Modified M-Sequence UWB-Radar

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***Short Abstract* — This article demonstrates some improvements of a basic M-Sequence approach for ultra wideband (UWB) high resolution radar. These improvements consist of the enhancement of equivalent sampling rate and an improvement of the overall measurement bandwidth. The presented method permits the omission of RF anti-aliasing filters, which drastically increases the operational flexibility of the radar.**

Keywords - ultra wideband; M-Sequence; sub-sampling; high resolution radar

I. Introduction

The goal of UWB radar is to provide the impulse response function (IRF) of a scenario under test. The quality of a measured IRF is mainly determined by the ability to separate closely located peaks and to avoid masking of smaller peaks due to noise or saturation effects caused by larger peaks. The first problem is a question of available bandwidth and the second one depends on the dynamic range of the receiver and transmitted power.

The classical UWB approach is based on impulse excitation, which implies that the whole transmission chain is burdened with high peak power shocks. Mainly analogue circuits tend to overload or saturate in such cases. Thus, the system performance degrades. In order to stress the electronics evenly, one is recommended to use continuous wideband signals. Typical examples of such signals are swept or stepped sine waves [1], [2], random noise [3], [4], [5], pseudo-noise (PN)-sequences, or others. However, this kind of target stimulation will not provide the IRF directly. It rather requires an appropriate impulse compression technique (i.e. Fourier Transform, correlation, or matched filtering), which is often the challenge for the different system concepts. After impulse compression, the even energy distribution of the signals is lost in order to form short impulses. Thus, the best one can do, is to carry out impulse compression in the digital domain. Digital dynamic range is only limited by the utilized number format, which usually can be selected freely.

A new UWB concept dealing with continuous wave excitation, a largely reduced analogue circuit part and a minimum of components was first introduced in 1999 [6]. It provides M-Sequence signals to stimulate the test objects. This original approach forms the basis for different extensions and improvements. At the current stage of development, the basic M-sequence modules can operate up to 7.5 GHz measurement bandwidth. Typical application covers the band from nearly DC to about 4 … 5 GHz. A first modification was introduced by adding an up-down conversion in order to shift the operational band to an arbitrary frequency band (e.g. 3 …. 10 GHz [7], [8] or 57 … 63 GHz [9]). The goal of this article is to introduce a further modification, which greatly improves the operational flexibility and basically triples the useable bandwidth of the basic module.

After a short summary of the basic M-Sequence concept, the introduced modifications will be explained and their effect will be demonstrated. Finally, some measurement results from an experimental system will be shown.

II. Basic M-Sequence Concept

Fig. 1 represents the basic configuration of an M-Sequence radar. For a detailed description of the working principle, the reader is referred to [10]. Here, only a short summery will be given: a single tone RF-clock pushes a shift register, which provides the stimulus signal, and a binary divider, which controls data acquisition. The shift register generates a PN-sequence defined by its internal feedback structure. An M-Sequence is a good choice in order to get a stimulus with a very short and clear auto-correlation function. Since PN-sequences are of periodic nature, data acquisition can be undertaken by means of a sub-sampling technique, which drastically reduces the technical requirements of the receiver electronics. An M-Sequence is composed of 2^n-1 chips and the binary divider takes care that after 2^m signal periods, one data sample has been taken from every chip of the sequence. This corresponds to an equivalent sampling rate of f_c, which results in a usable bandwidth from dc to $f_c/2$ according to the sampling theorem. The M-Sequence contains about 80% of its total energy within this band.

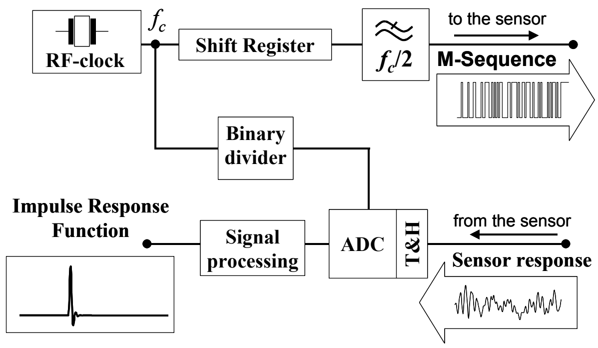

Figure 1. Basic M-Sequence concept using digital impulse compression.

Thus, from an energetic point of view, an increased equivalent sampling rate (i.e. higher receiver bandwidth) will only gain a small performance improvement since the captured noise power will dominate increasingly over the signal. Impulse compression after signal acquisition is undertaken either by Fast Hadamard Transform (i.e. a cross correlation referring to the ideal M-Sequence) or by Fast Fourier Transform. In this case a reference channel collects the actual transmitted waveform. The Fast Fourier Transform is more time consuming than the Fast Hadamard Transform, since the number of data points is not a power of 2. In the case

of the M-Sequence of the orders 6, 8, and 12, the performance degradation is, however, quite low [11].

The key features of the minimal configuration as shown in Fig.1 are excellent time stability and linearity of the time axis (note, the timing control exclusively deals with steep slopes and a stable single tone RF-oscillator) and all analogue signals exhibit low signal levels, which promotes an integration in a low-cost semi-conductor technology such as the SiGe-process.

By selecting the RF-clock rate, the bandwidth of the radar system can be matched to the actual needs, which already provides for great flexibility in its application. However, residual spectral power components of the M-Sequence are still to be found beyond $f_c/2$ making it necessary to use an anti-aliasing filter in order to satisfy the sampling theorem. In practice, this requires new filter designs every time the clock rate is changed and it will not be possible to arbitrarily change the RF-clock, i.e. in order to reduce interference and interception. In what follows, it will be shown how to avoid this inadequacy.

III. Increasing the Equivalent Sampling Rate

In order to be able to waive the anti-aliasing filter, natural frequency limiting effects, namely the final bandwidth of the sampling circuit and the generated M-Sequence, need to guarantee satisfaction of the sampling theorem. However, their bandwidth is usually far beyond $f_c/2$, particularly if one recalls that the considered cutoff cannot be a 3dB-point, rather the signal must be damped down to the actual noise level, e.g. -60 dB … -100 dB depending on the averaging number.

As a result, without an appropriate filter, the equivalent sampling rate must be largely increased. Or in others words,

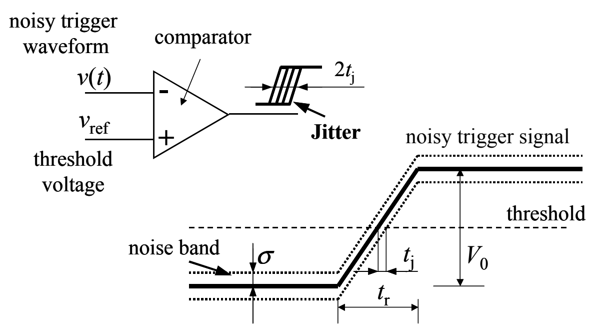

Figure 2. Generation of time instabilities, i.e. jitter or drift, by triggering with noisy ramps. Note, that variations of the trigger level result in the same effect as a perturbed waveform.

one has to take more than only one sample from each chip of the M-Sequence as in the basic system. For that purpose, either a controllable phase shifter can be inserted in the clock line before the binary divider or a steerable (pulse) delay circuit after the binary divider can be used to additionally retard the sampling clock. In both cases, the maximum variation of the additional delay is restricted to the length of one M-Sequence chip $\Delta t_{\max} = 1/f_c$. Since the number of necessary delay steps is also quite limited (usually less than 10), numerous circuit concepts can be employed, i.e. switched lines, stacked gate delays, "delay" ramp[1], phase shifters, IQ-modulators, or others.

It should be noted that by analogue methods such as phase shifters, IQ-modulators or a delay ramp, very small delay steps can be adjusted. In all these cases, an (sampling-) event is released, if the trigger waveform (sine wave or ramp) is crossing a threshold. Referring to Fig. 2, the uncertainty t_j of the trigger event is approximately given by:

$$t_j \approx \frac{\sigma}{c_v}. \tag{1}$$

Herein, σ represents the rms-value of noise and c_v is the slew rate of the trigger waveform. This results in a *relative* reproducibility of trigger events depending on the *SNR*-value:

$$\frac{t_j}{t_r} \approx \frac{\sigma}{V_0} \approx \frac{1}{\sqrt{SNR}} \tag{2}$$

in the case of a linear ramp, and

$$\frac{t_j}{T_0} = t_j f_0 \approx \frac{\sigma}{2\pi V_0} \approx \frac{1}{\pi\sqrt{8SNR}} \tag{3}$$

for a sine wave of frequency $f_0 = 1/T_0$ and a zero threshold. Obviously, the absolute stability t_j of the delay time degrades, if the maximum control range (t_r or T_0) increases. Many classical UWB approaches suffer from this effect.

In the case considered here, the control range of the delay circuit only extends over one period of the RF-clock rate, which is usually well below 1 ns; typically it is in the order of 100 ps. Thus, the additionally introduced delay circuit will not affect the time stability of the M-Sequence system.

The data acquisition of the modified M-Sequence approach is organized in the following manner:

1. The complete period of the M-Sequence is gathered as usual, i.e. one sample per chip, while the delay circuit keeps its delay time constant. The procedure can be repeated in order to reduce noise by averaging.
2. The delay time is changed by a portion of the RF-clock period length and the measurement procedure of step 1. is repeated. Delay time variation is carried out until a whole RF-clock

[1] The "delay" ramp method can be used to retard a pulse flank. The flank to be delayed starts a voltage ramp releasing a new impulse by crossing a trigger threshold. The delay control can be made either by variation of the ramp slope or by shifting the threshold voltage.

period is covered by fine and equidistant delay steps.

3. The data samples must be reordered into their natural order.

The result is a data vector of increased length with increased noise for individual data samples. The increase of noise results from two effects. First, the number of averages per measurement point must be reduced in order to keep the overall measurement time constant. Second, large areas of the spectral band additionally captured by the new approach do only contain a small amount of signal energy. Thus, it is advisable to low-pass filter and down sample the data before other processing steps are undertaken. In contrast to the basic approach, low pass filtering can now be made in the digital domain. This gains the new flexibility to arbitrarily choose filter type and width of passband without changing any hardware. The resulting signal vector after this pre-processing will have a comparable length and *SNR* as would have been captured by the basic M-Sequence module.

IV. INCREASING THE STIMULUS BANDWIDTH

In the case that the Track & Hold circuit (T&H) has a large input bandwidth, the enlarged equivalent sampling rate can also be exploited to increase the measurement bandwidth of the system, if the stimulus can excite the spectral band beyond $f_c/2$ with additional signal power. A simple way to do this is by mixing the M-Sequence with its RF-clock (see [7], [8]), which shifts the spectral band to higher frequencies centered around f_c. However, the low frequency parts are lost. By appropriately adding the original M-Sequence to the up-converted one, this loss can be removed. Fig. 3 shows the corresponding block schematics of such an extended M-Sequence system. Fig. 4 contains a simulated spectrum and the resulting auto-correlation function of a continuous M-Sequence. It is compared to the basic M-Sequence approach. The auto-correlation functions were calculated from truncated spectra as they appear typically at the corresponding approach.

The modified sampling approach theoretically permits a nearly “continuous” representation of the autocorrelation

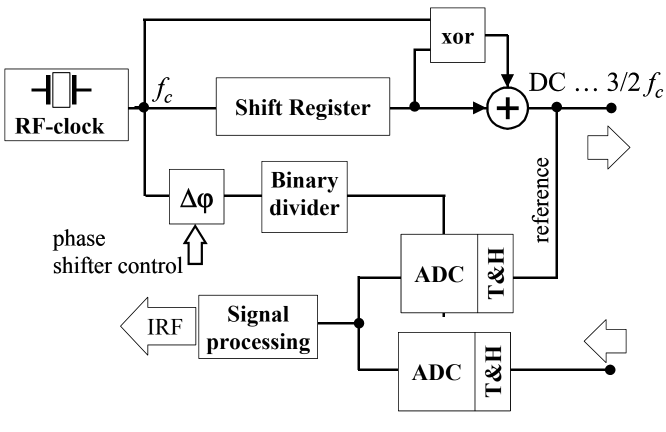

Figure 3. Block schematics of the extended M-Sequence. Note, that the phase shifter at the input of the binary divider can be replaced by a delay circuit which can also be placed at its output.

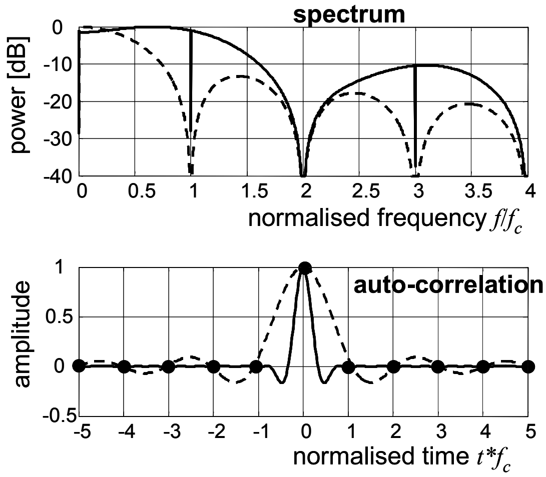

Figure 4. Idealized spectrum and (continuous) auto-correlation function of the basic M-Sequence- (dashed line) and extended M-Sequence-module (solid line). The auto-correlation function was calculated after truncation of the spectrum at $f_c/2$ (for the basic approach) and at $2\,f_c$ (for the extended approach), respectively.

function whereas the basic sampling method restricts the actual gathered data to the emphasized points.

Signal multiplication and addition can be made by a wideband mixer and a power divider. However, the better solution would be to use an XOR-gate and a difference amplifier instead, if an integrated circuit implementation is intended. As the estimation in Fig. 4 shows, the usable bandwidth can be extended from dc to $1.5\,f_c$ as long as the T&H-circuit can handle this bandwidth at its input.

It is wise to work with a reference channel, which acquires the actual time shape of the stimulus, since its structure is not as clear as in the case of the basic approach.

V. EXPERIMENTAL VERIFICATIONS

First trials were undertaken by using the available system components of the basic M-Sequence module [12] (still including the anti-aliasing filter), completed by a commercial double balanced mixer with about 4 GHz IF-bandwidth and a power divider for signal superposition. In order to avoid a spectral gap between the baseband and the modulated M-Sequence, the RF-clock f_c was chosen to be below 8 GHz due to the limited bandwidth of the mixer. For the experiments, a 7 GHz clock was used. Fig. 5 presents the spectrum of the generated waveform measured by a spectrum analyzer. The cutoff of the spectral energy at about 10.8 GHz is mainly due to mixer limitations and the retained low-pass filter.

The usable band up to about 11 GHz requires an equivalent sampling rate of at least 22 GHz in order to respect the sampling theorem. As mentioned above, the equivalent sampling rate provided by the binary divider is always f_c, i.e. 7 GHz in our case. Thus, the measurements needed to be repeated with 4 different phase values (e.g. 0°, 90°, 180° and 270°) to increase the equivalent sampling rate to 28 GHz. The actual rate of data acquisition (ADC-clock) used for the experiments was about 14 MHz.

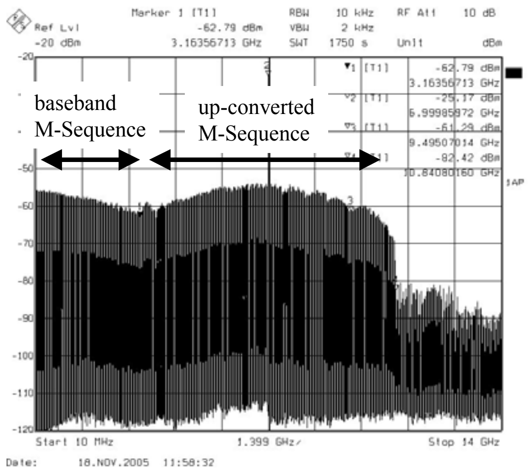

Figure 5. Spectrum of the generated signal.

Fig. 6 shows the measurement results. The spectrum calculated from the acquired data coincides well with the measurements of the spectrum analyzer. This indicates that the T&H-circuit does not yet limit the bandwidth of the system. The auto-correlation function shows a well pronounced sharp peak (FWHM-value of 71,4 ps) with two side lobes. They are still a bit disturbing, but they can be reduced by appropriate post-processing as well as better realizations of the mixing and superposition hardware.

VI. CONCLUSION

Some extensions of the basic ultra wideband M-Sequence radar principle were introduced. By adding a programmable phase shifter or a short delay line, the equivalent sampling rate of data acquisition can be increased. This enables broader operational bandwidths and helps to omit RF anti-aliasing filters. The bandwidth improvements were gained by shifting the spectrum of the M-Sequence to a higher band via mixing with the clock rate of the shift register and superimposing the resultant signal with the original M-Sequence.

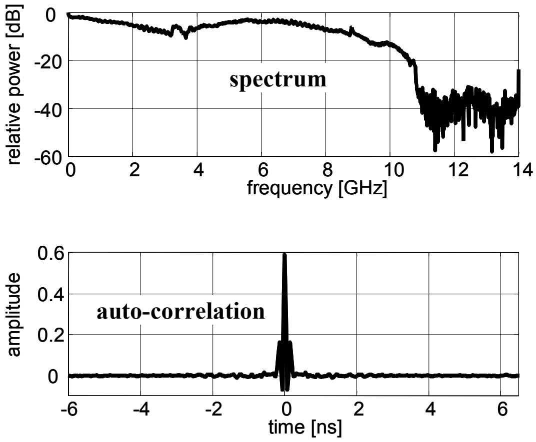

Figure 6. Spectrum and auto-correlation function determined from a data set acquired with an equivalent sampling rate of 28 GHz. The carrier frequency (due to the LO throughput of the mixer) as well as the DC components have been removed from the data.

It should be emphasized, that the approach gains a higher bandwidth by keeping the same semi-conductor technology. If the basic M-Sequence method is able to provide a sufficient bandwidth for a certain application (i.e. less than 7 GHz at the current stage), the presented methods permit to change to a less sophisticated RF technology. Especially power consumption can be reduced due to lower clock rates.

The renouncement of RF-anti-aliasing filters greatly increases the operational flexibility of the M-Sequence system, since an arbitrary clock rate can be selected without the need of any hardware changes.

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