Through-The-Earth (TTE) Communications

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***Abstract*—The abstract goes here.**

***Index Terms*—Through-The-Earth Communications, Extreme Conditions Communications.**

I. Introduction

Due to intrinsic characteristics of soil, electromagnetic waves penetration in TTE communication obeys diffusion equation instead of wave equation. The field intensity of plane waves decays exponentially with traveled distance and frequency square root in a homogeneous conductive medium, so it is necessary to use low frequencies in order to guarantee less propagation losses within soil. Such low frequencies usually are VLF (3-30 kHz) and sometimes LF (30-300 kHz) [22 Josua dissertation, US PAT 3900878, US PAT 7043204, US PAT 7149472], and very rarely in MF (300-3000 kHz) [us pat 2010/0311325]. The characteristic of transmitting at a electrically short distance due to low frequencies for TTE communication permits using electrically small antennas with very low radiation efficiency ["Transmit antenna for portable vlf to mf wireless mine communications", Robert lagard, 1977, USBM report]. Small and large antenas differ by the interaction medium. Small antennas interact primarily through the medium of reactive coupling over only relatively short distances, while large antenas may interact through both the reactive zone and also through the medium of electromagnetic radiation over long distances. Small antennas are normally smaller than $\lambda/10$ including any ground plane image [ARRL Antenna book, 20th edition, p. 5.1], and specifically for a small magnetic loop the current distribution is uniform, while in a large magnetic loop the current is not the same either in amplitude or phase in each part of the loop. It can be shown in [us pat 3967201], [1] that a magnetic field antenna is considerably more efficient for communication through a lossy medium than an equivalent electric field antenna, making magnetic loop antenna the natural choice for most of the work found in the literature. Transmission in uplink is more critical than in downlink. Regarding the receiver, the atmospheric noise is clearly stronger in the surface than in deep mines. And with respect to the transmitter, space and power limitations within mines limits magnetic moment to be generated. Small loop antennas with several turns could be an alternative to large single-turn antennas for using in transmitters in confined spaces within mines. However, high reactance of multi-turn loops imposes practical limitation in terms of high voltage needed to produce enough magnetic moment to traverse long distances. In many cases, tuning the antenna through an opposed reactor for resonance at a specific frequency is the only way to provide acceptable field gain at the cost of reducing bandwidth [2], [3].

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II. Field zones and effective volume of antenna

FIELD ZONES HERE

In TTE communication, receiving antenna usually is located at reactive zone of transmitting antenna, (i.e. inside its radian-sphere $V_s = \frac{4\pi}{3}(\frac{\lambda}{2\pi})^3$, and vice-verse, where majority of reactor's energy is located. Wheeler [3], [4], defines radiation power factor (RadPF) for small antennae as the ratio between active radiated power and reactive power. In some cases, RadPF also can be estimated with factor quality Q and, as a consequence of it, defines the bandwidth where impedance matching between antenna and source (or load) is possible. Wheeler calculated, for small antennas, RadPF as a function of its dimensions and defined antenna's effective volume with the following formula:

$$V' = \frac{9}{2} radPFV_s \tag{1}$$

This expression allows comparing different types of small antennas in terms of bandwidth.

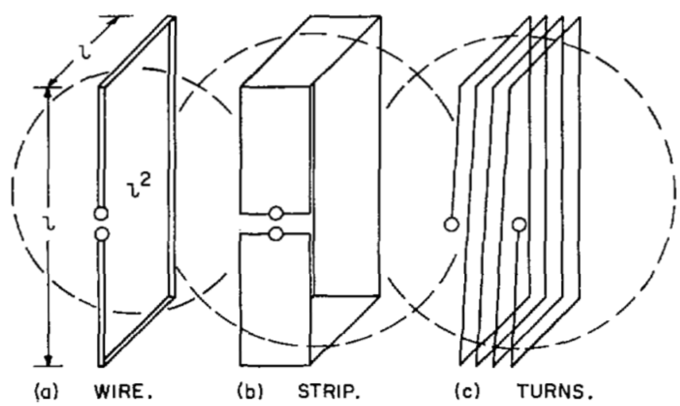

Fig. 1: Effective volume of square loop

III. Antennas for TTE communications

The choice between increase of bandwidth or passive gain at a tuned network depends on application and type of modulation. [2] presents a intermediate solution for robust digital modulation such as FSK transmitting in VLF. In order to minimize spurious frequencies in FSK modulation due linear distortion related to antenna's narrow bandwidth, Johannessen's solution implied the use of non-linear reactors, whose resulting reactance varies as a function of baseband modulating signal in order to automatically tune the antenna at the instantaneous FSK frequency. Specifically in [2], the author considers a electric antenna and two non-linear inductors connected in series with it. Using those non-linear reactors triggers the generation of odd harmonics due to its quadratic law characteristic. Canceling those undesired signals can be realized by filtering through a control auxiliary circuit perfectly balanced as shown in figure 2.

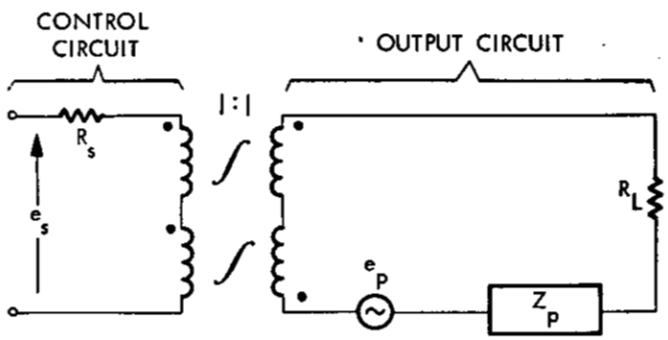

Fig. 2: Non-linear inductors modifying antenna's resonance and control circuit filtering undesirable harmonics.

It can be verified in [2] that, when measuring voltage on inductors terminals at output circuit, there is nothing but fundamental frequency for every FSK frequency. Several studies used electric field antennae such as electrodes for characterizing earth conductivity [5], [6], earth impedance [7], noise [8] and propagation channel [9]. E-Spectrum Technologies tested a prototype [10] through a NIOSH-sponsored study for underground to surface communications using surface E-Field antennas composed of two driven-rod ground beds separated by 30.5 meters.

Choosing type and dimension of antennae in TTE communication depends on communication range and local physical space. Magnetic field antennae, as loops (Fig. **??**), are preferred over electric field antennae, by cause of presenting less attenuation rates in conductive medium [1].

Magnetic moment produced by antenna depends on the input signal, antenna's geometry and its constituent material. On systems using loop antennae and mid-range transmission (> 300 m), it might be necessary using transmission antennae with diameter of about hundred of meters. Small loops with one or more turns are usually used in short-range communication for mines and caves.

Another type of antenna used in TTE communication receivers is the ferrite rod [1], [11] which is compound by a thin solenoid with several turns and magnetic material core (with tens of times bigger than vacuum permeability) (Fig. **??**). A higher number of turns and nuclear material compensate antenna's small transverse section. This structure, usually long (10 cm to 2 m), can offer a bigger mobility to radio equipment. Commonly, such arrangement is used at the underground end where atmospheric noise causes less interference. The fact of surface receivers being affected more significantly by atmospheric noise, creates the necessity of using large antennas connected to low-noise amplifiers and noise-matching circuits.

Comparing both antennae in transmission mode, a circular loop antenna of one turn, with 1 m diameter and 200 g of mass, produces a magnetic moment of $m_d = 30Am^2$ for 10 W of power dissipated. In the other hand, a small ferrite rod with less than 1 cm of radius and 20 cm long, produces the same equivalent magnetic moment, but dissipating twice as much the amount of power. Nevertheless, an circular loop with a mass of 8,5 kg and a diameter of 50 m, can produce up to $m_d = 30kAm^2$ dissipating 100 W. To reach such magnetic moment, the ferrite rod would dissipate a tremendous amount of power hindering its use in transmitters. Multiple ferrite windings may be oriented orthogonally on the X, Y and Z axis for receiving antennae [12]. Antenna outputs can then be added vectorially to obtain resultant signal and efficient noise cancellation.

David Reagor presents in [13] an active device very sensitive to magnetic flux able to be used as a receiver antenna for low frequencies and with a compact size. High-Temperature Superconducting Quantum Interference Device ($SQUID$) is a magnetometer based on superconductive loops composed of Josephson junctions, used as a compact receiver. This device is an alternative to ferrite rod, providing less noise interference [14]. Superconductive components have been widely used in applications where noise floor is critical as in radio-astronomy, non-invasive magneto-encephalography, submarine communication, etc. The superconductive effect is reached at -197°C using $100cm^3$ of liquid nitrogen for a man-portable receiver. This superconductor is called "high temperature" to differentiate it from those which works at -270°C. As a matter of fact, a SQUID is a magnetic flux to voltage converter of non-linear response. Using a Flux-Locked-Loop (FFL) it is possible to linearize the signal increasing its linear dynamic range and make the detector work as a magnetic field null detector. Figure 3 presents a SQUID working with a pick-up loop. Using a conventional magnetic antenna assures a larger quantity of flux as a function of a wider area. Flux is transferred to SQUID via short-distance magnetic induction, keeping low magnetic noise level.

Larry Stolarczyk presents a communication method for underground mines [15], [16] based on radio signal transmission in the MF band through magnetic induction on conductors usually located in mining projects as power lines, rails, metallic pipes, etc. Transceivers used as repeaters provide a high range of these systems even though those conductors are isolated from magnetic radios. As a matter of fact, it is more proper talking about a hybrid TTA-TTW (through the air/wire) system. Although MF band not be suitable for TTE communication, this method shows how to use loop antennae in fix, mobile and repeater terminals that is important for the following study of Stolarczyk that includes TTE. He also presented a wearable vertical loop antenna that keeps its shape during user movement to reduce field variation. Years later, Bunton et al. [US Pat. 7,043,195 B2] teach a communication system using a transmission technique similar to [15], [16] through loop antennae and conductors available in mine. In [17], Stolarczyk upgraded the method to work with several propagation media (including TTE), operation bands and modulations. ULF repeaters are located in the interior of the underground mine for providing a higher range without the use of conductors within the mine. A problem of this and other methods [18], [19] using repeaters and/or any conductive structure, is the high probability of propagation medium disruption as well as lack of repeater's reliability in case of burials inside mine.

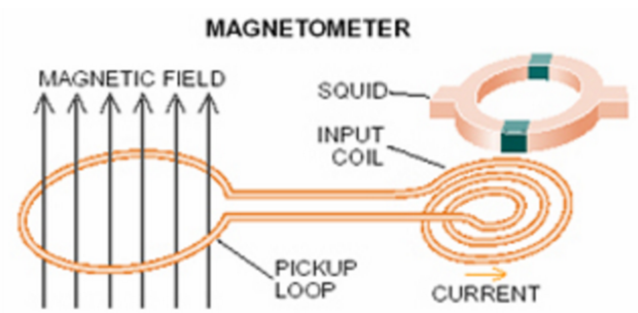

Fig. 3: SQUID working with a pick-up loop

Mark Rhodes in [11] proposed a TTE transmission system for low frequencies based on direct inductive communication or through repeaters. In order to assure system's compactness with high magnetic moment, the author proposed the use of 100 turns 50 cm radius loop antennae. Nevertheless, Rhodes did not elucidate in this paper the way that antennae would be driven by transmitter. Feeding 1 A in this antenna for generating a magnetic moment of 100 Am^2 would demand a voltage of 1.5 kV. It is due to the high antenna's reactive impedance (1600 ohm at 5 kHz), which is proportional to loop's square number of turns. Such voltage is prohibiting for underground transmitter due to security prerogatives and battery capacity. The reduction in current and, consequently, magnetic field needed for transmission, implies the use of several repeaters. Mark Rhodes presents in [20] a system with a planar antenna array in order to alleviate issues related to high impedance of large loop and multiple turn antennae. Using several coplanar loops of one or few turns, balanced and driven separately, can assure with less feeding voltage a magnetic moment equivalent to that of a multiple turn loop. Figure 4 shows a combination of nine loop antennae individually driven positioned on the same plane. Feeding ensures same rotation sense and phase of the current in each single sub-loop, canceling magnetic fields generated by intern currents. Resulting field behaves as field from an equivalent composite loop antenna.

Taking as an example the sub-loop at the center of the array, where net magnetic field tents to zero, the resultant inductance is almost nonexistent. Similarly, the resultant inductance proportional to the net current at the array's edge will be smaller when compared to isolated antennae. Consequently, the necessary voltage for driving all sub-loops would be less than in a equivalent single antenna of same size using the same amount of current.

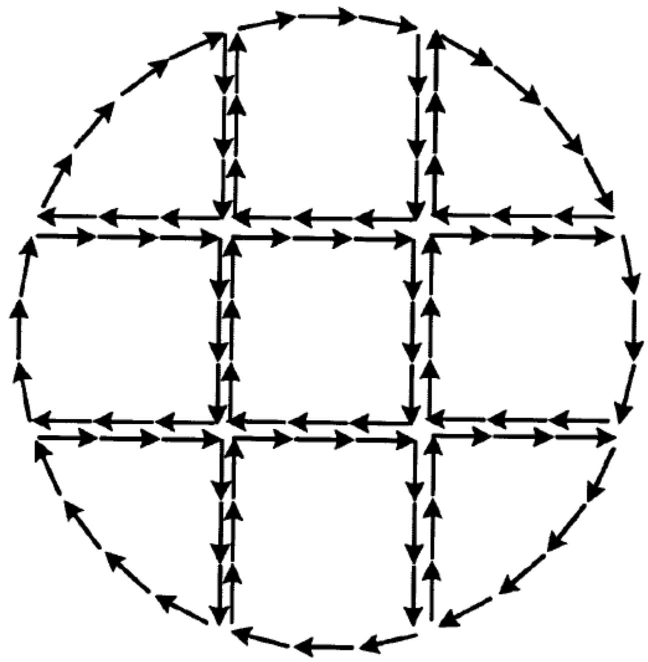

Fig. 4: Antenna composed of individually driven coplanar sub-loops

In [21], Rhodes utilizes multiple loops again but in coaxial configuration. As in [20], the loops are driven in parallel by independent amplifiers in order to guarantee lower voltage for each sub-loop than in a multi-turn loop driven by a single amplifier. If sub-loops are concentrically aligned, in close proximity and/or closely coupled, the signals arranged to be substantially in phase mutually, the composite antenna may reach equivalent levels of magnetic moment compared to the multi-turn loop but using less voltage per driver. This is achieved if the drivers are nominally identical and all supplied from the same common signal source. Sub-loops in [20] and [21] do not use any resonating component favoring bandwidth over gain.

In [22], Rhodes utilizes multiple coaxial sub-loops in order to increase bandwidth using multiple resonances. Sub-loops are fed by a single voltage driver, electrically connected in parallel to each other and partially coupled due to a controlled distance between them (see Figure 5). The circuits are tuned in different frequencies in order to assure impedance matching for the band of interest. The distance between sub-loops is decreased until a acceptable degree of coupling is seen, then the resonating and damping components may be adjusted to achieve the desired summed frequency characteristics. In opposition to the planar structure of [20], the coaxial configuration in [21] and [22] appears to be more practical from the viewpoint of equipment dimensions regardless the performance of each

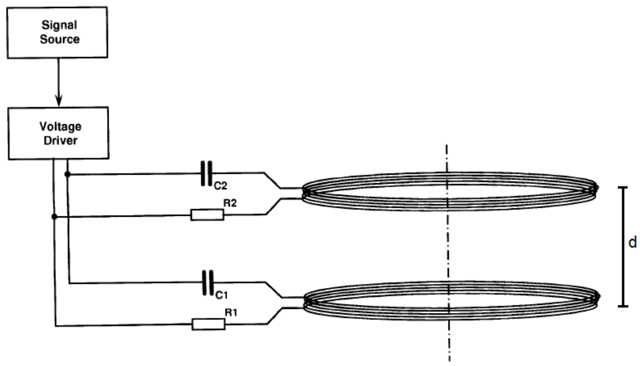

Fig. 5: Transmitting antenna composed of two partially coupled sub-loops with different resonances.

antenna. Differently from [22], Mark Roper in [12] uses concentric antenna loops to increase magnetic moment instead of bandwidth keeping moderate current. In fact, the secondary loop used in this configuration narrows the bandwidth of the primary loop. The equivalent circuit is seen in Figure 6, where only the primary loop is driven and there is no electric connection to the the secondary loop. The resonant capacitors are chosen to force a higher resonant frequency for the second loop. This makes the secondary loop to be capacitive at the resonance frequency of the primary loop which is the operating frequency. Then, the voltage induced in the secondary loop by the main loop drives the current in a direction which reinforces the magnetic field. The enough bandwidth needed for narrowband transmission is controlled through the damping resistances.

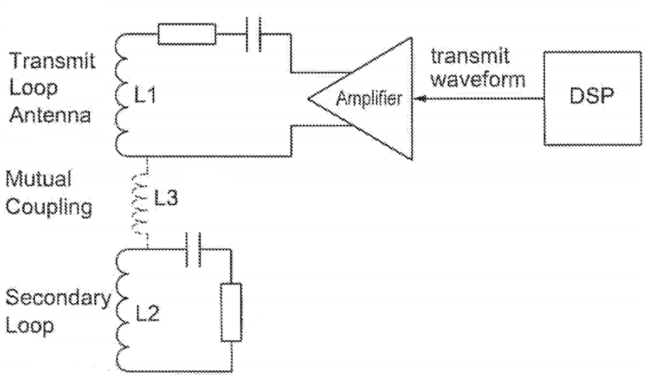

Fig. 6: Equivalent circuit of transmitting antenna composed of secondary loop coupled by a leading antenna with different resonances.

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