A Buried Cavity Backed Slot Antenna for Agriculture and Infrastructure Monitoring

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Abstract— While the earth provides a relative secure environment in the event of flood, fires and storm events, the design of antennas which operate satisfactorily to a receiver on or above the ground has been a design challenge. A cavity-backed slot antenna previously used for biomedical applications was modified for subsurface propagation at 433 MHz at shallow depths in soil. A 433 MHz +10 dBm beacon located in an aluminium box (163 × 114 × 42 mm) with a thin (1 mm width) slot buried to a depth of 100 mm. Vertical electric field measurements were made on the surface of the earth from the antenna buried in moist lawn-covered soil. The antenna was placed below the grassed surface with the slot directing radiation horizontally into the soil. Propagation across the surface suffered a loss of 0.53 dB/m. This technology shows significant promise in the case of sensors buried in soil.

Keywords—slot antenna, UHF, RSSI, surface propagation.

I. INTRODUCTION

The propagation of radio waves in forests and woodlands has been studied by Tamir at RF frequencies (1-100MHz) [1] where the top of the canopy and the earth form the bounds of a waveguide which supports a lateral wave and the sky wave is reflected from the ionosphere. At these frequencies the vegetation was assumed to have uniform electromagnetic properties ($1.01 < \epsilon_r < 1.5$, $10^{-3} > \sigma > 10^{-4}$ S/m where ϵ_r is the relative permittivity and σ is the conductivity).

Underground propagation at 433 MHz has been explored by numerous authors [2-5] using wire antennas for different applications such as agriculture, soil monitoring and mine environment. Communications from underground infrastructure is of increasing interest to monitor water pipes etc [6] and for precision agriculture applications monitoring soil nutrients and moisture [7].

In this paper we propose a novel idea of using slot antenna model where a monopole antenna is used inside an aluminium box. This configuration offers mechanical, moisture and thermal protection under extreme circumstances.

The line of sight (“direct wave”) is more than 60 dB less than the lateral wave. The electric field strength $E(d)$ increases at small distances d above the earth’s surface (so called “height gain effect”). The electric field $E(d)$ across the surface given by the equation:

$$E(d) = E_0 \frac{e^{-\alpha d}}{d} \quad (1)$$

where α is the attenuation coefficient and E_0 is the initial field strength. This relationship was found to be suitable for both vertical and horizontal polarisation. The path loss over 1 km at 400 MHz was estimated to be approximately 130 dB. The depolarisation is predicted using the lateral wave model [1]. A vertically polarised transmitter will yield both polarisations in the far field, however, a conducting earth plane will have a very small horizontal component at the earth’s surface.

Lateral waves have been the subject of ray path analysis for a buried and an above ground transmitter with both vertical and horizontal polarisations [8, 9], and the surface interference effect from a buried transmitter was modelled and measured at 433 MHz over beach sand in-situ with no vegetation ($\epsilon_r = 2.13$, $\sigma = 10^{-4}$ S/m) [10]. However, if the conductivity is too high ($\epsilon_r \epsilon_0 < \omega \sigma$ where ϵ_0 is the permittivity of free space), this interference pattern disappears. This was evident in ocean measurements at 433 MHz [11] where the transmitting antenna was located below the surface of the water in an air-filled plastic cylinder.

Fire has a significant effect in a forest. The most obvious change to a forest from before to after a substantial fire is the removal of foliage and the reduction in thin twigs and branches. Smaller trees and even large trees may be totally consumed or fall to the ground as glowing coals. The removal of foliage will reduce the radio attenuation coefficient. An additional effect is the removal of organic matter and the drying of the surface soil, however this effect is not likely to exceed a depth of 5 cm [12]. The removal of organic matter and soil moisture will greatly reduce the conductivity of the upper layer to this depth. Electronic instrumentation (transmitters and receivers) are therefore well protected from the very high temperatures observed in and above the flames of a wild fire.

II. METHODS

Slot antenna design and radio beacons

A 433 MHz radio beacon [10, 11] developed in-house has a transmit power of +10 dBm and is capable of logging the signal strength (RSS) received by a second unit 10 times each second. The master beacon with a monopole antenna (length 30 mm) was positioned inside an aluminium box (internal dimensions 163 × 114 × 42 mm) to couple into the lowest

TE₁₁₀ resonant mode of the cavity. A narrow (1 mm wide) slot in the smallest face (length 114 mm) ensured that the E field was perpendicular to the slot for maximum emitted radiation (Figure 1). The completed cavity-based slot antenna with master transmitter unit was buried to a depth of 100 mm (the distance of the top of the box to the ground surface) (Figure 2). The receiver was an identical unit and has a 178 mm monopole antenna. The cavity-backed slot antenna is a variation to the designs previously reported for in-body and off-body communications [13, 14].

The results from the buried transmitter were compared with transmission results for two above ground monopole antennas on the earth's surface. This "ground-wave propagation" has been the subject of numerous studies and includes analytical formulations by Sommerfeld and Norton [15, 16]. When the earth is not perfectly conducting, there is a radiation pattern minimum in the horizontal direction for vertical polarisation as the reflection coefficient is -1 resulting in radiation cancellation (see [15] Figure 16-9). In this experiment the ground wave attenuation for antennas close to the surface was compared using the attenuation rate α in dB/m. The buried transmitter with a horizontal slot is shown in Figure 2 and measurements were made across the grassed surface.

Fig. 1. The 433MHz cavity backed slot antenna with dimensions $163 \times 114 \times 42$ mm. The slot at the front is 1mm wide and extends across the width of the aluminium box. The beacon transmitter with 30 mm monopole is positioned in the centre of the box.

Fig. 2. Buried horizontal box (depth 100 mm) below a flat, grassed surface. The end slot was horizontal for the surface propagation measurements in 0.5 m steps. The front to back ratio across the surface was measured at 5 dB and the maximum received signal was immediately above the slot.

III. RESULTS

Experimental measurements

The received electric field at the surface of the earth was vertically polarised (i.e., normal to the earth's surface). This is the opposite polarisation [10] from the radiation from a horizontally polarised transmitter buried in a low loss material (dry beach sand).

The electric field $E(d)$ converted to the received signal strength in dBm was fitted to the spherical wave equation (1) for distance d and with attenuation coefficient α given by the equation:

$$20\log_{10}(E(d)) = 20\log_{10}(E_0) - 8.686\alpha d - 20\log_{10}d \quad (2)$$

Rearranging this equation gives:

$$20\log_{10}(E(d)) + 20\log_{10}d = 20\log_{10}(E_0) - 8.686\alpha d \quad (3)$$

The LHS of (3) versus d should be linear providing measurements are in the far field of the antennas and the received signal is above the noise level.

Figure 3 shows the received signal strength as a function of horizontal distance from the buried slot antenna, this is represented by the measured data and a linear fit for both the above and below ground transmitter locations using (3). Note that the Pearson's correlation coefficient r^2 is 0.89 and 0.90 for the above ground and below ground transmitter locations, respectively. The vertical electric field dominates the propagation so that all measurements were made using the same vertical monopole antenna. At ground level the received signal is a minimum, and it increases with height [15, 16]. The above ground transmission path has indications of a foreground interference with a series of undulations (see Fig. 3).

The same +10 dB transmitter circuit was used for both above and below the ground. Table 1 shows that at 100 mm below the ground, the loss determined from the intercepts in Figure 3 differs by 37.3 dB, while attenuation constants were 0.531 and 0.195 dB/m below and above ground correspondingly.

Fig. 3. Measured data and linear fit for the vertical electric field adjusted for distance using (3), at the surface for an on-ground monopole transmitter (continuous line, *) and a buried cavity slot transmitter (dashed line, *).

Table 1. Linear parameters from Equation (3) for the transmitter above and below ground.

Transmitter	Slope (dB/m)	Intercept (dB)	α (dB/m)	r^2
Above ground	-1.695	-49.5	0.195	0.89
Below ground	-4.61	-86.8	0.531	0.9

IV. CONCLUSIONS

The radiation from the buried slot antenna suffered significant attenuation when compared with a quarter-wave monopole transmitter above ground. The aluminium box buried 100 mm below the surface is mechanically and thermally robust under most environmental conditions including:

- Variations in soil moisture including flooding;
- Shallow surface disturbances including the soil compression from motor vehicles, shallow tillage; and
- Bush fire temperatures which might reach +1500°C above ground have been observed to be less than 50°C at 100 mm below the ground.

The deployment of an elevated receiver can increase the received signal strength. Further work is oriented towards improving the radiation characteristics through a more optimised antenna design, and numerical modelling for different top soil conductivities.

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