High Gain 2.4 GHz Two-Way Direction Wi-Fi Antenna for Underground Mine-Tunnel

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Abstract— **This paper shows A 2.4GHz two-way directional Antenna of Wi-Fi Systems for Underground Mine-Tunnel. The designed antenna enhances wireless transmission of signals in an underground mine-tunnel in a two-way direction. The research was carried-out through scientific design and simulation-using high frequency structure simulator (HFSS). This antenna has fabricated and tested. The antenna is in the shape of a rectangle, partitioned into 12 sub-rectangular rings hooked together, that work in a standing-wave mode. The high-gain two-way radiation property realized by the currents distribution in-phase on the vertical edges. The dimensions of the desired ring are 230 mm, 22 mm and 0.8 mm (1.84λ, 0.17λ and 0.006λ at 2.4 GHz). The simulated and measured -10-dB bandwidth is about 340 MHz (2.320-2.66 GHz), the simulated peak gain is 8.4 dBi. Presentation and discussion of the simulated results showed that the proposed antenna in two-way direction application is of high directional radiation gain, low profile and easy to build.**

Index Terms— ring antenna, Wi-Fi antenna, directional antenna, HFSS simulation, standing-wave mode.

I. Introduction

Antennas are of immeasurable significance to modern wireless communication technologies particularly those used for Wi-Fi in underground mining. A wireless signal that propagates in any medium goes through some level of impairments. In view of this, a basic understanding of the behavior of electromagnetic wave propagation through strata is fundamental in the design of a suitable antenna for wireless communication systems, especially for underground mines, as the characteristics are different from that of the earth surface. The inadequacies of wired communication, gave rise to wireless technology. The usage of advanced wireless network is proven to be an efficient way of communication in complex environments such as underground mine tunnels. Most Wi-Fi systems' antennas are omni-directional i.e. they radiate power uniformly in one plane in all horizontal directions. The radiated power decreases with elevation above or below the plane, dropping to zero on the antenna's axis. They are used to cover a large, horizontal area with connectivity that can't be overemphasized. This type of antenna has a very narrow vertical antenna pattern so it can be easily mounted on height, with no interference with ground-level devices; There is the need to have two-way antenna to function efficiently in the underground system. An obvious advantage this wireless communication system provides in an underground mining is that, the system does not require physical transmission lines nor cables. These systems are immune to communication outages caused by line breaks due to collapse of mineral bearing rocks, roof falls or damage from machinery. As there is an ever-increasing demand for accurate and real-time data information in underground mines, a 2.4GHz two-way directional Antenna of Wi-Fi Systems will offer the best solution. Wireless communication technique concept in underground mine describes a new and reliable wireless communication and data-transfer solutions [1]–[4].

Wireless connectivity for computers is now well-known and established and now almost all new laptops contain a Wi-Fi ability. Among many available standards on the market, the wireless local area network (WLAN), the IEEE 802.11 standard, usually termed Wi-Fi has become the de-facto standard [3]. With operating speeds of systems using the IEEE 802.11 standards of above 54 Mbps being common [4], Wi-Fi is able to compete well with wired systems. Wi-Fi is one of the popular technologies in the wireless communication systems that allows an electronic device to exchange data wirelessly over computer networks and connections. It can also be explained as a type of wireless networking protocol that allows devices to communicate without cords or cables. It is the most popular means of communicating data wirelessly, within a fixed place, today [5], [6].

An Underground mine refers to a place beneath the earth where hard minerals, mainly those metals ores containing gold, silver, iron, copper, zinc, nickel, tin, lead and diamonds, and soft minerals such as salt, coal, or oil sand are mined. The extracted mineral creates a big working tunnel underground as illustrated in Figure 1. For the purpose of communication in underground mining, there is a need to set up an advanced and reliable wireless communications system to enhance information and data transfer and to also ensure the safety of miners. Wireless communications appears to be the most flexible and effective means of communication systems in such a hostile working underground mining environment [7];

Most often, wireless communications in an underground mine tunnel is very difficult to realize due to the complex nature of the underground environment and interference due to the vibrations by some equipment being used in the mines. For example, radio waves propagation through bauxite and rock strata suffers from dispersion, absorption and scattering of electromagnetic waves due to their natural properties and space limitations [7]. The heterogeneous and complex structure of coal, rock strata and other minerals further complicates the process of radio signal propagation [7]. Radio frequency (RF) waves get attenuated much when traversing bauxite, coal or other mineral strata due to absorption.

Fig. 1 An underground mine-tunnel

Attenuation of signal mainly depends upon the dielectric constant and conductivity of bauxite, coal or other mineral strata. In other words, wireless communication systems used on surface cannot be applied straight-away in underground mines due to the complex geological structures, non-symmetric mine topology, uneven mine structure, and extensive labyrinths that put further hindrance on the wireless communication channels. Also, the sides of the mine-tunnel are full of rocks or other soil materials and there will be no need to use an omni-directional Wi-Fi system antenna, where signals propagate all-round, as this may result in serious energy wastage [8].

Based on the above, a basic understanding of the behavior of electromagnetic wave propagation through strata is also fundamental in the design of a suitable wireless communication system, especially for underground mines, as the characteristics are different from that of earth surface and the need to ensure that the signal radiates in a specific direction in the mine-tunnel [7].

In view of the above, this paper investigates the design and construction of a novel antenna to overcome or reduce the challenges encountered in under-ground tunnel mining and considerably improves the transmission mechanism. The rest is paper is presented as follow: section II deals with the related works, section III covers the antenna design, section IV presents the results and interpretations, section V presents the discussion and finally sections VI conclude the paper.

II. Related Works

A. Model of Wave Propagation Through Medium

In underground mine, the low frequency refractive index is predominately present, and is also greater than unity which may lead to considerable loss of signal. Suppose, some fractions (f_0) of the electrons are free in the sense of having initial frequency $\omega_0 = 0$, the low frequency dielectric constant takes the form of equation (1)

$$\varepsilon(w) = n^2(\omega) = n_0^2 + iN \cdot e^2 \cdot \frac{f_0}{\varepsilon_0} \cdot m \cdot \omega \cdot (\Gamma^0 - i\omega)^2 \tag{1}$$

Where:
n_0 is the contribution to the refractive index from all the other resonance, N the number density of electrons, m is the mass and e is the charge of an electron
$\Gamma^0 = \lim_{w \to 0} g_0$ where g_0 is the dimensionless damping constant.

For a medium, the contribution to the refractive index from the free elections is singular at $\omega = 0$.

Thus, using the Maxwell' s field equation, the dielectric constant is given by:

$$\varepsilon(\omega) = n^2(\omega) = n_0^2 + i \cdot \frac{\sigma}{\varepsilon_0 \cdot \omega} \tag{2}$$

Based on equations (1) and (2), the value of the parameter σ can be inferred as follow

$$\sigma = \frac{f_0 \cdot N_e^2}{m(\tau_0 - i \cdot \omega)} \tag{3}$$

where, σ = conductivity, τ_0 = relaxation time

It is important to note that, at low frequencies conductors have predominately real part of conductivity. However, at higher frequencies the conductivity becomes complex. At these high frequencies, there is little meaningful distinction in conductivity. The conventional way to present the complex refractive index of a conducting medium in the low-frequency limit is to express it in terms of real normal dielectric constant ($\varepsilon = n_0^2$) and a real conductivity (σ). Subsequently, equation (3) is derived as follow:

$$n^2(\omega) = \varepsilon + i \cdot \frac{\sigma}{\varepsilon_0 \omega} \quad (4)$$

Equation (4) indicates that the field energy is almost entirely magnetic. It is clear that an electromagnetic wave propagating through a good bauxite, coal or other mineral block has different properties to a wave propagating through a conventional dielectric. For a wave propagating in the x-direction, the amplitudes of the electric and magnetic fields attenuate following the expression,

$$exp\left(-\frac{x}{d}\right) \quad (5)$$

where,

$$d = \frac{\sqrt{2}}{\mu_0} \cdot \sigma \cdot \omega \quad (6)$$

d is called the skin depth.

Equations (5) and (6) are used in the design of this two-way antenna, specifically to model the RF wave propagation through bauxite, coal and other mineral strata.

B. *Wi-Fi Technologies*

This section presents a number of Wi-Fi technologies relevant for this study namely, IEEE 802.11a, IEEE 802.11b, IEEE 802.11n, IEEE 802.11ac and IEEE 802.11ad.

The 802.11a standard is alphabetically the first of the variety of 802.11 standards that are in widespread use today. It operated in the 5 GHz ISM band and not the 2.4 GHz band, and this made chips more expensive [9], [10].

TABLE 1 SUMMARY OF 802.11a WI-FI STANDARDS

PARAMETER	VALUE
Date of Standard approval	July 1999
Maximum data rate (Mbps)	54
Typical data rate (Mbps)	25
Typical range indoors (Meters)	≈30
Modulation	OFDM
RF Band (GHz)	5
Number of spatial streams	1
Channel width (MHz)	20

IEEE 802.11b appears as the first wireless LAN standard to be widely adopted and built into many laptop computers and other forms of equipment. The standard for 802.11b was ratified by the IEEE in July 1999 [4], [11], [12]

TABLE 2 SUMMARY OF 802.11b WI-FI STANDARDS

PARAMETER	VALUE
Date of Standard approval	July 1999
Maximum data rate (Mbps)	11
Typical data rate (Mbps)	5
Typical range indoors (Meters)	≈30
Modulation	CCK(DSSS)
RF Band(GHz)	2.4
Number of spatial streams	1
Channel width (MHz)	20

After introducing Wi-Fi with the 802.11a and 802.11b standards, the 802.11b standard became the most popular operating in the 2.4 GHz ISM band. This standard proved to be the most popular because the cost of producing chips to work at 2.4 GHz was much less than that of 5 GHz. In order to give higher speed of 802.11a while operating on the 2.4 GHz ISM band, a new standard 802.11g is introduced, that quickly took over from the b standard and became the dominant Wi-Fi technology [13].

IEEE 802.11n standard provides an improvement over the previous counterparts in terms of speed. With the improved performance offered by 802.11n, the standard became widespread by 2009.

TABLE 3 SUMMARY OF 802.11g WI-FI STANDARDS

PARAMETER	VALUE
Date of Standard approval	June 2003
Maximum data rate (Mbps)	54
Typical data rate (Mbps)	5
Typical range indoors (Meters)	≈30
Modulation	CCK, DSSS, OFDM
RF Band (GHz)	2.4
Number of spatial streams	1
Channel width (MHz)	20

Although initially few Wi-Fi hotspots offered the standard, 802.11n devices were compatible with the 802.11b and 802.11g based hotspots [14], [15].

The IEEE802.11ac Wi-Fi standard has been developed to raise the data throughput rates attainable on Wi-Fi networks up to a minimum of around 1 Gbps with speeds up to nearly 7 Gbps. With users requiring ever higher data rates, the IEEE developed their 802.11ac Gigabit standard also known as VHT, Very High Throughput which enables absolute maximum data rates of nearly 7 Gbps with all options running. With these features, the

IEEE802.11ac can effectively handle video streaming [14].

TABLE 4 SUMMARY OF IEEE 802.11n SALIENT FEATURES

PARAMETER	VALUE
Date of Standard approval	October, 2009
Maximum data rate (Mbps)	600
Modulation	CCK, DSSS, or OFDM
RF Band (GHz)	2.4 or 5
Number of spatial streams	1, 2, 3, or 4
Channel width (MHz)	20 or 40

TABLE 5 SUMMARY OF IEEE 802.11ac SALIENT FEATURES

PARAMETER	DETAILS
Frequency band	5.8 GHz ISM (Unlicensed) band
Maximum Data Rate	6.93Gbs
Transmission Bandwidth	20, 40, & 80MHz. 160 & 80 + 80MHz optional
Modulation Formats	BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM optional
FEC coding	Convolutional or LPDC (optional) with coding rates of 1/2, 2/3, 3/4, or 5/6.
MIMO	Both single and multi-user MIMO with up to 8 spatial streams.
Beam-forming	Optional

The IEEE 802.11ad standard is meant to provide data throughput and speeds equal or greater than 7 Gbps. Using frequencies in the millimeter range, IEEE 802.11ad microwave Wi-Fi has a range that span over few meters. The aim is to be used for very short range (across a room) high volume data transfers such as HD video transfers. Longer ranges communication will still rely on the 802.11ac [16], [17].

TABLE 6 SUMMARY OF IEEE 802.11ad SALIENT FEATURES

PARAMETER	DETAILS
Operating frequency range	60GHz ISM band
Maximum data rate	7Gbps
Typical distance	1-10m
Antenna Technology	Uses beam-forming
Modulation format	Various: single carrier and OFDM

C. *Empirical Review*

Many researchers have done a series of work with the view of enhancing the gain of antennas for Wi-Fi for many applications in the mines.

From basics, two unidirectional antennas such as the Yagi Uda give bidirectional radiation function [18], pointing in opposite directions. However, such architecture needs a good matching network which may add extra cost or complexity. Moreover, an array antenna like a dipole array, excited in phase provides solutions to the bidirectional radiation problem [19] with addition of extra feed network. Subsequently, an extra circuit board would also be needed, which will not make the design compact.

A slot antenna etched on a finite ground will also have a tow-way directional radiation pattern, but the greatest gain is usually around 5 dBi [20]. A back-to-back patch antenna having a simple feeding method reported in [21], where the max gain was 5 dBi. However, when working in a low-frequency band, large cross-section size of such broadside two-way directional planar antennas [20]–[22] is inevitable. Consequently, slot antenna etched on a finite ground would hinder ventilation when applied in underground mines, where wind speed of 2–6 m/s is guaranteed.

Furthermore, a spiral antenna [23] is known to have a wideband circularly polarized two-way directional properties but, the maximum gain is also low. A bidirectional narrow patch antenna (BNPA) with narrow patches of the same size on both sides of a thin substrate (0.02 λ) was presented in [24]. However, it also suffers from low-gain (about 2 dBi), and parasitic elements needed to improve the gain.

To meet high two-way directional gain, waveguides are a good candidate. Theoretical analysis and experiments have been performed in [25], [26] but this is also followed by high fabrication cost. A Cascaded Ring Antenna [22], will also have the bidirectional functionality with good gain, but the dimensions of the antenna are usually long, making it bulky.

An Array antenna designed by Bruce [27] which has in-phase electrical/magnetic current equally achieves bidirectional property and a gain (8.5 dBi). Also, the grid antenna [22], introduced by Kraus in 1964, has high directivity due to the in-phase excitation of all the radiation elements. It is classified as a traveling wave antenna. These are etched on a conductor-backed printed circuit board to support the special traveling wave mode, which makes the antenna radiate only in broadside.

III. ANTENNA DESIGN

A. *Antenna Design*

High Frequency Structure Simulator Software (HFSSS) is used to design the desired antenna structure as illustrated in Figure 2.

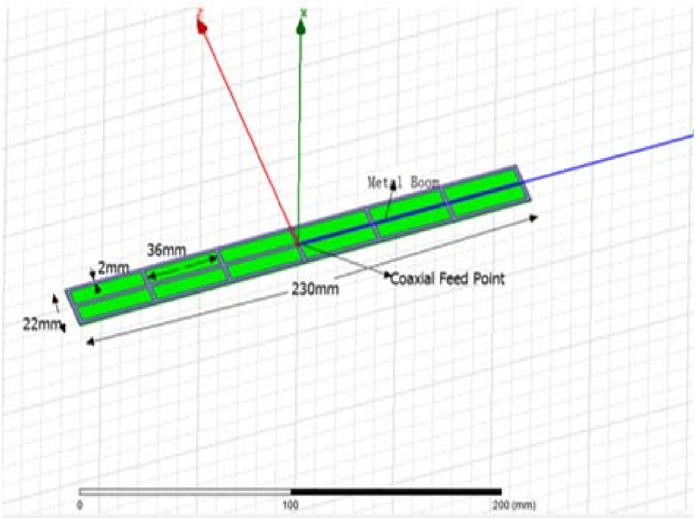


Figure 2. The desired antenna design structure.

The main radiators are the in-phase currents on the two vertical edges, as well as the metal boom. The radiation character is controlled largely by the aspect ratio of the rectangular ring (*h/w*). When the antenna gets excited in the center, the effects are realized simultaneously in the rings on either side of the antenna leading to a higher two-way gain.

A power divider network is possible for the feeding, but such an addition will add more cost and make the design not compact. Therefore, it's good to adopt the idea of a design without a feeding network.

Considering the two loops aligned, the two vertical currents of the two loops are in-phase. The two hooked rectangular rings on either side share the two in-phase currents. In view of sacrificing one radiating edge, the three in-phase currents get excited without any feeding network. Based on this assumption, hooked rectangular ring window-like shapes extends together for higher antenna gain. A coaxial cable connected at the center is used to feed the antenna through the center.

TABLE 7 SUMMARY OF ANTENNA DESIGN SPECIFICATIONS

Parameter	Value
Frequency	2.4 GHz
Total Length(*W*)	230 mm
Line width(*wl*)	2 mm
Width(*h*)	18 mm
Length(*w*)	36 mm
Relative permittivity	4.4

B. Design Considerations

The antenna is two hooked rectangular window-like ring aligned together. The two edges' vertical currents of the two loops are in-phase. The two loops are merged together; the current distribution of the antenna after merging is the combination of the original one, because the two loops share the two in-phase currents. By giving up one radiating edge, three in-phase currents are excited without any feeding network. By this assumption, more hooked rectangular shaped rings can be tumbled together for higher antenna gain.

Based on the above-mentioned assumption, this research showed an antenna design with twelve hooked rectangular rings tumbled. The structure is of copper (FR4) with the thickness of 0.8 mm and relative permittivity 4.4, other details is in table 7. The simulated electric current distribution, shown in Figure 4a, validates the assumption and addresses a reasonable insight into the two-way directional radiation mechanism [12], [16], [28]. There is an induced coupling between the hooked rings by the current mode. The combine rings and the current mode of each ring joins perfectly, which make the structure work in a special standing-wave mode. This also allows higher directivity to be achieved based the radiation of fourteen hooked in-phase vertical currents. The directivity gets high as more loops tumbled. However, the advantage of sixteen or more loops is insignificant compared to the twelve loops, as the energy coupled to the loops in the end gets lower, and the 1 λ standing wave mode becomes difficult to support.

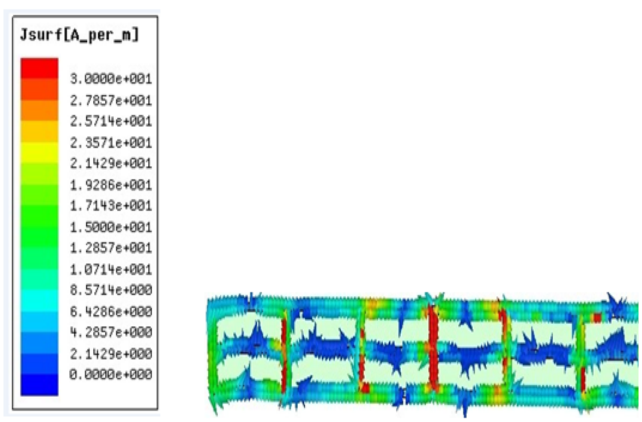
The design realizes two benefits from 1 λ resonant mode of the loop element. Firstly, the 1 λ mode is the lowest resonant mode that a ring structure can support, which helps to control the overall antenna length after tumbling. Secondly, when the rings in the same dimensions gets tumbled, all the rings can still remain in the 1 λ mode synchronously. It means that currents on all the vertical edges are in-phase. The magnitudes of the currents on the vertical edge decrease progressively from the center to the end. This phenomenon is best explained by the traveling wave, although the structure works in a standing-wave mode. As the antenna is excited in the center, the currents distributed away from the center suffer radiation loss and ohmic loss along the path from the excitation point to the end of the antenna structure. From the array antenna point perspective, such a current distribution will have impact on the higher directivity achieved [12].

Figure 3 Fabricated Prototype of desired antenna.

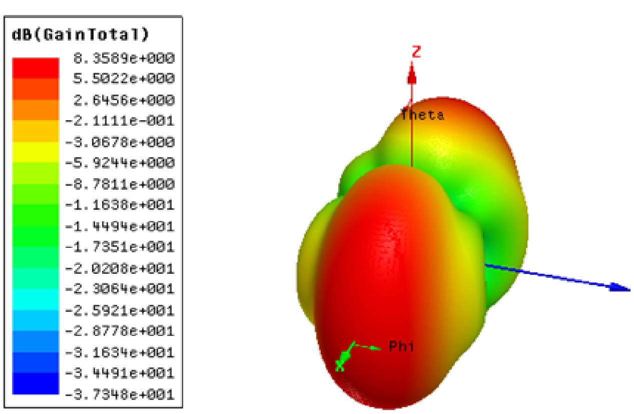
IV. RESULTS AND INTERPRETATION

As shown in Figure 3, the fabricated prototype of the desired antenna is made up of twelve hooked rectangular rings in series, with each ring having the same dimensions. All the copper lines have the same width of 2 mm. A coaxial cable is attached to the antenna and used to feed it from the center. The antenna parameters were kept varying to make good impedance matching. Ansoft's HFSS software was used to study the effect of the key geometrical parameters on antenna radiation and impedance matching performance. Figures 4 (b, c), and 5(a-f) show the 3D radiation gain, S_{11} value and radiation pattern of the design simulation.

The impedance, as well as the two-way directivity behavior changes with variation of *S*. As indicated earlier, the in-phase currents on the vertical edges are the main radiators. When *S* gets smaller, the distance between the two vertical edges gets longer, and the directivity gets higher based on the array factor. A single ring determines the Impedance of the antenna. When S gets smaller, the distance between the two horizontal edges gets shorter. As the cancellation between the currents gets more severe, more energy gets stored in the near-field, and the Q value of the antenna gets larger. Consequently, the inherent bandwidth of the antenna gets narrower. Hence, there is a tradeoff between the directivity and the inherent bandwidth and the size.



a)



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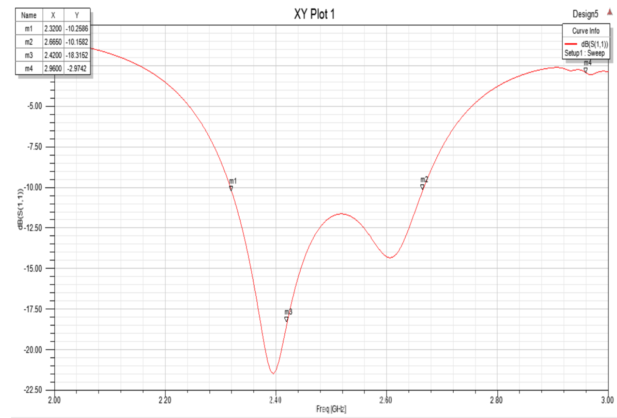
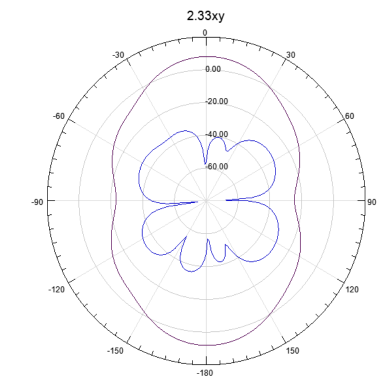


b)

Figure 4 Simulated results of the desired antenna: a) Current distribution, b) 3D Radiation Gain and c) $|S_{11}|$ of the proposed antenna



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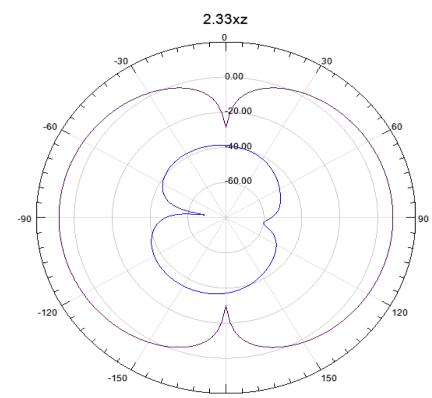

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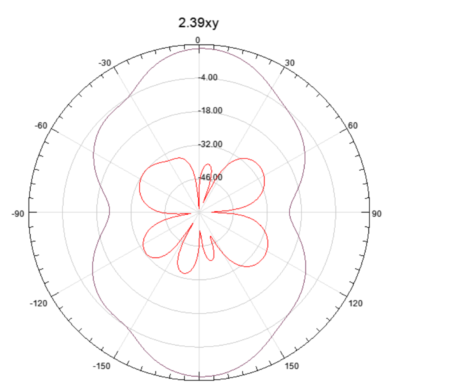

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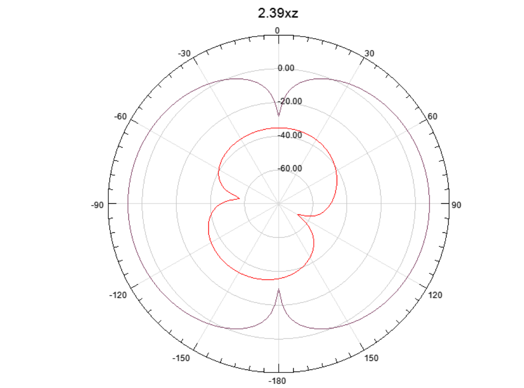
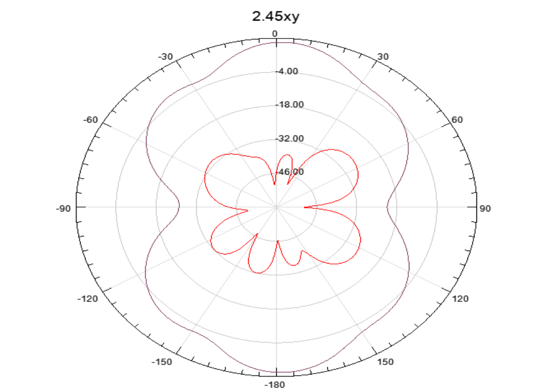
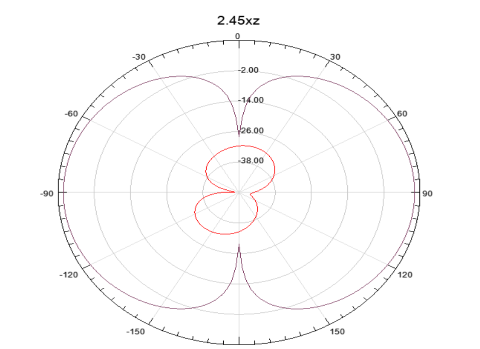


d)



e)



f)

Figure 5 (a-f) Simulated radiation pattern of the desired antenna on H-plane (*XY* -plane) and E-plane (XZ-plane).

The fabricated prototype antenna has worked effectively at 2.4 GHz which was measured experimentally to confirm the design. For the purpose of excitation and measurement, a 50 ohm coaxial cable was attached from the antenna to a network analyzer (Agilent N5247A) as illustrated in Figure 6. The simulated and measured impedance bandwidths for S_{11} were as follow: $|S_{11}| \leq -10\ dB$ are 340 MHz (2.32 – 2.66 GHz) and 395MHz (2.28 – 2.675 GHz). The measured values are also illustrated in Figure 7. The slight difference between the simulated and measured results mainly comes from the measurement and fabrication errors.

V. DISCUSSION

The two-way directional Wi-Fi antenna proposed in this study outperforms counterpart combination of two unidirectional Yagi-Uda antenna pointing in opposite direction. Many literatures including [18], supported this assertion. Consequently, the designed two-way directional Wi-Fi antenna does not need a matching network and this makes it less costly and less complex.

Similarly, the two-way directional Wi-Fi antenna equally outperforms an array antenna like a dipole array, that excites in phase to give the two-way radiation pattern. This is justify because the latter will need an additional circuitry to enable the radiation in the two-way direction and subsequently the design is bulkier and costlier. [29]–[32] support the same view from their studies that the two dipoles antenna needs extra circuitry to radiate properly in two directions.

The designed two-way bidirectional Wi-fi antenna as presented above, has a gain of 8.35dBi, which is a greater advantage as compared to many antennas achieving the same purpose. More specifically, it is better that using a slot antenna etched on a finite ground for which the greatest gain is usually around 5 dBi [20]. Moreover, a back-to-back patch antenna with a simple feeding method [21], can meet the two-way directional transmission but it also has a greatest gain of 5 dBi. A bidirectional narrow patch antenna (BNPA) with narrow patches of the same size on both sides of a thin substrate (0.02 λ) [24], can also meet the two-way transmission, however, it has a low-gain (about 2dBi [33]), and has parasitic elements that inhibit a good radiation of the antenna signals.

Another important advantage of the proposed antenna is the flexibility given in terms of ventilation. Underground mining systems requires wind speed of 2 to 6 m/s. Contrary to the design, large cross-section size of two-way directional planar antennas [20]–[22] is inappropriate for good ventilation. Additionally, slot antenna etched on a finite ground would hinder ventilation when applied in underground mines.
Furthermore, a spiral antenna [23] is known to have a wideband circularly polarized two-way directional antenna, but, the maximum gain is also low.

To meet high two-way directional gain, waveguides are a good candidate. Theoretical analysis and experiments shown in [25], [26] but this will not come without a cost factor. A Cascaded Ring Antenna [22], will also have the two-way directional functionality with good gain, but the dimensions of the antenna are a bit longer, making it bulky.

Figure 6. Vector Network Analyzer (Agilent N5247A) for measuring $|S_{11}|$.

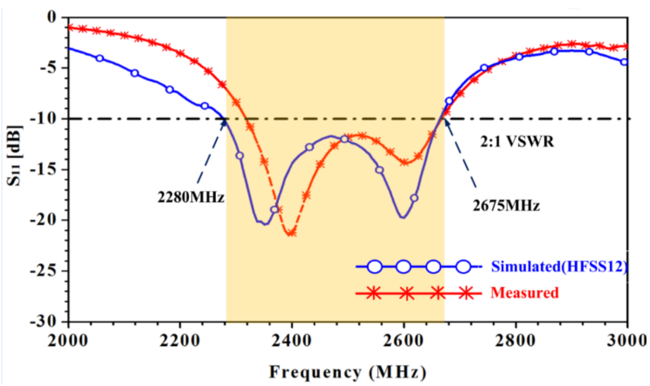


Figure 7 Simulated and measured $|S_{11}|$ of the proposed antenna.

VI. CONCLUSION

In conclusion, though wireless communications suffers a lot of impairment in mines, due to the factors mentioned in the earlier sections, this report has shown that with a careful design and a tumbled High-Gain Two-Way Direction Wi-Fi Antenna for Underground Mine-Tunnel, it is possible to improve wireless communications in underground tunnels at 2.4 GHz. For high directivity, there are two major design challenge. Firstly, the working mode of the single ring need be selected carefully considering the tradeoff between directivity and impedance matching. Secondly, the combination method of the twelve hooked rings need be designed carefully to support the working mode of each ring and keep the currents on all vertical edges in-phase. Each ring of the proposed antenna works in 1λ mode. By combining the rings in series and adjusting the aspect ratio of the rectangular rings, good impedance matching and high two-way directional gain be achieved. The desired antenna has the advantages of easy fabrication, less-expensive, minimum size, low profile, resistance to wind, and high two-way directional gain, which are suitable for wireless communication in underground mines. Future research can look at the use of time-saving semi-automatic genetic algorithm with HFSS for optimization process in the geometric parameters, which can enable achievement of characteristics like, good impedance matching, good return loss, high gain and directivity.

ACKNOWLEDGMENT

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