TIME SPACE COHERENCE INTERFEROMETRY

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ABSTRACT

Streaming SDR (software defined radio) communication receivers are now high performance, common place and cost effective. Yet these receivers are not easily used for antenna measurements for a variety of reasons including their inability to accept phase reference and measurement trigger information. A new technique called Time Space Coherence Interferometry (TSCI) solves this problem in a simple and elegant manner. TSCI combines the concepts of temporal phase coherence with spatial division multiple access (SDMA) to directly encode phase and spatial information into a single continuous receiver data stream. The stream can be recorded for later analysis or efficiently decoded in real time producing conventional spatially sampled S21 amplitude and phase measurements. Additional data including antenna pulse timing, dynamics and signal quality metrics can be extracted from the TSCI data stream. Several representative TSCI systems are described.

Keywords: Near-field measurements, RF data streams, metadata, Software Defined Radio (SDR), interferometer

1. Introduction

Commercially available streaming software defined radios (SDR) provide high quality radio communications using cost effective and versatile technologies. These radios vary over a wide cost and performance range with stream data rates varying from thousands to billions of samples (measurements) per second. Low cost, yet very high performance streaming SDR systems are popular in the amateur radio community. These radios range in cost from less than \$20 to \$5K and provide measurement sample rates up to 25 MSPS. The receiver interface is simple; a single RF input and a single continuous output data stream using analog audio, USB, Ethernet or PCIe. Vector signal analyzers (VSA) are laboratory versions of software defined radios. The VSA generally provides higher sustained sample rates, often in excess of 100 MSPS using multilane PCIe or other high speed streaming interfaces. Typically the SDR or VSA data stream consists of a single side band (SSB) signal in the form of complex I/Q pairs but double sideband (DSB) real value only streams can also be used.

The most commonly available SDR receivers and VSAs do not include an ability to directly produce phase coherent vector S21 transmission measurements as is needed for near-field antenna measurements. In addition, relating S21 measurements in the receiver output stream to spatial measurement locations is not straight-forward as there is no measurement trigger capability. This paper proposes and demonstrates a new technology: "Time Space Coherence Interferometry" (TSCI) that solves both of these problems.

2. Overview

Near-field antenna measurements require a spatially distributed set of vector S21 measurements corresponding to the complex path loss between the test article and field probing antenna [1]. The spatial distribution typically forms a planar, cylindrical or spherical surface. The measurements are made with a robotically scanned microwave interferometer. The microwave interferometer has two independent signal paths, a test path and a reference path. The test path includes the antenna under test and a field probing antenna. The reference path is usually an arbitrary fixed length of coaxial cable. The complex ratio of the antenna test path to the reference path is the desired vector S21 transmission measurement.

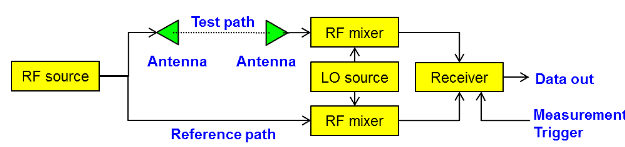

Figure 1 - A conventional two arm interferometer directly computes the complex S21 transmission ratio between a test path and a reference path.

3. Time Space Coherence Interferometry (TSCI)

Time space coherence interferometry is a relatively simple technology that allows commonly available single input streaming SDR receivers to operate effectively as two channel phase-coherent antenna instrumentation receivers. The term “time space” is used in this paper to identify the time or location of a measurement. Measurements can be at specific times, for example a receiver gain and phase stability test, or at specific locations, for example a near-field antenna phase front measurement. Motion tracking interferometry (MTI) is an example that requires simultaneous time and space knowledge [2].

TSCI measures the signal and reference paths at different times using Time Division Multiple Access (TDMA). If there is sufficient temporal coherence in the system, it is possible to accurately infer the reference signal phase at the antenna test signal measurement time and therefore compute the vector S21 transmission.

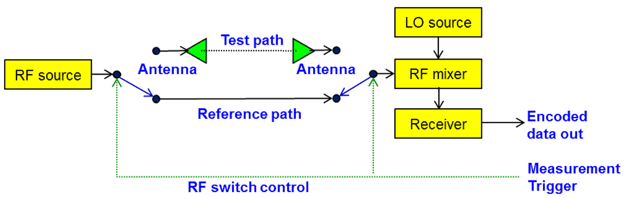

Figure 2 - This two-arm TSCI interferometer switches between a test path and a reference path. Temporal coherence is used to infer the reference path phase when the antenna test path is selected.

The TDMA slot sequencing is spatially locked by asynchronously triggering TDMA sequences at the desired measurement locations. The result is that measurement position information is encoded into the RF data stream. Later, in the decoding process, this metadata will be used to associate individual vector S21 transmission measurements with the corresponding spatial locations.

The TSCI concept can be summarized as:

1. The antenna path and phase reference path are measured at different times using time division multiple access (TDMA).

2. Measurement trigger events are asynchronously encoded as the TDMA slot sequence timing. TDMA that uses spatial, rather than temporal slot sequencing is SDMA (spatial division multiple access).

3. The SDMA data stream is decoded to produce conventional vector S21 measurements. The phase reference signal at the antenna path measurement time can be inferred because of temporal phase coherence.

3.1 TSCI system architectures

A TSCI system, at minimum, requires two elements; an encoder and decoder. The encoder uses TDMA or SDMA to embed phase reference, timing and other metadata into the antenna measurement data. The data is processed by the TSCI decoder which creates a two dimensional S21 phase front measurement array.

TSCI implementations are usually stream-based but streaming is not a fundamental requirement.

3.2 A simple TSCI implementation

This relatively simple TSCI example can use a streaming or non-streaming approach. Antenna measurements are frequently time division multiplexed so that many antenna operating states can be observed during a single spatial scan. The TSCI technique requires an additional direct measurement of the RF source. This measurement must be completely independent of the antenna path.

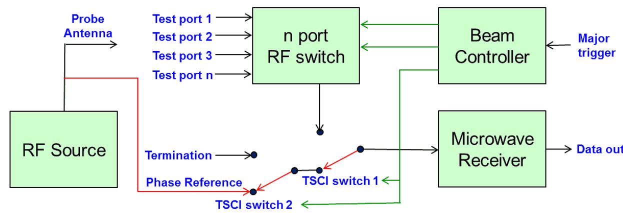

Figure 3 - This diagram shows a simple TSCI system which can be streaming or non-streaming. A pair of RF switches under control of a conventional TDMA antenna measurement beam sequencer is used to implement TSCI. Note that no separate phase reference channel input is needed by the microwave receiver. The red line shows the added TSCI phase reference signal path which is momentarily selected at each spatial measurement point or after a frequency change. The cascaded switch design insures high isolation between the test path and reference path.

TSCI using a conventional two channel S21 instrumentation receiver: TSCI requires the addition of a direct phase reference measurement at each spatial location and usually one additional direct phase reference measurement after each frequency change. If the receiver is operated in a conventional phase coherent two channel mode, the phase reference array will have constant amplitude and constant phase. The more useful case is to reassign the original reference channel input for use as a new second measurement channel. At this point, the receiver could operate as pair of TSCI single channel receivers or accept quadrature inputs.

TSCI using a single channel receiver: As in the previous case, TSCI requires the addition of a direct phase reference measurement at each spatial location and usually one additional direct phase reference measurement after each frequency change. The phase reference measurement will be an array with constant amplitude and random phase. An S21 array is the ratio of the measurement array to the phase reference array.

Streaming TSCI can be demonstrated with a standard near-field antenna measurement system. An additional pair of RF switches under control of the measurement sequencer samples the phase reference and zero signals. The phase reference state is a direct connection to the RF source. An optional RF terminated zero signal assists with the TSCI stream decoder synchronization process.

The following example used an RFspace SDR-IQ amateur radio receiver to convert the TSCI encoded single channel 20 MHz IF signal into a complex digital stream. The digital stream was saved as an audio wave file and later processed to extract a conventional S21 measurement array.

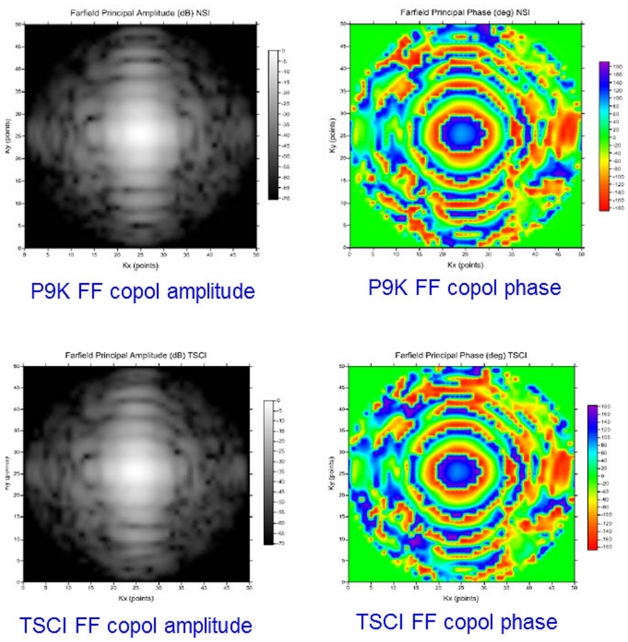

Figure 4 – These far-field images are transformed planar near-field measurements of a 10 GHz horn antenna. The data on the top row was acquired with a standard NSI Panther 9000 receiver. The bottom row data was acquired simultaneously using the single input streaming SDR receiver. The TSCI encoding method is shown in figure 3.

3.3 Streaming TSCI systems

TSCI systems require, at minimum, a TSCI encoder and decoder. This is sufficient for many software defined Digital Beam Forming (DBF) antenna test applications. Most other TSCI implementations require additional hardware. Figure 5 shows a representative analog IF TSCI system. A single channel streaming SDR receiver or VSA continuously converts a TSCI encoded analog IF signal into a digital stream with reduced spectral bandwidth and sample rate. Other optional stream processing elements may include stream compressors, user information encoders, recorders and stream monitors. Finally the stream is decoded into conventional near-field measurements.

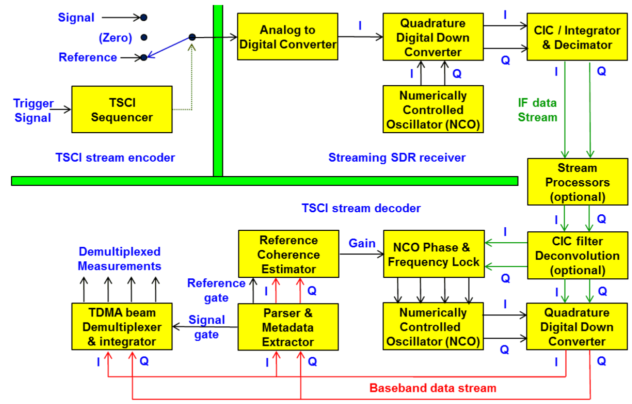

Figure 5 – TSCI stream data flow when using a typical IF input SDR receiver or vector signal analyzer.

3.4 TSCI encoder

The TSCI encoder uses SDMA or TDMA to insert phase reference and timing information into an RF, IF or digital data stream. TSCI encoding can be implemented in the analog or digital domains. Analog encoding is used for most antenna measurement applications. Digital stream encoding is used for Digital Beam Forming (DBF) antennas or to add time correlated user metadata.

In the quiescent state, the encoder passes only the phase reference signal. When an antenna measurement is to be made, the encoder selects the antenna measurement port(s) for a specified time interval and then selects a zero reference for another specified time interval. The encoder then returns to the quiescent phase reference signal state.

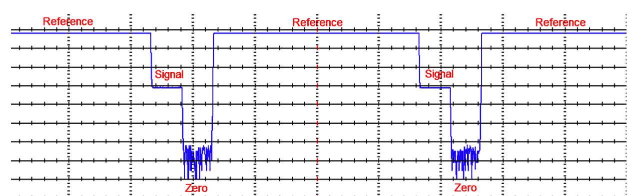

Figure 6 – This plot shows an encoded TSCI signal magnitude waveform consisting of two antenna path transmission measurements along with the associated phase reference and zero signals. Vertical scale is 10 dB / division. Horizontal scale is 10 msec / division.

3.5 Streaming receiver or vector signal analyzer

The TSCI encoder output is usually connected to a single channel streaming SDR receiver, a streaming vector signal analyzer (VSA) or a streaming digitizer. The receiver or VSA performs two functions; digitizing the RF signal and then reducing the stream data rate with a frequency domain spectral compression.

TSCI is directly compatible with common SDR receivers that have a single RF input and produce a single continuous I/Q digital data stream. TSCI is also directly compatible with other receivers including phase coherent and non-streaming variants. The rapidly emerging Digital Beam Forming (DBF) antennas are software defined antennas that internally include one or more streaming transceivers. As such, DBF antennas are conceptually similar to streaming SDR transceivers and are well suited to TSCI methods.

There are several SDR and VSA architectures but a common design uses a single analog to digital converter (ADC) followed by an FPGA based quadrature digital down converter (DDC) and a PCIe, Ethernet or USB stream output. The DDC provides a frequency domain compression that significantly reduces the stream data rate. The DDC consists of a numerically controlled oscillator (NCO) driving a digital quadrature mixer followed by a low pass decimation filter.

It should be noted that a quadrature downconverter is optional. A conventional single sideband superhetrodyne receiver tuned to produce a single sided measurement spectrum is sufficient. The single sided real signal can be converted by a Hilbert Transform into a complex analytic signal [1].

Another option is to use a continuous RF or IF signal digitizer without following it directly with a digital down converter. In this case, the data rate is higher and is real data only. An example would be using a high speed digitizing oscilloscope or waveform recorder. Real superhetrodyne or complex DDC based frequency domain compression can be implemented later in the stream if desired. Modular PXIe instrumentation that includes digitizer and FPGA modules is another variation.

3.6 TSCI stream compression

Even with frequency domain compression in the SDR or VSA, the TSCI data streams can be large and fast. Various other types of stream compression are possible, ranging from simple time domain decimation to full TSCI stream decoding into conventional antenna near-field or far-field measurement data arrays.

3.7 User information encoder

Additional time space correlated information such as scanner axis encoder readings and antenna status signals can be merged into the stream. An effective approach is to use the software defined VRT (VITA Radio Transport) information protocol as a container for both the TSCI stream and additional user metadata. [3]

3.8 TSCI stream recording

One option is to record the raw TSCI data stream for later analysis. Slower RF data streams (up to 2 MSPS) are often recorded as audio PCM wav files. Many SDR software programs, particularly those used in the amateur radio community can read and write these data files. Faster streams can be written to RAID disk arrays using PCIe, Gigabit Ethernet, or USB. Multilane PCIe can currently support I/Q pair data rates in excess of 500 MSPS.

3.9 TSCI stream decoder

The TSCI stream decoder processes the digital IF data stream to remove systematic receiver errors, reconstruct missing phase reference signal intervals and separate the antenna data from the metadata. The stream decoder can operate in real time or as a batch postprocessor. The decoder requires careful design, optimization and testing to provide reliable and efficient operation with the high speed data streams. Host software can efficiently process moderate speed streams in real time. Higher performance modular PXIe VSA systems would typically include PXIe FPGA stream processors capable of producing extensive real time S21 data along with TSCI metadata and VRT user metadata.

The incoming stream is preprocessed to correct receiver errors such as bias offsets and quadrature unbalance. Many common SDR receivers use CIC (Cascaded Integrator Comb) decimation filters that cause TDMA slot distortions. These slot distortions can be deconvolved using an analytic or measured filter time response.

There are several different methods of time aligning the phase reference to the antenna measurement signal. One approach is to perform an additional quadrature down conversion to baseband using a reference oscillator that is precisely phase and frequency locked to the intermittent TSCI phase reference signal. Under these conditions, the antenna path measurements do not require further phase normalization to produce vector S21 data. The reference oscillator is conceptually similar to a flywheel. It regenerates the missing phase reference information during the antenna path measurement. Additionally, the adaptive phase and frequency lock process removes reference signal phase noise by averaging over a longer time interval than the antenna path measurements.

A demultiplexer separates the antenna measurements from the phase reference and other metadata. A zero reference signal inserted at the start or end of an antenna measurement TDMA sequence provides synchronization. Once synchronized, the individual antenna measurement streams are extracted from the composite baseband TSCI data stream. The antenna measurement signal streams, if multi-beam, are then further parsed into short individual S21 time series associated the individual beam states.

Each individual measurement time series is collapsed into a single complex S21 value corresponding to the vector norm. This produces a TDMA matched filter response maximizing the measurement SNR in the presence of additive white Gaussian noise. The individual S21 measurements are then placed into the appropriate 2D near-field data arrays.

3.10 TSCI stream metadata

Metadata has two broad definitions; one is that metadata is structured data about data. This type of antenna measurement metadata includes data acquisition start and end times, scan area, scan speed, test frequencies and antenna configurations. Another definition of metadata is more literal, combining the Greek word "meta" which means "alongside, with, after or next" with the primary data. This type of metadata results from associated measurements such as RF system drift checks using tie scans or motion tracking interferometry [2].

With TSCI, the primary data is the spatially sorted complex S21 transmission measurements and the metadata is everything else. It is important to note that each individual measurement time series contains additional information beyond a single S21 measurement. A 100 MSPS stream data rate provides a 10 nanosecond time resolution with 100 samples over a 1 microsecond S21 integration time. The properties of each individual RF measurement time series can be examined with high temporal resolution by using various complex signal demodulators. A pulse profile corresponds to the vector magnitude of the time series. Phase or frequency demodulation can be used to examine time dependent frequency shifts including T/R module switching phenomena, group delay variations and, over longer time scales, even scanner vibration [4]. The vector time series can be examined in other ways to derive the timing, jitter and measurement uncertainty associated with individual S21 measurements. The individual antenna measurement metadata elements can be coalesced into global statistics including receiver noise power, RF pulse statistics and measurement gate time variances.

The metadata associated with individual measurements can be formed into 2D data arrays similar to normal S21 antenna phase-front arrays. As an example, far-field processing of different segments of a measurement time series vector array can be used to observing time varying changes in a far-field pattern during a phased array beam steering state transition.

Other TSCI metadata is available that is independent of the actual antenna measurements. Analysis of the TSCI phase reference signal can provide statistics including receiver bias and orthogonality errors, reference power level drift, SNR and general RF source quality including in band spurs. Of particular importance is the measurement of the reference signal coherence which is used to adaptively tune the TSCI decoder. Other metadata includes the IF frequency, and frequency variance, phase error statistics, TDMA switching statistics such as the receiver IF filter time response (used for CIC filter deconvolution), timing jitter, instantaneous scan motion velocity and other dynamics. TSCI switch leakage metadata is available from the zero reference.

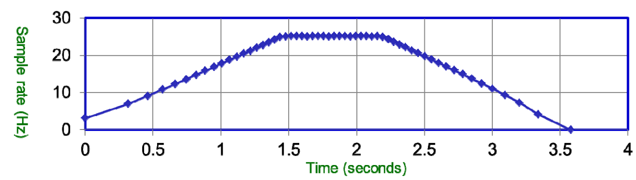

Figure 7 – This plot shows the scan velocity during a single cut as derived from TSCI metadata.

4. Time Space Encoded Interferometry (TSEI)

Most RF sources lose phase coherence during a frequency change. Therefore the TSCI reference signal phase estimate is no longer valid until it is measured again. An additional reference signal measurement is needed after each frequency change but this can result in a significant 50% loss of throughput. Organizing the test to minimize the number of frequency changes can help to maintain a high measurement speed. In many cases this approach is more than adequate. Another approach that maintains full measurement speed is the addition of a streaming reference channel but this adds hardware and doubles the size of the stream.

A TSCI variant, Time Space Encoded Interferometry (TSEI) can maintain full measurement speed during multi-frequency measurements. The idea here is to stream internally computed S21 data from the receiver. In some ways, this is simpler than TSCI as there is no need for temporal insertion of a phase reference signal. The receiver needs firmware modifications to stream S21 data and insert time space metadata. The advantage is that RF coherence is no longer an issue. Care is needed to minimize reference path signal leakage which can become significant in a physically small SDR receiver package. Hardware and firmware is generally more complex, expensive and non-standard with fewer commercial options.

5. Streaming TSCI implementations

Several streaming TSCI systems were built using both off the shelf and custom hardware.

A TSCI test fixture (TF1) was developed as an aid for technology development, training, field service and other activities. TF1 has a number of capabilities, one of which is operating as a fairly fast phase coherent 20 MHz antenna instrumentation receiver. Although simple and low cost, this unit is capable of producing high quality results with measurement stream rates up to 192 KSPS. The stream can be recorded as an audio wave file or processed in real time. The TSCI decoder software makes TF1 appear as a conventional phase coherent antenna measurement receiver so that it can operate with standard antenna test software.

A relatively high performance RF interferometer was built using a modified amateur radio transceiver. This transceiver includes an internal RF source and, when combined with a suitable high speed RF switch, can operate as a self-contained RF subsystem suitable for near-field antenna measurements up to 6 GHz. Alternately it can operate in a TSEI configuration as a conventional 2 channel IF receiver without RF source coherence restrictions.

6. Summary

TSCI and its derivatives provide a high performance yet cost effective alternative to conventional phase measuring antenna test receivers and vector network analyzers. TSCI technology is patent pending.

Commonly available, off the shelf, non-coherent, non-triggered communication transceivers, vector signal analyzers and digitizers can be used to make high accuracy spatially defined phase coherent interferometric measurements. TSCI is directly scalable from very low cost educational systems to very high performance aerospace systems. The RF subsystem can be further simplified by placing the TSCI encoder switch ahead of a single channel non coherent RF downconverter.

RF and IF signal leakage is well controlled because of the lack of a system wide phase reference signal during the antenna path measurement time interval. The reference signal estimation process can provide reference signal integration times much longer than the actual antenna path measurement interval. This reduces reference channel phase noise which improves the overall phase measurement accuracy.

TSCI is directly compatible with software defined DBF antennas that use VRT or similar software defined information streams [3]. In addition to the normal near-field phase-front measurement, a full S21 vector time series can be associated with each individual measurement point. Analysis of these S21 vector arrays is useful in characterizing the dynamic beam steering behavior of advanced AESA and software defined antennas.

Like all technologies, TSCI also has disadvantages. The RF sources must have adequate temporal coherence but so far this has not been a significant problem. CW multiport measurements suffer from a slight (5-10%) loss of available measurement time. This problem becomes worse with multi-frequency measurements with up to a 50% loss of available measurement time. In many cases, this loss of available measurement time is not a significant issue. TSEI, a variation of TSCI, can completely solve this problem although the hardware becomes more complex, non-standard and costly. Additionally, there is lots of raw data to process and/or store in the streaming implementations but currently available computers and FPGA coprocessors are up to the task.

7. REFERENCES

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8. ACKNOWLEDGMENTS

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