Electrically small antenna for maximising transmission into HF ground waves

S. Lim, H. Choo, R.L. Rogers and H. Ling

A top-loaded, inductively-coupled, electrically small antenna is designed for HF ground wave transmission. A genetic algorithm is used to optimise the antenna parameters. Two prototype antennas have been built and the test results match well with simulations. Both antennas have an electrical size *kr* of 0.2, greater than 65% efficiency and transmission performance within 1 dB of a commercial whip.

Introduction: It is well-known that HF ground waves are useful for non-line-of-sight communication over extended ranges. A key challenge is the design of small antennas that can couple efficiently to HF ground waves. Previously, the design of electrically small, arbitrarily shaped wire antennas was investigated using genetic algorithms (GA) [1, 2]. Subsequently, a class of planar, inductively coupled antennas was proposed in [3]. While these antennas were optimised for bandwidth and efficiency using GA, the test results at HF frequencies showed high transmission losses for ground wave links. We believe this is due to low directivity to the horizon. Therefore, it is important to take ground wave coupling into consideration in the design for such applications.

In this Letter, we present an electrically small antenna design that maximises transmission into HF ground waves. The antenna structure entails three design concepts including (i) a vertical antenna body to maximise coupling to ground waves, (ii) top loading to achieve self-resonance in a small size, and (iii) an inductively coupled feed to step up the input resistance. The design parameters are chosen by using a genetic algorithm in conjunction with the Numerical Electromagnetics Code (NEC). Two prototype antennas with a *kr* of 0.2 (where *k* is the wave number and *r* the radius of the hemisphere enclosing the antenna) have been built and measured at 30 MHz to confirm the design performance.

Antenna design: Fig. 1 shows the antenna design. It consists of an inductively coupled feed structure at the bottom. The primary loop is fed by a coaxial line at one end and shorted to ground at the other. The secondary loop is located at the base of the antenna body. It starts from the ground, goes through multiple turns (Fig. 1 shows 1.5 turns) before connecting to the vertical antenna segment. This inductively coupled feed serves to step up the input resistance of the small antenna, which is much less than 50 Ω. The step-up ratio is controlled by the areas, the number of turns and the distance between the primary and secondary loops. In contrast to the planar design presented in [3], the present design can achieve much tighter inductive coupling and thus a larger step-up that is necessary for very small antennas.

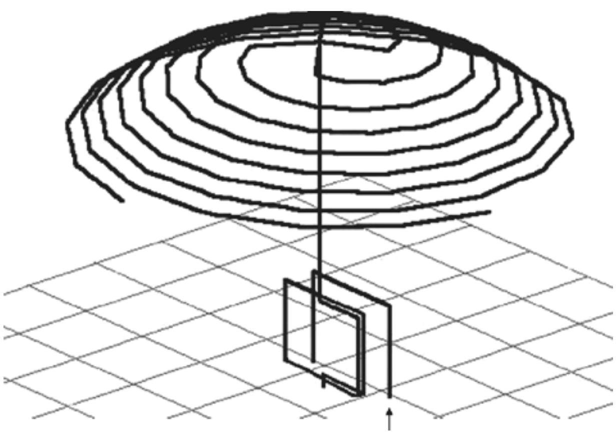

Fig. 1 *Design of four-arm, top-loaded, inductively coupled antenna*

Dimensions of primary loop: 8.3 × 10 cm; secondary loop: 7.2 × 10 cm; spacing between loops: 3 cm; length of straight segment: 23.7 cm. Spherical helix contains two turns for each arm and has projected radius of 21.8 cm

The vertical antenna body is extended straight up to the uppermost point of the antenna to maximise coupling to the HF ground wave, which is vertically polarised. We have carried out GA optimisation of arbitrarily shaped wire structures similar to those reported in [1, 2], and found that this particular feature resulted in maximum directivity in the horizon.

The top of the antenna is top-loaded by a multi-arm spherical helix structure to achieve self-resonance, while at the same time maximising any reduction in the ground wave coupling. Note that several spherical helix structures have been proposed recently for circular polarisation and folded monopole applications [4, 5]. Here, we have chosen the shape to decrease the vertical current component that flows in the opposite direction as the current on the vertical antenna segment.

GA is used in conjunction with NEC to optimise the antenna design parameters. The realised gain in the horizon is used as the cost function. The design parameters are the dimensions of the feed and the length and pitch of the spherical helix. A simple binary GA is implemented and the result typically converges after 50 generations with a population of 100 chromosomes.

Results: A two-arm and four-arm GA antenna were designed and built, using 18-gauge wire. Fig. 1 shows the optimised four-arm antenna. The physical size of the antenna fits within a 32 cm hemisphere, which corresponds to a *kr* of 0.2 at 30 MHz. A 1.2 × 1.2 m ground plane was used in the measurement. For the two-arm GA antenna, the simulated resonant frequency and 3 dB bandwidth are 30.3 MHz and 1.16%, while the measurement results are found to be 30.1 MHz and 1.99%. For the four-arm GA antenna, the simulated resonant frequency and the 3 dB bandwidth are 30.2 MHz and 1.03%, while the measurement results are 30.0 MHz and 1.97%.

Fig. 2 shows the simulated and measured efficiencies of the four-arm GA antenna. The simulation is based on NEC and the measured result is obtained by the Wheeler cap method. Note that in the standard Wheeler cap technique, the efficiency is obtained by assuming that the antenna can be modelled as a simple RLC circuit. However, our inductively coupled antenna has an equivalent circuit shown in the inset of Fig. 2. In this case, it is not as straightforward to obtain the efficiency of the antenna from the input impedance measurements. We assume $R(\omega)$ in the circuit models the radiation plus the loss resistance of the antenna. A Taylor expansion is used to model its frequency dependence. We use an optimiser to extract all the lumped element values R, L, C, and M from the measurement data about the resonant frequency (for both the with-cap and without-cap cases). The optimiser combines a GA-based global search followed by a local gradient-based refinement. After parameter extraction, the efficiency is computed based on the resistance $R(\omega)$. The results based on simulation and measured data show good correlation and are both above 65%. Even higher efficiency can be expected if thicker wires are used.

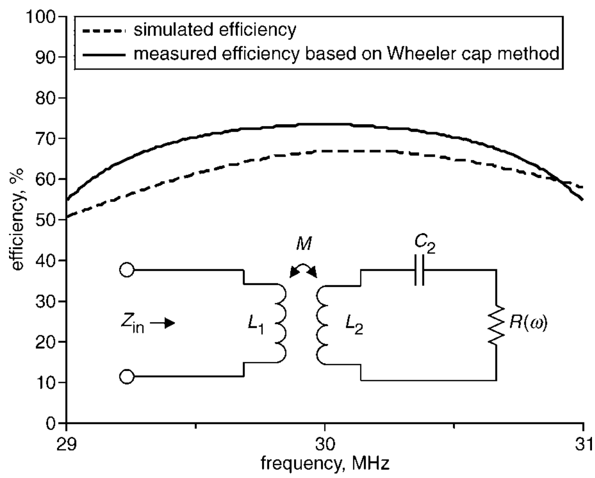

Fig. 2 *Efficiency against frequency of four-arm GA antenna and its equivalent circuit*

The antennas were also tested outdoors on flat grassy ground to characterise the transmission loss. Four different transmitting antennas were tested: a commercial whip (from GLA Systems), a planar GA antenna based on the design in [3], the two-arm GA antenna, and the four-arm GA antenna. Another commercial whip was used for the receiving antenna in all cases. The distance between the transmitter and receiver was 15 m. Fig. 3 shows the measured transmission loss taken using a network analyser for the four different transmitting antennas. It shows that the planar GA antenna design was about 5 dB worse than the commercial whip. However, the transmission losses of the two-arm and the four-arm GA antennas are both within 1 dB of the commercial whip. The transmission loss difference between the two-arm and four-arm GA antennas is negligible. The NEC transmission loss simulation based on the exact Sommerfeld integral with dry soil ($\varepsilon_r = 3$, $\sigma = 0.0001$ S/m) shows that the four-arm and two-arm GA antennas are better than the planar GA antenna by 3.3 and 3.1 dB, respectively. These numbers are comparable to the measurement results of 3.7 and 3.5 dB.

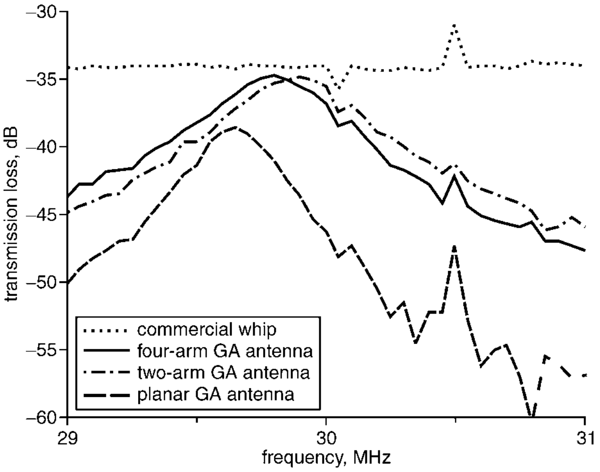

Fig. 3 *Measured transmission losses of four different antennas against frequency*

Spikes in curves are due to RF interference

Conclusions: A top-loaded, inductively-coupled, electrically small antenna is proposed to maximise transmission into HF ground waves. Both a two-arm and four-arm antenna of size $kr = 0.2$ have been designed, built and tested at 30 MHz. Despite their extremely small electrical size, these antennas have an efficiency of greater than 65% and a transmission loss within 1 dB of a commercial whip.

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