The Up Converter – A Critical Synthetic Instrument Technology

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Abstract – This paper provides a brief overview of the characteristics of RF/Microwave Frequency Translation Devices and associated Frequency Synthesis technologies which are commonly employed to implement their functionality. The paper then briefly reviews the concept of Synthetic Instruments (SI) and the role of the Up Converter in the context of the SI paradigm. The authors then characterize and compare traditional approaches to RF/MW stimulus generation & modulation vs. a modern day Up Converter / Frequency Synthesizer architecture employing a flexible modulation capability and provide insight on the need for a new breed of frequency translation device: The Synthesized Up Converter (SUC). The authors also address the importance for such Frequency Translation Devices to embrace the emerging digital modulation paradigm in order to satisfy both current and future SI user needs in support of the Defense, Signal Intelligence, and Telecom communities. The paper then introduces the reader to some critical Synthesized Up Converter functions & specifications that should be considered when satisfying a broad array of RF/Microwave CW and modulation user needs. The paper concludes with a summary statement by the authors about this critical Synthetic Instrument technology.

I. INTRODUCTION

One of the most critical technologies employed by the test and measurement RF/Microwave designer is the Frequency Translation Device (FTD), or Frequency Converter. FTDs are typically integrated component assemblies which translate or convert test signals into either lower (intermediate) or higher frequencies in order to affect further signal processing, in either the Stimulus or Measurement signal paths of synthetic instrument based test & measurement systems.

RF/MW FTDs are primarily available in two basic configurations: Up Converters and Down Converters. As its name implies, Up Converters are primarily utilized to transform Radio Frequency (RF) signals from a lower frequency spectra to a higher frequency Microwave (MW) range or band (i.e., L Band to C Band). Conversely, Down Converters transform RF/Microwave signals from a higher frequency to a more manageable Intermediate Frequency (IF) range where more readily available components (i.e. digitizers or demodulators) can be utilized for signal processing. Some variations of Frequency Translation Devices employ multiple Up Converters and Down Converters whereby the devices can be utilized to translate transmitter (stimulus) or receiver (response) signals either up or down in frequency.

A linear device such as a filter will only affect the amplitude and phase of an input signal. Its primary purpose is to attenuate certain frequency bands while allowing others to pass with minimal loss – no signal frequencies are added to the device's output frequency spectrum. FTDs, on the other hand, are non-linear devices by definition. That is, if a frequency appears at the output of a device that is not present at its input, it is said to have non-linear effects. A FTD is designed to utilize its non-linear effects to shift one or more of its input signals by a fixed predetermined amount via a frequency mixing process employing either an internal or external signal frequency source, commonly referred to as a Local Oscillator (L.O.). Except for frequency translation, FTDs are expected to behave linearly. Similar to filters and amplifiers, they exhibit gain or loss, a particular frequency response, and all the other characteristics of linear devices. They also exhibit many of the same undesired non-linear behaviors of amplifiers such as compression and intermodulation distortion.

Up Converters utilizing local oscillators often perform their frequency transformation function by employing any number of direct and/or indirect "frequency synthesis" technologies when Up Converting ("mixing up") the target baseband modulation or IF signal in frequency. Frequency synthesis may be defined as a process by which a set of frequencies with pre-defined upper and lower bounds may be generated from a single time base (frequency reference) in such a way that the ratio of the output to the reference frequency is a rational fraction. Frequency synthesizers are essential to Test and Measurement (T&M) applications where flexible stimulus sources are required to produce variable or programmed frequency signals in support of both Continuous Wave (CW) and signal modulation applications. Frequency synthesis technologies often employed in a T&M context include Phase-Locked Loop (PLL) Frequency Synthesizers, Direct Analog (DA) Frequency Synthesizers, and Direct Digital Synthesis (DDS).

Frequency Synthesizers employing PLL technology, an indirect frequency synthesis technique, are commonly used throughout the electronics industry. The PLL employs a feedback mechanism locking its programmed or selected output frequency to a highly stable reference frequency. PLL synthesizers are extremely popular due to their simplicity, availability in a variety of integrated circuit formats, and relatively low cost. Direct Analog Frequency Synthesizers, a direct frequency synthesis technique, typically employ a number of crystal oscillators, frequency multipliers/mixers, filters, and switches to affect the frequency synthesis function. Using this technique, it is possible to generate a vast array of frequencies with the same time base accuracy as the fundamental crystal oscillator employed. This frequency synthesis technique often offers excellent spectral purity and switching speed (frequency hopping from frequency to frequency) but is often more complex, more costly, takes up more volume and consumes more power than indirect synthesis techniques. Lastly, Direct Digital Synthesis is a Digital Signal Processing (DSP) discipline which employs direct digital synthesis techniques to create, manipulate, and modulate a signal digitally and subsequently convert the digital signal to its analog form by employing a Digital to Analog Converter (DAC). DDS is an extremely powerful technique; in T&M applications signal generators employing such techniques are referred to as Arbitrary Waveform Generators (AWG). As the name implies, the output is completely arbitrary and only limited by the user's imagination. However, the DDS technology is not without its limitations; current, state of the art, DDS technology may be limited in terms of stimulus bandwidth to 1GHz. Often, signal generator and L.O. manufacturer's utilize a "hybrid" approach employing a combination of these technologies to optimize price, speed, spectral performance, power consumption and/or volume and weight in order to satisfy end user test requirements.

The ensuing paragraphs of this paper focus in on stimulus generation, and particularly the Up Converter (UC) component, in the context of a Synthetic Instrument (SI) and provide an overview of critical stimulus parameters, as well as a flexible stimulus architecture, that should be considered when employing this class of Frequency Translation Device.

II. UP CONVERTER IN THE CONTEXT OF A SYNTHETIC INSTRUMENT

The genesis of Modern Day instantiations of Synthetic Instruments (SI) find their roots in the communications revolution of the past decade and the emergence of a concept called "Software Defined Radios," or SDRs. Simply defined, an SDR consists of a Digital Signal Processor or DSP, a Transmitter, a Receiver, and a transmission antenna. The transmitter and receiver convert digital data to and from modulated radio waves for wireless communication purposes. The DSP provides the radio functionality, via its software component, whereby application specific algorithms generate or process digitally represented signals for transmission or reception by the SDR.

The concept of Synthetic Instruments (**Fig.1**) leverages off of the SDR paradigm. SI is predicated on the concept that most stimulus and measurement functions can be implemented in software employing "Core" SI hardware & Digital Signal Processing software components supplemented, as required by the user's envelope of test requirements, by commercial–off-the–shelf hardware (i.e., power supplies, fixturing, loads, etc.).

The stimulus or digital to RF/MW path/functionality of a SI is often referred to as a Stimulus Hardware Emulator and is comprised of Digital to Analog Conversion (DAC) , Frequency Up Converter, and Signal Conditioning functional blocks, or in some lower frequency SI instantiations the DAC may be replaced by an Arbitrary Waveform Generator (AWG). In many instances, the Up Converter may incorporate signal conditioning circuitry within its functionality. In a SI context, the Up Converter must provide the frequency translation function and, via a combination of mixing and filtering, faithfully translate a baseband or IF signal from the DAC or AWG onto a RF/MW Carrier signal. Minimal or no spurious stimuli should be generated along with the desired / programmed Continuous Wave (CW) or modulated output signal.

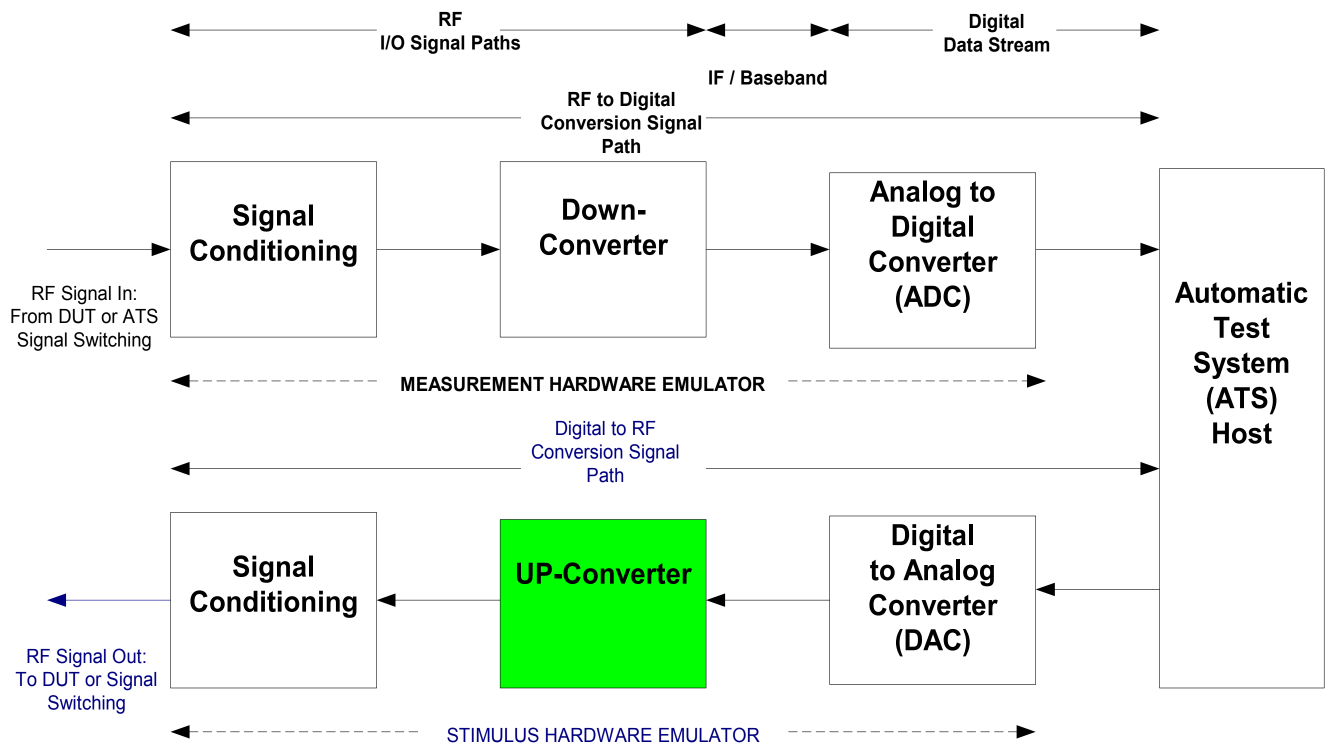

Fig. 1 The Up Converter in a Synthetic Instrument Context

III. A FLEXIBLE UP CONVERTER ARCHITECTURE

A traditional "legacy" instrument architecture (vintage ~ 1980) employed by prior generations of RF/MW stimulus generators is depicted in **Fig. 2.** This class of instrument architecture has served the T&M industry and its customer base well over the past few decades. The instrument's functional capability consisted of RF/MW CW signal generation and classical analog Amplitude, Frequency, and Pulse Modulation capabilities. This functional capability was adequate to support the test and measurement needs of older/legacy Aerospace & Defense Communication Systems. Over the past decade a new breed of communication system has evolved employing Complex Modulation concepts utilizing extensive use of Digital Signal Processing (DSP). This new class/type of Unit Under Test cannot be adequately tested by legacy RF Stimulus generators due to their limited/fixed signal modulation capabilities.

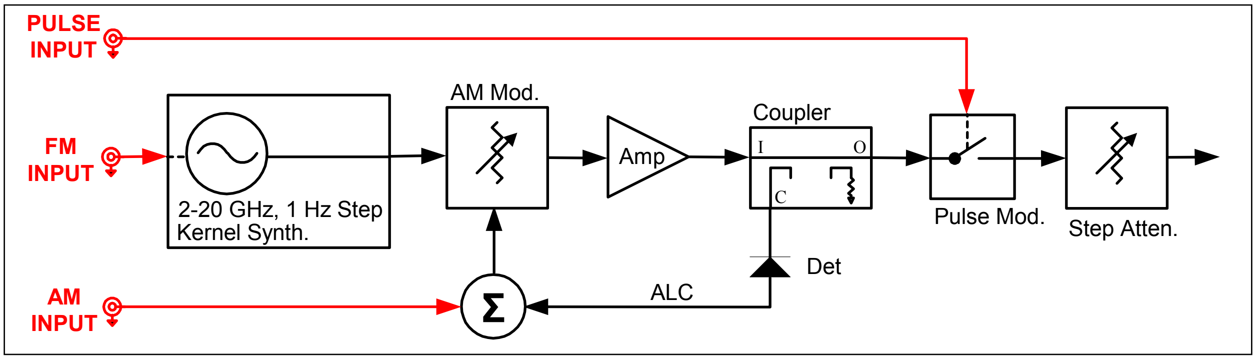

Fig.2 Legacy RF Stimulus Generation/Modulation Architecture

Because of this “Digital Revolution” in the Aerospace & Defense sector, a need has emerged for a new class/type of RF Stimulus Generation architecture and capability in Automatic Test Systems that can accommodate both legacy and new/emerging Complex Digital Modulation (CDM) formats. CDM involves the control of the phase of a signal through a device referred to as an I/Q Modulator. **Fig. 3a** below depicts a high level physical model of an I/Q modulator; where a carrier wave $S_i(t)$ with an applied phase shift θi is represented mathematically as the sum of two components, a Cosine wave and a Sine wave,**Fig.3b**, where:

$$S_i(t) = ACos(\omega t + \theta_i) = \mathbf{I(t)}XCos(\omega t) + \mathbf{Q(t)}YSin(\omega t)$$

I(t) represents a binary bit stream in time that controls the real, or in-phase, “X” component of the modulated carrier signal and conversely **Q(t)** controls the imaginary, or quadrature-phase, “Y” component of the signal. As can be seen in Fig. 3a, the two carrier waves of the same frequency, a Cosine and Sine, are combined to form the composite output signal. For Digital Signal Processing purposes, the two components are normally represented as a complex number I+jQ, hence the term Complex Digital Modulation.

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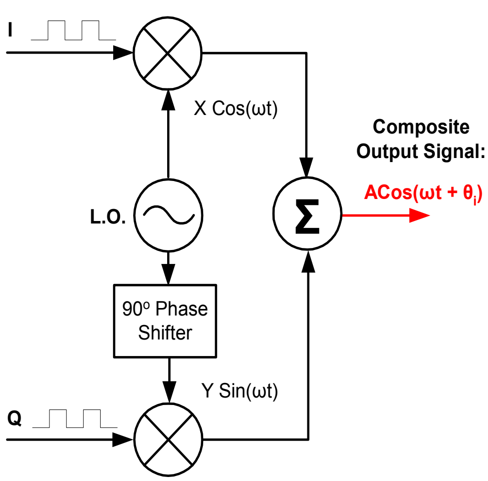

Fig.3a I/Q Physical Model

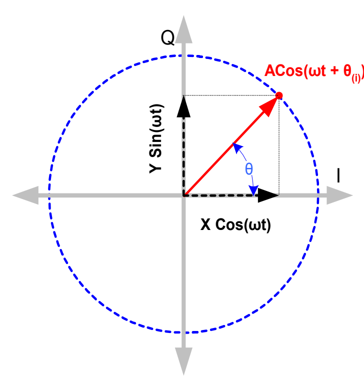

Fig.3b Mathematical Model

Fig. 4 below depicts an example of a state of the art Up Converter architecture/reference design employing a flexible mix of primary functional modules (Frequency Synthesizer, Mixer, Yttrium Iron Garnet (YIG) band pass filter, RF amplifiers, modulation circuitry, programmable output Step Attenuator, and a versatile IF Function Module) and technologies encompassing critical SI user needs such as frequency synthesis, analog & Complex Digital Modulation, and Up Conversion. In essence, modern day Up Converters must encompass, besides their fundamental frequency translation function, the dual functionality of a generic frequency synthesizer integrated with the frequency modulation attributes of both traditional and emerging CDM technology. This dual "Synthesized Up Converter" (SUC) functionality is needed to address user needs in terms of both a broad and flexible CW and modulation capability when employed within an SI context. The flexible Synthesized Up Converter Architecture depicted in **Fig. 4** can be tailored /adapted in a modular fashion to address the unique needs of each custom application. A brief description of this flexible Up Converter architecture is provided in the ensuing paragraphs.

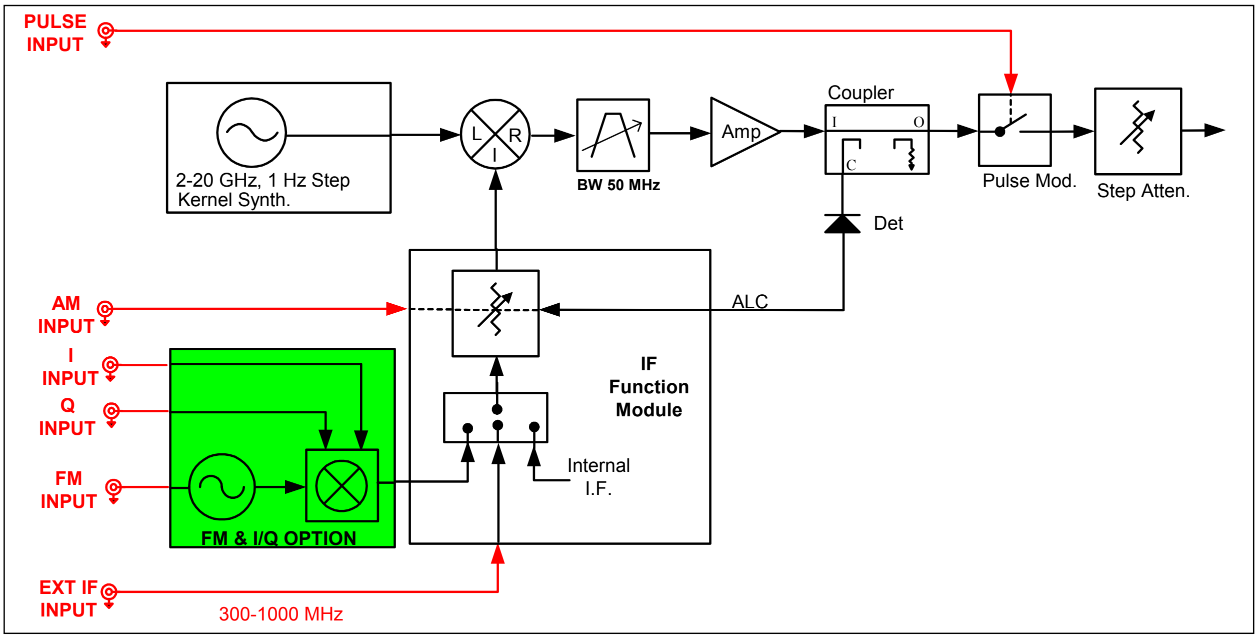

Fig. 4 A Flexible Synthesized Up Converter (SUC) Architecture

In the CW mode of operation, the architecture employs a hybrid mixture of frequency synthesis techniques described in section I of this paper to generate stable spectrally pure RF/MW CW signals in the range of 2-20 GHz, with a 1 Hz resolution. The output signal of the mixing process is filtered by a tunable YIG filter with a minimum 50 MHz bandwidth and amplified. To illustrate, suppose a 10GHz signal is desired from the Up Converter/Synthesizer. In order to generate this signal, the kernel synthesizer internally sets its fine and coarse loops to generate a 9.0 GHz signal from the "Kernel" Synthesizer's output to the "L" input of the mixer. This signal is then mixed with an internal 1000 MHz signal from the IF Driver functional block to produce the 10 GHz output. The YIG filter is programmed to 10 GHz to eliminate superfluous mixer products and ensure that a spectrally pure 10 GHz signal is subsequently transmitted to the Up Converter's signal output port. This signal generation/architectural technique is employed to keep the "mixer in play" in support of both classical CW synthesis and modulation applications and eliminate RF/Microwave mode switching and its associated signal degradation effects.

With the architecture depicted in **Fig. 4**, it is a simple process to translate or up/down convert an IF to any microwave output frequency in the range of 2 to 20GHz. Besides providing the fixed 1000 MHz internal signal, the IF Function Module has the flexibility to also pass through an external signal in the 300 – 1000 MHz (UHF band) from the front panel IF input. This attribute enables any external complex modulation (i.e. CDM signals or sophisticated signal jamming scenarios) present on an external IF signal (within the band pass limit of the YIG filter) to be incorporated into the up converted output signal at the target microwave carrier frequency. If desired, the microwave carrier frequency of the complex modulated signal can be changed to any value between 2 and 20 GHz via setting/programming the kernel synthesizer to the new desired value. Also, the subject architecture can provide further signal conditioning beyond the capabilities of the modulator, both pulse modulation and step attenuation for both the CW and complex modulation Up Converter modes. The architecture allows the Automatic Leveling Control (ALC) loop to control the output level of the up converted signal or, if the level of the IF input is to be maintained, the leveling loop can be turned off.

Besides having the facility to perform complex external modulation, the SUC architecture depicted can perform classical AM, FM, and Pulse Modulation as well as Complex Digital Modulation. CDM is affected via employing the I/Q Modulation capability previously described whereby a binary digital stream (e.g.,"1010,0010, ….) can be represented by a unique RF composite signal, or signals, in the I/Q domain that is characterized by the magnitude and phase of both its in-phase and quadrature components (or I and Q). That is, an I/Q capable stimulus generator provides the capability to transform **Bits to Microwave** signals and provide a virtually unlimited signal modulation capability (e.g., Binary Frequency Shift Keying (BFSK), Quadrature Phase Shift Keying (QPSK), Quadrature Amplitude Modulation (QAM), etc.) within the bit error constraints of a target application. Therefore, it is imperative that Modern Day Up Converters incorporate modulation capabilities that can accommodate a broad range of both legacy analog and current CDM formats, as well as be easily upgradeable in support of emerging/custom CDM formats in support of the DOD, signal intelligence, and Telecom communities.

IV. UP CONVERTER CRITICAL FUNCTIONS & SPECIFICATIONS

A number of RF/MW frequency translation related functions and specifications should be considered when designing or specifying an Up Converter's functionality. Probably one of the most important considerations is its physical attributes in terms of an Up Converter's form factor & modularity/ flexibility – the ability to add/ incorporate functional capability (i.e., Modulation, Output Power) based on user needs.

An ever increasing emphasis on test equipment down sizing, interoperability, & mobility in the DOD test and measurement community has placed an increased focus on Synthetic Instrumentation and its implementation in modular and relatively small form factors, such as VXI, PXI, and LXI. Specifying and designing an Up Converter capability into a small form factor format provides a number of challenges to both the SI designer and user. Unless the Up Converter design approach is modular in nature, the functional (CW & modulation signal synthesis) and small form factor needs of the customer may be at risk. Thus, form factor and modularity/flexibility should be primary considerations when specifying an Up Converter capability. Summarized below are a number of critical Up Converter functions and their associated specification parameters that should be considered and specified in support of SI user needs:

- RF/MW Output Specifications:
  - Frequency Range, Power Setting Range (Leveled), Source Impedance, Output Connector Type, Resolution, Accuracy.
- Spectral Purity Specifications:
  - Spurious: Harmonic & Power Line Related, Non – Harmonically Related Spurious, Residual Modulation: FM & AM, Single Sideband Noise.
- Pulse Modulation Specifications:
  - Pulse Repetition Frequency, Minimum Pulse Width, On/Off Ratio, Rise/Fall Time, Pulse Overshoot/Ringing, Pulse Width Compression, Video Feed through, Delay time, Peak-to –CW level Accuracy, Input Level Type (i.e., TTL), Input Level Tolerance, Polarity.

- Amplitude Modulation Specifications:
  - Rate, Depth, Distortion, Sensitivity, Modulation Index Accuracy, Input Impedance, Input Level Tolerance
- Frequency Modulation Specifications:
  - Rate, Deviation, Distortion, Sensitivity
- IF (Complex Modulation) Input Specifications:
  - Input Frequency, Input Level, Instantaneous 3 dB Bandwidth, Spurious Output (specified at a specific power (dBm) output and input level), Linearity
- I/Q Modulation Specifications:
  - I/Q Bandwidth, I/Q Sensitivity , I/Q Input Impedance, I/Q Linearity
- Reference Frequency Input/Output:
  - Frequency, Level
- Internal Time Base Specifications:
  - Frequency, Aging Rate, Temperature Stability

In particular, the specification of an Up Converter's IF Input's bandwidth is of critical importance. As mentioned previously in Section III, the IF Modulation input provides the means to up convert complex digital communication signals or sophisticated jamming scenarios to microwave frequencies. The IF input's instantaneous bandwidth supports wideband frequency, phase, and amplitude modulation as well as noise injection in any combination. Consequently, the complex signals needed to test cutting edge digital technology receivers may be easily produced, co-channel and adjacent channel interference simulated, and sub-microsecond frequency hopping affected if sufficient IF input bandwidth is provided in an Up Converter's IF (Complex Modulation) Input port or channel.

V. SUMMARY/CONCLUSIONS

The Up Converter is a complex Frequency Translation Device which must be precisely specified and designed to satisfy the unique needs of a customer's end use application. In the context of a Synthetic Instrument, the Up Converter is a critical component and should provide, in addition to its fundamental frequency translation function, the dual functionality of a RF/Microwave CW Frequency Synthesizer and a flexible modulator, employing both classical analog and Complex Digital Modulation functionality. It is the authors' opinion that the Synthesized Up Converter (SUC) architecture described in this paper possesses these attributes and should be considered for use in Synthetic Instrument applications targeted for DOD Automatic Test Systems with long service lives and broad based /evolving test requirements.

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