepts

Many factors affect the time that is required to completely characterize an antenna such as the spatial range to be measured, the density (spacing) of measurements, the number of frequencies, and the number of channels.

For simple acquisitions with minimal data collection, the maximum speed of the scan axis can be the limiting factor. Antenna positioners are typically designed for high accuracy, implying heavy, stiff designs. Typical rotary scan axis speeds are up to 3 RPM, but can be much slower for large positioners. If measurement requirements are not strenuous, the positioner may run at full speed with plenty of time to spare. For example, if a single frequency, single channel measurement is to be made with a 1 degree spacing at 3 RPM, 1 measurement is required every 55 milliseconds. The system architecture and speed of the instrumentation is not critical – almost any architecture discussed would work.

For more complex acquisitions, the timing parameters of the instrumentation can have a dramatic influence on the total measurement time. The key system timing contributors from the instrumentation are: (1) Receiver measurement speed, (2) Multiplexer switching speed, (3) Signal Source frequency switching speed, and (4) Timing overheads.

Receiver measurement speed sets the fundamental maximum speed of the instrumentation system. The speed of the Receiver is proportional to its IF Bandwidth and inversely proportional to its sensitivity. Higher speed measurements mean a higher noise floor. A tradeoff between the two must be made to maximize system speed while maintaining adequate measurement accuracy. As an example, the MI-750 Receiver sensitivity vs. sample rate is shown in Figure 7. For this example, the measurement time ranges from 0.25 microseconds to 1 second.

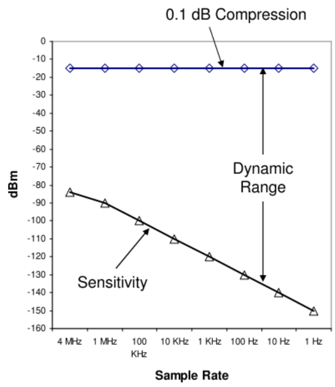

Figure 7. Receiver Sensitivity vs. Sample Rate

The test engineer should select the minimum Receiver sensitivity needed to provide sufficient signal to noise ratio for the level of accuracy required at lower signal levels. For example, if system measurement accuracy is defined for the first side lobe level or the depth of a null, the test engineer may allocate a portion of the system error to the signal to noise ratio of the Receiver. This can be used to define the minimum Receiver sensitivity. Once this is settled, the Receiver IF Bandwidth is defined and the measurement time can be determined. Multiplexers are a practical way to provide sequentially measured channels. The switching speed of the multiplexer is small, typically falling in the range of 0.1 to 1 microsecond.

Making multi-frequency measurements during every scan of an axis can provide tremendous gains in range productivity. But switching frequencies requires time during which measurements cannot be made. Frequency switching times are applicable to the transmit source used as the test stimulus as well as the LO source used to tune a Receiver or VNA. Since these two sources can usually be switched simultaneously, only the slower of the two devices needs to be considered for system timing. Signal sources used for antenna measurements typically have switching times in the range of 0.1 to 1.5 milliseconds. Older sources may take 10 milliseconds or longer, and some systems use more expensive very high speed switching sources that switch in less than 1 microsecond.

Timing overheads are sometimes assumed to be zero, but in many cases, they cannot be overlooked. These overheads generally fall into one of four categories: (1) Overhead per position trigger, (2) Overhead per measurement, (3) Overhead per frequency trigger, (4) Overhead per frequency sweep.

Position trigger detection using GPIB or Ethernet can take 1 to 30 milliseconds, depending on implementation. This time delay is treated as an overhead associated with each position trigger. Hardware triggering can be implemented in ways that effectively have zero overhead, but some implementations may incur a few microseconds of latency.

Each measurement requires that the Receiver has time to complete its sample of the incoming RF signal and process it. In addition, some overhead time may be required to trigger the Receiver or to read the data from it.

If hardware triggering is not used, it can take 0.5 to 10 milliseconds to send a command over GPIB or Ethernet to the Receiver to begin its measurement. Hardware triggering effectively removes this overhead.

Without data buffering, each trigger results in a set of measured points that must be read from the Receiver or VNA. Reading each point over GPIB or Ethernet can take 1 to 5 milliseconds for some instruments. Parallel digital interfaces take minimal time that can be ignored. With data buffering, measurements can continue before the data is read, so the overhead is effectively eliminated. However, buffering can be tricky to implement with some instruments [1]. Raw measurement speed is important, but it can be overshadowed by how the data must be read from the device.

Frequency trigger overheads can be effectively zero by using both a hardware trigger signal and a hardware lock signal (frequency change complete). Otherwise, sending frequency change commands over GPIB or Ethernet can take 0.5 to 10 milliseconds, and without a hardware lock line, fixed delays must be assumed, adding 0.1 to 0.5 milliseconds to the frequency change time.

Some vector network analyzers have delays associated with each frequency sweep. These are due to retrace time and display updates that can take 0.25 to 10 milliseconds [1]. Display updates can sometimes be disabled to keep the overhead to a minimum. Standalone signal sources usually do not have these delays.

V. System Timing Calculations

System timing can be estimated based on all of the factors previously described. Acquisitions are usually conducted as a series of nested loops, with multi-channel Receiver measurements being the innermost loop. The frequency change loop is the next higher level, and the position trigger loop is at the top. Assuming that the scan axis speed is not the limiting factor, the time for a single scan can be calculated as shown in Figure 8.

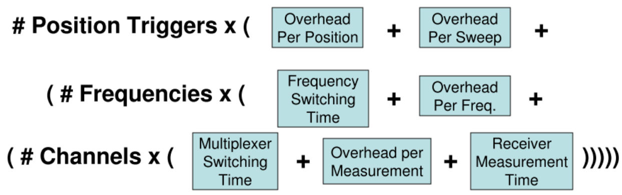

Figure 8. Single Scan Timing Calculation

Exploring some examples will help clarify the impact of various timing parameters. Consider a case with a 0 to 360 degree scan and 0.25 degree spacing between measurements (1440 points). Using 20 frequencies and 4 channels illustrates the impact of multi-frequency and multi-channel timing. Five cases are considered to illustrate the effect of timing overheads. In every case, the following timing parameters are fixed:

- Frequency switching time: 1 millisecond
- Multiplexer switching time: 1 microsecond
- Receiver Measurement time: 100 microseconds

In the first case, all timing overheads are zero. Then 1 millisecond delay is added independently for overhead per position, overhead per frequency, and overhead per measurement. Finally, all overhead delays are included. The results are shown in the Total Scan Time column of Table 1.

Note that any overhead per sweep, such as incurred with some network analyzers, has the same impact as overhead per position, since it is outside the frequency change loop.

Since multiple scans are usually required, the total test time is a multiple of the total scan times shown. In addition, there is usually a step axis that must be moved and there may be some additional time required to set up instruments for the next scan. The total test time calculation is illustrated in Figure 9.

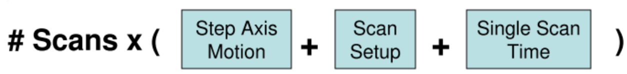

Figure 9. Total Test Time Calculatione

Extending the previous examples, if the step axis is varied from -15 degrees to +15 degrees using a spacing of 0.25 degrees, 121 scans are required. Using 15 seconds for step axis motion plus scan setup time yields the results shown in the Total Test Time column of Table 1

TABLE I. SINGLE SCAN CALCULATIONS

Overhead timing			Total Scan Time	Total Test Time
Per Position	Per Freq.	Per Meas.		
0	0	0	40.4 sec	1.8 hrs
1 mS	0	0	41.9 sec	1.9 hrs
0	1 mS	0	69.2 sec	2.8 hrs
0	0	1 mS	155.6 sec	5.7 hrs
1 mS	1 mS	1 mS	185.9 sec	6.8 hrs

This table illustrates that milliseconds of overhead repeated many times result in hours of lost productivity, especially if they occur in the innermost acquisition loops.

VI. EXAMPLE SYSTEM IMPLEMENTATION

These examples illustrate the need to eliminate overhead delays throughout the acquisition. They show that additional delays in the innermost loop have a greater impact on the total measurement time than delays in the outer loop. Using a fast Receiver with no overhead per measurement has the most impact on reducing single scan time and total test time. Frequency switching time is also a significant factor.

The MI Technologies MI-350 Advanced Microwave Measurement System, (see figure 10), is a system based on these concepts that minimizes all timing overheads, implements hardware triggering using the Trigger bus described in this paper, and uses a fast, flexible measurement Receiver. It uses the strengths of Ethernet for control and buffered data transfer, but provides precise timing communication between instruments through a hardware interface. Basic MI-350 systems can operate without specialized control hardware for data acquisition by using a distributed triggering architecture.

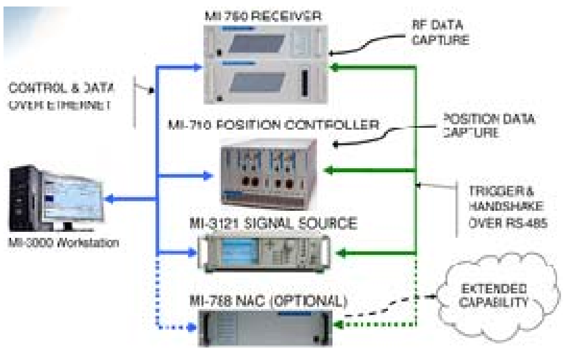

Figure 10. MI-350 Advanced Antenna Measurement System

Extended capabilities, such as beam steering, are optionally provided with additional hardware. This system architecture has the flexibility to support future enhancements as new instruments are developed with advanced capabilities, such as sub-interval position triggering, beam/frequency state tables, and simultaneous multi-frequency measurements.

VII. FURTHER ADVANCES

Further advances in system throughput are being explored by creating multiple frequency channels within the IF bandwidth of a measurement Receiver. The MI-750 Receiver was modified to accept and measure 2 separate frequency channels simultaneously in a proof of concept study [2]. In this study, 2 signal sources transmit slightly different frequencies through the horizontal and vertical polarization ports of a dual-ported probe. Both frequencies are received by the antenna under test and are simultaneously measured by the Receiver. This technique has the advantage of doubling the measurement speed of the Receiver for tests requiring both polarizations, such as near field systems.

With a maximum IF bandwidth of 10 MHz, the MI-750 is classified as a narrowband Receiver. However, a second proof of concept study has been conducted that could lead to a new wideband Receiver based on the MI-750 platform, but with an IF bandwidth of 500 MHz or more. The study conducted measurements of pulse transitions in antennas using IF processing hardware with sample rates of 1.5 GHz. Several other interesting applications could be supported with such a receiver that could significantly impact system timing. Across a wider band, 20 or more frequency channels could be created and measured simultaneously for a 20x improvement in Receiver measurement time. In addition, the frequency switching delays are reduced or eliminated. For frequency ranges wider than 500 MHz, the Receiver and Transmit Source can be tuned to cover multiple 500 MHz bands. Each 500 MHz band requires a frequency switching delay, but the total number of frequency changes is reduced by a factor of 20.

While all of these concepts require further exploration and refinement, the potential for significant gains in measurement speed is high.

VIII. SUMMARY

As measurement system architectures continue to evolve, the factors that affect system measurement times and their significance need to be understood. By paying close attention to small delays and carefully architecting measurement systems, antenna test range productivity can be enhanced. The MI-Technologies MI-350 Advanced Microwave Measurement System combines an efficient trigger bus, distributed buffering and the fastest Receiver on the market to set the standard for the state of the art for highly productive measurement systems.

IX. REFERENCES

[1] Nichols, S., Advanced Antenna Measurement System Architectures, AMTA Proceedings, 2011.

[2] Dygert, R., "Using frequency diversity to improve measurement speed", AMTA Proceedings, 2011.