Combined Frequency and Time Domain Moisture Sensing by an Ultra Wideband IQ-M-Sequence Approach

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ABSTRACT: Current activities to regulate the emission of electromagnetic waves in the spectral band up to 10 GHz for sensor applications opens new perspectives for microwave moisture sensing. Therefore, improved and cost effective ultra wideband measurement principles become more and more of interest. The article deals with two variants of an M-Sequence approach which permit a bandwidth beyond 10 GHz. Different versions of data representation in the time and frequency domain will be shown by means of simple measurement examples.

Keywords: M-Sequence, ultra wideband, quadrature modulation, time domain reflectometry

1. Introduction

Moisture sensing by electromagnetic waves is undisputed an interesting measurement approach due to its non-destructive nature, easy handling, continuous and fast operation and further more. But it is also an indirect measurement method and by that it suffers from multifaceted cross sensibilities to unwanted physical parameters and phenomena. There is no way to completely prevent from these ambiguities. However as a general rule of thumb, one can reduce the ambiguities by collecting as much as versatile data from the material under test (MUT) and to gain the wanted information by applying these data to an appropriate model of the MUT. If one is restricted to exclusively electromagnetic sounding signals, the data versatility can only be achieved by measuring over a large frequency band.

Different substances or substance components are usually connected to a specific frequency behaviour. Thus, one can expect with some probability to be able to separate the water effects from superposed perturbation effects as long as the measurements were performed over a sufficient wide bandwidth. Furthermore, inhomogeneous material distributions and an irregular moisture profile provoke variations within the propagation path of the sounding wave which also strongly affect the frequency behaviour of the measurement date. Also here, wideband measurements can improve the measurement performance due to their ability of a high range resolution.

For practical applications, wideband measurements were often out of scope up to now because of the quite restrictive rules for radiation of electromagnetic waves and the need of sophisticated equipment. This situation is changing now:

- Currently the radiation rules are revised and adapted to today's demand. The FCC, the US radio regulation authority, has been relaxed the radiation restrictions for a couple of years. It permits radiations to about 10 GHz with an EIRP[1]-level of -41,3 dBm/MHz, excepted for the band from 1 to 3 GHz [1]. This frequency band is practically closed for sensor applications. In Europe and Asia, also some effort is made to find appropriate rules. The current situation in Europe is still confusing and difficult to predict. At the one hand, the European regulation authorities insist on quite restricted power levels (perhaps 10 or 20

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[1] EIRP - Effective isotropic radiated power

dB below the US limit) for large scale applications as the ultra-wideband communication (wireless USB etc.) in order to protect the existing communication systems against ultra wideband interference. On the other hand, they appear to be more "friendly" concerning applications which involve operations under controlled conditions and a low activity factor. The activity factor indicates an average value of simultaneously active devices referred to a specified area (e.g. per km²). So it seems for example, that the ETSI[2] will open the whole frequency band up to 12.6 GHz (without any frequency gap as in the US) for Ground Penetrating Radar (GPR) in the frame of trained professional use (controlled condition!) [2]. Comparable circumstances as for GPR can be observed also for other sensor applications e.g. microwave moisture sensing. But up to now beside the GPR-rules, there was no effort undertake to prepare appropriate radio regulation rules. Recently however, the ETSI has been established a new task group TG31C, which is charged with corresponding topics. The new task group covers notable European enterprises.

- The classical wideband measurement device is the network analyser. It offers extremely flexible measurement conditions and provides a high resolution and precision. Thus, it is widely used for wideband moisture sensing. However its cost, weight, size and handling banish it to the laboratory. Referred to certain aspects, the classical time domain reflectometer (TDR) represents an interesting alternative. But often, the cost effective devices only have a low bandwidth and suffer from drift phenomena which unfavourably affect the data processing. The current developments in the ultra-wideband technique and circuit technology open however new perspectives of devices concepts, which can overcome the indicated inadequacies.

The goal of the article is to familiarise the reader with a new device approach, which offers the opportunity to perform the measurements over a large frequency band respectively to adapt the spectral band to the actual need. As mentioned above, the frequency band covered by the sounding signal is important for the information which can be extracted from the measurements. It should be noted, that due to the (in general) linear[3] and time invariant nature of the considered MUTs the actual time shape of the sounding signals has no influence on the achievable information but rather on the technical implementation of the measurement device. This opens some flexibility in the device conception. The article will deal with ultra-wideband pseudo random codes, i.e. M-Sequences, as sounding signals. Their use enables a technical solution which is characterised by a highly integrated RF-part, a large bandwidth, a stable and drift free operation and a flexible operation due to the largely digital operation.

The basic idea of a M-Sequence device initially be intended for base band operations at e.g. 0 … 5 GHz is known from a couple of former publications, see [3]. In what follows, the current state of its development will be summarised and a measurement example will be demonstrated. Furthermore it will be shown how the operational spectrum of this device can be shifted to an arbitrary frequency band. The device concept involves an ultra-wideband IQ (inphase-quadrature phase)-down conversion, which results in the representation of complex valued time signals. A simple measurement example will illustrate what this means. The example refers to the frequency band from 3 to 10 GHz which is conform to the FCC radio regulation rules in the US.

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[2] ETSI – European Telecommunications Standards Institute

[3] Here, the term "linear" is considered concerning the behaviour of the MUT with respect to different sounding signals. In that sense, a system is linear if the law of superposition holds. That is, if the reaction of the MUT to a stimulus $x(t)$ is given by the function $y(x)$, than superposition implies $y(x_1(t)) + y(x_2(t)) = y(x_1(t) + x_2(t))$. The consequence is, that linear transformations as the Fourier transform, convolution etc. are permitted to apply.

2. The ultra wideband M-Sequence baseband module

For completeness and as starting point for the following consideration the basic approach of a M-Sequence (also called maximum length binary sequence) device will be shortly revised. The reader is addressed to [3] and [4] for details.

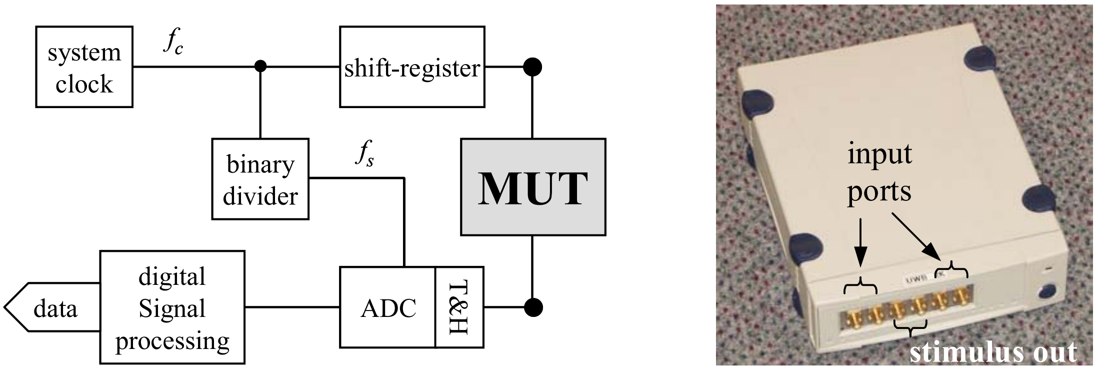

Fig. 1: Basic structure of the M-Sequence measurement head and photo of a device equipped with two receive channels and one stimulation port. The impedance of all ports is either 50 Ω for grounded operation (coax cable) or 100 Ω for symmetric applicators. The data exchange and the operational control act via an Ethernet interface.

Fig. 1 shows the elementary structure of a wideband M-Sequence device and a practical implementation. The M-Sequence – the stimulus signal of the MUT – is generated by a digital shift register, which is pushed by a stable RF-clock f_c. The shift register, binary divider and the T&H-circuit are manufactured in a low cost SiGe-semiconductor technology. Current designs permit a clock rate up to 15 GHz. This results in a maximum usable bandwidth of about 7.5 GHz. One of the most important features of the M-Sequence approach is, that the actual sampling rate f_s can be derived by a simple and stable way (i.e. by a binary divider) from the RF-master clock $f_c = 2^n f_s$ (see [4] for details). The digital signal processing can be freely adapted to the actual need, so that the provided data can be given in the frequency domain or the time domain (i.e. impulse or step response) or in some other form.

The baseband module provides signal energy from dc to $f_c/2$. Thus it can be profitably applied for TDR-moisture sensing since the probing cables do operate down to dc. Fig.2 summarises a TDR-experiment which involves symmetrically fed flat band cables. Two types were used:

- cable 1: conductor spacing 2,3 cm, flat conductors of 5 mm width, impedance in air 290 Ω;
- cable 2: conductor spacing 4,6 mm, round conductors of 0,8 mm diameter, impedance in air 240 Ω.

The length of both cables was 66 cm. However, only the central part of about 21 cm extension was surrounded by the MUT. The cables were left open at their end. The signal processing covers three parts: the correlation of the gathered data with a reference waveform in order to gain the impulse response function of the measurement arrangement; removal of systematic errors from the impulse response function and finally the temporal integration in order to gain the desired step response function. The results clearly show the water effect on the cable impedance as well as on the propagation time. Furthermore a detailed analysis (not shown here) of the open end cable reflections also indicates the growing suppression of high frequency signal components by increasing the moisture content.

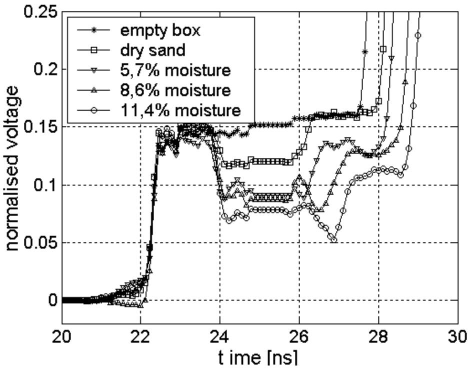

Fig. 2: Example of a TDR-measurement with cable 2 for moist sand.

3. The ultra wideband IQ-M-Sequence Approach

By adding an up-down-converter (see Fig. 3), the operational band of the M-Sequence head can be increased without turning to an improved (and thus more expensive) semi-conductor technology for the RF-components.

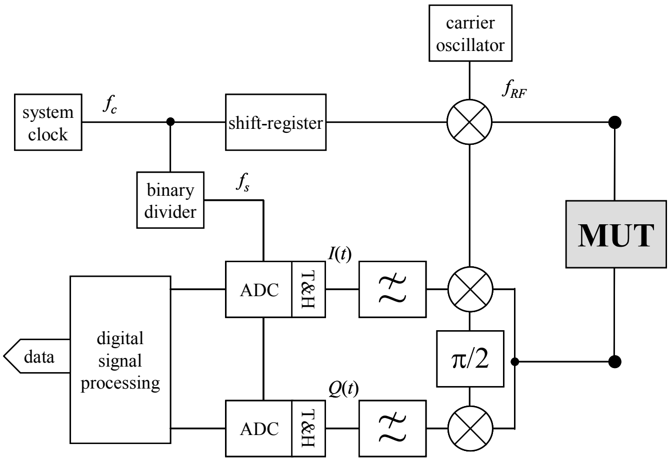

Fig. 3: Basic concept of a direct up- and down conversion via IQ-demodulation.

The key-components of the RF-front-end are commercially available double-balanced wideband mixers or Gilbert-cells. On the transmitter side, the spectrum of the original M-Sequence is shifted to a higher spectral band by mixing it with the carrier signal of frequency f_{RF}. This implicates that about 80 % of the stimulation energy is concentrated now in the frequency band $f_{RF} - f_c/2$ to $f_{RF} + f_c/2$. Thus, not only the spectral power is shifted to an arbitrary frequency band but also the usable bandwidth has been doubled compared to the baseband device.

On the receiver side, the captured signal is directly down-converted back to the base band by the carrier signal and then converted into the digital domain by the same approach as in the base band module. It should be remarked, that a simple direct down conversion causes some ambiguities due to the overlapping of spectral parts with positive and negative frequency.

This ambiguity can be overcome by introducing a second orthogonal channel. It is gained from a local signal which is delayed by a quarter period i.e. 90°. By doing that, one channel captures the parts of the measurement signal which are in phase with the carrier signal and the other one captures those which are in quadrature phase. This is a widely used principle, that is called IQ-demodulation.

The digital signal processing applied to the I- and Q-channel is quite the same as for the base band concept. That is, by subjecting the data to the Fast Hadamard Transform for example, one gets two impulse response functions $I(t)$ and $Q(t)$ characterising the behaviour of the test object. The usual approach is to joint both functions to a single, complex valued time domain function $\underline{Y}(t)$

$$\underline{Y}(t) = I(t) + jQ(t)\,. \tag{1}$$

The function $\underline{Y}(t)$ represents a kind of a complex envelope of the actual (real) system response $y(t)$, which is given by

$$y(t) = \Re\{\underline{Y}(t)\exp(-j2\pi f_{RF}t)\}\,. \tag{2}$$

A simple example shall illustrate the utility of a complex response function in the time domain. Let's consider for simplicity a wideband delay line of variable delay as measurement object. The shape of its complex response $\underline{Y}(t)$ will have a pulse form. The angle between the real and imaginary part is the same for the whole time. Thus $\underline{Y}(t)$ lies in a flat plane as demonstrated in Fig.4. The inclination of the "pulse plane" depends from the actual delay time of the test object. That is, if the delay time will be continuously increased, the tip of the pulse will move along a screw thread track having a "flank lead" corresponding the wavelength of the carrier signal f_{RF}. This leads to the opportunity of precise delay time measurements. If additionally the transmission channel is subjected to a frequency depended behaviour, the pulse will get an arbitrary shape in the t-I-Q coordinates (see next paragraph).

4. Modified IQ-M-Sequence measurement head

The basic concept of an ultra wideband IQ-system as demonstrated in Fig. 3 is not yet very practical. First, it still demands too much components and second it is quite difficult (if not impossible) to build a precise IQ-demodulator which is working over a bandwidth of several GHz. The key-point of an IQ-demodulator is the identical behaviour of both sub-channels I and Q. This cannot be guaranteed if the bandwidth exceeds the GHz-range.

Therefore it is proposed to deal with a single down-conversion channel and to remove the ambiguity by capturing the I- and Q-data one after another. This can be done by introducing a switchable phase shifter (see Fig. 5). In an experimental sample, the clock rate f_c of the shift register and the carrier frequency f_{RF} were chosen identically and fixed to 7 GHz. This implies an operational band which well coincides with the FCC rules for UWB radiation.

Due to the large bandwidth, it is impossible to build the sub-components with nearly perfect behaviour i.e. flat frequency response, constant group delay, matched ports etc. This will provoke systematic measurement errors even if all system components are properly designed. The only way to reduce these errors is to perform a system calibration as it is common in the work with network analysers. The prerequisite for a successful calibration is a time stable measurement device and the availability of sufficient reference objects with know behaviour. As shown in [5], the M-Sequence approach is time stable by principle. Thus for many applications, an initial device calibration should be sufficient over a long running time. The number and type of calibration standards strongly depends on the error types which should be eliminated and the required quality of correction. The wideband calibration of the IQ-down-converter is a challenging task since both signal paths are working in parallel and they don't have identical parameters. In contrast to that, the calibration of the modified IQ-down-converter is a straight-forward procedure since the I- and Q-channel are identical by principle.

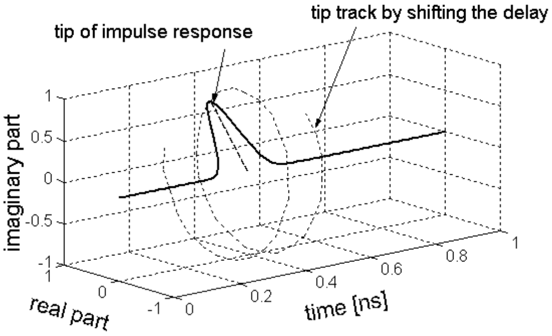

Fig. 4: The complex impulse response of a variable delay line

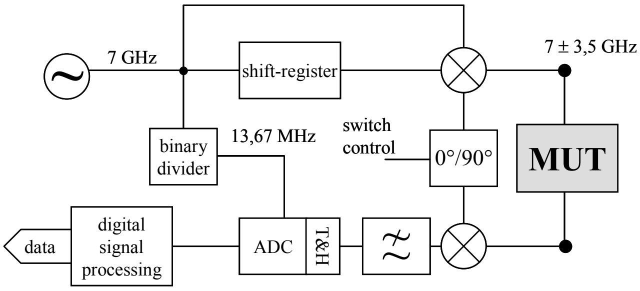

Fig. 5: Block schematics of the modified IQ-M-Sequence head respecting the FCC frequency mask. The order of the shift register and the binary divider was 9.

Fig. 6 demonstrates the results of a simple response calibration. For that purpose, the length of a mechanically variable delay line was increased by 400 µm increments. The bandwidth of the delay line was beyond that of the test signal. Thus one should expect the following behaviour if the measurement device would be perfect:

- Within the t-I-Q-coordinates, the complex impulse response function should lie in a flat plane which includes the time axis (compare Fig. 4).
- The shape of the function should be a short single impulse with FWHM ≈ 300 ps.
- The tip of the pulse should move along a circle in the complex plane by elongating the delay line. The angular spacing between two adjacent points should be 3.3°.

Fig. 6 shows that this is not the case in reality. The frequency response of the measurement chain is not flat and its group delay is not exactly constant which cause a looping waveform instead of an impulse waveform (Fig. 6 right). Furthermore, the phase switch does not work exactly between 0° and 90° thus the impulse tips does not form a circle (Fig. 6 left) but an ellipse. By the calibration, these effects are removed and the expected behaviour was gained.

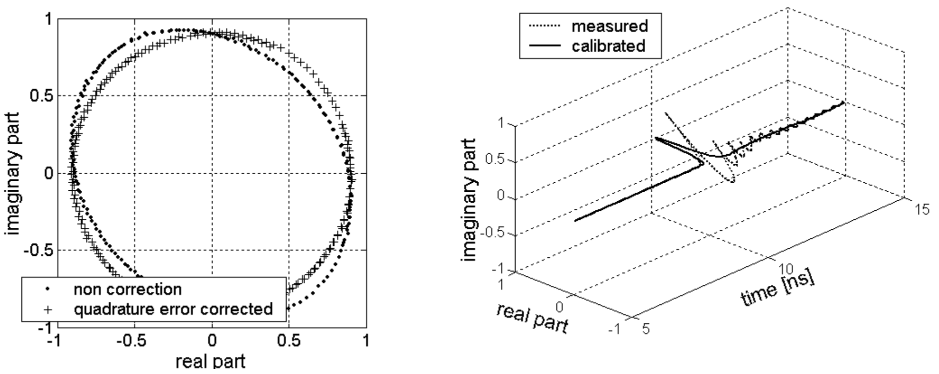

Fig. 6: Response calibration of a measurement channel based on the modified IQ-M-Sequence approach.

Finally, a simple transmission experiment shall show the moisture effect onto the shape of the complex impulse response function (see Fig. 7). Sand of different moisture was filled in a plastic box and exposed by an electromagnetic field. Transmit and receive antennas were common double rigid horns. The sounding signal occupied the spectrum from 3,5 GHz to 10,5 GHz, its power was below 0 dBm. Both, the frequency response function and the complex impulse response function were gained from the captured data. The frequency response function has been shown the expected behaviour i.e. a growing attenuation by increasing the moisture content and the enhancement of the water influence at higher frequencies. The frequency response function was gained from the complex impulse response function by gating out signal components which were not caused from the test object e.g. multiple reflections.

Fig. 7 faces different impulse response functions. In order to enhance the dispersion effect, they are represented in the complex IQ-plane rather in t-I-Q-coordinates. That is, the time axis is standing perpendicular to the paper. Though the fundamental delay due to the moisture can not be seen by that representation, this effect is always known from common data representations (see Fig. 2). The antennas as well as the dry sand only show little dispersions, since their impulse response function are close to a straight line in the IQ-plane. The fundamental propagation delay between the antennas has been changed by adding the sand, indicated by the variation of the inclination angle and an overall time shift of the complete function (not to be seen in this representation). The remaining graphs refer to moist sand. The dispersion due to the water is in evidence. Increasing water content splits up the impulse response, provokes more and more loops and it reduces the magnitude of the response function.

5. Summary

Current radio regulation activities and new cost effective measurement principles will promote the application of ultra wideband devices for moisture sensing operating in the GHz range. The article presents two variants of an ultra wideband measurement device dealing with M-Sequence stimulation signals. A baseband principle was presented, which can operate as a TDR or a network analyser, so that the behaviour of the MUT can be described in the time as well as the frequency domain. Its test signal also contains spectral power at frequencies quite below 1 GHz, so it can be applied for moisture profile measurements over a long distance. A second principle – gained by adding an up-down converter - operates within a very wide spectral band centred at a carrier frequency. Here, the measurement results also can be represented in the time and frequency domain. It was shown, that the use of a complex time domain representation may be advantageous. Due to the high operational frequency band, the device is mainly thought for investigation of small volume MUTs respectively surfaces. The unambiguous derivation of a moisture value from wideband measurement data under different experimental conditions still requires some investigations.

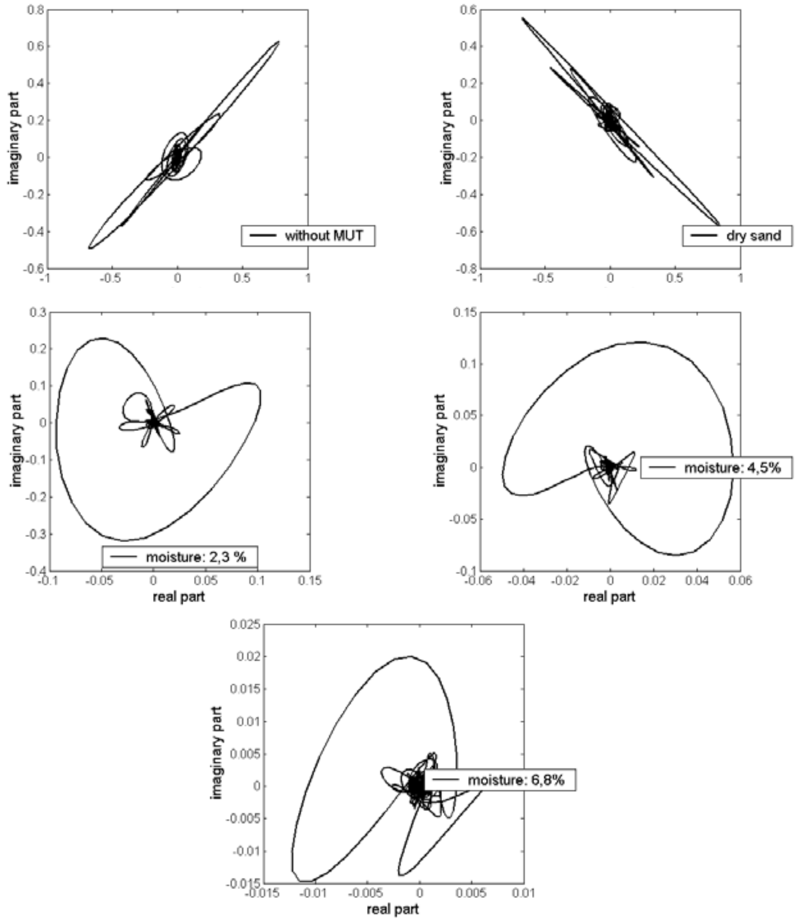

Fig. 7: Transmission experiment with moist sand.

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