In-Pipe Wireless Communication for Underground Sampling and Testing

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***Abstract*—In this paper, we present an effective and low-cost wireless communication system for extremely long and narrow pipes that can replace the extant wire system in underground sensor network applications such as soil sampling and testing with the Cone Penetration Test (CPT), the most widely used underground sensor device. Different from existing in-pipe wireless techniques, we consider real-world pipelines that are very narrow and long. In particular, in our design data are first modulated at a commercial frequency and then converted to high frequency, between $14-15$ GHz, to be transmitted along of the pipelines under the circular waveguide mode TM01. Especially, we design a cone-shaped antenna to overcome the aligning problem of feeds between the transmitter and receiver. To evaluate the applicability and efficiency of our design, we conduct realistic simulations as well as experiments with real prototypes. The results of experiments are consistent with our theoretical design and simulations and show that our proposed wireless system can transfer sensory data up to 20 m in narrow CPT pipes with a diameter of 17 mm when using the LoRa modulation with a transmitting power of 1 W, whereas existing underground radio techniques can transfer data from a depth of 2 m at maximum in the same condition. In our approach, it is also possible to add repeaters to extend the communication range when needed.**

***Index Terms*—Cone Penetration Test, in-pipe communication, underground monitoring, circular waveguide, TM01 mode**

I. Introduction

Underground monitoring has been widely studied for many applications, such as well monitoring, building foundation monitoring, groundwater monitoring, and underground soil testing. In most underground sensing networks, the daunting challenge is data transmission from a sensor buried deeply underground to the surface due to the diversity of soil property and groundwater [1]. Typically the sensing device for underground monitoring is a geotechnical cone Cone Penetration Test (CPT) that is equipped with various kinds of sensors including pressure sensors, temperature sensors, and PH sensors. In some cases, advanced sensors such as laser-induced fluorescence, X-ray fluorescence, soil electricity conductivity/resistivity, and cameras are also integrated into the CPT.

There are different wireless techniques to transfer the sensory data from the CPT to the ground surface. Examples include ultrasonic, magnetic field [2], underground radio [3]. However, these techniques are not reliable and hard to be realized in practice due to heavy path loss by water, soil moisture, and temperature. Shadowing and multipath fading are also significant because of the reflection and refraction effects on multiple soil layers. Because of such constraints, current wireless techniques can be only applicable for shallow underground monitoring, preferably less than several meters in depth. In [2], the Magnetic Induction (MI) communication link without a relay suffers a high pass loss of -40 dB/m. Using the underground radio even results in a higher loss with the minimum of -60 dB/m [1]. Even for the high sensitivity of -137 dBm in Lora [4], it turns out that such underground communication links can only transfer data from a very shallow depth, approximate 3 m $(137/40)$ for MI and 2 m $(137/60)$ for underground radio. For deeper underground monitoring, most current systems use wire connection, threading a data cable through a long and narrow steel pipeline such that the data sampled by the CPT can be transferred to the ground surface, from where the data can be further disseminated by in-air wireless sensor networks [5].

In fact, using such pipeline is a common technique to deploy a CPT deep under the ground with a sonic drilling truck as shown in Figure 1. The machine drives the CPT through soil layers with a set of steel rods, called CPT strings. By applying a controllable force or vibration to the CPT strings on the ground, the CPT will be gradually plugged deeper in ground. The CPT strings are cylindrical steel rods that can be screwed together so that the CPT can go as deep as desired. The CPT strings are then left on the field to protect the wire cable or used to retrieve the CPT later on. In practice, a data cable has to be threaded via all the tubes as shown in Figure 2 before

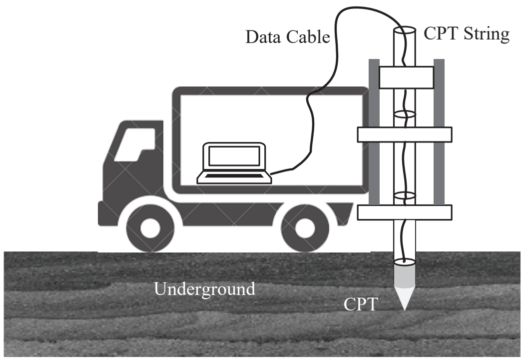


Fig. 1. CPT sonic drilling truck.

Fig. 2. Wiring for CPT strings.

drilling to allow acquisition and analysis of data, especially for real-time soil sampling and testing with various depth levels during pushing the CPT. Hence, this wiring method is time-consuming and inconvenient, which results in slowing down the drilling process and maintaining.

To this end, a wireless system that can transmit data from deeply underground CPT to a receiver on the ground is fundamental for underground wireless sensor networks. Since that the tubes are typically made of alloy steel with low permeability and fastened together forms a medium-like circular waveguide, we propose to transmit data through radio frequency based on circular waveguide as an alternative method to overcome the disadvantage of the wire technique, while it still assures a high data throughput. In particular, we modulate the raw data with a high Radio Frequency (RF) in between $14-15$ GHz to ensure that the RF signal is well propagated through the circular waveguide in the CPT strings. At the end of the pipeline, we convert the signal to a frequency of typical wireless sensor networks on the ground such as WiFi and LoRa. In addition, we design a special antenna for an efficient in-pipe radio communication in terms of signal loss and reflection. Simulation and experiment results show that our in-pipe wireless transmission system is practical and promising. It is shown that sensory data can be reliably transmitted from a depth of more than 25 m to the ground surface using a transmitting power of 1 W.

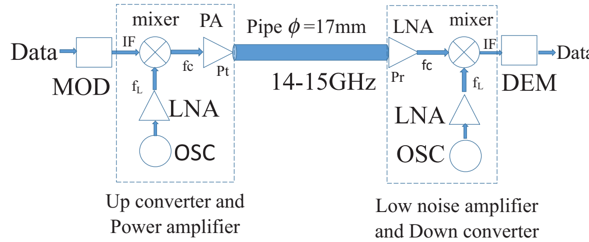


Fig. 3. Proposed in-pipe waveguide transmission system

The organization of the remaining portion of the paper is as follows. Section II present our proposed in-pipe wireless communication system, which includes signal modulation, signal propagation in circular waveguide, frequency, and antenna design. Simulations to verify the loss and fine-tune our design parameters are described in Section III. Section IV test our simulation-based design with real-world CPT strings. Finally, the paper is concluded in Section V.

II. CPT Communication Channel Design

Motivated by the harsh environment due to very narrow and long CPT rods, in this section, we propose a communication system design including modulation, circular waveguide, frequency, and antenna.

A. System Architecture

In Figure 3, we propose the system configuration to establish a communication link in pipelines. Sensory data from the CPT is modulated by available commercial modules (MOD) such as LoRa, Zigbee, and WiFi. The output signal of these modules is the Intermediate Frequency (IF) signal of upconverter input. An oscillator generates the local frequency supply to convert IF signal to RF signal in range from $14-15$ GHz. The high-frequency Power Amplifier (PA) power up the RF signal to transmit to the pipe via a transmitting antenna.

At the other end of the pipeline, the receiver antenna receives the RF signal and sends it to the Low Noise Amplifier (LNA). Then, the RF signal out of the LNA will be down-converted to the expected frequency of the demodulator (DEM). These DEM modules are also commercial modules resistive to the MOD modules of the transmitter.

B. Transmission with Single Mode in Waveguide

The circular waveguide is a tubular structure with a circular cross section that is constructed from enclosed conductor medium as shown in Figure 4. There are two kinds of wave modes that are applicable to the cylindrical structure of the CPT robs. These are the transverse electric TE_{mn} mode and the transverse magnetic TM_{mn} mode, of which wave equations and field patterns are presented in [6], [7]. Each mode has its own phase velocity, group velocity, and

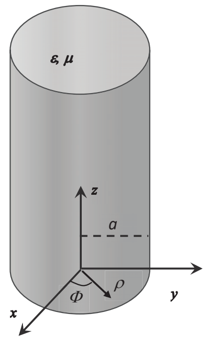


Fig. 4. Circular waveguide model and cylindrical coordinates.

wave impedance [6], [8]. The experiments of S.E. Miller [8] prove that the multiple modes propagating causes distortion, interference and decreasing the signal to noise ratio. Therefore, it is essential to propagate the signal in a single mode.

The carefully selecting frequency in the range of low order mode will remove higher modes in the waveguide. A thoughtful design of feed method allows transmitting one dominant mode. Mode filter is the additional method to reject unnecessary modes.

C. Single Mode Selection for Data Transmission in CPT Applications

The first mode that supported in the circular waveguide is TE_{11} and the next is TM_{01} [6], [7] are often used in communication systems. The mode TE_{01} has the lowest transmission loss [6], [8]. Each mode has its own cutoff frequency that is relevant to the diameter of the waveguide. Selecting a mode to propagate radio signal in the waveguide depends on frequency, feed methods, and mode filter. Moreover, the selected mode have to be suitable to the harsh, unstable environment of steel waveguide during the drilling operation.

Mode TE_{11} is the first dominant mode waveguide supports with the lowest cutoff frequency. There are many techniques to excite mode TE_{11}, such as the probe feed [9], [10], waveguide ports [11], and coaxial to waveguide [12]. The directional field pattern of this mode in Figure 5 requires accurately aligning feed structures (antennas) between the transmitter and the receiver. In the CPT technique, pipes are fastened together with each other by screwing before being pushed to underground. Hence, it is difficult or even impractical to align the feed antennas between the transmitter and the receiver. Although the aligning problem can be overcome by the dual circularly polarized feed technique [13], it is very costly and complicated to design. Whereas, the next order mode TM_{01} has the circular symmetric field pattern as Figure 5. Furthermore, if the feed antennas are designed as in [14], [15], the antennas can be inserted inside the waveguide and directly connected to the inner conductor of the coaxial cable. Since these antennas are in the form of round shape, an analogy antenna design is reasonable for applications with data transmission inside the rotatable CPT strings.

Higher order modes, as well as the low loss mode TE_{01}, are not applicable for our considered harsh condition, long and narrow pipelines. They are either not circularly symmetrical, complicated to excite mode, or requiring a special mode filter. Moreover, the gap between pipe junctions and defects of inner pipe surface cause mode conversion to lower and higher modes, resulting in reducing signal power and increasing interference as well as noise.

D. Frequency Range to Excite Mode TM01

As the reasons discussed in previous section, we select mode TM_{01} to propagate RF signal through the pipes. The frequency is chosen such that not only this mode is supported in waveguide but also not many higher order modes are supported to exist in waveguide. At the range of frequency $f_{cTM_{01}} < f \leq f_{cTE_{21}}$, modify [6] we have:

$$f_{cTM_{01}} = \frac{2.4049}{2\pi a\sqrt{\varepsilon\mu}} \tag{1}$$

and

$$f_{cTE_{21}} = \frac{3.0542}{2\pi a\sqrt{\varepsilon\mu}}, \tag{2}$$

where a is the radius of the circular waveguide, ε is permittivity of medium inside waveguide, and μ is permeability of dielectric medium inside waveguide [6].

The waveguide supports two modes that are TE_{11} and TM_{01} [7]. In order to transmit nearly a single mode TM_{01} in the waveguide, it is necessary to propose suitable feed techniques such that only mode TM_{01} is excited to the waveguide.

E. Antenna Design

There are may works that propose the antenna structure for exciting mode TM_{01} [14]–[20]. In [15], [18], [19], the authors propose models and conduct experiments for narrow band response. Whereas, [20] presents the feed method by converting rectangular waveguide to circular waveguide that is inapplicable for data transmission during drilling process of the CPT strings.

Inspired by the antenna in [14], [15], we design a conical antenna as shown in Figure 6. The tip of the cone is connected to the inner conductor of the coaxial cable. Its structure is rather simple and circularly symmetric. At high frequency, the errors in fabricating cause the far error of antenna's impedance. In our design, there is a hole at the tip of the antenna that allows adjusting the relative position of the antenna for impedance matching.

F. Attenuating in Waveguide

According to [6], the attenuation coefficient for the TM_{01} modes inside a circular waveguide for CPT strings are given by

$$\alpha = \frac{R_S}{a\eta}\frac{1}{\sqrt{1-\left(\frac{f_{cTM_{10}}}{f}\right)}}, \tag{3}$$

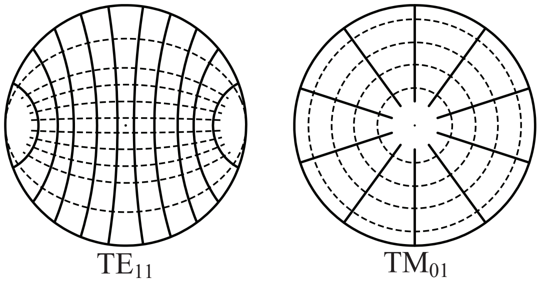


Fig. 5. Field pattern of the TE_{11} and TM_{01} mode.

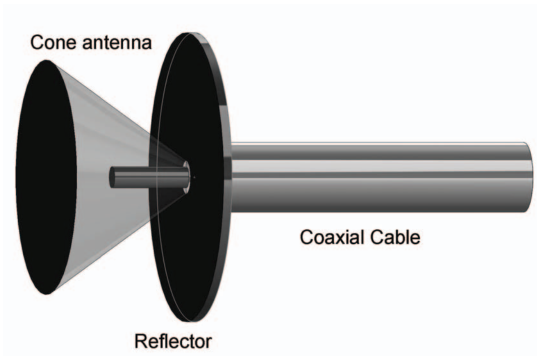


Fig. 6. Antenna CAD drawing

where η is the intrinsic wave impedance and R_S is the surface impedance of waveguide:

$$R_S = \sqrt{\frac{\omega\mu}{2\sigma}}, \tag{4}$$

where σ is the surface conductivity.

Most CPT strings are made of steel of which permeability μ is higher than good conductors, such as copper and silver, but the conductivity is lower. Typically, the inner surface of CPT rods can be rough, dusty, and wet. These factors result in significant loss in the waveguide.

Since there are gaps between the junctions of the pipes, the loss and scattering can affect the signal-to-noise ratio [21]. [8], [22] present theory and experiment for mode conversion due to imperfect. However, if the frequency intentionally is chosen as in Section II-D and antennas are designed to excite mode TM_{01} as in Section II-E, these conversion effects are reduced significantly.

III. Simulation

This work uses the HFSS software to simulate and fine-tune the parameters of feed antennas. The pipe is modeled by a lossy waveguide with the length of 1 m and diameter of 17 mm. The inner surface of the pipe has the roughness of 1 μm. The material is alloy steel with a permeability of 4.

From Equation 1 and Equation 2, the cutoff frequencies are $f_{cTE_{11}} = 13.5157$ GHz and $f_{cTE_{21}} = 17.1648$ GHz. Therefore, we select the simulation frequency from $14-15$ GHzz.

Fig. 7. Model to simulate mode selection of cone antenna.

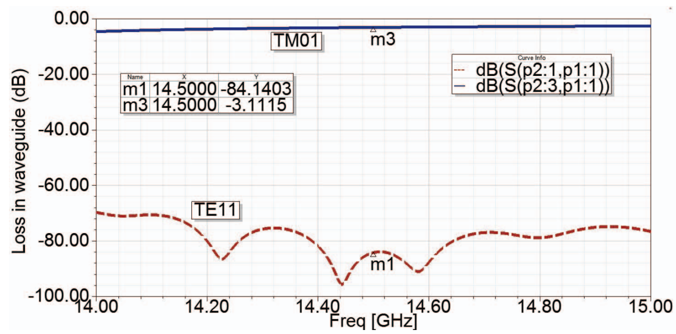


Fig. 8. Mode TM_{01} selection by cone antenna.

A. Simulating Mode Selection in Waveguide

In this simulation, the mode selection of the antenna between TE_{11} and TM_{01} mode is investigated. The HFSS model for antenna mode selection is built as in Figure 7. The RF signal is fed to waveguide by TEM mode through a coaxial cable model. The inner conductor of the cable runs into the closed end waveguide and is connected to the sharp point of the cone antenna inside the waveguide as shown in Figure 6. The power at the coaxial supply is 1 W. The other end of the waveguide is sourced by the wave port that is defined by the HFSS software as the model of the infinitive circular waveguide. This waveguide port model at the receiver allows perfect matching. At this point, no RF signal reflects back the waveguide. In the range of frequency from $14-15$ GHz, this wave port model fully supports both modes TE_{11} and TM_{01}.

Figure 8 explains the mode TM_{01} selection by the conical antenna in waveguide. At the receiver, the attenuation of mode TM_{01} is presented by the solid line. Nearly, in the range of frequency $14-15$ GHz, the received signal decreases -3 dB, when compared to the input signal. This loss is mainly caused by the lossy characteristics of the waveguide. Meanwhile, the TE_{11} mode signal is attenuated about -70 dB as plotted by the dashed line. Consequently, this simulation proves that this cone antenna generates mostly RF signal in mode TM_{01}.

B. Simulating the Total Loss in Waveguide

In this simulation, the waveguide is excited by coaxial at both ends. Figure 9 presents the model that is built in the HFSS software. The simulation outcome of this model is used to design the real antennas to transmit and receive the RF signal through the waveguide. The coaxial cables are connected to the antennas with the configuration described in the previous section but at both the ends of the waveguide. The frequency is selected in range $14-15$ GHz. As presented in Figure 10, the RF signal loss in waveguide in this case is between -3.2 dB

Fig. 9. Model with antennas at the transmitter and the receiver.

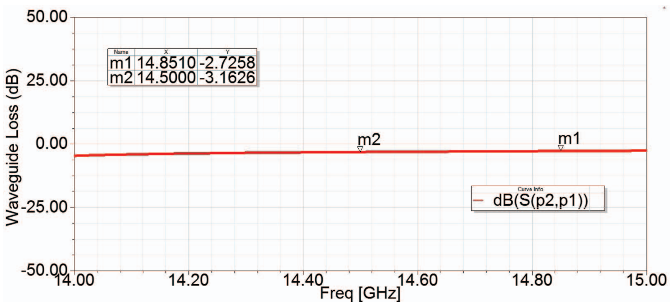


Fig. 10. The loss result in waveguide excited by two coaxial cables to two antennas at two ends of waveguide.

and -2.7 dB. There is more loss in this simulation when compared to the loss of mode TM_{01} in Figure 8. There is no reflection with the receiver port model in Section III-A; however, the reflection takes place with the receiver antenna in this model. Thus, the loss in this model increases a little.

C. The Antenna's Standing Wave Ratio (SWR)

The feed antenna is connected to the 50 Ω coaxial cable as shown in Figure 6. In the simulation, the SWR value is measured at the input port of coaxial cable. The feed antennas in the waveguide are thoroughly designed in cone shape such that they have wide band frequency response with a total impedance of 50 Ω at the coaxial input. For this purpose, we use the model described in Section III-A (see Figure 7). In this model, no wave reflection occurs at the receiver position. The simulation results in Figure 11 show that in frequency band 14 GHz to 15 GHz we can design the wide band antenna in the waveguide. The SWR is about 1.2 in the given band.

If the cone antenna is placed at the receiver instead of ideal wave port model, there is a certain reflection at the receiver. Therefore, the SWR slightly increases to 1.3 as shown in Figure 12. The wide band response with these SWR value is good enough for RF circuits to connect to them.

IV. Experiment

In this section, we present our experiment to test the loss our proposed in-pipe wireless communication system with real-world CPT rods, which are extreme narrow and can be fasten together to be as long as wanted.

A. Measurement Setup

The loss in pipes is investigated by the Network analyzer Rohde&Schwarz ZVB 20 as Figure 13(a). The cone antenna is designed and connected to an SMA connector as shown in Figure 13(b). The sharp tip of the antenna is connected to the inner conductor of the SMA connector. A rounded copper

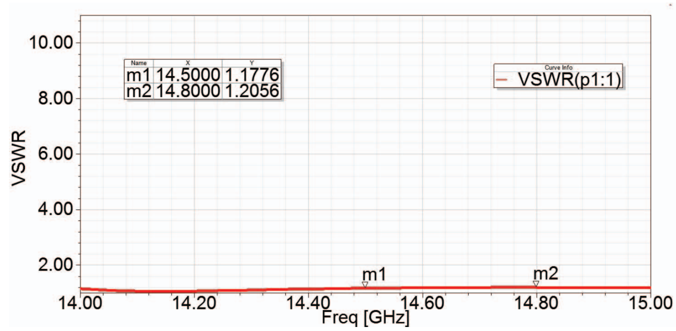


Fig. 11. Standing Wave Ratio of feed antenna in waveguide with perfect match at the receiver.

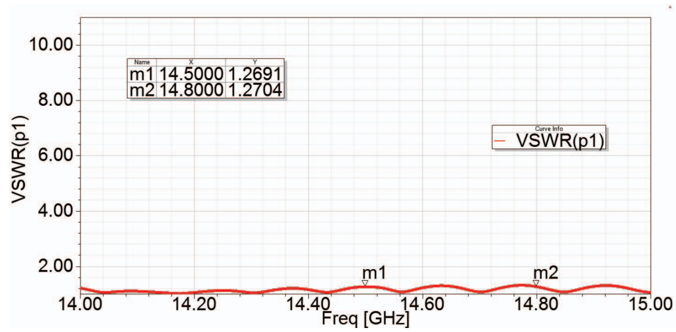
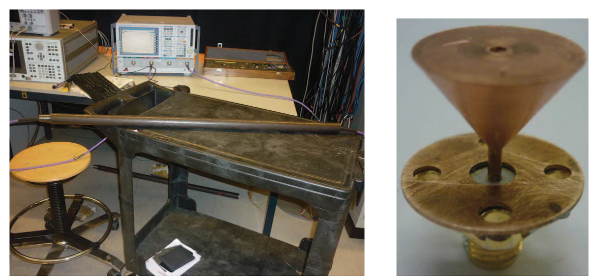


Fig. 12. Standing Wave Ratio of feed antenna in waveguide with the cone antenna at the receiver.



(a) (b)

Fig. 13. a) Pipe measurement setup with Network analyzer. b) Feed antenna.

sheet with a diameter of 17 mm is soldered to the ground plane of the SMA connector. This sheet is used to enclose the pipe. Antennas are inserted into the pipe. Port 1 and 2 of the network analyzer are connected to the SMA connectors at the transmitter and receiver positions, respectively. They are inserted into two open ends of the pipe. Using two ports of Network analyzer to investigate the loss via the S_{21} parameter in 1-m pipe and antenna's SWR via the S_{11} parameter.

B. Antenna's SWR Measurement

In the range of frequency from 14 to 15 GHz, the measured standing wave ratio (SWR) of the antenna is about 1.45 as shown in Figure 14. These results are higher than those of the simulations in Section III-B. The higher reflection is probably due to the antenna fabricating, soldering, installing and positioning in waveguide cause. Nevertheless, these measurements

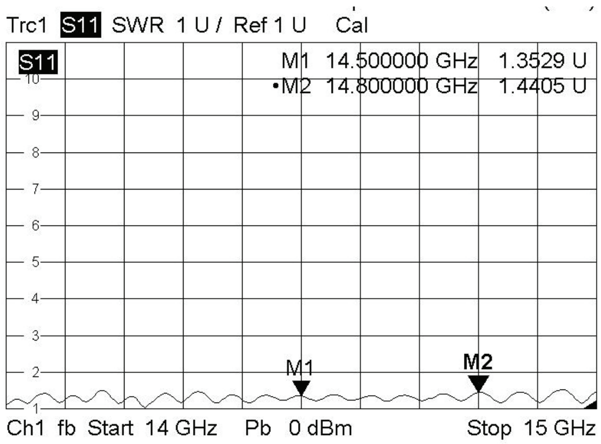


Fig. 14. The standing wave the antenna.

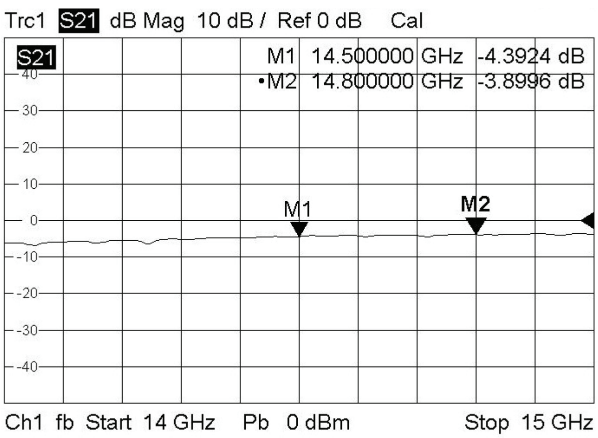


Fig. 15. Measurement Loss in waveguide excited by mode TM_{01}.

are still wide-band and acceptable for designing impedance matching circuit to improve the total antenna's gain.

C. Total Loss in 1-m Pipes

As shown in Figure 15, loss is from -3.8 dB to -4.5 dB for 1 m pipe. These measurement results are lower than those of simulation approximately from 1 to 2 dB. The reasons are that real antennas are less matching since in the inner surface of real steel pipes has a higher and unpredictable roughness due to the effect of water and dust in the field. The CPT pipes (rods) are in situ made for drilling purpose, not for waveguide communication link. Hence, certain unexpected defects inside the pipe also increase the loss.

D. Loss by The Join Between 2 Pipes

For further information to design communication link, we further measure the loss in two pipes connected together. In this case, the loss increase includes the loss by double length and the loss by reflection and mode conversion at the junctions. The test results in Figure 16 is approximate 10 dB, while the loss of each is -3.8 dB to -4.5 dB. Thus, we infer that the junction between pipes causes 1 to 2 dB loss more.

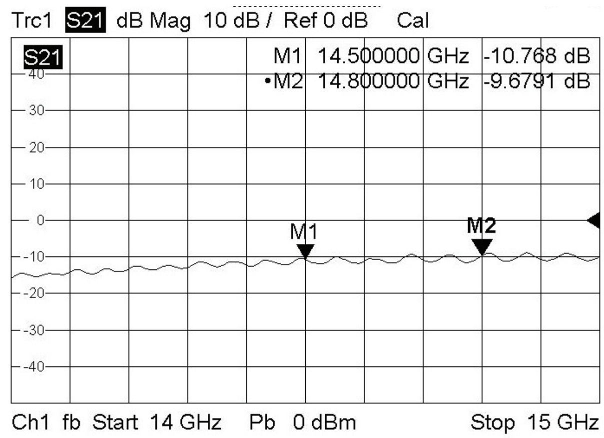


Fig. 16. Measurement Loss in two waveguides connected together.

In other words, this small loss allows reaching a depth of 20 m (20 pipes connected together with 19 junctions in between). The total loss is calculated -128 dB for 20 m. This path loss is practical for designing the communication link with LoRa, of which sensitivity is up to -137 dBm [4].

V. Conclusion

In this paper, we proposed an efficient and economic approach for data transmission from underground sensors to the ground surface, which is one of the most fundamental problems in underground sensor networks. Different from existing approaches, we designed a communication link via the circular waveguide to transfer data along the steel CPT robs. While circular waveguide is not new, we are the first to enhance this technique for extremely long, narrow, lossy, and imperfect-permeability pipeline. Additional higher layer performance analysis and experiments will be done for more pipes that connected together and placed underground. In particular, in our system data are first modulated a low-power noise-resistant wireless protocol such as WiFi, LoRa at a low frequency. In order to transfer the radio signal along the inner pipeline, the low frequency is then converted to a high frequency, for instance, $14-15$ GHz for pipes with a diameter of 17 mm. At the end of the pipeline on the ground, the signal is down-converted to the low frequency to allow data dissemination with wireless sensor networks on the ground. Moreover, we design a conical antenna to exciting the circular waveguide and eliminate the alignment of antennas. The simulation and empirical results show the realization of our proposed approach in real-world deep underground monitoring applications with CPT systems.

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