

## RESEARCH PAPER

# A time domain transmission measurement system for dielectric characterizations

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*Delay time measurements are a commonly used technique for the characterization of dielectric materials. Especially with regard to the characterization of water–solid mixtures like soil or grain delay time measurements, e.g., time domain reflectometry offers a powerful method. However, the accuracy of reflection measurements is limited due to multiple reflections caused by inhomogeneities of the environmental material of the sensor. This contribution deals with an improved sensor design based on time domain transmission (TDT) measurements. Thus, the first received impulse includes the necessary information. Multiple reflections are received at later time steps and their influence on the measurement accuracy is nearly negligible. To improve the performance and the applicability of the designed sensor, a cost-efficient TDT system is designed, which is integrated in the sensor. Additionally, a so-called “concentric reversion coupler” is used, which offers the possibility to perform TDT measurements without the necessity of external measuring ports.*

**Keywords:** Characterization of material parameter, Microwave measurement

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## 1. INTRODUCTION

There are several well-established techniques available for the determination of the permittivity in homogeneous and inhomogeneous materials [1]. In particular, time domain reflectometry (TDR) measurements are an often applied method for the determination of the dielectric properties of various materials like soil, grain, or coal [2, 3]. The popularity of these reflection measurements is based on the advantage that microwave measurements like TDR are non-destructive and are available in real time. Additionally, baseband signals used for TDR measurements are highly sensitive against the water content due to the extraordinary dielectric properties of water at lower frequencies [4]. Nevertheless, the accuracy of TDR measurements is limited due to multiple reflections caused by inhomogeneities of the material under test. In contrast to this, time domain transmission (TDT) measurements [5] yield accurate measurement results independent of the constitution of the surrounding material due to the fact that the first measured impulse is unique and presents the useful signal, which is only slightly influenced by multiple reflections [6]. To validate this assumption, an electromagnetic simulation inside layered materials is performed for TDR and TDT measurements. For this purpose, a two-wire line is inserted in a layered material with varying permittivities of

the different layers as shown in Fig. 1. For the investigation of the influence of multiple reflections on the measurement accuracy, layer III, with a permittivity of  $\epsilon_r = 20$ , is displaced within layer II with a permittivity of  $\epsilon_r = 3$ . Based on the delay time, the mean value of the permittivity of the layers I–IV is determined for every position of layer III as shown in Fig. 1. Ideally, this mean value should be constant independent of the position of layer III. These results show that the accuracy of the TDR system is decreased due to multiple reflections caused by the layered surrounding material. In contrast to this, the TDT results only show a small variation caused by a displacement of layer III. Hence, TDT measurements offer advantages concerning permittivity measurements in inhomogeneous materials like soils. However, TDT measurements are mainly performed with vector network analyzers under laboratory conditions [7], since portable TDT systems are only rarely available [8]. For this reason, this contribution introduces a TDT measurement system, which is based on existing TDR measurement techniques. Thus, a portable and cost-efficient measurement system is obtained.

Concerning the suitability of a TDT sensor the necessity of two different measuring ports can cause difficulties. Especially with regard to measuring tasks in soils, a second measuring port at the end of the sensor is difficult to realize. In order to deal with this challenge, this contribution introduces an improved sensor design, which enables TDT measurements without the requirement of external measuring ports. The sensor design is based on a specific coupling structure, the so-called “concentric reversion coupler”. This concentric reversion coupler enables the integration of the feeding lines in the inner part of the sensor. Additionally, the described

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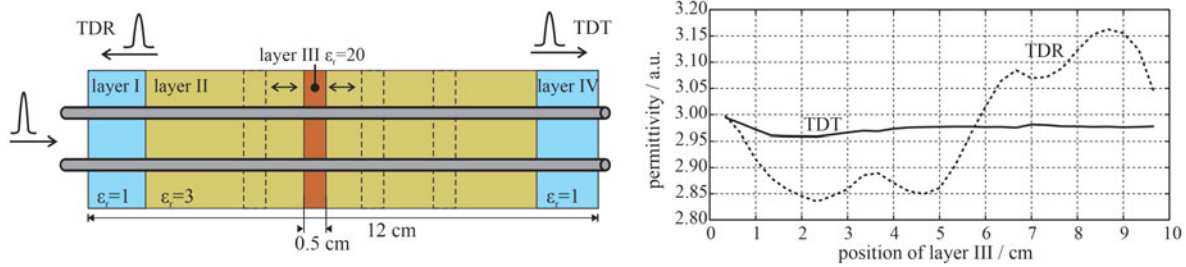


Fig. 1. Left: Schematic assembly of the simulated layered material with a mean value of the relative permittivity of  $\epsilon_r = 2.98$ . Right: Evaluated permittivity (mean value) inside a layered material.

TDT system is integrated in the sensor. Hence, no external radio-frequency connectors or sensitive measuring cables are necessary. Thus, a compact TDT sensor for permittivity measurements is realized, which is suitable for various applications due to its optimized design and the fact that the dimensions of the sensor can be adapted to the geometrical dimensions of the particular application.

## II. TDT SYSTEM

The TDT system, which is integrated in the sensor is based on an industrial TDR system. To enable TDT measurements, this TDR system is extended to a TDT system by adding one further measuring port. A schematic of the resulting TDT system is shown in Fig. 2. Here mixer 1 is used to measure the generated excitation pulse, which serves as a reference. Mixer 2 is a part of the second measuring port, which offers the possibility to measure the TDT signal. This measuring port is used to receive the transmitted pulse. Hence, in contrast to conventional TDR systems, the described TDT system allows transmission measurements in the time domain. This TDT system can be divided into three main parts: 1) the time-base, 2) the pulse generation, and 3) the sequential sampling unit including the signal processing. The time-base includes a crystal oscillator (XCO) with a fundamental oscillation frequency at 15 MHz and the corresponding third harmonic frequency at  $f_{XCO} = 45$  MHz, which is used within this setup. Additionally, a direct digital synthesizer (DDS) is used to obtain a second oscillation frequency, in this case at  $f_{DDS} = 10.714485$  MHz, which is

required for the sequential sampling. For the generation of the signal frequency  $f_s$  and the sampling frequency  $f_{s\text{amp}}$  with a small frequency offset, the two frequencies are divided by  $M$  and  $N$ , respectively. These divisions are performed by using a complex programmable logic device (CPLD). The values of the division factors  $M$  and  $N$  are chosen to be  $M = 5$  and  $N = 21$ . Thus, the signal frequency  $f_s$  results in 2.142857 MHz and the sampling frequency  $f_{s\text{amp}}$  is given by 2.142897 MHz, which yields a difference frequency of  $\Delta f = 40$  Hz.

Both frequencies are used to generate short electromagnetic pulses. For the realization of the pulse generators feedback D flip-flops are used, which are triggered by square-wave signals with the respective frequency  $f_s$  or  $f_{s\text{amp}}$ . Fig. 3 shows a schematic of one feedback D flip-flop. In this case, the output “Q” is fed back to the “Clear” input. Thus, a level change at the output immediately yields another level change due to the feedback. This results in short electromagnetic pulses with a pulse duration of approximately 1.2 ns at the output “Q” and “Q̄”, respectively. The measured time signal of the developed TDT system is shown in Fig. 3. The pulse train generated with a pulse repetition rate of  $f_s$  is sent to the transmitter of the TDT system and the corresponding transmitting port of the sensor. Subsequently, the transmitted pulse train is received by the transmission measuring port and forwarded to a sampling mixer. This sampling mixer belongs to the sequential sampling unit where the received pulse train with the repetition rate  $f_s$  is mixed with the slightly frequency-shifted pulse train with the repetition rate  $f_{s\text{amp}}$  by use of a harmonic balanced diode mixer. Hence, the two pulse trains are shifted against each other versus time. After one sampling

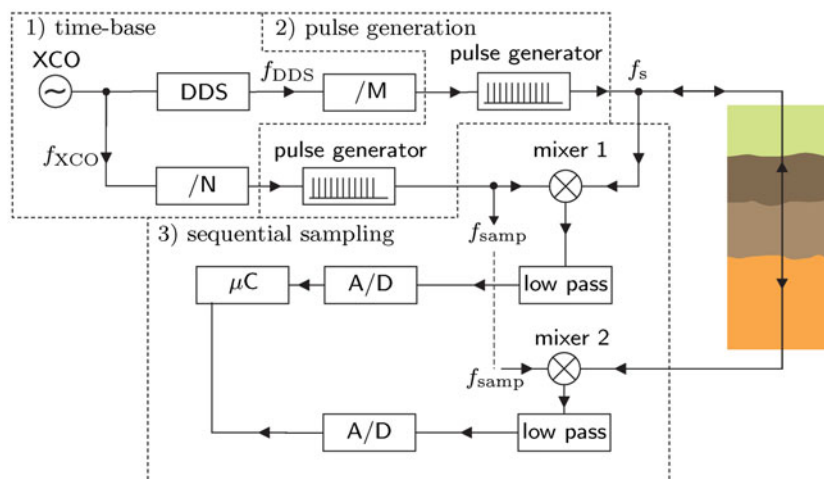


Fig. 2. Schematic of the TDT system subdivided into 1) the time-base, 2) the pulse generation, and 3) the sequential sampling unit.

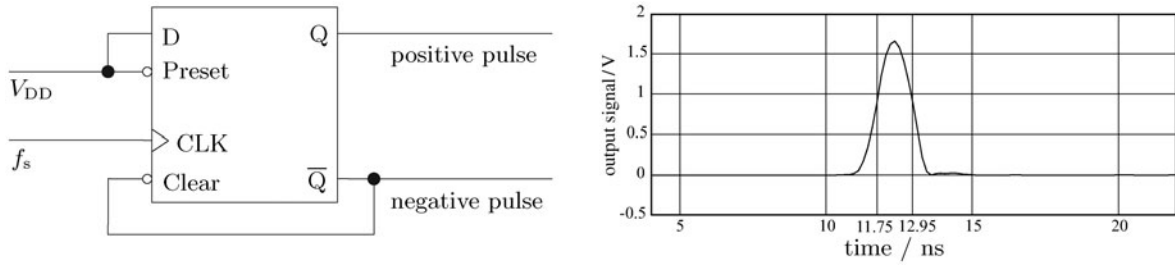


Fig. 3. Left: Schematic of a feedback D flip-flop for the pulse generation. Right: Time signal of the designed TDT system.

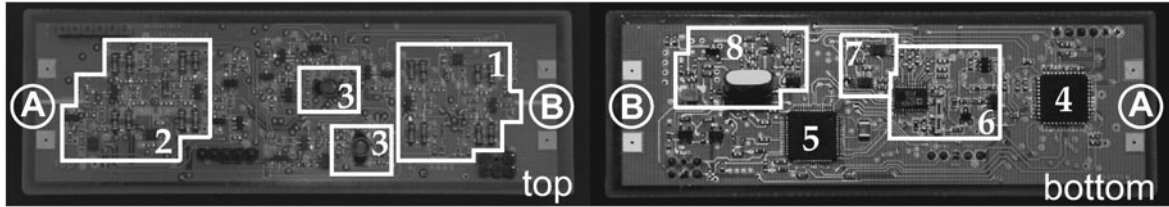


Fig. 4. Realized TDT system on a four-layer pcb with the two measuring ports A and B and the following functional components: 1 – transmission measuring port B with a harmonic balanced diode mixer, 2 – transmitter and reflection measuring port A with a harmonic balanced diode mixer, 3 – low-pass filter, 4 – CPLD, 5 – microcontroller, 6 – DDS, 7 – pulse generators, and 8 – XCO.

cycle  $1/\Delta f$  the complete waveform can be reconstructed based on the time extended signal. For this purpose, the time extended signal with a maximum frequency below 50 kHz is low-pass filtered and sent to a conventional analog-to-digital converter (A/D). In this case the acquisition time for one complete sampling cycle is given by  $1/\Delta f$ , which yields an extension of time of  $f_s / \Delta f = 53272$ .

The described TDT system is realized on an FR-4 substrate. In combination with D flip-flops and a DDS a cost-efficient design is achieved, which is advantageous with regard to cost-sensitive applications of moisture measurement systems. In order to integrate the TDT system in the sensor described in section III the dimensions of the printed circuit board (pcb) are chosen to be 10 cm  $\times$  3.5 cm. Fig. 4 shows the realized TDT system on a four-layer pcb with its functional components. Additionally, the two measuring ports A and B are depicted in Fig. 4. Here, port A is used to measure the reference signal, given by the generated excitation pulse. The TDT signal is measured at port B.

III. SENSOR DESIGN

The improved sensor design described in this section offers the possibility to perform TDT measurements inside water-solid mixtures. This comprises the advantage that

multiple reflections do not influence the measurement accuracy compared to reflection measurements. A main task concerning the sensor design is given by the requirement that all necessary connectors must be placed on one side of the sensor. In order to deal with this challenge, concentric reversion couplers, which are introduced in [6], are used. The concentric reversion coupler consists of two concentrically arranged coaxial lines as shown in Fig. 5. The coupling intersection circuit of the two coaxial lines mainly depends on the distance  $d$  between the outer conductor of the inner coaxial line and the position of the short circuit at the end of the outer coaxial line. This distance and the dimensions of the two coaxial lines are numerically optimized in order to obtain the best possible matching for frequencies up to 3 GHz, thus covering the frequency range which is suitable for moisture measurements [3]. A numerically optimized distance  $d$  combined with equal wave impedances  $Z_0$  (here 50  $\Omega$ ) for both coaxial lines yields a matching better than 26 dB for baseband signals up to 3 GHz as shown by the transfer functions  $|S_{11}|$  and  $|S_{21}|$  in Fig. 5. With regard to the sensor design, two concentric reversion couplers are used, one to transmit the measuring signal to a one-wire line and the other to receive the measuring signal from a one-wire line. Additionally, a thicker metallic discontinuity, the so-called obstacle, is placed on the one-wire line to obtain a higher influence of the surrounding [9]. Thus, the

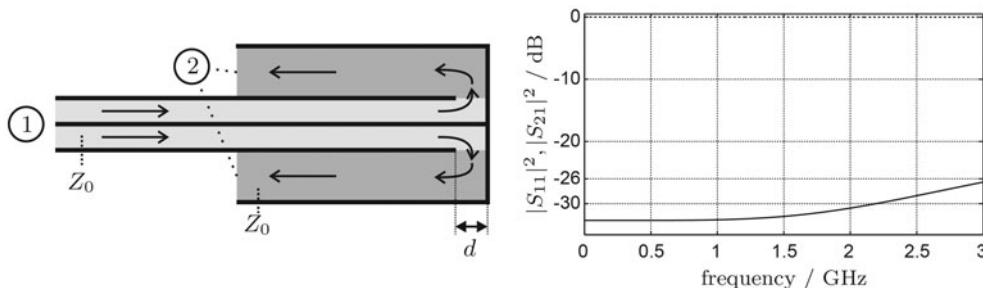


Fig. 5. Left: Schematic of the concentric reversion coupler. Right: Corresponding frequency domain transfer function  $|S_{21}|^2$  (dashed) and return loss  $|S_{11}|^2$  (solid).

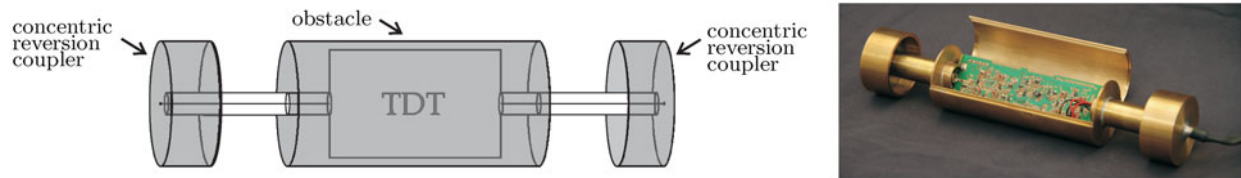


Fig. 6. Left: Schematic of the sensor design with an integrated TDT system and two concentric reversion couplers. Right: Picture of the realized prototype.

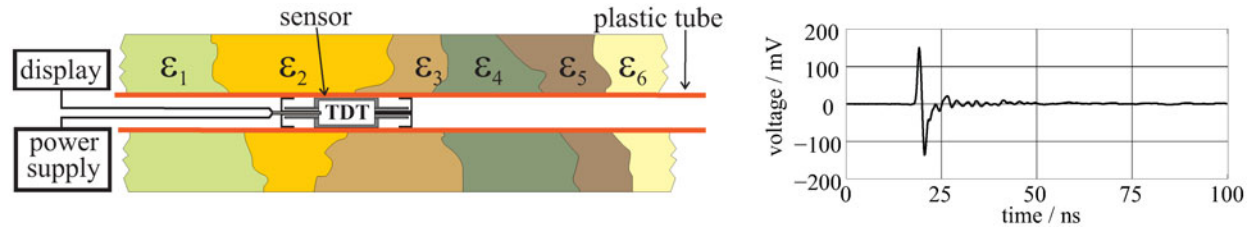


Fig. 7. Left: Application of the sensor in water–solid mixtures. Right: Impulse response of the designed prototype.

sensor possesses a planar concentric surface and is suitable for applications in bore holes, for example. Furthermore, it is advantageous to perform the signal generation and processing inside the sensor thus avoiding any external feeding lines that would have to carry sensitive high frequency measuring signals. For this purpose, the described TDT system is placed inside the metallic obstacle. Thus, the measuring signals are directly processed and converted into digital signals. Hence, external feeding lines only carry digital low frequency signals. Consequently, this setup is less prone to errors especially if the sensor is moved inside the material under test. Fig. 6 shows a schematic of the improved sensor design and a picture of the realized prototype with a length of 26 cm and a diameter of 4.5 cm, respectively. For measurement purposes the realized prototype is sealed and thus protected by a thin plastic tube to avoid a contamination of the sensor by the material under test as shown in Fig. 7. For the

connection of the TDT system low frequency cables are inserted in the inner conductor of the inner coaxial line. These low frequency cables connect the power supply and a display to the TDT system. The key benefits of this setup are given by the short unshielded signal path compared with previous sensor designs [9]. Thus, the influence of external disturbing signals is reduced. Furthermore, its fixed mechanical length does not depend on the measuring position. Hence, displacements of the sensor have no influence on the measurement accuracy. Moreover, the use of the described concentric reversion couplers and the integrated TDT system allows for performing real transmission measurements within various applications like soil moisture measurements. The measurement of the delay time of the first transmitted impulse is advantageous since the first impulse is not affected by multiple reflections as shown in Fig. 7.

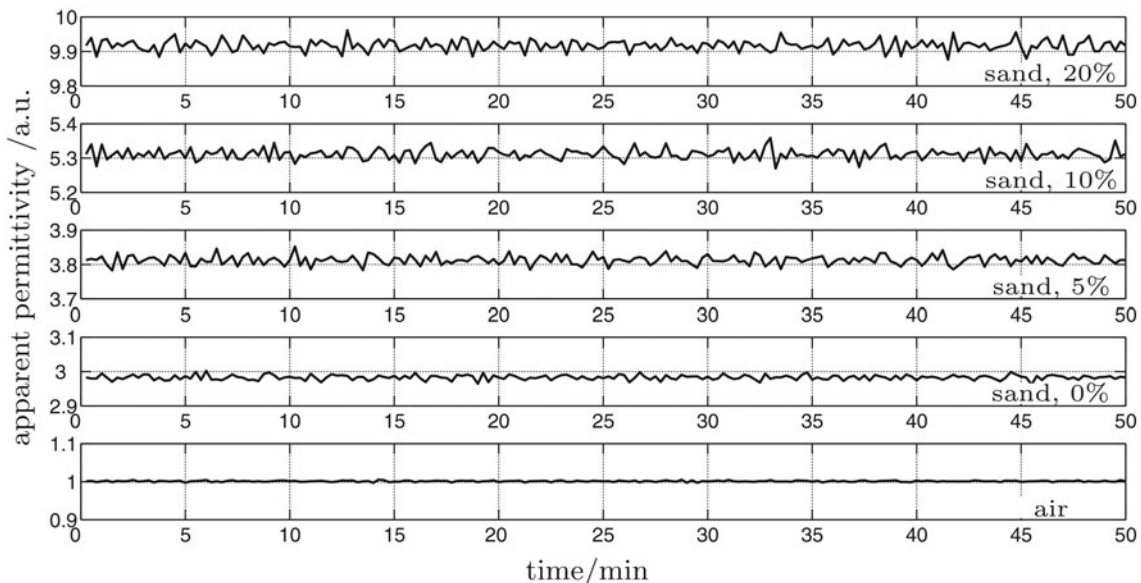


Fig. 8. Measured apparent permittivity versus time for air and sand with different water contents.

Compared with the sensor described in [6], this setup offers the advantage that the external feeding lines do not carry high-frequency measuring signals. Thus, a movement of the sensor inside the material under test has no influence on the measurement accuracy, due to the fact that only digital data signals are carried on the connecting cables.

IV. ALGEBRAIC ALGORITHM

The described TDT sensor makes use of the relation between the delay time of electromagnetic waves and the complex permittivity  $\underline{\epsilon} = \epsilon_0(\epsilon'_r - i \cdot \epsilon''_r)$  of the surrounding material. Concerning lossy dielectrics, the measured delay time  $t_{meas}$  depends on the mechanical length  $l_{mech}$  of the sensor and the so-called apparent permittivity  $\epsilon_a$  as follows [10]:

$$t_{meas} = \frac{l_{mech}}{c_0} \cdot \sqrt{\epsilon_a} \text{ with } \epsilon_a = \frac{\epsilon'_r}{2} \left( 1 + \sqrt{\left(\frac{\epsilon''_r}{\epsilon'_r}\right)^2 + 1} \right). \quad (1)$$

The apparent permittivity of the material under test can be determined by measuring the delay time of an electromagnetic impulse. Based on the apparent permittivity, a determination of the real part and the imaginary part is possible [11] with some additional information. Furthermore, the volumetric water content  $\Theta$  of mineral soils can be determined by using the following empirical mixing rule [4] without any further information:

$$\epsilon_a = 3.03 + 9.3 \Theta + 146.0 \Theta^2 - 76.7 \Theta^3. \quad (2)$$

With regard to the described sensor, the mechanical length in (1) is given by the length of the obstacle  $l_{obs}$ . Due to the fact that the measuring signal is already influenced by the surrounding material in the boundary areas of the obstacle, a so-called effective obstacle length  $l_{obs,eff}$  is required to achieve precise measurement results. For the determination of this effective obstacle length a two-point calibration with two known permittivities, e.g.,  $\epsilon_{ref}$  and  $\epsilon_{cal}$  yields the following calibration factor  $\alpha$  and the corresponding relation between  $l_{obs}$  and  $l_{obs,eff}$ :

$$\alpha = (\sqrt{\epsilon_{cal}} - \sqrt{\epsilon_{ref}}) \cdot \frac{1}{t_{cal} - t_{ref}} \cdot \frac{l_{obs}}{c_0} \text{ and} \quad (3)$$

$$l_{obs,eff} = \frac{l_{obs}}{\alpha}.$$

Measuring the delay time in a material with a known permittivity  $\epsilon_{ref}$  yields a reference delay time  $t_{ref}$ . Subsequently, one can use the difference between this reference delay time and the delay in the material of interest to determine the apparent permittivity  $\epsilon_a$  of the investigated material. By using the effective obstacle length, it holds:

$$\epsilon_a = \left( \frac{(t_{meas} - t_{ref}) \cdot c_0}{l_{obs,eff}} + \sqrt{\epsilon_{ref}} \right)^2. \quad (4)$$

As shown by this relation the measured apparent permittivity solely depends on the permittivity of the surrounding of the sensor and the effective length of the obstacle. Neither the measuring position nor permittivities in other

Table 1. Average of the measured apparent permittivity  $\bar{\epsilon}_a$  and volumetric water content  $\Theta$  of the materials under test.

Material	$\bar{\epsilon}_a$	$\Theta$ (vol. %)
Air	1.001	-
Sand, 0 %	2.983	-
Sand, 5 %	3.812	4.83
Sand, 10 %	5.307	9.89
Sand, 20 %	9.921	19.66

regions along the measured profile influence the measured permittivity. Additionally, spatially resolved measurements can be performed by displacing the sensor in the investigated material as described in [6].

V. MEASUREMENT RESULTS

For the verification of the improved sensor design some exemplary measurement results are illustrated in this section. With regard to the characterization of water-solid mixtures, the sensor is placed in different materials. Fig. 8 shows the measured apparent permittivity for air and sand with 0, 5, 10, and 20 % volumetric water content. For every material 200 measurements with a time distance of 15 s are performed. Based on these measurement results the volumetric water content is determined by using (2), which is a commonly used mixing rule for the determination of the water content of mineral soils [12, 13]. Hence, the determined water contents, shown in Table 1, are suitable for the verification of the TDT sensor. As the results show, the described sensor yields accurate and stable measurements. The evaluated apparent permittivities only show very small variations. Additionally, there is good agreement between the real water contents and the water contents determined by using the apparent permittivity. Thus, the developed TDT sensor is suitable for moisture measurements with their associated attenuation and for long-time applications, as well.

The key benefits of the TDT system are based on the use of a short one-wire signal path and the fact that real transmission measurements are performed. Thus, multiple reflections caused by the discontinuities in the surrounding only slightly influence the measurement accuracy. It is an advantage that no external radio-frequency feeding lines are required. Hence, evidently, a displacement of the sensor has no influence on the measurement accuracy and the corresponding measured permittivity.

VI. CONCLUSION

The sensor design with an integrated TDT system presented in this contribution enables transmission measurements without the necessity of external radio-frequency feeding lines. Additionally, performing TDT measurements offers the possibility to reduce the influence of multiple reflections. Thus, the designed TDT sensor is applicable inside layered materials as well as for the measurements of smooth permittivity variations and yields highly precise measurement results. Furthermore, spatially resolved permittivity measurements can be performed by displacing the sensor inside the material of interest. Thus, the compact sensor design

presented in this contribution offers a very powerful solution for the measurement of permittivity in soils and e.g. in boreholes.

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