Real-time Ultra-Wideband Channel Sounder

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ABSTRACT

A new real-time Ultra-Wideband (UWB) channel sounder is introduced that allows the measurement of the time-variant radio propagation channel in the extreme wide band ranging from nearly zero to 5 GHz. The RF interface comprises of integrated digital circuits in SiGe technology. A Maximum Length Binary Sequence (MLBS) is used as transmit signal. At the receiver, fast track-and-hold and interleaved sampling is applied for data recording. The received signal is correlated with the reference by a DSP. Excellent timing stability, low power consumption and miniature size support synchronous multi-channel operation which is a prerequisite to build a Multiple-Input-Multiple-Output (MIMO) sounder.

INTRODUCTION

Recently, UWB wireless transmission has been discussed as an alternative technology for application in short range indoor and personal area networks and for fixed wireless access [1], [2]. The UWB-term relates to systems and signals having a fractional bandwidth $b = 2(f_u - f_l)/(f_u + f_l)$ larger than 25 % in which the frequency borders f_u and f_l refer to -10 dB levels. UWB systems work in the baseband by using carrierless modulation with very low power spectral density as a result of extreme data bandwidth spreading. This makes UWB a potential candidate for a cheap licence free system which may share the spectrum with other systems. An excellent multi-path resistance can be expected because of the large frequency range and precise geolocation becomes a possible add-on feature. However, it should be notified that the FCC has restricted the use of UWB systems to the frequency bands DC to 0.96 GHz and approximately 2 to 10 GHz by their (preliminary) rules published in February 2002 [3].
The proper design of UWB communication systems requires the knowledge of the deterministic and stochastic behaviour of the transmission channel in typical radio environments. This is described by the time-variant Channel Impulse Response Function (CIRF) which includes information about multi-path delay, Doppler spread, and the time-varying path weights. There is a great deal of effort directed to investigating the behaviour of the CIRF by theoretical modelling and measurements by channel sounders in a real environment [4], [5]. However, existing real-time systems are narrowband systems that do not meet the extreme requirements of bandwidth and baseband operation. The UWB-system introduced here currently works over a frequency band from 0,8 to 5 GHz corresponding to a fractional bandwidth of nearly 150 %. In the future, the upper cut-off frequency shall be expanded to 10 GHz leading to 170% of fractional bandwidth. Such devices are able to cover all commonly used frequency bands of current and planed wireless networks.
Starting from some basic requirements of UWB sounders this article mainly deals with a new greatly digitised and integrated UWB measurement principle which can be used profitably in channel sounders.

PARTICULAR DEMANDS ON UWB CHANNEL SOUNDERS

Apart from the extreme bandwidth, the basic requirements posed on the electronics of UWB-channel sounders are:

- a high measurement rate in order to complete a full set of measurement within the coherence time of the channel under test (CUT),
- MIMO capability in order to provide data for polarimetric or smart (array) antenna configurations,
- a high degree of hardware configuration flexibility in order to avoid oversized systems and to adapt their performance to the actual requirements of the individual user.

There are several UWB-measurement principles available for instance impulse-, sinewave- or different correlation-techniques. However, these methods inherently possess a number of constraints (the limited bandwidth, the low measurement rate, the susceptibility to jitter and drift, the complex electronics and many others) that prevent their effective application in real-time UWB-sounders. Present sounder concepts have critical performance and cost factors as represented by inter-channel stability/synchronisation, the number of channels, the measurement rate as well as the data throughput (particularly considering that current MIMO-sounders organise their data gathering via RF-switches). An extension of bandwidth, number of channels and measurement speed by these concepts will be met with technical limits.

The presented principle will open the opportunity to overcome these drawbacks. It is based on a strongly synchronised circuit structure, which can be easily adapted to different speed requirements and a number of channels.

At this point, it should also be emphasised that an UWB sounder must be equipped by so-called impulse radiating antennas instead of any wideband antenna in order to avoid the use of a spatial de-convolution of the antenna influence by determining the CIRF but this will not be considered in detail here.

THE BASIS CONCEPTION

The key to a powerful UWB-sounder is the use of an appropriate stimulation signal because the whole device structure and the sounder efficiency depends upon it. With regards to this point, the most important aspects may be summarised in what follows:

- *The stimulus must be an UWB signal* – sequentially stepped narrow band signals prevent real time operation because of the dead time during the system/CUT settling.
- *The stimulus must be generated* in a stable manner *by simple means* up to several GHz bandwidth.
- *The stimulus must be periodic* in order to apply cost effective under-sampling methods for signal gathering and to avoid a spectral bias error [6]. It is allowed to work with a certain degree of under sampling without data loss since the time variation of the channel is comparatively small with respect to its settling time.
- *The stimulus must have a low crest factor*. The spectral energy content of the stimulus signal determines substantially the effect of random errors onto the measurement result. Low crest factor signals distributes their energy regularly over the time, so that such signals have a high energy even at low peak voltages. However, they require an impulse compression (correlation, matched filtering express the same in other words) in order to get the CIRF.

Signals which meet these requirements are pseudo-random-binary-sequences (e.g. MLBS). By pushing a digital shift register with a stable single tone RF-oscillator, they can be generated up to tenths of GHz of bandwidth. These signals have a high energy at even small amplitudes. Small voltage signals are suitable to be handled by integrated circuits and they may be switched extremely fast. Thus low crest factor signals promote a high bandwidth and an excellent jitter performance. The impulse compression by analogue circuit principles within the receiver front-end should be avoided in order to maintain the advantages of the low crest factor also for the signal gathering.

Fig. 1 presents the basic concept of the baseband MLBS channel sounder. Controlled by a single tone clock, a digital shift register generates the MLBS signal and a binary divider (2^m) provides the sampling clock. The measurement data are captured by a T&H-circuit, transformed into the digital domain (ADC), synchronously averaged (Σ) and finally stored (MEM) for off-line processing or immediate processing (DSP) in an appropriate manner. As mentioned above, the CIRF results from an impulse compression which is usually performed by the FHT (Fast Hadamard-Transform). The FHT-algorithm is very close to the FFT-algorithm except that it is based on a pure summing of data samples which promises very fast operation for special hardware implementation.

The main features of the system electronics are summarised below.

Bandwidth: $B \leq f_c/2$

Dynamic range: $L_n\,[\mathrm{dB}] = 6\,ENOB + 3n + 10\log_{10} p$

Measurement rate: $r_m\,[\mathrm{CIRF/s}] = f_c \big/ \left(p\,2^{n+m}\right)$

Length of measurement window: $T_w = \left(2^n - 1\right) \big/ f_c$

Herein, *ENOB* is the effective number of bits of the receiving front-end (T&H + ADC). The residual variables can be drawn from Fig. 1. As seen from the relations above, the clock rate f_c is given by the required temporal/spatial resolution of the CUT. The data rates r_m in the observation domain are fixed by the minimum coherence time of the CUT. The data sampling rate f_s (dividing factor 2^m) can be freely chosen as long as it respects the data needs of the observation domain. A high sampling rate promotes a better noise suppression by averaging but it can also increase the system costs since faster ADCs and averager must be employed.

For more details on the basic principle, the reader is pointed to [7], [8], [9]. Here, the superior jitter and drift behaviour because of the system control by steep signal flanks and the extremely linear (in comparison to sequential oscilloscopes) time axis representation because of the digital controlled sampling should be highlighted once again.

In case of a practical implementation, the shift-register, the binary divider and the T&H-circuits must be integrated in semi-conductor chips in order to achieve the highest possible clock rates. The rest of the measurement system may be built from commercial components. It is simple to adapt this part of the system to the actual requirements of the application. The RF-components are not altered in this case as they work at any frequency within their technical limits with this versatility they may be used in different applications.

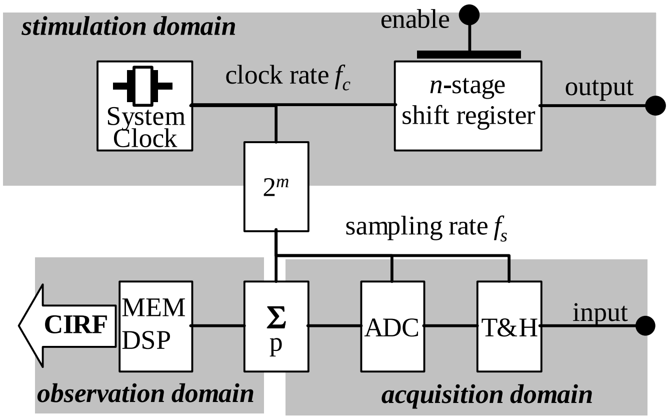

Fig. 1. Basic block diagram of the UWB radar head.

THE MIMO-CONFIGURATION

As seen from Fig. 1, the circuits for signal generation and signal capturing have a very simple structure. They are built from cost effective large scale components or customer integrated circuits as such the number of components is not an important cost factor for the overall system. Thus, the creation of multi-transmit and multi-receive structures causes scarcely more problems than in the single channel configuration.
Fig. 2 demonstrates one possibility of a MIMO-structure. In the version shown, all receiving channels work in parallel continuously providing the shortest possible measurement time. It is also possible to multiplex several receiving channels on any analogue or digital level to reduce system cost, but this also reduces the measurement rate and/or the dynamic. The transmit array works sequentially by activating only one shift register per measurement cycle. Thus, the overall measurement time increases by the number of transmitter channels. It does not depend on the number of receiver channels as in classical approaches where the single channel structure is extended to MIMO-systems by RF-multiplexer. The strong synchronisation concept guarantees once again good jitter and drift performance.

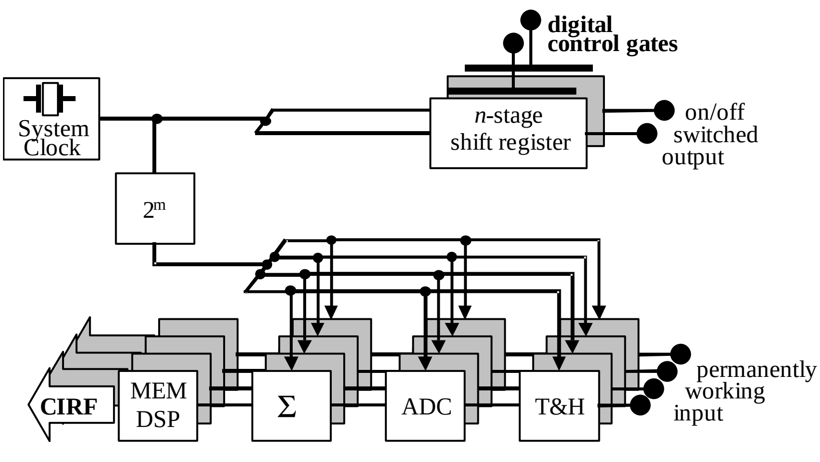

Fig. 2. Example of a completely equipped multi-channel arrangement (two generator/four measurement channels)

EXPERIMENTAL SYSTEM

An experimental system applying the new UWB-principle was implemented resulting in UWB electronics covering the band from near DC to 5 GHz. The RF-part is manufactured from customer SiGe-ICs wired on multi-layer LTCC (low temperature co-fired ceramics). The circuit schematics was completely laid out in a symmetrical manner providing the opportunity to feed all types of antennas. Signal capturing, averaging and impulse compression were managed by commercially available components mounted on a 150 x 90 mm PCB. Fig. 3 and 4 represent a typical LOS response by using a symmetrical fed LBT (loaded bow-tie)-antennas [10] and a simple example of a time variant channel.

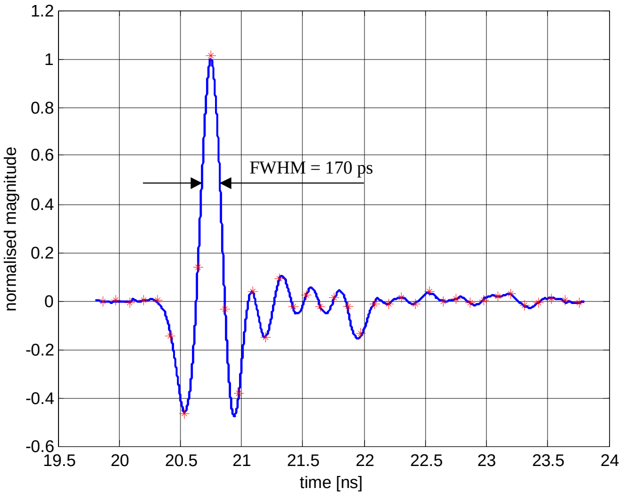

Fig. 3. Part of the CIRF representing the direct transmission. The asterisks concern the actual data samples as they are gathered by the basic concept.

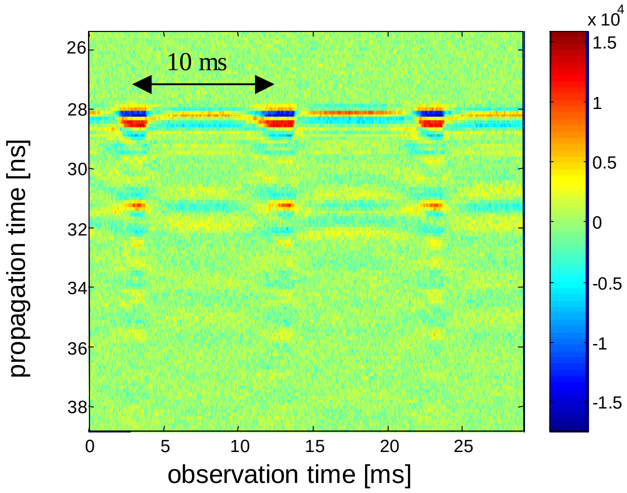

Fig.4. Part of the CIRF showing the scattering at a Neon tube

CONCLUSION

The basic version of a new UWB-principle was introduced. Key advantages of the new method are its high measurement speed, its stability in time, its multi-channel capabilities and its flexibility in adapting to different user requirements.

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