Propagation Measurement of a Natural Cave-Turned-Wine-Cellar

Qi Ping Soo, *Student Member, IEEE*, Soo Yong Lim, *Senior Member, IEEE*, David Wee Gin Lim, *Senior Member, IEEE*, Kian Meng Yap, *Member, IEEE*, and Sian Lun Lau, *Senior Member, IEEE*

***Abstract*—Caves have been used as a natural habitat since ancient times, and our ancestors once resided in them. As time and age evolve, caves slowly lose their original functionality, yet never ever lose their significance as a place. In this letter, we present field measurement results taken from inside a beautiful cave-turned-into-a-wine-cellar site, which is the first of its kind for such tourist caves rich with stalagmites and stalactites. This cave, named Jeff's cellar operated by the Sunway Group, is one of the famous tourist hot spots in Malaysia, and it has never failed to attract tourists from near and far each year. Needless to say, ensuring that wireless communications are available inside this cave fondly frequented by tourists is important. In this letter, we present field measurement results taken from inside Jeff's cellar at three frequencies, namely, 900 MHz, 2.4 GHz, and 5.8 GHz in both line-of-sight and non-line-of-sight scenarios. These measured results are useful for the practical planning and implementation of wireless communications not only in the said cellar but also other tourist caves such as meditation cave, thermal steam cave, crystal cave, and others.**

***Index Terms*—Caves, propagation measurement, underground electromagnetic propagation.**

I. Introduction

IN THE early human civilization age, caves were used as natural shelters and they made up the main habitat for men's earliest ancestor. Nowadays, fewer caves are still employed as habitats for anchorites, devout people, and also for temples. Besides, some caves are exploited as wine cellars and also for growing mushrooms or storing cheese due to their relative constant and cooling temperature inside.

The search and rescue operations in cave environments require that effective wireless communications be made accessible at all times. The availability of wireless signals inside caves will be highly beneficial to much scientific research that is cave-related such as volcanology, hydrology, speoleo-archeology and speoleo-biology, military surveillance, and the management of tourism caves. As are the real scenarios, caves are likely to have rough surfaces and dimensional unevenness on a number of facets. This scenario in natural cave passages is clearly different from the conditions in underground mine tunnels that are straighter and more regular [1], [2].

Due to the geometry of the intervening space, the dielectric parameter of the surrounding would have an influential role on the propagation of electromagnetic waves in a natural cave. All rock stones contain a definite quantity of water. From our theoretical knowledge, water greatly influences the parameter of rock, which separately reflects its composition. The evaluated conductivity of the ground water in addition to its reliance on frequency was considered in [3]. There are various cases in speoleogy where it is required to adopt radio communications to communicate over comparably long distances [4]. Due to the irregular passages of natural caves, they are weaker estimation to lossy waveguide. In addition, the signal strength will likely get more attenuated because the diameters of cave passages are usually much less than those of tunnels.

Previous works conducted in caves environment are scarce; [5]–[7] are some prime examples of them. In [5] and [6], an empirical approach was adopted to study wild caves scenarios, while in [7], a simulation approach was employed. Specifically, in [5], an experimental study of the propagation of UHF-band radio waves in straight subterranean galleries was presented. It was demonstrated in this letter that for the typical situations in the experiment, an empirical linear model of path loss could be used. However, the established model was reported to be only suitable for regular galleries such as those presented in that paper, for mines but not for irregular profiles that frequently appear in caves. Whereas in [6], an approach for modeling the attenuation of radio signals at microwave frequencies in natural cave passages was developed. This letter shows the potential application of radio communication along the passages of natural caves and the validity of modeling to predict performance to a first approximation. On the other hand, in [7], Pingenot *et al.* from the Lawrence Livermore National Laboratory have presented a computational study of signal propagation and attenuation of a 200 MHz dipole antenna in a cave environment. They performed simulation for a series of random meshes to generate statistical data for the propagation and attenuation properties of the cave environment. During the simulation, the cave was modeled as a straight and lossy random rough wall. After applying the high-order time-domain vector finite-element methods to the case of RF electric field propagation in the lossy rough wall tunnel, the

Manuscript received February 12, 2018; revised March 2, 2018; accepted March 2, 2018. Date of publication March 8, 2018; date of current version May 3, 2018. The work of Q. P. Soo was supported by the University of Nottingham through a Dean's Scholarship for the Ph.D. studies. *(Corresponding author: Soo Yong Lim.)*

Q. P. Soo, S. Y. Lim, and D. W. G. Lim are with the Department of Electrical and Electronic Engineering, University of Nottingham Malaysia Campus, Semenyih 43500, Malaysia (e-mail: ecxqs1@nottingham.edu.my; Grace.Lim@nottingham.edu.my; Lim.Wee-Gin@nottingham.edu.my).

K. M. Yap and S. L. Lau are with the School of Science and Technology, Sunway University, Selangor 46150, Malaysia (e-mail: kmyap@sunway.edu.my; sianlunl@sunway.edu.my).

Digital Object Identifier 10.1109/LAWP.2018.2813310

authors concluded that the particular calculation has proven to be difficult to solve using direct theoretical analysis.

Unlike what were previously reported on the propagation conditions inside wild caves, in this letter we present for the first time the measurement results collected from inside a tourist cave in Malaysia named Jeff's cellar. Tourist caves differ from wild caves in a number of ways. For one, tourist caves are meant for tourists, which means there will be people movement inside the caves. Also, the dimension of tourist cave passages is normally greater than wild caves. In addition, when compared to wild caves, the ground surface of tourist caves is relatively smoother, and in some instances, their grounds are covered with stone bricks or wooden tiles so they can be a lot smoother than wild caves' ground.

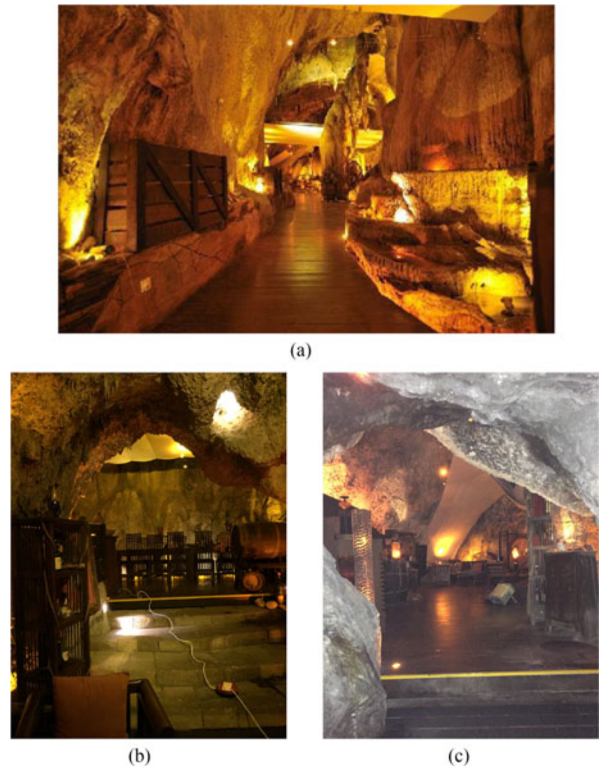
This letter presents the outcome of a field measurement operation carried out at the frequencies of 900 MHz, 2.4 GHz, and 5.8 GHz in a real tourist cave environment for three different antennas polarizations, namely, vertical/vertical (VV), horizontal/horizontal (HH), and horizontal/vertical (HV) polarizations.

II. Natural Cave-Turned-Wine-Cellar

The natural caves of hundreds of years ago were regarded and treated as nature's own refrigerator. In some European countries, many natural caves have been exploited as wine cellars due to their high humidity and a consistent temperature of around 58 °F. Sheltered from the high temperature of the hot sun, the natural caves do indeed possess the ideal atmosphere for wine storage.

The tourist cave from which we have conducted a series of field measurements is situated in Banjaran Hotsprings Retreat in Ipoh, Malaysia. Set within a limestone cave, this cave named Jeff's cellar is one of the most unique wine bars in the world. Inside, tourists can savor a wide range of organic and rare wines in a setting where ethereal lighting, intimate cave interiors, and breathtaking natural water intersect. What is lacking now is wireless communication inside such an exotic environment, and it became our goal to explore how signal propagates therein. Fig. 1 illustrates the three separate areas of Jeff's cellar such as a line-of-sight area (LoS) and two non-line-of-sight areas (NLoS1 and NLoS2) of approximately 37 m in total distance. The top view of Jeff's cellar is shown in Fig. 2. Our transmitter (Tx) is placed stationary at the starting point of the cave passage. Meanwhile, the first receiver (Rx) is located 1 m away from Tx, with consecutive Rx's separated 1 m apart from one another.

Entry to Jeff's cellar is through a door that is near NLoS2 area [this door is not visible from Fig. 1(c)]. Throughout the measurement campaign, this door was kept closed at all times so the entire measurement was completed in a closed environment. Although Jeff's cellar is a natural cave, it has been touched up nicely by the Sunway Group to make it suitable for tourists. As an example, inside Jeff's cellar, the floor has been covered with wooden panel so the ground is a smooth surface. However, the surrounding cave surfaces such as the sides and the tops are kept original featuring flowstones, stalactites, and stalagmites. There is a mini staircase situated between LoS and NLoS1 areas (in the middle of 22 m and 24 m). This natural stone staircase has around four steps, as illustrated in Fig. 1(b), and this constitutes the turning point from LoS to NLoS areas.



(a) (b) (c)

Fig. 1. Pictures showing the three measurement sites of Jeff's cellar. (a) Jeff's cellar cave passage (LoS). (b) Turning between LoS NLoS area (NLoS1). (c) Jeff's cellar entrance passage (NLoS2).

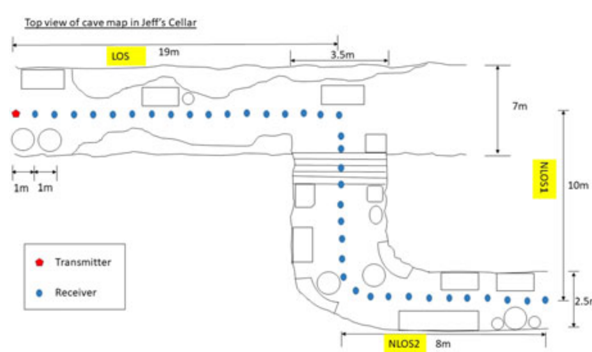


Fig. 2. Top view of Jeff's cellar (not to scale).

III. Setup of a Data Acquisition Unit (DAU)

We have assembled a DAU for conducting field measurement inside Jeff's cellar at the above-mentioned three frequencies, as presented in Fig. 3. Mainly, our Tx is made up of a signal generator (Agilent E4428C) while our Rx is made up of a spectrum analyzer (Agilent E4404B). This equipment is connected to a dipole antenna, i.e., a 6 dBi wireless omnidirectional antenna at 900 MHz (L-Com HGV-906U), an 8 dBi omnidirectional wireless-LAN antenna (HyperLink Technologies HGV-2409U) at 2.4 GHz, and an 8 dBi ISM/UNII band omnidirectional wireless-LAN antenna (HyperLink Technologies HG5808U) at 5.8 GHz. We have selected these common

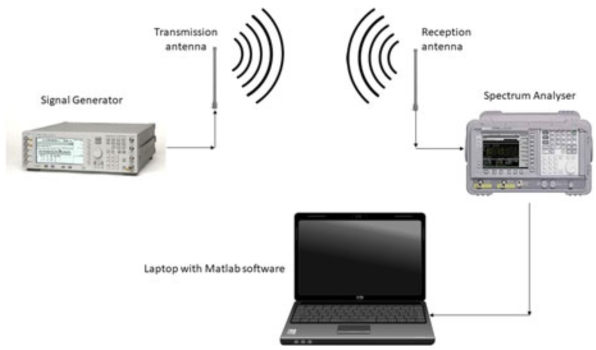


Fig. 3. Assembled data acquisition unit.

TABLE I
TX AND RX HEIGHT WITH DIFFERENT ANTENNA POLARIZATIONS

Frequency	Polarization	Tx height (m)	Rx height (m)
900 MHz	VV	1.50	1.50
	HH	0.98	0.96
	HV	0.95	1.46
2.4 GHz	VV	1.40	1.40
	HH	0.90	0.90
5.8 GHz	VV	1.25	1.27
	HH	0.90	0.90

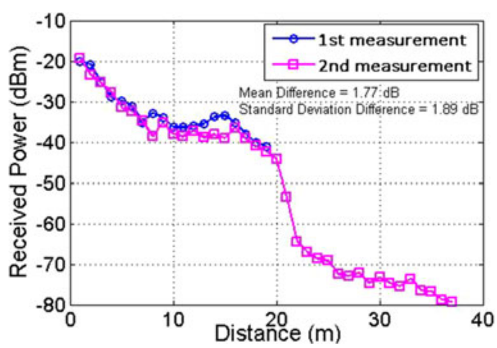


Fig. 4. Repetition test of VV polarization at 2.4 GHz.

frequency bands as a first approach to make wireless communication such as WiFi signals available inside the cave. Table I outlines the various antenna polarizations and the heights of Tx and Rx.

IV. MEASUREMENT RESULTS

In the beginning, the Tx antenna was positioned static in a location illustrated by a star shape in Fig. 2. The Rx antenna was mounted on a 33 cm long wooden rod attached to a tripod, and subsequently rotated 360° at each Rx location to filter out the small-scale fading effects, a similar concept used in [8]. In other words, during each Rx antenna rotation, 400 received signals were recorded and afterward averaged to yield a single mean value. Fig. 4 shows the two repeated measurement results for VV polarization at 2.4 GHz, which indicates very good repeatability with a standard deviation difference of 1.89 dB. Beyond this, we also plot Fig. 5 to demonstrate the frequency effects on signal strength.

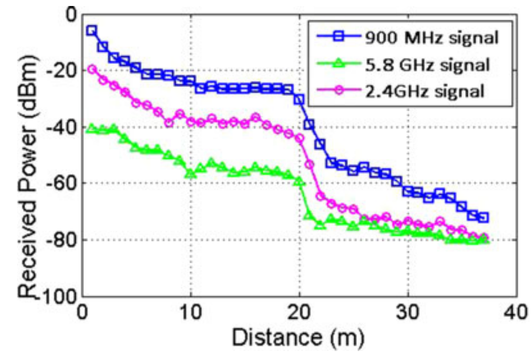


Fig. 5. Frequency effects of signal strength for VV polarization.

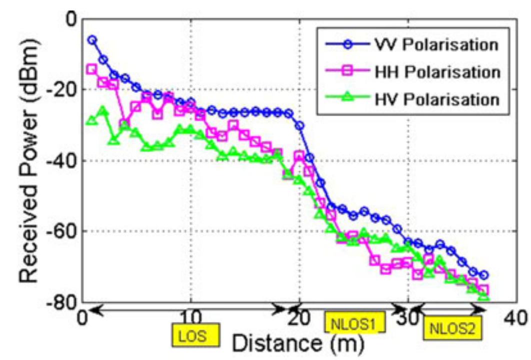


Fig. 6. Co- and cross-polarizations effects at 900 MHz.

In both Figs. 4 and 5, we could observe the downward trend of signal strength as the Rx moved away from the Tx gradually. There was a drastic drop of signal at a location between 20 and 22 m at all three frequencies when LoS signal was lost at the staircase [see Fig. 1(b)]. Among these three frequencies, 900 MHz signal can propagate stronger for a greater distance, but 5.8 GHz signal, being higher frequency, attenuated faster to reach the noise floor. This finding is consistent with what was reported earlier on frequency effects in a different propagation environment [9]. Hence, we put forward a notion for lower frequency signal to be adopted in caves environment, even though this goes counter to the current trend of many jumping on the millimeter-wave bandwagon.

V. FURTHER ANALYSIS FOR HH AND CROSS POLARIZATION

To give a more comprehensive view of the signal behavior, in this section we present both co- and cross-polarizations results. For reasons stated in Section IV, we compare VV, HH, and HV polarizations for 900 MHz only (see Fig. 6). However, for higher frequencies, i.e., 2.4 and 5.8 GHz, we are only interested to see copolarization effects (see Fig. 7).

From Figs. 6 and 7, we observe that VV polarization has consistently recorded the highest signal strength in both LoS and NLoS scenarios. HH polarization, though being copolarization, does not fare as well especially when a dominant LoS exists. When this dominant LoS is lost, depolarization effects can be seen; a similar observation recorded in a previous study for an indoor stairwell scenario [10]. As for the second turning

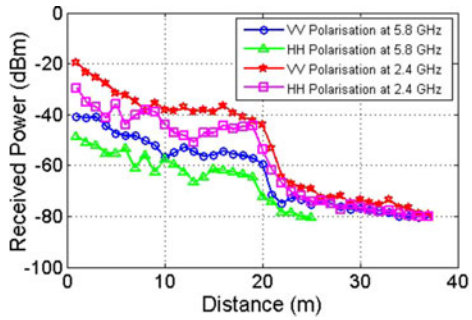


Fig. 7. Copolarizations effects at 2.4 and 5.8 GHz.

TABLE II
PATH LOSS EXPONENT AND STANDARD DEVIATION VALUES

Frequency	Polarization	Path loss exponent, n		σ_m (dB)	
		LOS	NLOS	LOS	NLOS
900 MHz	VV	1.65	12.45	0.98	3.34
	HH	1.85	11.99	3.79	4.08
	HV	1.01	10.2	2.66	2.50
	Average	**1.50**	**11.55**	**2.48**	**3.31**
2.4 GHz	VV	1.77	9.26	1.57	4.47
	HH	1.31	7.38	2.89	3.16
	Average	**1.54**	**8.32**	**2.23**	**3.82**
5.8 GHz	VV	1.55	4.89	1.85	2.64
	HH	1.35	8.65	2.24	0.97
	Average	**1.45**	**6.77**	**2.05**	**1.81**

from NLoS1 to NLoS2, there was no significant power drop. In all three frequencies, note that HH polarization fluctuates more than VV polarization, indicating that HH polarization is more sensitive to the elliptical passage of the cave and to the stalactites. Beyond this, we have also extended the findings of [11] to cave environment, that the probability density function for random field amplitude propagating in a cave is Ricean, implying there is a dominant signal component. Our measurement results collected from the LoS section proved that. Furthermore, our findings also support the notion put forward in [12] that a deterministic approach works best for such cave scenarios.

To further support the notion that the field propagation inside a cave environment is Ricean, we have compiled Table II to show the initial path loss exponent n values and their associated standard deviation in both LoS and NLoS scenarios. It can be observed from Table II that there exist waveguiding effects in the LoS sections at all three frequencies since the recorded n values are all smaller than the free-space two. As for the NLoS sections, the recorded n values are generally larger than those reported from other indoor environments especially at 900 MHz, indicating much faster power drop in a cave environment when the dominant LoS signal is lost. The standard deviation values are all satisfactory, signifying good accuracy in calculating path loss.

VI. CONCLUSION

In this letter, we present an unprecedented study of a tourist cave environment marked by limestones, stalagmites, and stalactites. This natural cave, which has been beautifully turned into a wine cellar (Jeff's cellar), is a famous tourist hot spot in Malaysia. Therefore, making wireless communication available inside such an exquisite environment is a worthwhile effort. Our study shows that contrary to the current popular trend to go millimeter-wave, in this cave environment, a conventional approach should be undertaken to adopt lower frequency signal since it can propagate stronger and further, hence more practical. Also, our study shows that VV polarization has the best received power in most scenarios that is around 10 dB gain over HH polarization and 20 dB gain above HV polarization for the LoS region of the cave passage. This study lays a good foundation for more works to be conducted in actual caves environment, be it experimental, theoretical, or by simulations since there is still little known of the stalagmites and stalactites and their combined effects of accumulated water in a cave passage. In fact, we believe the impact of stalagmites and stalactites in limestone cave passages remains inadequately explored to date, a similar concern raised in [5], and should be followed up.

ACKNOWLEDGMENT

The authors would like to thank the Banjaran Hotsprings Retreat of the Sunway Group for their kind approval to conduct a series of field measurements inside Jeff's cellar. In particular, the authors thank Raymond Fei Ming Koh for his logistics assistance with the field work.

REFERENCES

[1] M. Boutin, A. Benzakour, C. L. Despins, and S. Affes, "Radio wave characterization and modeling in underground mine tunnels," *IEEE Trans. Antennas Propag.*, vol. 56, no. 2, pp. 540–549, Feb. 2008.

[2] M. Ndoh and G. Y. Delisle, "Underground mines wireless propagation modeling," in *Proc. IEEE 2004 60th Veh. Technol. Conf.*, Los Angeles, CA, USA, Sep. 2004, pp. 3584–3588.

[3] J. Chiba, T. Inaba, Y. Kuwamoto, O. Banno, and R. Sato, "Radio communication in tunnels," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-26, no. 6, pp. 439–443, Jun. 1978.

[4] R. T. a. G. G. B. Bruninga, "Cave link radio communications test," *Speoleonics*, vol. 8, no. 1, pp. 5–9, Jul. 2013.

[5] M. Rak and P. Pechac, "UHF propagation in caves and subterranean galleries," *IEEE Trans. Antennas Propag.*, vol. 55, no. 4, pp. 1134–1138, Apr. 2007.

[6] M. Bedford and G. A. Kennedy, "Modeling microwave propagation in natural cave passages," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 6463–6471, Dec. 2014.

[7] J. Pingenot, R. Rieban, and D. White, "Full wave analysis of RF signal attenuation in a lossy cave using a high order time domain vector finite element method," in *Proc. IEEE/ACES Int. Conf. Wireless Commun. Appl. Comput. Electromagn.*, Honolulu, HI, USA, Apr. 2005, pp. 658–661.

[8] S. Y. Lim, Z. Yun, and M. F. Iskander, "Propagation measurement and modeling for indoor stairwells at 2.4 and 5.8 GHz," *IEEE Trans. Antennas Propag.*, vol. 62, no. 9, pp. 4754–4761, Sep. 2014.

[9] S. Y. Lim and C. C. Pu, "Measurement of a tunnel-like structure for wireless communications," *IEEE Antennas Propag. Mag.*, vol. 54, no. 3, pp. 148–156, Jun. 2012.

[10] S. Y. Lim, Z. Yun, J. M. Baker, N. Celik, H. Youn, and M. F. Iskander, "Propagation modeling and measurement for a multifloor stairwell," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 583–586, 2009.

[11] H. Y. Pao, "Probability density function for waves propagation in a straight rough wall tunnel," in *Proc. IEEE Int. Symp. Antennas Propag.*, Monterey, CA, USA, Jun. 2004, pp. 2975–2978.

[12] T. Laborra, L. Azpilicueta, P. L. Iturri, E. Aguirre, and F. Falcone, "Estimation of wireless coverage in complex cave environments for speleology applications," in *Proc. USNC-URSI Radio Sci. Meeting*, Memphis, TN, USA, Jul. 2014, p. 120.