INJECTION OF DIRECT-SEQUENCE SPREAD SPECTRUM PILOT TONES INTO BEAMLINE COMPONENTS AS A MEANS OF DOWNCONVERTER STABILIZATION AND REAL-TIME RECEIVER CALIBRATION*

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Abstract

Beamline components used for diagnostic elements often rely on thermal stabilization, continual physical maintenance (ie. tuning), and frequent beam-based calibrations to maintain specified performance. Direct-sequence spread spectrum (DSSS) pilot tones injected into a particular element and combined with the beam-derived signal can subsequently be separated and used to assess performance degradation. In addition, the DSSS tone can be used as a real-time calibration signal, without interference to the intended diagnostic signal. This paper demonstrates such a technique in the design of a Beam Current Monitor downconverter system, as an intended upgrade to the CEBAF Beam Loss Accounting system. A brief spread-spectrum primer is included, as well as a description of appropriate spreading codes and their generation.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) employs a system of passive 1497 MHz TM010 cavities as the basis for a beam current loss accounting system (BCM/BLA) for machine protection [1]. The 1497 MHz RF signal is downconverted, and routed to a VME-based IF receiver system capable of resolving hundreds of nanoamps of instantaneous beam loss [2,3]. In addition, a 1% absolute accuracy provides accelerator operators and experimenters with a convenient means of continuous, non-invasive beam current measurement. The present system has two limitations. Firstly, confidence tests of the cavity performance can only be preformed off-line, i.e. when the beam is not present. Secondly, the RF-to-IF downconverters, located in the beam enclosure, are no longer available and will require replacement for the 12 GeV CEBAF upgrade. A new system is desired, which is capable of continuous performance assessment, able to stay within calibration limits for long periods of time, and requires minimal operator or system expert intervention. The proposed design employs a CW pilot tone, orthogonal to the electron beam signal, as a means to evaluate proper performance in real time, as well as introduce a calibration reference for long-term stability.

DIRECT-SEQUENCE SPREAD SPECTRUM (DSSS)

The problem of intentional co-channel interference (ie. “jamming”) has long been an issue with RADAR and tactical communications systems. An effective countermeasure involves spreading the carrier energy over an extreme bandwidth, often hiding beneath the thermal noise floor. If the mechanism with which the spreading is known, carrier reconstruction can be performed at the receiver using cross-correlation techniques [4].

The basis for DSSS involves multiplying the carrier with a pseudo-random bit sequence, which although looks like noise to other receiving stations, is actually a correlated, repeating sequence which has the effect of encrypting the carrier energy.

Spreading Codes

Mathematically, a spreading code serves to map the low-dimensional CW carrier tone to one having a high degree of dimensionality. Furthermore, each of the dimensions should consist of orthogonal signals, which form the new basis. Then, the D equiprobable and equienergy orthogonal signals within an n-dimensional space can be re-represented in the new signal space by considering an orthonormal basis, $\varphi_k(t)$, which is defined by [5]:

$$\phi_k(t);\ 1\leqslant k\leqslant n$$

$$\int_0^T \phi_l(t)\,\phi_m(t)\,dt=\delta_{lm}=\left\{\begin{matrix}1 & l=m\\ 0 & l\neq m\end{matrix}\right\} .$$

Then, the new signal representation is:

$$S_i(t)=\sum_{k=1}^{n} S_{ik}\,\phi_k(t)\qquad 1\leqslant i\leqslant D;\qquad 0\leqslant t\leqslant T$$

where

$$S_{ik}=\int_0^T S_i(t)\,\phi_k(t)\,dt\quad .$$

The resulting average energy for each of the signals is represented by:

$$\int_0^T \overline{S_i^2(t)}\,dt=\sum_{k=1}^{n}\overline{S_i^2}=E_s;\qquad 1\leqslant i\leqslant D$$

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Since S_{ik} represents coefficients describing the space, they can be chosen, independently. The idea is to select them, such that their energies are uniformly distributed, have zero mean and correlation, and are only known by the intended receiver (hence unobservable by the primary BCM receiver). The energy occupied by each coordinate then becomes:

$$\overline{S_{ik}S_{il}}=\frac{E_s}{n}\delta_{kl} \qquad 1\leqslant i\leqslant D$$

For the sake of illustration, the relatively narrowband beam signal can be represented by

$$J(t)=\sum_{k=1}^{n} J_k \phi_k(t); \qquad 0\leqslant t\leqslant T$$

which results in a total energy

$$\int_{0}^{T} J^2(t)\,dt=\sum_{k=1}^{n} J_k^2=E_J$$

and ultimately combines with the DSSS signal within the BCM cavity. Since each signal represents only a fraction of the other's energy, within the narrow bandwidth of the beam signal, an arbitrarily high SNR can be maintained, and is dependent on the dimensionality of the spreading code.

The resulting spectrum of a DSSS signal is shown in Figure 1. The envelope follows a $(\sin(x)/x)^2$ function, whereby the first nulls occur at +/- $1/f_c$, with f_c defined as the clock rate for the spreading code (known as the "chip" rate). Interestingly, the original carrier is further nulled by $1/n^2$, where n is the length of the sequence, resulting in a spectral notch [4].

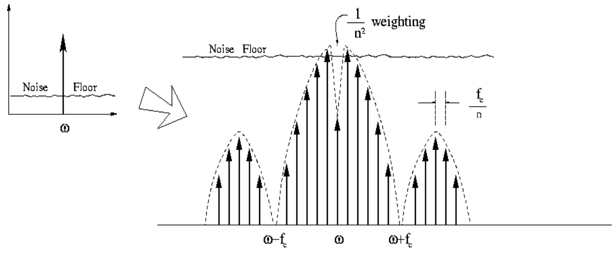

Figure 1. DSSS spectrum created from a CW carrier, showing $(\sin(x)/x)^2$ envelope, as well as $1/n^2$ notch.

A bench test was devised to examine the feasibility of generating necessary tones, and combining them within an actual BCM cavity, employing a pseudo-random (PRN) code generator, as shown in Figure 2.

A pair of 1496 MHz free-running oscillators were chosen for both the pilot tone and the beam signal, as a matter of convenience; the actual downconverter design will utilize 1497 MHz for both signals. Although the cavity resonance is centered at 1497 MHz, our test was contained within the 6dB passband, and therefore representative.

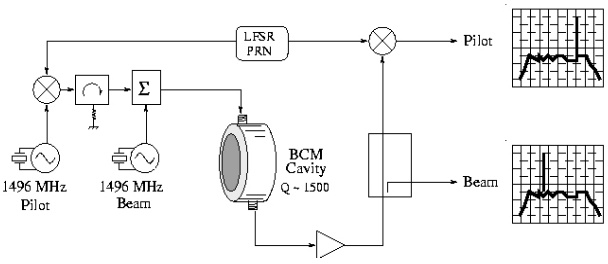

Figure 2. Bench test setup of DSSS system, utilizing near-frequency 1496 MHz oscillators to represent pilot tone and beam signals. PRN generates the sequence.

Figure 3 demonstrates the DSSS process for a single tone, with 2 spreading codes of n=15 and n=65535, respectively, after being passed through a 1497 MHz BCM cavity with 3dB bandwidth of ~ 1MHz. In each case (i.e. for any n), the envelope is the same, dictated solely by the 1 MHz chip rate. Within the envelope, the narrowband carrier (ie. pilot tone) is disassembled into n-dimensional components, which, although lacking in performance, is most easily seen in the n=15 case.

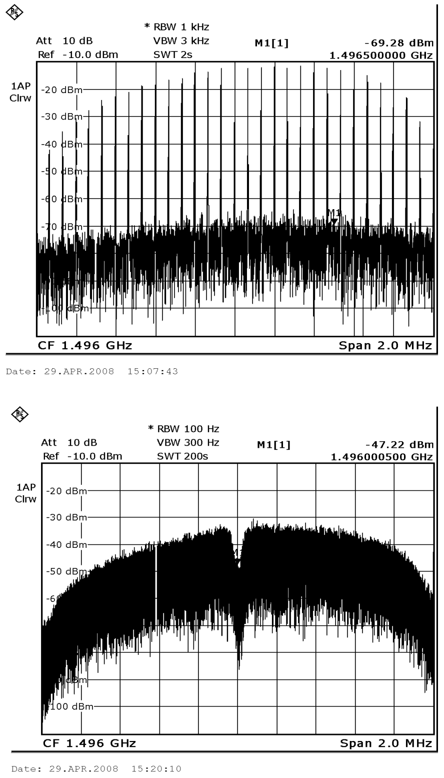

Figure 3. DSSS spectra of 1496 MHz tone for n=15 and n=65535. All cases were subsequently passed through a 1497 MHz cavity (Q ~ 1500), replicating in-situ conditions. The n=15 case clearly demonstrates the spreading process, whereby energy is "re-binned."

When this spectrum is subsequently cross-correlated with the original code, the carrier is re-assembled, but with some loss of accuracy as seen by degraded SNR for each of the three codes, given by Figure 4. The extent to which the SNR is retained is called "processing gain," simply stating that the carrier power is distributed evenly amongst n bins, and follows:

$$PG = 10 \cdot \log(n), \qquad n = sequence\ length$$

A designer can use this relation to determine the length of a PR code necessary to achieve a given SNR or carrier supression. The chip rate will then determine the first nulls in the actual spread spectrum.

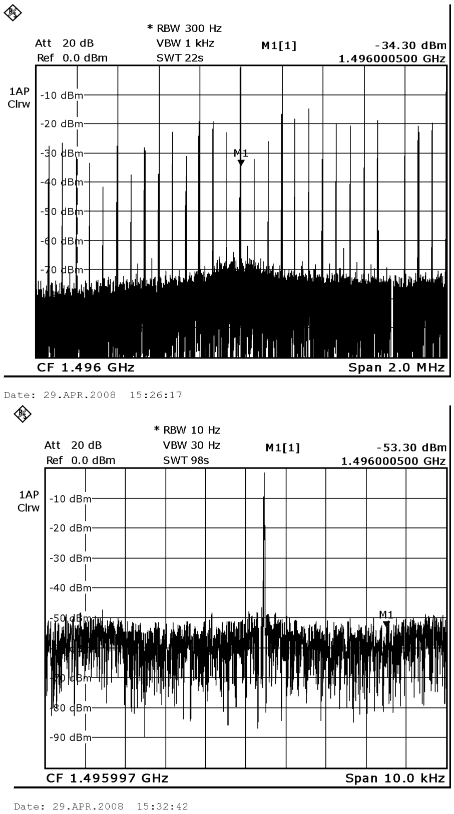

Figure 4. Reconstructed spectra for n=15 and n=65535. Processing gain (ie. SNR) follows the expected predictions of 12dB and 48dB, respectively, demonstrating the ability to spread and de-spread pilot tones to at-or-below the noise floor.

Linear Feedback Shift Register (LFSR)

Pseudorandom (PR) sequences are at the heart of cryptography and identity verification, which have each contributed countless methods for generating long PR codes. Although not completely random, in the strict sense, a good algorithm will produce a sequence (or set of sequences) which satisfy reasonable tests for randomness. These tests, or properties, include [5]:

Independence Property. Any preceding or subsequent sequence should not determine the present value.

Balance Property. There should exist an equal number of ones and zeros for the entire sequence.

Run Property. Continuous occurrences of all ones or all zeros should be minimized by $\tfrac{1}{2}^{(\text{number of consecutive occurrences})}$.

Correlation Property. Any bit-shifted version of a sequence should not cross-correlate with the original sequence.

For the application outlined in this paper, only loose adherence is required for the stated properties, allowing the use of a simple PR generation algorithm, known as a Linear-Feedback Shift Register (LFSR). A LFSR scheme uses a serial shift register of r bits, whose input is determined by exclusive-OR-ing (XOR) several of the output taps. Proper selection of feedback taps will result in a maximal-length sequence, which has a cycle length of 2^r-1, and inherently satisfies the PR properties [5,6]. A 16-bit (sequence length = 65535) LFSR algorithm was implemented on an Altera Cyclone II FPGA, with selectable sequence lengths, and clocked at 1 MHz [6].

DOWNCONVERTER

Replacement of the downconverter electronics will require that existing performance specifications are met. For this paper, the most relevant requirements are minimum and maximum beam loss values of 1 uA and 200 uA, respectively. Therefore, a minimum dynamic range of the system is 46 dB. As a proof-of-concept, we spread the pilot tone using a sequence of n=65535, thereby achieving at least 46 dB of processing gain. This resulted in the the supression of a 200 uA pilot tone to that of a representative BCM signal near 1 uA. The combined signals were then run through a de-spreader, reconstructing the pilot tone, but spreading the beam signal, as demonstrated in Figure 5.

It must be noted that mixer selection requires a very wideband (1 MHz – 1497 MHz) performance, particularly for the despreader. Several common units were tried, with varied output efficiencies. The output coupler provided a look at the simulated CW beam frequency with spread pilot tone, while the despreader output demonstrated the switch in spectra, maintaining 46 dB of SNR.

In practice, an additional 13 dB of margin is added so as to provide a S/N consistent with a false-alarm rate <=15min/yr (10^{-8}) [7]. A sequence of length n = 10^6 (20 bits) would then be required.

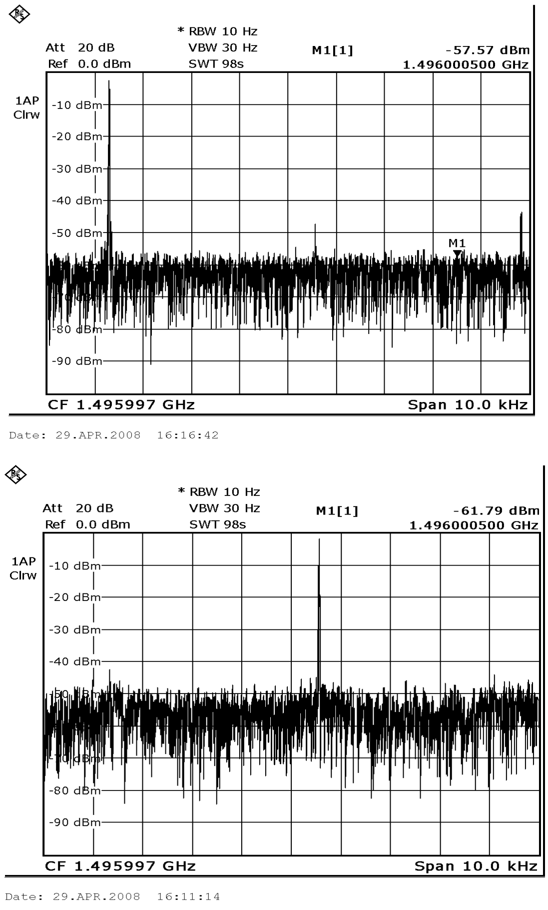

Figure 5. Signal representing beam is shown, with DSSS pilot tone, demonstrating 46 dB of supression (a). Upon reconstruction, the pilot tone re-emerges, while supressing the beam signal by the predicted 46 dB (b).

Figure 6 is the block diagram for the proposed 12 GeV downconverter, with pilot tone oscillator stabilization. Preliminary component analysis and SystemVue simulations are currently underway, and prototyping is expected for Summer, 2008.

IF RECEIVER IMPLEMENTATION

While the primary intent of the DSSS pilot tone was to provide downconverter gain stabilization and real-time performance information, it is not limited to synchronous demodulation. If the IF receiver is also capable of de-spreading the pilot tone, it can be used for comparative analysis with the demodulated beam cavity signal. Stabilization of the pilot tone oscillator to within the requirements of the BCM/BLA system (~0.25 dB) allows it to be used as an absolute reference, reducing the need for beam-based calibrations. The CEBAF BLA system uses a dual-channel, direct-digital downconverter receiver for IF signals. Currently, only one channel is used, with minimal processing. Since the DSSS pilot tone is present, along with the beam signal, it is possible to dedicate one receiver channel for de-spreading and detection of the DSSS tone. An approach commonly used for asynchronous despreading is known as a delay-locked loop [DLL], whereby a promptly arriving signal is compared with one which is ½-bit early and ½-bit late [5]. A triangular correlation function is produced by differencing the early and late signal amplitudes obtained by the correlator, which then adjusts the clock rate. The prompt signal emerges perfectly de-spread, since it is fed by the properly aligned sequence.

We would exploit the fact that only a few codes are used, and there is never more than a single DSSS signal present on any given BCM channel. Subsequently, all utilized codes (in the form of their LFSR implementations) reside in each IF receiver, and is tested by “sliding” against the incoming signal. If no match is found, the next LFSR code is tried, and so on. Each IF receiver is able to independently determine to which downconverter and cavity system it is connected, and applies the appropriate scaling constants, etc.

Oscillator stabilization could be accomplished through the use of a dual-channel, logarithmic comparator, used for cellular communication base stations. Although the ADL5519 is a wide-band part, narrowband stability over wide temperature ranges appears promising, with data sheets suggesting <0.25 dB stability, sufficient for use as an absolute reference to 1%. Frequency stabilization is not required; free-running oscillators for pilot tone and LO are acceptable, since no phase-sensitive measurements are performed. This removes any requirements for Master Oscillator signals.

CONCLUSIONS

DSSS provides a convenient method for creating orthogonal signals for pilot tone injection, as well as mulitplexing signals on a single channel. This work demonstrated the feasibility of simultaneously detecting beam and pilot tones, thus providing performance feedback for stabilization. In addition, real-time calibration and confidence testing can be run while beam is present in the accelerator. The choice of frequencies used in the demonstration were arbitrary, and are easily extended to many applications. The use of independent, free-running oscillators also demonstrated worst-case, asynchronous operation.

ACKNOWLEDGMENTS

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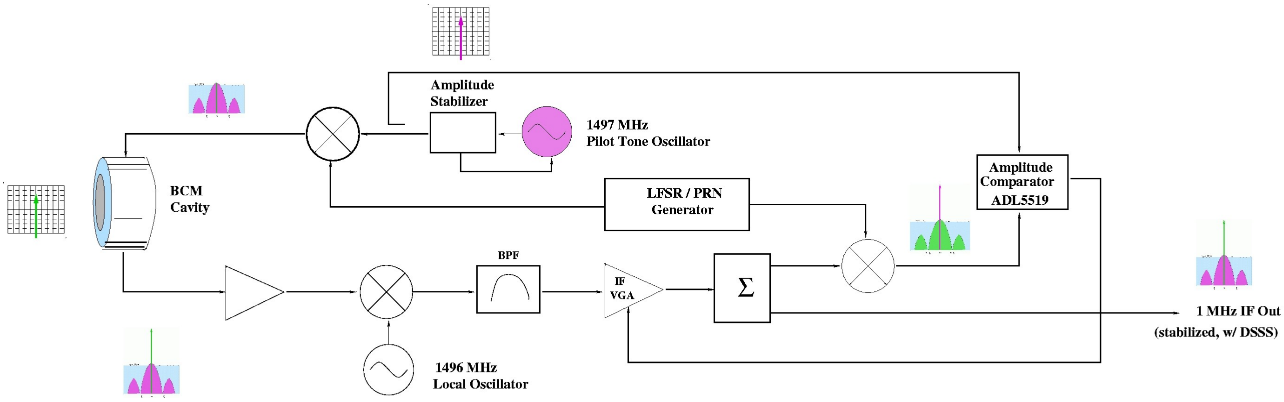

Figure 6. Block diagram for proposed downconverter. A 1497 MHz pilot tone is spread, and combined with the 1497 MHz beam signal, in the cavity. Despreading facilitates orthogonal detection of the 2 separate signals, for the purpose of gain stabilization.

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