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# A TDR wireless device for volumetric water content sensing

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## ABSTRACT

Time Domain Reflectometry (TDR) is a widely used technique to estimate the soil volumetric water content ($\theta$) and bulk electrical conductivity ($\sigma$). This paper presents TDR-WiFi, a wireless, portable and low cost interface to ease sensing of $\theta$ and $\sigma$ by connecting TDR cable tester with a smartphone. TDR-WiFi consists of a microprocessor equipped with a WiFi microcontroller (M5Stack unit) and connected to the TDR device through an RS232-TTL adapter. The M5stack firmware is programmed in MicroPython language to act as a server between the user and the TDR device through a web page accessible from any smartphone web browser. TDR-WiFi is compatible with the Campbell TDR100 device and allows storing the TDR waveforms as well as estimating $\theta$ and $\sigma$. A complementary web page for subsequent analysis of the TDR waveforms was developed and is publicly available at http://swi.csic.es/tdrwifi/. The system was satisfactorily demonstrated in laboratory and tested in the field. The field trial allowed water content measurements in a steep road slope. TDR-WiFi demonstrated to be operative in the field and it can be satisfactorily used in difficult access areas.

*Keywords*: Time Domain Reflectometry; Cable tester; Apparent permittivity; Soil water estimation

## 1. Introduction

Time Domain Reflectometry (TDR) is an accurate, non-destructive, versatile and widely used technique for real time and *in situ* estimation of soil volumetric water content ($\theta$) and bulk electrical conductivity ($\sigma$). Estimation of $\theta$ is related to the apparent permittivity ($\varepsilon_a$,) (Topp et al., 1980) and the bulk electrical conductivity is estimated by analysing the amplitude of a long-time TDR waveform (Lin et al., 2008).

Although early in the development of the TDR method, $\theta$ was estimated from visual analysis, specific software for automatic TDR waveform analysis soon began to be developed. Examples of software developed include TACQ (Evett, 2000), WinTDR, WinTrase (Soil Moisture), PC-TDR

(Campbell Sci.) and TDR-Lab 1.0 (Moret-Fernández et al., 2010). Although these programs allowed more accurate estimates $\theta$ and $\sigma$, the cable that connects the TDR with the PC together with the relatively large size and weight of a laptop can complicate the measurements, especially in those cases where the TDR equipment must be carried over long distances or used in steep slopes. These limitations could be solved, however, by employing a wireless interface and replacing the laptop with a smartphone. This paper presents a wireless, portable and low cost TDR-smartphone interface to determine $\theta$ and $\sigma$. The laptop is replaced with a smartphone that connects to the TDR via a WiFi connection generated with a WIFI-equipeed microprocessor (M5Stack unit) connected to the TDR cable tester. The system allows recording the TDR waveforms and estimating $\theta$ and $\sigma$. A web page for subsequent and accurate analysis of the recorded TDR waveforms was also developed. The TDR-WiFi system was demonstrated in laboratory and tested in a field trial where water content was determined in a very steep road slope.

## 2. Theoretical TDR background

Estimation of $\theta$ is based on previous calculus of $\varepsilon_a$, estimated according to (Topp et al., 1980)

$$\varepsilon_a = \left(\frac{ct_L}{2L}\right)^2 \qquad (1)$$

where $L$ (m) is the probe rod length embedded in a media, $c$ ($3 \times 10^8$ m/s) is the speed of light constant and $t_L$ (s) is the two-way pulse travel time along $L$. The travel time is calculated as the difference between the time at which the signal enters the TDR probe's rods (first peak) and the time when the trace arrives at the end of the TDR probe (second reflection point). This last point is calculated with the widely accepted *tangent method* (Heimovaara, 1993). The Topp et al. (1980) polynomial function was used to estimated $\theta$ from $\varepsilon_a$. The bulk electrical conductivity, $\sigma$, was calculated with the long-time TDR waveform analysis, according to

$$\sigma = \frac{K_p}{Z_r}\left(\frac{1-\rho_{\infty,scale}}{1+\rho_{\infty,scale}}\right) \qquad (2)$$

where $Z_r$ is the output impedance (50 Ω), $K_p$ (m$^{-1}$) is the probe-geometry cell constant and $\rho_{\infty,scale}$ is the scaled steady-state reflection coefficient, calculated according (Lin et al., 2008)

$$\rho_{\infty,Scale} = 2\frac{(\rho_{air}-\rho_{SC})(\rho-\rho_{air})}{(1+\rho_{SC})(\rho-\rho_{air})+(\rho_{air}-\rho_{SC})(1+\rho_{air})}+1 \qquad (3)$$

where $\rho$, $\rho_{air}$ and $\rho_{SC}$ are the long-time reflection coefficients measured in the studied medium, in air and in a short-circuited probe, respectively.

## 3. Hardware description

The wireless TDR system consists of the following components (Fig. 1): (i) TDR-100 cable tester (Campbell Scientific, Inc., Logan, UT, USA), (ii) Null modem serial cable DB9 male-DB9 male; (iii) RS232 to TTL serial port converter module (Elecfreaks, Inc., Shenzhen, Guangdong, China); (iv) M5Stack processing unit (M5Stack, Inc., Shenzhen, Guangdong, China); (v) M5Stack battery module (700mAh); (vi) M5stack base26 proto industrial board module; and (vii) generic smartphone. The M5Stack was connected to a 700 mAh battery, and the UART port of the M5Stack was connected to an RS232-TTL adapter (Fig. 1b). Wiring connections between battery module board and output pins of the RS232-TTL adapter (Fig. 1b) were as follows: GND => pin number 35; VCC => pin labelled BAT; RXD => pin number 16; TXD => pin number 17 (Fig. 1b). To connect the RS232-TTL adapter with the TDR cable tester, the RTS and CTS pins of the RS232-TTL adapter were soldered (Fig. 1c) bypassing the serial flow control implemented in the TDR-100 device. The RS232-TTL adapter, the M5Stack and the battery module were assembled together in a 125 cm3 box (Fig. 1d). The M5Stack can be also connected to a 12V battery through a UART port. The TDR cable tester was connected to the processing unit using the null modem serial cable DB9 male-DB9 male (Fig. 1a).

## 4. TDR-WiFi software and M5Stack firmware

The microprocessor was programmed using *M5 UI Flow*, a development tool for M5Stack compatible with Blockly and MicroPython programming languages. The software enables the

M5Stack to act as a server between the user and the TDR device through a web page accessed from a smartphone. The software is compatible with the Campbell TDR-100 device. To connect the TDR device with the smartphone, the M5stack and the smartphone WiFi should be previously connected. Once the phone recognizes the M5stack WiFi, a web browser should be opened in the phone and the 192.168.4.1 entered in the web browser's address bar. Chrome or Firefox browsers are recommended. The default 123456789 password should be introduced to log into the system. This password can be changed by updating the m5Comunication.py file. Once logged in, a user-friendly user interface is displayed in the browser. The main web page has three sections (Fig. 2a): (i) a drop down menu for project management, (ii) a table that displays recorded TDR waveforms and (iii) an exporting data function to download the data from the M5Stack to the phone.

The TDR-WiFi RS232 port is set to 9600 bits per second (bps) by default, so, the TDR100 device should be accordingly configured. TDR-WiFi data are organized in projects where the families of TDR waveforms and corresponding $\theta$ and $\sigma$ are saved. All projects are created, selected or executed through the project manager drop down located at the top of the main web page (Fig. 2a). By clicking the configuration button, a new window to define the project characteristics opens (Fig. 2b). A new name should be defined every time a new project is created or the configuration of a former project is modified. The configuration includes the TDR window position (Cursor) and amplitude (Dis/Div), geometry of the TDR probe (Probe length, Constant K) and characteristics to estimate $\sigma$. Once the project is configured, a TDR waveform is acquired to check that the signal is correctly located. The waveform can be recorded by pressing the *Refresh* button (Fig. 2b). TDR waveforms are expressed as the reflection coefficient as a function of time. The first peak of the TDR waveform should be defined before saving the project. The location of the first peak can be set by pressing on the TDR waveform screen or by introducing the corresponding time in the text box. Once the project is saved, the configuration data for that project cannot be updated.

Once defined, any project can be selected by pressing on the drop down menu (Fig. 2a) and TDR waveforms can be acquired by clicking on the *Refresh* button. This button opens a new window that shows the current TDR waveform (blue line in Fig. 2c) and the first peak previously defined in configuration (red line in Fig. 2c). However, given that environment temperature affects the TDR signal, and hence the position of the first peak, this value can be modified once the project has been saved. The TDR waveform can be saved by clicking on the *Save* button (Fig. 2c). The value of $\theta$ is automatically estimated with the tangent method by clicking on the $\theta$ *(*$m^3$ $m^{-3}$*)* (yellow lines in Fig. 2c). A manual definition of the second reflection point also can be chosen by pressing the *Manual 2*$^{nd}$ *reflection* option. The 2nd reflection point can be redefined on the TDR waveform screen or by introducing its location in the text box. Once the 2nd reflection point is fixed, the $\theta$ *(*$m^3$ $m^{-3}$*)* button should be clicked again. The value of $\sigma$, which can be estimated by pressing the *EC* button, is calculated from a long-time TDR waveform (green line in Fig. 2c) recorded by the system.

All saved data are contained in the table located below the project management drop down menu (Fig. 2a). The table has four columns: the first column contains check boxes that allow the user to select one or multiple projects and either export their data or delete them from the local storage by clicking the “Export data” or “Delete” buttons, respectively (Fig. 2a); the second and third columns show the project name and the date and time of the recorded TDR waveforms, respectively; the fourth column includes the *Results* buttons, which open the windows containing the stored TDR waveforms and the values of $\theta$ and $\sigma$ (Fig. 2c). The $\theta$ value can be recalculated by modifying the first peak and/or the second reflection point as described above.

Exported data are saved in JavaScript Object Notation (*.json)* format files. By default, the exported .json files are stored in the download folder defined in the web browser settings. The names of the files can be redefined before they are exported. The exported data include all configuration settings and the calculated $\theta$, $\varepsilon_a$ and $\sigma$.

## 5. Web page for TDR waveform analysis

A complementary web page (http://swi.csic.es/tdrwifi/) for subsequent estimates of $\theta$ and $\sigma$ was also developed. The web page presents the same layout as the M5Stack web-based interface and is designed to import the *.json* files exported and downloaded from the M5Stack to the smartphone. All waveform-related analysis can be done in the same fashion that has been described above for the smartphone application. The TDR waveforms can be individually opened and analysed by clicking the buttons located in the fourth column, or analysed in groups after selecting the desired data to be analysed and clicking the *Calculate Selected* button. Manual TDR waveform reanalysis is also allowed. Instead of the "Export data" button, a button labelled "Export selected results" allows for exporting the results of selected projects to a comma separated values (*.csv)* file, which includes the name of the project, the date and time of the measurement, configuration data, TDR waveforms, $\varepsilon_a$, $\theta$ and/or $\sigma$ estimates.

## 6. Laboratory and field experiments

Two laboratory experiments were performed to test the viability of the device to estimate $\theta$ and $\sigma$. In a first step, the $\varepsilon_a$ measured with TDR-WiFi by immersing a 9.3 cm length three-rod TDR probe (3-mm rod diameter) on distilled water (i.e. Fig. 2c), ethanol and air were compared to their theoretical values. Next, TDR-WiFi was tested on six different NaCl–water solutions (0, 0.1, 0.5, 1, 2 and 4 dS $m^{-1}$) as measured with an electrical conductivity cell (Conductimeter Model 522, Crison Instruments, Barcelona). A robust relationship was obtained between the theoretical $\varepsilon_a$ and the corresponding values measured with TDR-WiFi for air, ethanol and distilled water ($y = 1.03x - 1.45$; $r^2 = 0.99$; $p < 0.0001$). A good relationship was also found between the $\sigma$ values measured with the electrical conductivity cell and those obtained with TDR-WiFi ($y = 0.99x + 0.15$; $r^2 = 0.99$; $p < 0.0001$). To this end, a $K_p$ value of 22.1 $m^{-1}$ was employed. These results indicated that TDR-WiFi was suitable for the subsequent field experiment.

The usability of TDR-WiFi in severe experimental conditions was tested in a field trial consisting of determining $\theta$ in a steep road-cut of 50º average slope. Nine two-rod 20-cm long TDR probes (3 per transect) were vertically installed in three transects parallel to the slope gradient: T1, transect placed on the road cut; T2, located over materials deposited on the road-cut by an old landslide; and T3, transect placed over the same landslide material where vegetation clearly indicated higher soil water content. This field trial was representative of an ecological restoration study in road building (Bochet et al., 2007). The water content determined in T1 (0.37 $cm^3$ $cm^{-3}$) was significantly smaller ($p < 0.05$) than that determined in T2 and T3 (0.42, 0.52 $cm^3$ $cm^{-3}$, respectively). The field experiments demonstrated that TDR-WiFi allowed obtaining robust and reliable water content estimates in locations where access with a TDR plus a PC system would be difficult or not viable. On the other hand, the high stoniness of the soil did not pose a problem for installing the TDR probes, consisting of simple rigid rods.

## 7. Conclusions

This paper presents TDR-WiFi, a wireless system to determine $\theta$ and the $\sigma$ by connecting a TDR device to a smart phone. The system consists of a WiFi-enabled microprocessor (M5Stack unit) that, connected to the TDR device, acquires the TDR signal and sends it via WiFi to a smart-phone. The software is compatible with the Campbell Scientific, Inc. TDR100 device and allows simple $\theta$ and $\sigma$ *in situ* determinations. A complementary web page for subsequent and more accurate estimates of $\theta$ and $\sigma$ was also developed. The system was validated in laboratory and satisfactorily applied in a field experiment consisting of soil water content readings in a steep slope. The new TDR-smartphone interface, which was shown to be operative, portable, low cost, and versatile, allowed robust and reliable estimates of water content, even in difficult to access areas. A list of the components and an example where to acquire them can be found in http://swi.csic.es/wp-content/uploads/2020/05/Material.pdf. The cost of all components of the wifi interface is about 47 €. Instructions and a video-tutorial to install the TDR-WiFi software into the M5Stack and the open source code of the software are summarised in the Soil and Water Infiltration (SWI) group web page (http://swi.csic.es/?page_id=283).

## *Disclaimer*

This work was completed outside Dr. Vicente's duties at the U.S. Food and Drug Administration (FDA). This manuscript reflects the views of the author and should not be construed to represent FDA's views or policies.

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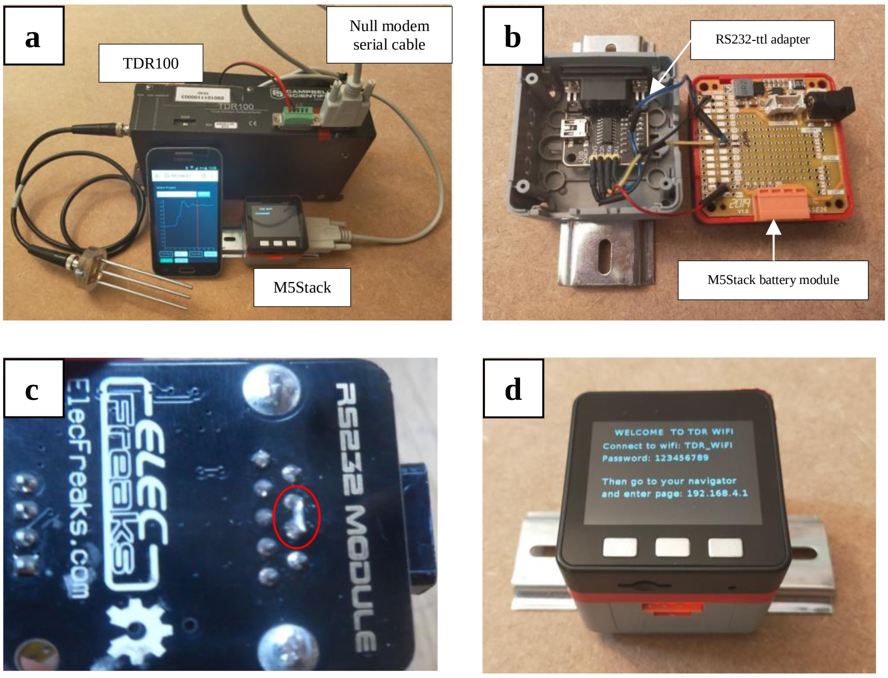
## Figure captions

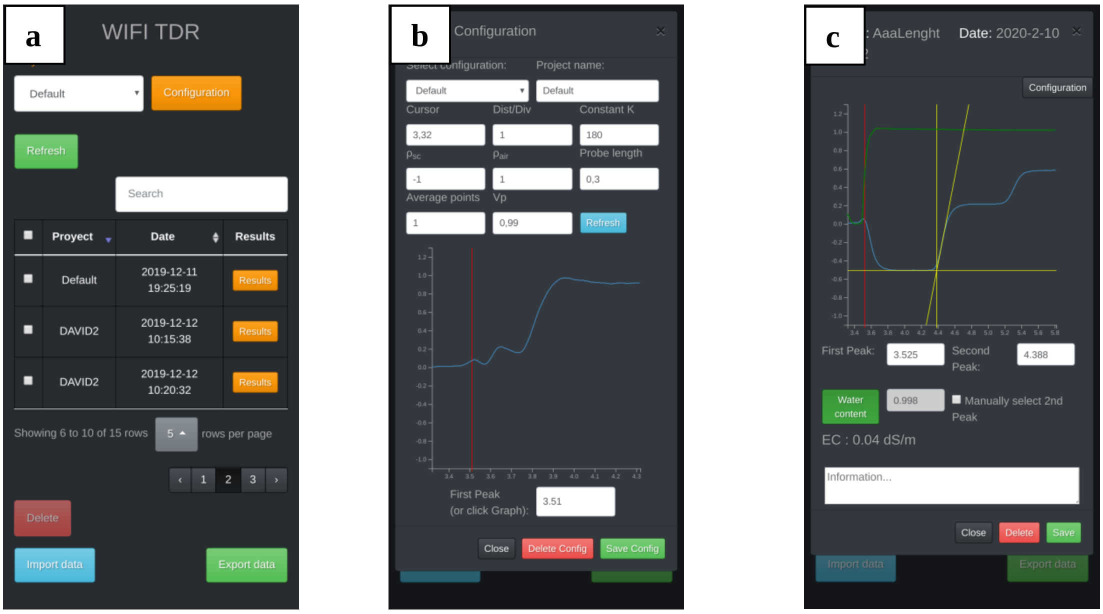
**Figure 1.** (a) TDR-WiFi components, (b) pin configuration to connect the M5Stack UART port and the RS232-TTL adapter, (c) detail of the RS232-TTL adapter modification, and (d) M5Stack module fully assembled.

**Figure 2.** (a) Main page of the WiFi-TDR web page, (b) configuration web page, and (c) refresh TDR waveform web page.



WELCOME TO TDR WIFI
Connect to wifi: TDR_WIFI
Password: 123456789
Then go to your navigator and enter page: 192.168.4.1

**Figure 1.**



WIFI TDR

Default

| ☐ | Proyect | Date | Results |
|---|---|---|---|
| ☐ | Default | 2019-12-11 19:25:19 | Results |
| ☐ | DAVID2 | 2019-12-12 10:15:38 | Results |
| ☐ | DAVID2 | 2019-12-12 10:20:32 | Results |

Showing 6 to 10 of 15 rows 5 rows per page

‹ 1 2 3 ›

Configuration

Select configuration: Default
Project name: Default
Cursor: 3,32
Dist/Div: 1
Constant K: 180
$\rho_{sc}$: -1
$\rho_{air}$: 1
Probe length: 0,3
Average points: 1
Vp: 0,99
First Peak (or click Graph): 3.51

: AaaLenght Date: 2020-2-10

First Peak: 3.525
Second Peak: 4.388
Water content 0.998
☐ Manually select 2nd Peak
EC : 0.04 dS/m
Information...

Figure 2