Ultra-Wideband Channel Sounder – Design, Construction and Selected Applications

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Abstract **— The paper describes construction, design, and application of a real-time ultra-wideband channel sounder. Its specific architecture allows measurements of time-variant radio propagation channels in different frequency bands. The sounder's stimulation signal is the maximum length binary sequence. Synchronous multi-channel operation is supported by its excellent timing stability and by its low power consumption of miniature sized low temperature co-fired ceramics modules that comprise custom integrated SiGe circuits. This is a prerequisite to build a multiple-input-multiple-output sounder which is suitable for sounding even in distributed scenarios such as sensor networks. Selected application examples demonstrated the performance and possibilities of the sounder.**

Keywords **— channel sounder, UWB systems, localization, imaging**

I. Introduction

THE ultra-wideband (UWB) wireless transmission systems have found many applications in short range indoor and personal area networks and for fixed wireless access [1], [2]. The term "UWB" applies to systems and signals that have their fractional bandwidth larger than 25 % or their absolute bandwidth larger than 500MHz. UWB systems may be applied in the base-band by using carrier-less modulation with very low power spectral density as a result of extreme data bandwidth spreading. This makes UWB a potential candidate for a cheap license free transmission system which may share the spectrum with other systems. Due to the large frequency range, the UWB communication systems feature an excellent multi-path resistance and UWB sensors allow high precision localization.

The proper design of UWB communication and sensing systems requires knowledge of the deterministic and stochastic behavior of the transmission channel in the application specific radio environment. Channel statistics are described by the time-variant Channel Impulse Response Function (CIRF) which includes information about multi-path delay, Doppler spread, or time-varying path weights. A great deal of effort was directed to the investigation of the CIRF behavior by theoretical modeling and measurements using channel sounders in a real environment [3] [4], [5]. Although those existing real-time sounding systems are often called "broadband", they do not meet extreme requirements of bandwidth and base-band operation. The UWB-system described here works in a frequency band from almost DC to 10 GHz leading to almost 170% of fractional bandwidth.

The paper starts with a discussion about basic requirements that should be imposed on UWB channel sounders. Then, an architecture and a design of a custom integrated UWB sounder using analog and digital SiGe-circuits is described. Selected measurement examples give an impression about the performance of the UWB channel sounder and its diverse applications.

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II. Requirements on UWB Channel Sounder Design

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

- a high data recording rate which allows measurements of the time variant radio channels,
- a multiple-input-multiple-output (MIMO) capability in order to allow polarimetric measurements and multiple antenna configurations,
- a high degree of flexibility to adapt the system performance and the hardware configuration to requirements of individual users.

Up to now mainly sine wave excitation has been used for UWB channel measurements. Network analyzers can easily meet the UWB bandwidth. However, their real-time operation is prohibited. Other existing systems that rely on the channel excitation by short impulses are often subjected to a number of constraints like a limited bandwidth, a too low measurement rate, their susceptibility to jitter and drift, too complex electronics and many others. All these prevent their effective application in the field of real-time UWB channel sounders.

Existing broadband MIMO sounders are based on a single channel radio frequency (RF) transmitter and receiver architecture. The MIMO antennas are accessed by RF switches. This results in an expensive multistage heterodyne up- and down-converter and real-time sampling [3], [4], [5]. Moreover, in order to meet the demanding phase coherence and stability requirements the narrowband high-resolution estimation of the direction of departure and the direction of arrival relies on phase difference processing [6], [7]. It seems impossible to meet typical UWB requirements by simple scaling of this architecture. Therefore, the UWB sounder described in the paper is based on a true multichannel architecture. It can easily be adapted to the needs of final users. The adaptation is in terms of measurement rates, length of measured CIRF, number of channels and operating frequencies. The described channel sounder was designed by using miniaturized and integrated modules. This allows distributed antenna configurations. Here, antennas are located in a wider distance as the usual half-lambda-spacing known in the field of the narrowband direction of arrival estimators.

III. The Basic Sounder Architecture

The key to design a powerful UWB-sounder is the use of an appropriate stimulation signal. The most important aspects in its selection are:

- The stimulus must be an UWB signal. Sequentially stepped narrow band signals prevent real time operation.
- 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 sub-sampling methods.
- The stimulus must have a low crest factor, which distributes the signal energy uniformly over the time and so maximizes signal's energy even at low peak voltages.

Signals which meet these requirements are pseudo-random-binary-sequences (e.g. MLBS – maximum length binary sequence). MLBS can easily be generated up to tenths of GHz of bandwidth by a digital shift register which is clocked by a stable single tone RF-clock like dielectric resonance oscillator. Besides the advantage of having a reasonable correlation gain, MLBS are characterized by small amplitudes allowing extremely fast digital switching in integrated circuit technology. This supports the demanding requirements on bandwidth and low jitter. Fig. 1 presents the basic architecture of the baseband MLBS UWB channel sounder. A digital *n*-stage shift register generates the MLBS signal and a binary divider (DIV) provides the receiver sampling clock. The measurement data are subsampled by a Track-and-hold circuit (T&H), transformed into the digital domain (ADC), optionally synchronously averaged (*p*) and finally stored (MEM) for off-line processing or on-line processing (DSP). The CIRF results from an impulse compression which is performed by correlation techniques in DSP.

IV. MIMO Configuration of the Sounder

Fig. 1 illustrates a simple structure of channel sounder architecture with one transmitter (Tx) and one receiver (Rx). Since it is built from cost effective large scale components or customer integrated circuits the number of components is not an important cost factor for the overall system. This allows cost effective construction of a true multichannel sounding system. The advantage of such a multichannel system is an easy emulation of distributed MIMO antenna systems and a fast measurement rate. The switched sounder architecture, on the other hand, requires sequential recording of all receive antennas by one ADC. This drastically reduces the measurement rate of the sounding system and prevents its application in realistic time-varying scenarios.

Fig. 2 demonstrates an example of a MIMO UWB sounder architecture. Here, all receiving channels work in

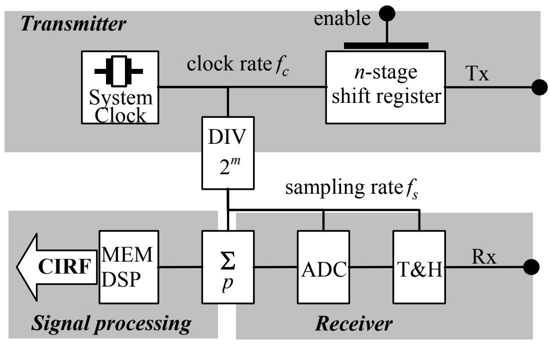

Fig. 1. Basic architecture of the baseband UWB channel sounder.

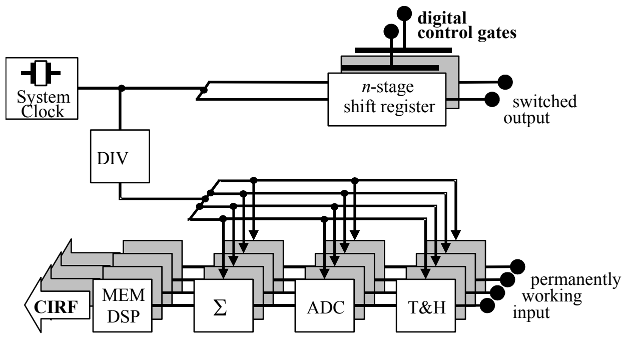

Fig. 2. Example of a parallel 2Tx 4Rx MIMO UWB channel sounder.

parallel and provide the shortest possible measurement time. The transmitter modules work sequentially in time by activating only one shift register output per a measurement cycle. Thus, the overall measurement time increases by the number of transmitter channels. It does not depend on the number of receiver channels.

V. Channel Sounder Design

Fig. 3 shows the multi-channel baseband UWB sounder, which is built in a 19 inch rack. The sounder has 2 transmitters and 4 receivers. It has been designed at Ilmenau University of Technology in the frame of the EU project PULSERS.

The presented channel sounder covers the band from near DC to 3.5 GHz and the band from 3.5GHz to 10.5GHz which is similar to the FCC (Federal Communications Commission) US standard. The superior jitter and drift behavior is a result of the integrated implementation in very fast SiGe-Technology (fabricated at IHP Frankfurt/Oder). The extremely linear time axis (compared to traditional sequential sampling oscilloscopes) is the result of the synchronous digital controlled sampling. Besides the custom designed SiGe chips (shift-register, binary divider and T&H), the RF modules use multi-layer low temperature co-fired ceramics circuit technology. The DSP module of the sounder is based on standard off-shelf printed circuit board products. The ADC is a 12-Bit-Video ADC and the sampling frequency was about 13MHz.

The UWB modules of the sounder can also operate separately and emulate a distributed sensor network. Each module has one transmitter and two receivers. One baseband module with the up-down converter in an external casing is shown in Fig. 4. For more details on the construction, system and circuit design, the reader is pointed to [8], [9], [10].

Fig. 3. Construction of the real-time 2Tx 4Rx MIMO UWB channel sounder.

Fig. 4. 1Tx 2Rx baseband module and the up-down converter in an external casing.

VI. Sounder Performance

The sounder operates in different frequency bands. Its operational frequencies depend on the system clock that drives the generation and acquisition of MLBS signals. Even passband operation is possible. By means of mixers the baseband signal may be shifted into higher frequencies. In this way a sounding system for e.g. FCC band (standard in USA), ECC (Electronic Communications Committee) band (standard in Europe), or 60GHz band may be achieved.

The sounder can continuously measure in real-time. Its measurement rate for continuous measurements is in an order of hundreds CIRF per second. In special cases, when extremely fast measurements are necessary the measurement rate may reach 40 thousands CIRF per second. However, in this case the measured data are stored in the internal memory with a constrained capacity. In the continuous mode the measured data are transferred into the computer via the universal serial bus, or Ethernet interface.

The main features of system electronics are summarized below:

- Bandwidth: $B \le f_c/2$
- Dynamic range: $L_n[\text{dB}] = 6\,ENOB + 3n + 10\log_{10} p$
- Measurement rate: $r_m[\text{CIRF/s}] = f_c \big/ \left(p\,2^{n+m}\right)$
- 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 and ADC). Other variables are explained in Fig. 1. As seen from the relations above, the clock rate f_c is given by the desired measurement bandwidth which determines the delay resolution of the tested radio channel. The minimum measurement rate r_m is determined by the coherence time of the tested radio channel. The data sampling rate f_s at the T&H is controlled by dividing factor 2^m. It can be chosen much lower than the Nyquist limit as long as the observation time window meets the coherence time requirement of the channel. Thus, the required ADC sampling rate can be scaled by choosing the dividing factor. A high sampling rate and a subsequent averaging result in better noise suppression. However, it increases the system costs since faster ADCs and averaging must be used.

VII. Application Examples

The scope of the channel sounder application is very wide. We demonstrate it by three selected application examples. The first one is a “traditional” application of the sounder for analyses of the radio channel. Since the UWB technology promises interesting perspectives for the location estimation and object identification in short range environments, the second and the third example demonstrate application of the sounder for analysis of an UWB localization and imaging system.

For wireless communication applications, the aim of the channel sounding is to measure a sequence of CIRFs in order to obtain information about the radio channel. If the channel is time variant the measurement must be performed in a real time. Recorded CIRFs are used for the extraction of relevant statistical information. Extracted parameters are subsequently used for the channel modeling. There exist a variety of UWB channel models. Some of them are straightforward extensions of narrowband channel models with an increased delay resolution. Other channel models, e.g. the statistical tapped delay line (STDL) model of the UWB indoor channel introduced in [11], are more specific in terms of the UWB frequency response and various reflecting, scattering and diffracting effects. The STDL channel model describes received UWB signal as a sum of echoes at the receiver. The echoes are time shifted, attenuated and distorted in the delay domain according to

$$h(\tau,t)=\sum_{i=1}^{N_{path}} c_i(t)\,w_i(\tau-\tau_i)+n(\tau,t) \qquad (1)$$

where $c_i(t)$ is the time variant attenuation coefficient of the i^{th} path, τ_i is its time shift, $w_i(\tau)$ represents its shape and $n(\tau,t)$ is the measurement noise.

In our first example, the above described channel model was used to interpret data measured by the channel sounder operating in the passband. The measurement was performed in an office scenario, in a room equipped with computers and some measurement devices. The size of this room was about 10.2m x 4.5m x 2.8m. Omni-directional bi-conical (exponentially shaped) UWB antennas were used for this measurement. The receiving antenna was static and the transmitting antenna was carried randomly around the office by a person. Although the whole measurement lasted for only about 70 seconds more than 3500 CIRFs were measured by the sounder in the real-time. A part of measured and calibrated data is displayed in Fig. 5. The line-of sight (LOS) signal as well as multi-path components are clearly visible.

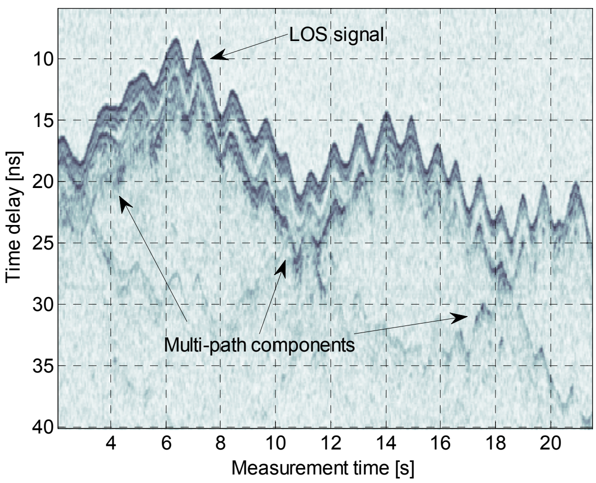

Fig. 5. Example of CIRFs measured in real-time.

Fig. 6 illustrates an example of the typical power delay profile measured in our scenario. This power delay profile was obtained from measured CIRFs in the following way. Firstly, we performed a time delay axis translation. This translation shifts LOS components to the time zero. It provides an appropriate relative delay reference for the statistical analysis. Then, the short-term averaged power delay profile $p_i(\tau)$ was computed according to

$$p_i(\tau)=\frac{1}{2K}\sum_{k=K}^{K-1}\left|h_{i+k}(\tau)\right|^2 \qquad (2)$$

where K determines the number of averages. The averaging was done in order to remove small scale effects. Fig. 6 illustrates one selected power delay profile after the time delay axis translation and the short-term averaging. It is evident that the log power delay profile can be modeled by a linear function.

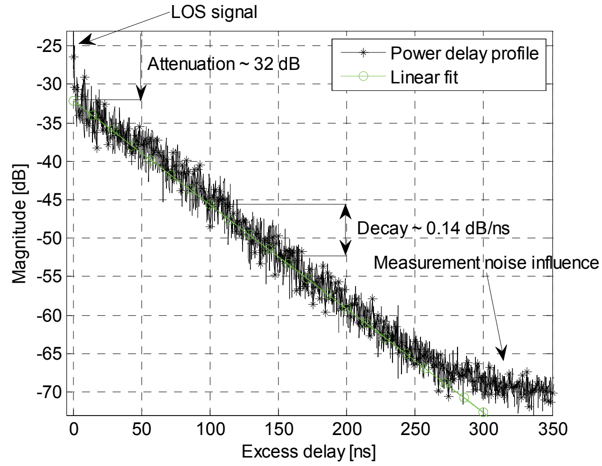

Fig. 6. Signal power as a function of time delay.

Linearized log power delay profile is characterized by the attenuation (offset) and the decay constant (slope) as depicted in Fig. 6. Since these two variables are computed from the short-time averaged power delay profile, they represent large scale statistics in terms of the above described STDL channel model. The large scale statistics characterize changes in the radio channel when the Tx-Rx distance and/or the environment significantly vary. The changes of the environment can be caused by e.g. moving persons, windows, doors, or even by pulsating plasma in neon tubes.

According to [11], statistics which describe the short term averaged power delay profile, such as the attenuation and the decay, can be modeled by the lognormal distribution. In order to approve these conclusions from [11] we estimated empirical probability density function (PDF) of the attenuation and the decay constant from our measured data. Fig. 7 and Fig. 8 show estimated PDFs altogether with the best fit modeled by the lognormal distribution.

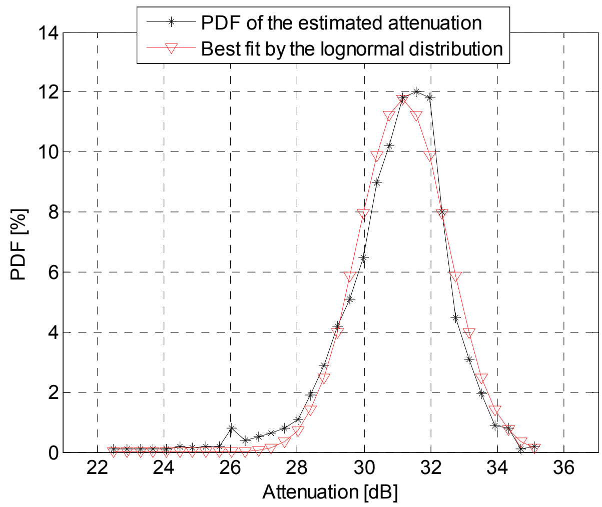

Fig. 7. Histogram of the attenuation and the best fit by lognormal distribution.

Our results obtained from data measured by the real-time channel sounder coincide with results reported in [11] that were obtained by a vector network analyzer (VNA). The use of the VNA was allowed due to the time invariance of the measurement scenario. The measurements described in this example could also be performed by a VNA. However, the measurement time would be significantly larger. Instead of 70 seconds it would last hours to record all CIRFs. Within this time, it would be necessary to exclude the time variance within the scenario such as the movement of Tx antenna and operators of the sounding equipment.

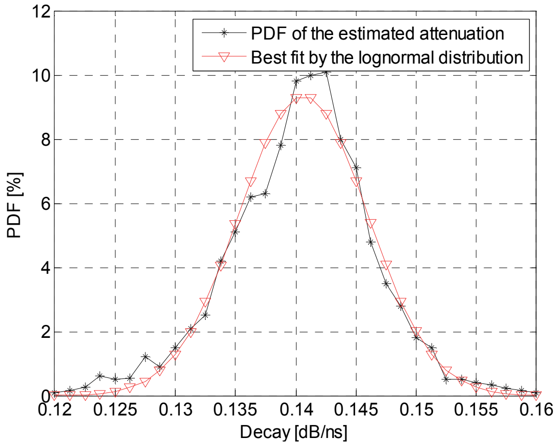

Fig. 8. Histogram of the decay and the best fit by lognormal distribution.

The second example demonstrates precise real-time localization of one transmitting antenna Tx. This application uses a SIMO (single input multiple output) setup and relies on the time-of-flight (TOF) estimation which takes advantage of the excellent range resolution of UWB signals. The localization precision depends on the arrangement of reference receiving antennas Rx, on the measurement system performance (jitter and noise) and on a priori knowledge of the temporal antenna radiation characteristics. In this application example, the receiving antenna array consisted of 3 collocated Vivaldi antennas. These antennas were arranged in the horizontal plane as a triangle (equal-sided, antenna distance 0.5m). The Tx biconical antenna was mounted on a 2D positioning unit which allowed positioning of objects with 0.75 mm precision in two directions. The Tx antenna was moved along a predefined track (see Fig. 9).

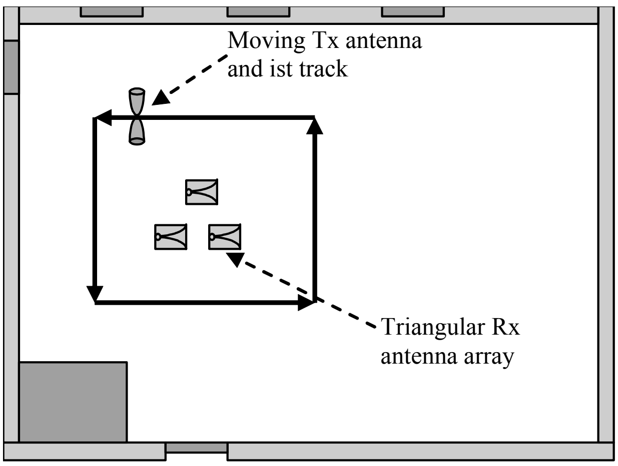

Fig. 9. Ground-plan of the measurement scenario.

The data were recorded by the UWB channel sounder. Fig. 10 shows results of 3 different estimation algorithms together with the true track of the Tx antenna. The first algorithm had no knowledge about antenna characteristics and performed no interpolation of measured channel impulse responses. The second one improved the results by interpolation and the third algorithm took into account antenna characteristics gained by a calibration measurement. The improvement of the position estimation is clearly visible. The third algorithm has a standard deviation of the range estimation in an order of 3mm and the standard deviation of the azimuth in an order of 0.75 degree.

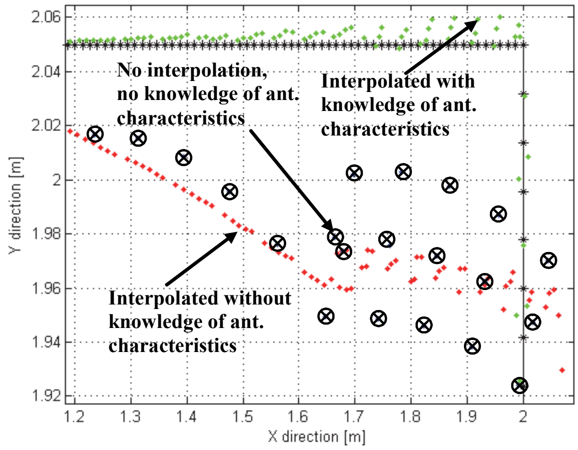

Fig. 10. Location estimation of a moving Tx antenna.

The third application example illustrates UWB imaging that relies on SISO (single input single output) measurements. Those algorithms take the necessary spatial information from the motion of only one Tx antenna. If this antenna is moved along a suitable trajectory, the recorded CIRF provides enough information for the geometrical reconstruction of the actual propagation environment in terms of location, shape, and size of the scattering objects. Example of an obtained image is illustrated in Fig. 11. Walls, the Rx antenna array and the computer table are clearly visible in this figure.

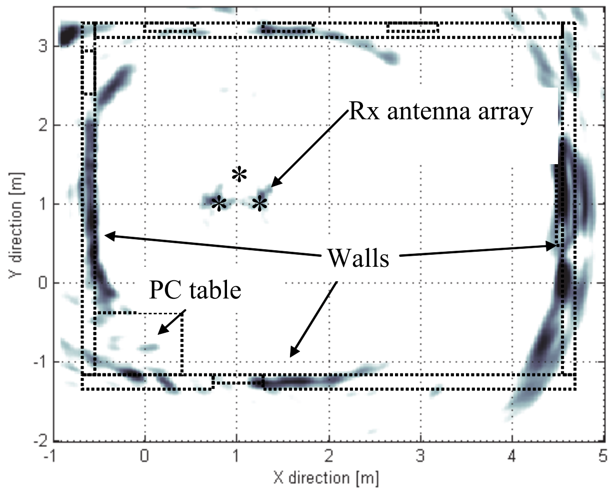

Fig. 11. Imaging of the propagation environment.

A more detailed description of further diverse application examples of the UWB channel sounder can be found in [12]-[17].

For readers interested in the application of measured propagation data in the research and development of wireless communication systems we can recommend to visit the web site [18]. This web site is devoted to the narrow band and UWB channel sounders, their principles, architectures and it provides examples of data measured in 5 different scenarios. This data can be downloaded and used by research and engineering communities. This web site is run by MEDAV, one of the leading suppliers of channel sounder devices, capable of capturing many different effects of radio wave propagation.

VIII. Conclusion

The article described real-time UWB MIMO channel sounder and its applications. Key advantages of this sounder are its high measurement speed, excellent stability in time and low jitter, multi-channel capabilities, its flexibility and high instantaneous dynamic range of 60dB.

Measurement examples showed the sounder's application for SISO and SIMO UWB channel sounding. They indicated that the sounder can be used, except of conventional channel sounding measurements, also for evaluation of localization and imaging systems. The sounder is suitable for analysis of scenarios with collocated antenna systems as well as for analysis of systems with distributed antennas such as sensor networks. Its measured data may serve as an input to various analyses that aim at performance evaluation of communication or sensing systems in realistic scenarios without the need of extensive electromagnetic simulation of complex measurement environments.

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