Stimulation of UWB-Sensors: Pulse or Maximum Sequence?

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Abstract—**The stimulus signal applied in UWB sensors has the decisive influence on the architecture of the UWB sensor electronic. The aim of the article is to compare different UWB methods that apply different perturbation signals on the base of their elementary device architectures. For that purpose, different performance parameters are summarised and their dependence on structural elements of the system architecture is discussed.**

***Index Terms*—UWB-sensor, pulse excitation, maximum sequence, undersampling**

I. INTRODUCTION

THE signal applied in UWB sensors to stimulate the test objects has a decisive influence on the whole architecture and the behavior of the sensor electronics. Independently from the actual use of an UWB sensor, the fundamental task of the RF measurement electronics is to provide data from which the impulse response function (IRF) and respectively the frequency response function (FRF) of the objects under test can be determined.

A sensor arrangement in our sense is a configuration of electrodes (antennas) which interact with the scenario under test. The goal of such a measurement is usually to get information about the geometrical or material state of the test objects and respectively its variations. Such systems behave mostly linear. Moreover, they can be considered as time invariant as long as the duration necessary to collect all data to determine a response function is short enough compared to the temporal change of the system parameters. In what follows, we will consider a sensor arrangement which approximates to a LTI (linear time invariant) system.

From theory, it is well known that all external accessible information about the internal states of a LTI system are encoded in the response functions IRF and respectively FRF. Both functions contain the same information and both can be mutually converted by the Fourier transform. Furthermore, the theory says that a LTI system can be stimulated by a signal of any shape in order to gain one of its response functions. The stimulus may have any shape, however its bandwidth must exceed that of the object under test.

This fact opens up a great deal of different measurement approaches. Thos mostly applied are:

- the sweep or step sine technique
- the pulse excitation
- the stimulation by pseudo random codes, and
- natural noise.

All of these methods have advantages and disadvantages but for general purpose sensors with volume application many principles are excluded due to cost, size, power consumption etc. and respectively due to insufficient technical parameters. Currently, three principles seem to be favoured in UWB sensor applications. These are the FMCW-method, the pulse technique and the MLBS (maxim length binary sequence) approach.

The FMCW-method however only provides the real part of the FRF which results in incomplete information about the test object. Thus, this method is only useful for simple measurement tasks such as distance measurement and will therefore be excluded from the following considerations.

II. ASSESSMENT PRINCIPLES

In order to decide in favour of a certain measurement configuration – pulse or maximum sequence or even others - for a specific application numerous aspects must be considered carefully. In what follows some points of assessment will be shortly summarised.

Bandwidth: This is certainly the key parameter which provided the name of that technique (UWB). The challenge is to provide a large bandwidth at a low central frequency.

SNR; dynamic range: The dynamic range of a measurement system is limited by the noise (random and quantisation) at the lower end and by saturation effects at the upper end. The maximum SNR value can be used to quantify this range. It is given by (1)

$$SNR = \frac{E}{N} = \frac{\eta P_{av} T_m}{N} \tag{1}$$

where E is the total accumulated energy during the measurement and N is the spectral noise power density.

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Measurement time T_m: The time T_m needed to accumulate this energy refers to the time over which the object is "observed" to get one of the response functions. Referring to (1), it is closely connected to the efficiency η of the measurement device and the average power P_{av} of the stimulus which is usually limited by overloading of any system component. During the measurement time T_m, the measurement arrangement should behave time invariant. This is approximately given if there is no motion within the test scenario which speed v exceeds the limit

$$v_{\max} < \frac{c}{4 T_m B} \tag{2}$$

herein c corresponds to the propagation speed of the wave und B is the bandwidth of the stimulus.

Spurious level: If the transmission of a simple wideband delay line is measured then it results in an IRF consisting of a sharp pulse having a flat base line. Deviations from such a flat base line are either given by noise or by spurious signals. In contrast to noise, spurious signals show a deterministic behaviour. Nevertheless, they limit the dynamic range of the system as long as they cannot be removed from the measured data.

Jitter: Jitter occurs by low-Q-oscillators or by flank triggering if for example a noisy voltage ramp (characterised by v_V - speed of the voltage rise [mV/ns]; n - rms-value of additive noise [mV]) crosses a threshold. Equation (3) gives an estimation of the rms-jitter t_j [ns] caused by triggering at a flank.

$$t_j = \frac{n}{v_V} \tag{3}$$

Measurement architectures based on a single tone frequency reference (high-Q-oscillators) or steep flank triggering show major jitter suppression.

Drift: Drift phenomena concern time and respectively frequency stability, offset variations and changes in the (complex) gain. Sophisticated signal processing requires high long term stability of devices particularly if correction of systematic errors is included. Note, the time drift of trigger events can be estimated by a relation such as (3) if it is caused by temporal offset changes of a threshold or a ramp (compare Fig. 2 below).

Non-linearity: Both abscissa value (time or frequency) and ordinate value (magnitude) may be subjected to a non-linearity which cause spurious signals due to signal processing. The non-linearity of magnitude values is mostly caused by saturation and respectively limiting effects of amplifiers or others. Non-linear errors of abscissa values are usually caused by simple analogue sweep methods for signal gathering.

The parameters mentioned above are certainly the most important but not all which should be considered. Further aspects concern power consumption, size, weight, robustness, costs, availability and others. These things are important issues for large scale applications. They have to be considered carefully for the actual case.

Last but not least, the operational mode in mind can pose some prerequisites on the system architecture. Thus, further questions can arise as for example: Must strong perturbation signals be gated out? How many receiver and stimulation channels are necessary? Are there special constraints regarding the synchronisation between different measurement channels? Should an error-correction be applied? … and so on. It can be expected that error-correction procedures as known from network analysers will play an increasing role also in UWB-sensor applications. Thus the last of the above mentioned questions will gain in importance with future developments.

III. THE PULSE- AND MAXIMUM-SEQUENCE-APPROACH

Both the pulse as well as the Maximum-Sequence-method belong to the so called time domain approaches. That means, the system under test is stimulated by signals having a large instantaneous bandwidth. The pulse train and the maximum sequence are periodic signals, thus the system response can be captured by an under-sampling principle. This reduces the technical requirements of the data gathering system. Fig. 1 shows the basic sensor structure which is common for both approaches.

The trigger source pushes the signal shaper which stimulates the sensor. The stimulus represents a wideband signal of period $T_0 = 1/f_0$ i.e. a pulse train or a maximum sequence. This value fixes the maximum length of the IRF respectively the step size of the frequency grid of the FRF. The sampling circuit captures the DUT response successively point by point. There are two basic sampling principles in use.

- Multiplicative sampling: A sampling strobe acts on a gate, which connects or disconnects the measurement signal with a hold capacitor. Two operation modes are distinguished – sample & hold respectively track & hold.
- Additive sampling: A strobe pulse is added to the input signal resulting in a voltage which can overcome a threshold. The difference value to the threshold gives the measurement quantity. The electronic circuits for additive sampling are very simple and power efficient but they are sensible to offset-drift and thus less usual for applications requiring stable electronics.

The sampling circuit is triggered by the digitising rate f_{sa} which can be quite low in the case of under sampling. Only a few points or even less can be captured during each period of the stimulus signal. Supposing the DUT response (i.e. the IRF) is measured in a regular time grid with spacing Δt_s corresponding to an equivalent sampling rate $f_s = 1/\Delta t_s$. This would result in $N_s = 1/f_0 \Delta t_s$ equally spaced data points within

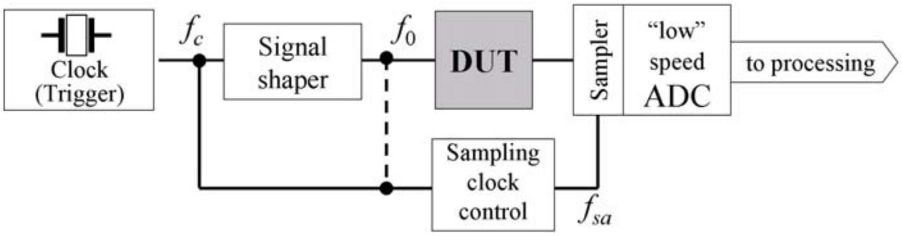

Fig.1 Basic device architecture for the time domain approach. The sampling clock control system may be triggered either from the main trigger (solid line) or directly from the signal former (dashed line). The arrangement of sensor electrodes and the scene under test are summarised by the DUT.

one period of the stimulus. It can be shown, that any sampling rate fsa can be chosen which respects (4) in such a way that N_s and u_{sf} don not have a common divider.

$$u_{sf} = \frac{f_s}{f_{sa}} = N_s \cdot \frac{f_0}{f_{sa}} \quad (u_{sf}, N_s \text{ integer numbers}) \tag{4}$$

herein u_{sf} is the under sampling factor. With exception of a special case – the sequential sampling - the natural order of the data samples will be generally destroyed. They must be reordered before the next processing steps can be undertaken. Sequential sampling occurs if $u_{sf} = n \cdot N_s + 1 \quad (n = 1, 2, 3, \cdots)$. Following (2), a measurement device which works with under sampling limits the maximum target speed to

$$v_{\max} < \frac{c}{8 N_s u_{sf}}, \tag{5}$$

if no averaging is applied. It should also be mentioned, that under sampling reduces the efficiency $\eta \sim 1/u_{sf}$ of a receiver which leads to an increased measurement time (see (1)).

The main differences between pulse and maximum sequence approach consists in three points:

- the configuration of signal source,
- the method of sampling strobe control, and
- the nature of the gathered data.

The pulse approach: The usual pulse sources are fast switches, avalanche stages, step recovery diodes or tunnel diodes. Clock rate f_c and the repetition rate f_0 of the stimulus are always the same. The peak power of the pulses is crucial for the dynamic range. Thus the electronics has to cope with high voltage or high current shocks which poses problems for monolithic circuit integration. The energy provided by an individual pulse of amplitude V_p and width t_i is approximately

$$E_p \sim V_p^2 t_i \tag{6}$$

The signal capturing is based on a sweep process. The crossing of a ramp which is triggered by the stimulating pulse with a moving threshold releases a sampling pulse (see Fig. 2). This is a proven and effective approach used in sampling scopes and similar devices. However any imperfections of the ramp, of the threshold or of the comparator causes timing errors. That is why a big effort is necessary to stabilise the sampling pulse generation i.e. to linearise the ramp and to avoid offset-drift and noise (threshold, ramp, comparator) in order to limit time drift and jitter. Due to the slow voltage rise of the ramp this is a true challenge (compare (3)). Usually the chosen equivalent sampling rate exceeds the requirements of the Nyquist theorem by many times in order to provide a continuous curve on the screen.

The main advantages of the previous method is its "relative" simple circuit implementation. It is a widely introduced and known principle, which can be designed for a very power efficient operation. Diverse commercial available devices cover a bandwidth of one GHz to tens of GHz. 100 GHz bandwidth is announced. The sampled data represent immediately the IRF of the scenario under test, thus there is no data processing required for simple applications. Furthermore strong, perturbing signals with a fixed time position can be gated out as long as they do not coincide with the wanted signals. The above mentioned points are however opposed by some critical aspects. These are:

- the low time stability (drift and jitter) which prevents a sophisticated signal processing and error correction,
- a non equidistant sampling interval (non-linear ramp) which causes signal distortions, and
- the handling of short high-power signals, which complicates a monolithic integration.

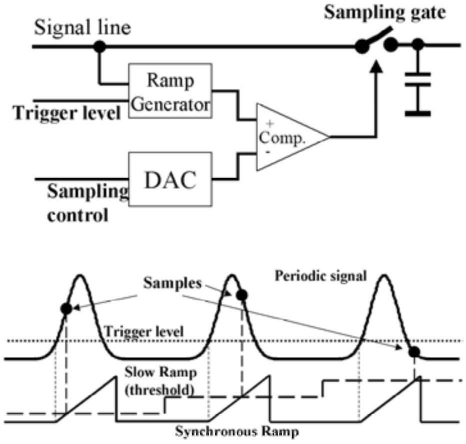

Fig. 2 Strobe control for sequential sampling by a ramp and a moving threshold

The maximum sequence approach [1] –[4]: The stimulus signal is a maximum sequence which is provided by a digital shift register which is appropriately fed back. Let us suppose the shift register is built from *n* flip-flops and it is pushed by the clock rate f_c. One period of the provided output signal consists of $N=2^n-1$ chips of width $t_c = 1/f_c$. This results in a stimulus repetition rate f_0 of

$$f_0=\frac{1}{T_0}=\frac{f_c}{N}=\frac{f_c}{2^n-1} \tag{7}$$

The power spectrum of a maximum sequence has a sinc^2-shape with zeros at f_c. Nearly 80 % of signal energy is concentrated within the range from DC to $f_c/2$. If V_{ms} is the amplitude of the maximum sequence, the total energy provided by one period is

$$E_{ms}\sim V_{ms}^2\,T_0=V_{ms}^2\left(2^n-1\right)t_c \tag{8}$$

Compared to the pulse approach this gives a reduction of signal amplitude by the factor

$$\frac{V_p}{V_{ms}}\approx 2^{n/2} \tag{9}$$

under identical conditions. The use of low voltages results in a short switching time of the circuits and it promotes monolithic circuit integration which again improves the RF behaviour of the electronics.

The sampling pulse generation can be undertaken in a surprisingly simple and above all stable way. It should be underlined, that stability is a general prerequisite to use any UWB-method in applications with sophisticated post-processing. As mentioned above, most of the spectral energy is below $f_c/2$. Consequently, the restriction to this band would scarcely limit the performance of the measurement principle. Thus, in order to respect the Nyquist theorem, an equivalent sampling rate of f_c would be sufficient. This gives $N_s = N = 2^n-1$ data samples. In analysing (4) it is obvious, that any under sampling factor $u_{sf} = 2^m$ can be used since N_s can never be divided by 2.

Therefore the strobe clock control is built from a simple binary divider (compare Fig.3). The number m of divider stages can be chosen arbitrarily according to the requirements of the measurement speed or the processing capacity of the following stages. This approach guaranties an absolute linear time grid of sampled data and a superior jitter and time drift performance. All processes controlling the data gathering as well as the stimulus generation are based on triggering by steep flanks from which the jitter and time drift suppression profits. Furthermore, the absence of any variable frequency source contributes to the stable operation of the measurement system.

An operational bandwidth exceeding 1 GHz is hardly to reach by commercial components. That is why a monolithic circuit integration is recommended for a higher bandwidth. Depending upon the semiconductor technology applied, a maximum bandwidth of tens of GHz can be expected. Fig.3 shows an example of a RF-front end which is used to run an UWB-array for mine detection (European project: ESPRIT 29902 DEMINE [5]; IST-2000-25351 DEMAND). Circuit integration and the simple control of shift registers makes it easy to build multi-channel arrangements and respectively arrays without RF-switches. Every stimulation channel has its own signal generator (shift register) which is switched on/off by a TTL enable-signal.

The maximum sequence approach requires a signal processing since the captured data cannot be immediately interpreted as in the case of the pulse approach. On the other hand, it promotes the use of digital processing due to its stability which is comparable to that of a network analyser. The power consumption of the RF-front end exceeds that of a power optimised pulse front end. However, it is still low compared to the usual power needs of digital post processing. Thus, it will not excessively burden the overall power budget.

I. SUMMARY

The goal of the previous consideration was to compare two UWB methods – pulse and maximum sequence – on the base of their elementary device architectures. For that purpose, different performance parameters were summarised and their dependence on structural elements of the system architecture were discussed. With regard to the above mentioned facts it can be concluded:

- UWB-systems based on the pulse approach are advantageous in applications in which the power consumption is a critical parameter and which require only a simple - preferably non digital - data interpretation.

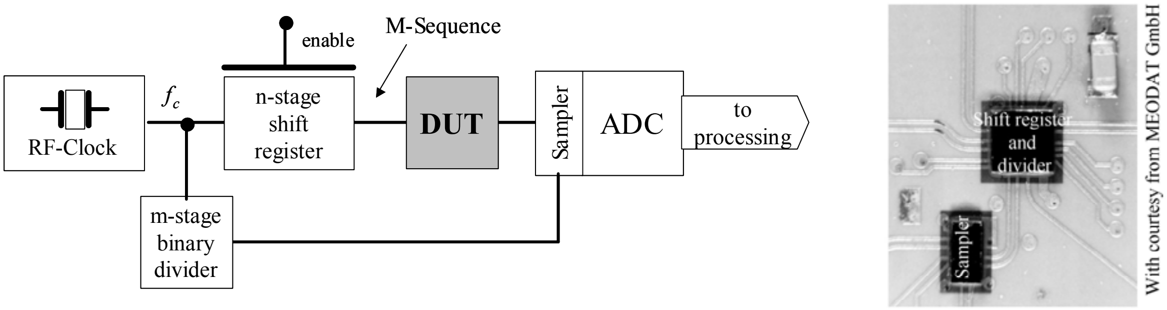

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Fig. 3 Block schematics of the maximum sequence sensor head and example of a RF-front end manufactured in SiGe-technology and multi-layer low temperature co-fired ceramics (LTCC). The operational bandwidth is about 5 GHz.

- The maximum sequence approach is advantageous where a sophisticated data processing is needed and highly stable data are required. Power restrictions should play an inferior role in such applications. Furthermore, due to the well distributed signal power, the base band module can be used in conjunction with modulators to shift the stimulation spectrum to a higher frequency band (carrier based systems).

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