Coupling Effects and Performance of Loran Transmitter Antennas

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***Abstract*— It is known that if a conductor resides in the neighboring of an antenna with a small distance relative to the wavelength, it induces a reverse current on the conductor. This paper involves the unavoidable coupling effects on some common types of LF antennas, due to the large wavelength in this frequency band. In particular, after some discussions about top-loaded antennas, the coupling effect of wire supports is studied for these antennas. In addition, the effect of support masts on the radiation resistance is shown for three kinds of Loran transmitter antennas with four masts. Furthermore, some formulas for the impedance of small monopole antennas with neighboring masts are proposed and some simulation results of practical antennas are reported. Finally it is indicated that the coupling effect is more destructive for sectional Loran transmitter antenna compared with square top loaded antenna.**

***Index Terms*—** Dipole antenna, LF antennas, Monopole antenna, Wire antennas, Mutual coupling effects.

I. INTRODUCTION

Loran system uses at least three transmitter antennas to send simultaneous signals and constructs hypothetical analogous hyperbolas between the main antenna and other ones. The cross points of these hyperbolas determine the position of passive receivers. More transmitter antennas are usually used to compensate the ambiguities found where the hyperbolas are tangential. The defined frequency for pulsed hyperbolic navigation system (Loran C) is 100 kHz which is in the low frequency (LF) band. The LF electromagnetic waves have lower attenuations and therefore the Loran system can cover larger regions [1- 4]. Among various kinds of antennas such as ferrite rod antennas [5], loop antennas [6, 7], horn antennas [8], helical antennas [9], microstrip antennas [10], and finally monopole and dipole antennas [11-23], the best candidate for this frequency band as a transmitter antenna are monopoles or dipoles with some modifications due to their vertically polarized omnidirectional pattern and the capability of high power transmission.

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The design considerations for low frequency antennas are quite different from high frequency antennas, since physically large distances are electrically small for these antennas. The wavelength for the LF band is from 1 km to 10 km which results in large sizes for transmitter antennas. For example, the height of a 100 m monopole antenna is $\lambda/30$ in 100 kHz, and therefore it is considered as a short antenna since short antenna size is considered between $\lambda/50$ and $\lambda/10$ [3, 4]. Consequently, some limitations for the antenna appear such as radiation resistance, bandwidth, efficiency etc. An important limitation for LF antennas due to the low radiation resistance is the impedance matching problem. Usually two methods can be used for the impedance matching: 1) LC circuits with high power capacitors and inductors. 2) High power transformations with $n_1/n_2 = \sqrt{Z_1/Z_2}$. Moreover, limitations for the LF antennas are not only related to electrical and electromagnetic considerations, but the mechanical, environmental and economic issues should be considered as well. One limitation that can be considered both as mechanical and economical is the unavoidable use of conductive masts and supports to construct the desired shape for the antenna. It is observed that for almost all antennas these supports lead to performance deterioration. One theoretical solution is using non-conductive materials. However, it generally leads to a week structure or an expensive assembly.

This paper studies the effect of these conductive supports on the radiation resistance for a top loaded antenna and the antenna with four masts. As well as indicating the coupling effects of wire supports, an improvement at almost no cost is introduced for the monopole antenna with top-loadings in the following section [19]. In the third section, the effects of supporting masts on the radiation resistance are shown for three kinds of Loran transmitter antennas with four masts. The first one is the sectional Loran transmitter (SLT) antenna [20], the second is the inverted cone antenna [21] and the third is the modified SLT antenna [22, 23] which is named square top loaded (STL) antenna. Some illustrations and simulations of this paper use NEC [24].

II. STRAIGHT MASTS NEAR A MONOPOLE ANTENNA

In the beginning, let’s see the coupling effect of one mast near an antenna with h = 100 m at 100 kHz. The radius of the antenna is assumed to be 0.25m. The effect of this mast with the same height and radius as the antenna is shown in Table 1 using NEC for different separations and the schematic is provided in Fig. 1a. It can be observed that even for a 100m distance the effect on the radiation resistance is considerable. It is also observed that the coupling reduces performance of the antenna, since the direction of current on the neighboring mast is in the opposite direction due to the Lenz’s law.

The next step is to see the coupling effects of multiple (N) neighboring masts on the performance of the antenna. This is also shown in Table 1 and the schematic is provided in Fig. 1b. The results appear to be predictable and can be presented as a diagram for a given distance, d, as shown in Fig. 2a and Fig. 2b. The effects of five and six masts are predicted using exponential and logarithmic curves for

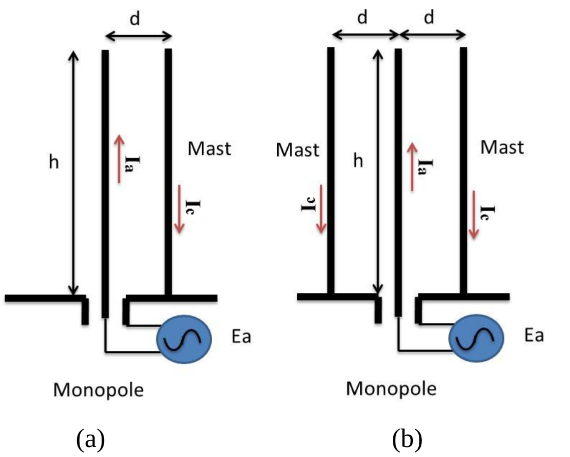


Fig. 1. Schematic of a monopole with a distance 'd' from (a) one grounded mast and (b) two grounded masts.

TABLE I. THE EFFECT OF A NEIGHBORING MAST ON THE RADIATION RESISTANCE AND REACTANCE OF A MONOPOLE ANTENNA

	One Mast		**Two Masts**		**Three Masts**		**Four Masts**	
d (m)	Rr (Ω)	X (Ω)	Rr (Ω)	X (Ω)	Rr (Ω)	X (Ω)	Rr (Ω)	X (Ω)
10	0.22	-1330	0.11	-1245	0.066	-1197	0.037	-1157
50	0.38	-1444	0.32	-1437	0.28	-1432	0.24	-1426
100	0.42	-1450	0.4	-1449	0.38	-1449	0.36	-1448
500	0.44536	-1451	0.44505	-1451	0.44474	-1451	0.44444	-1451
∞	0.44567	-1451	0.44567	-1451	0.44567	-1451	0.44567	-1451

TABLE II. FORMULAS FOR RADIATION RESISTANCES AND REACTANCES AS A FUNCTION OF THE NUMBER OF MASTS IN DIFFERENT DISTANCES

d	Radiation Resistance	Reactance
10	$R_r = 0.3793e^{-0.586N}$	$X = 123.78\,ln(N) - 1330.6$
50	$R_r = 0.4388e^{-0.151N}$	$X = 12.536\ln(N) - 1444.7$
100	$R_r = 0.4427e^{-0.051N}$	$X = 1.2786\ln(N) - 1450$
500	$R_r = 0.4457e^{-0.0007N}$	$X = -1451$

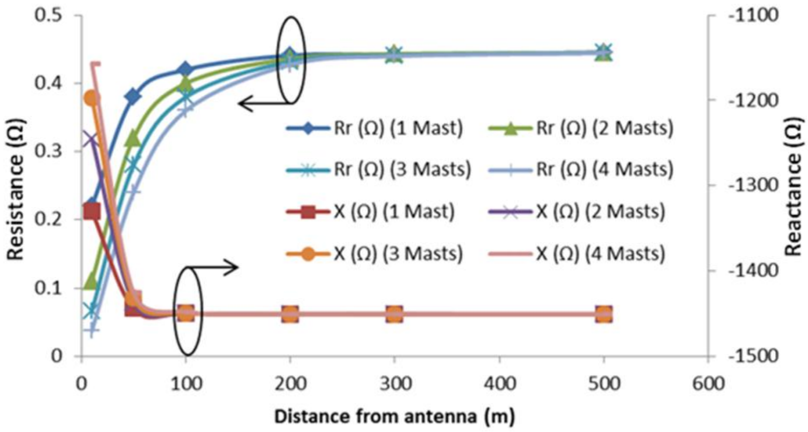
radiation resistances and reactances, respectively and the formulas for each distance is shown in Table 2. It can be observed that the equations have similar forms for all situations and one can find a general equation for the impedance by using curve fitting tools. Consequently, the impedance $Z = R_r + jX$, can be obtained using

$$R_r = \left[0.467 - \frac{0.787}{d} - 0.003\ln(2d)\right] \times e^{-\left(0.34e^{-0.026d} + \frac{3.29}{d} - 0.0076\right)N} \quad (1a)$$

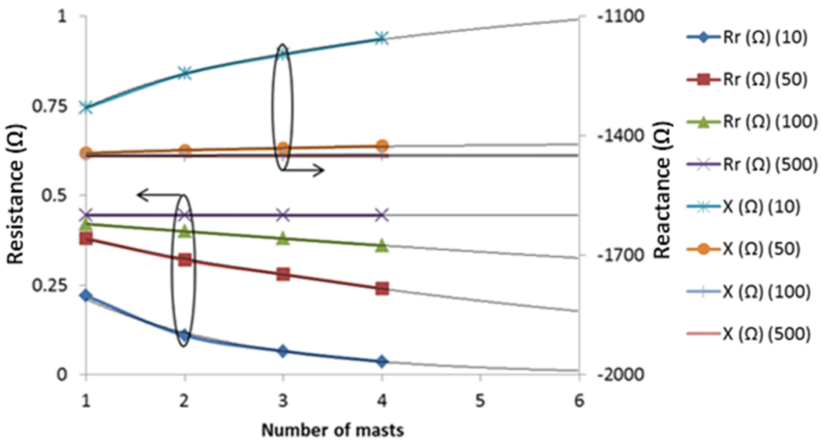
and

$$X = \left[\frac{1}{d}\left(2707 - 837.5\sqrt[4]{d}\right) + 2.08\right]\ln(N) - \frac{1}{\sqrt{d}}\left(57.3 - \frac{4306}{d}\right) - 1449 \quad (1b)$$

with $10 < d < 750\ m$. These equations are obtained by finding the equations of the constants of the



(a)



(b)

Fig. 2. Radiation resistances and reactances of a 100 m monopole near mast(s) as a function of (a) distance and (b) the number of masts.

equations in table 2. For example the term $[0.467 - 0.787/\mathrm{d} - 0.003\ln(2\mathrm{d})]$ in (1a) is obtained by curve fitting on the points (10, 0.3793), (50, 0.4388), (100, 0.4427) and (500, 0.4457). Other terms are obtained, similarly.

A comparison between the radiation resistances of some simulated antennas with equation (1a) is shown in Fig. 3.

III. LORAN ANTENNAS

A. *LF Antennas with One Isolated Mast*

A widespread antenna for LF transmitters is the monopole antenna with top-loadings. The height of this antenna is normally more than 100 meters and it should be isolated from the ground. A typical structure of this antenna with 12 top-loaded wires and the radiation pattern is shown in Fig. 4a. It should be mentioned that the ends of wires are attached to the ground with nonconductive ropes and

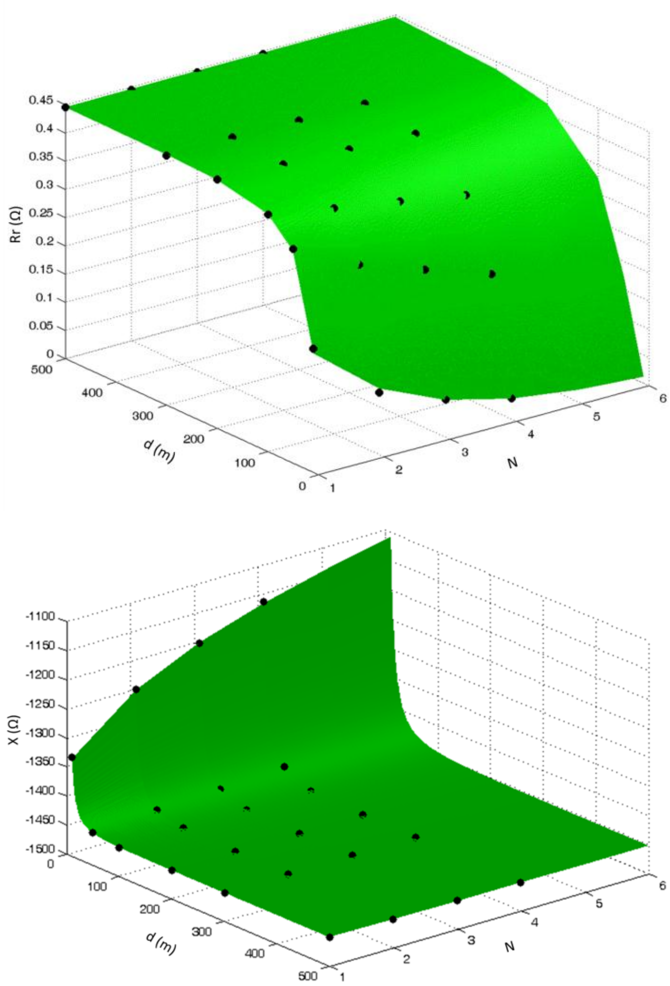


Fig. 3. Radiation resistance and reactance of the 100m monopole near mast(s); the plane is obtained from equation (1a) and the dots are for simulated antennas.

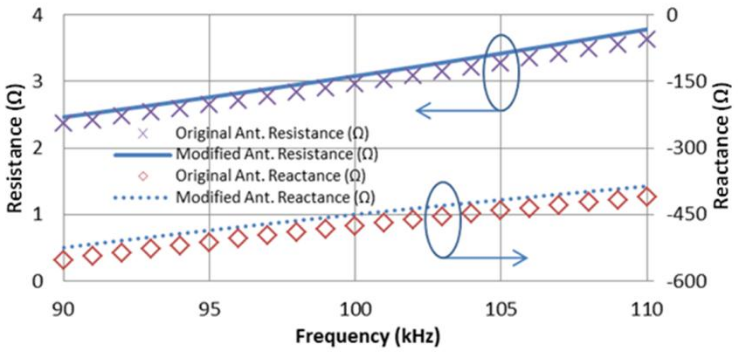
for larger angles of the wires with the mast the antenna performance will be enhanced. Therefore the locations of ropes on the ground should be as far as possible from the mast and this structure is best suited with a circular ground.

Consequently, when the antenna site is rectangular at least four of the ropes can be placed farther from the mast and the forms of antenna wires changes as shown in Fig. 4b. Therefore the angles between four 60m top-loaded wires are changed from 30° to 45° and their lengths are scaled by 1.22. It is observed that the radiation pattern is not a function of the antenna shape while the antenna is smaller than $\lambda/10$. It will be seen for all structures of these antennas that the radiation patterns are omnidirectional and similar to a simple monopole, since they are all categorized as small antennas.

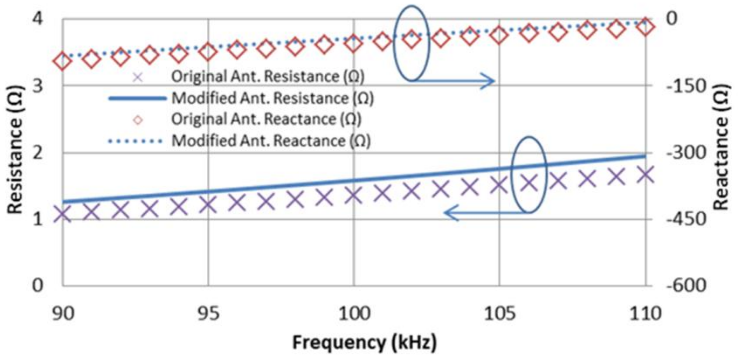
The radiation resistances and reactances of these antennas with 60m and 190m top-loadings are shown in Fig. 5a and Fig. 5b. It can be observed that increasing the height of four top-loaded wires increases the radiation resistance without additional costs. In addition, it can be observed that the improvement is more significant for the antenna with 60m top-loadings.

(a) (b)

Fig. 4. Top-loaded antennas with their radiation patterns, (a) original antenna, (b) modified antenna.



(a)



(b)

Fig. 5. Radiation resistances and reactances of the original and modified antennas, with (a) 60m and (b) 190m top loadings.

It is known that upholding an isolated mast with such a height without wire supports is difficult and costly. Therefore, it is common to use wire supports for the main mast of this antenna. The wires are of course isolated from the mast, at more than one point, since the coupling effect is important for this antenna. For example if the wires are isolated at each 40 m distances, the radiation resistance decreases about 0.75 Ω while if they are isolated from the mast to ground on the distances 6, 9, 12, 15, 18, 21, 24, 27 and 40 (all in meters) the radiation resistance decreases about 0.25 Ω. The form of the wire supports are shown in Fig. 6 and the results are provided in Fig. 7.

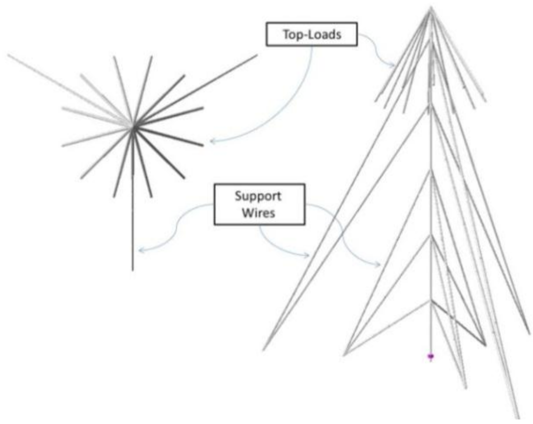


Fig. 6. Schematic of the original top-loaded antenna with support wires.

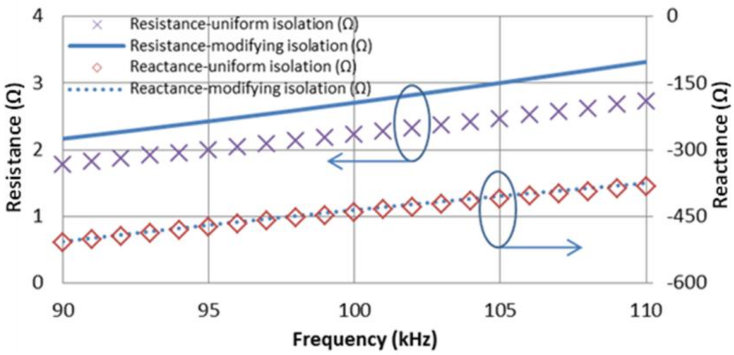


Fig. 7. Radiation resistances and reactances of 60m top-loaded antenna with supporting wires isolated on each 40m (uniform isolation) and on the distances 6, 9, 12, 15, 18, 21, 24, 27 and 40 (all in meters) (modifying isolation).

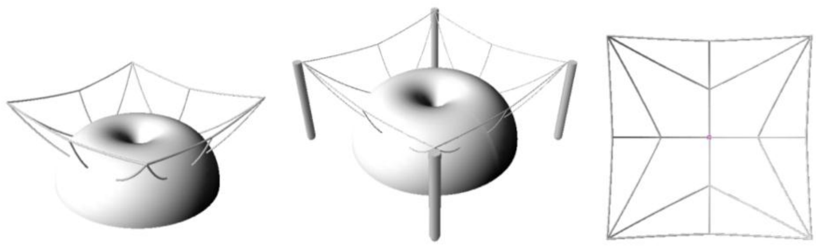


Fig. 8. SLT antenna without and with the masts and the radiation pattern.

B. Antennas with Four Masts

An alternative for the monopole antenna with an isolated mast is an antenna composed of isolated wires from the ground. The supports for these wires can be two, three, four or even more non-isolated masts. A prevalent choice for this kind of antenna is the antenna with four masts. The radii of masts are 0.25m and their separations are assumed 200m for all structures. For example SLT antenna with 100m height and its radiation pattern is shown in Fig. 8. The radiation resistance and the reactance of this antenna without and with coupling effects of the masts are shown in Fig. 9. It is observed that the non-isolated masts cause about 0.14Ω reduction of the radiation resistance.

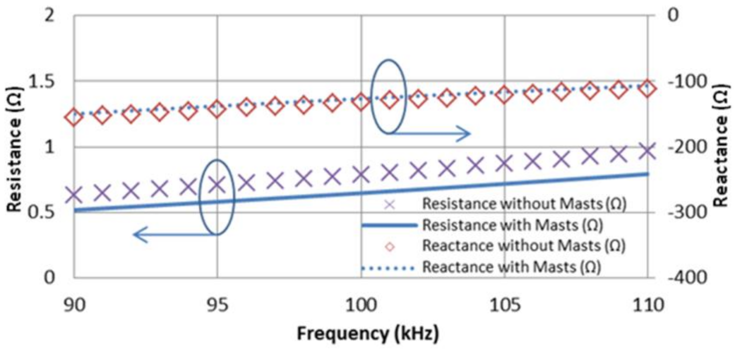


Fig. 9. Radiation resistances and reactances of SLT antenna without and with the masts.

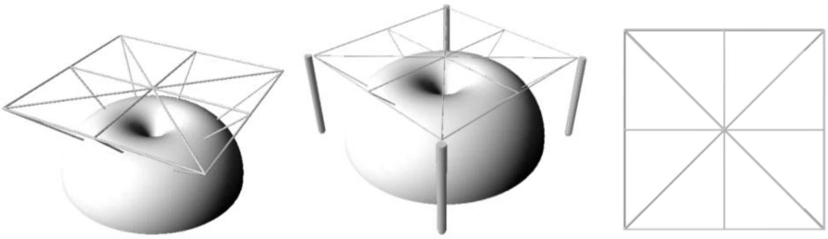


Fig. 10. TIP antenna without and with the masts and the radiation pattern.

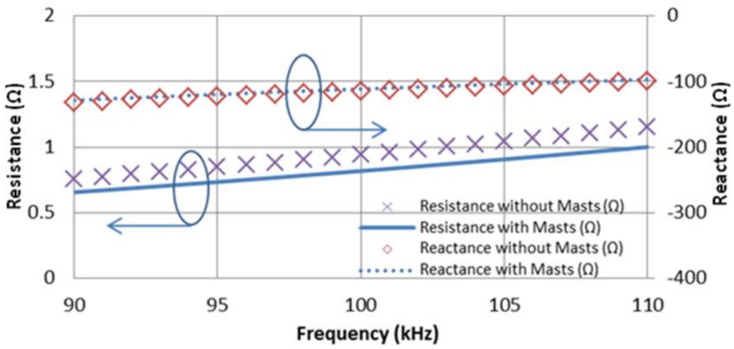


Fig. 11. Radiation resistances and reactances of TIP antenna without and with the masts.

Another example of antennas with four masts is the inverted cone or top inverted pyramid (TIP) antenna shown in Fig. 10. The results of the input impedance of this antenna are shown in Fig. 11. It can be observed that the effects of the masts are similar for these antennas.

Also it should be mentioned that the performance of this antenna is almost similar to the SLT antenna and the small difference is due to the bends of the wires.

Finally, the coupling effect of the masts for the Square Top Loaded antenna, i. e. the modified version of SLT antenna is studied (Fig. 12). It can be seen in Fig. 13 that both, the radiation resistance and the reactance of this antenna are significantly better than previous antennas. The effect of the

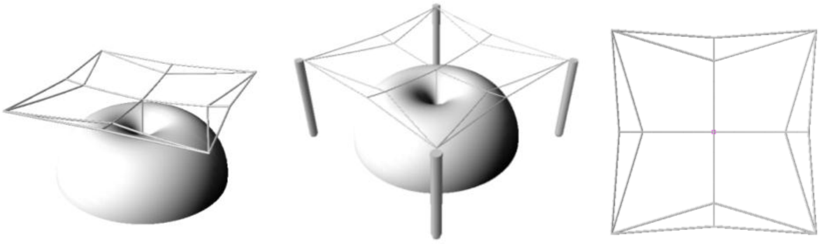


Fig. 12. STL antenna without and with the masts and the radiation pattern.

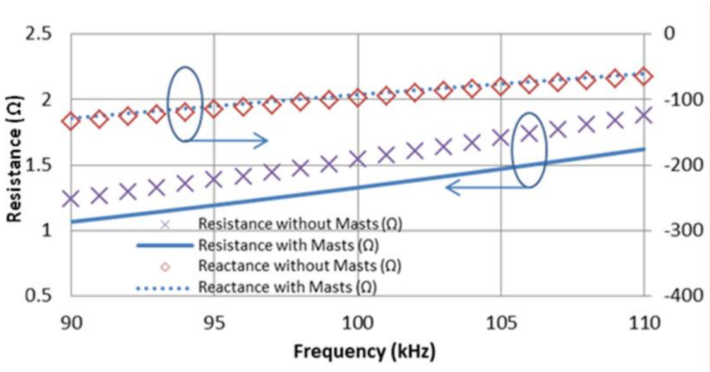


Fig. 13. Radiation resistances and reactances of STL antenna without and with the masts.

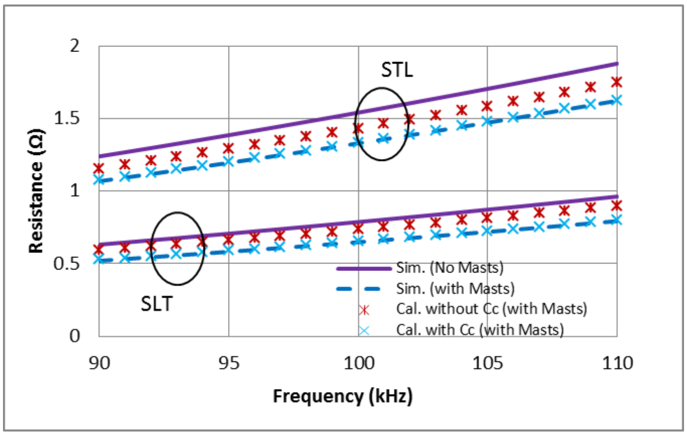
masts in the second plot of Fig. 13 indicates about 0.21 Ω reductions in radiation resistance which is similar to previous antennas.

C. *Resistances of SLT and STL antennas*

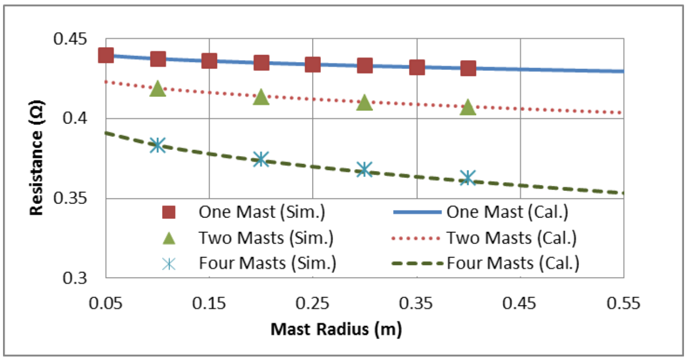
It is now interesting to compare the effects of the four holding masts on the radiation pattern of SLT and STL antennas. Radiation resistance of a simple monopole with similar distances from the masts, $100\sqrt{2}$, can be obtained from (1). However, the points on the wires of SLT and STL antennas have different distances from the masts. Therefore, a correction factor (C_c) is required for the distance (d) in (1) and the radiation resistance will be

$$R_r = R_{r0}\left[1.048 - \frac{1.766}{C_c d} - 0.0067\ln(2C_c d)\right] \times e^{-\left(0.34e^{-0.026C_c d} + \frac{3.29}{C_c d} - 0.0076\right)N}, \quad (2)$$

where, the radiation resistance of an antenna without masts is given by R_{r0}. For a simple monopole we have $C_c = 1$ and the larger value for C_c indicates a smaller coupling effect. C_c is a function of the antenna structure and can be calculated explicitly. Accordingly, one can obtain R_r and R_{r0} of the antenna with a separation d_1 between masts and the feed point and find the required distance d_2 for a simple monopole with similar R_{r0}/R_r. The correction factor will be $C_c = d_2/d_1$. In addition, R_{r0}



(a)



(b)

Fig. 14. Radiation resistances of (a) SLT and STL antennas and (b) a monopole antenna near four masts.

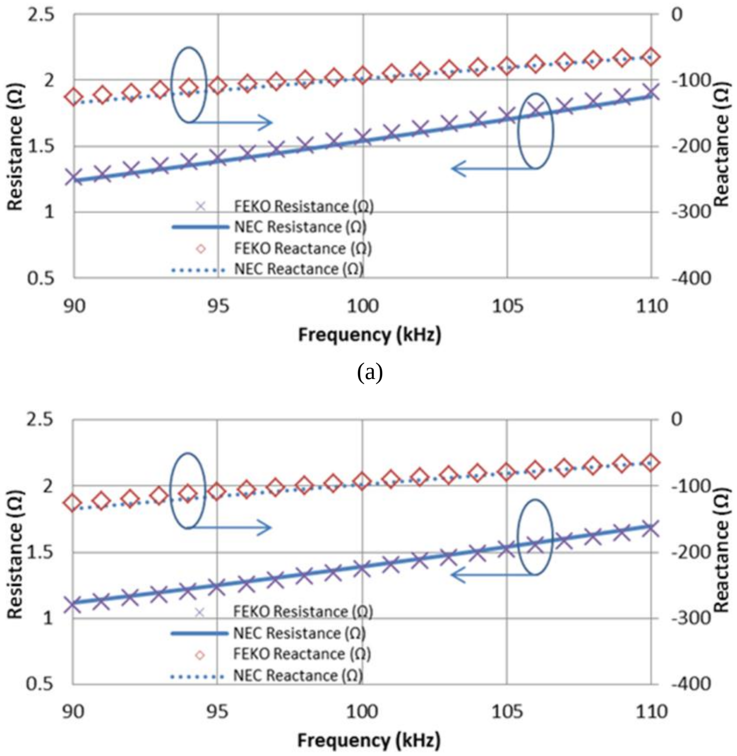
may be obtained using MoM or the method introduced in [22] and R_r should be calculated with MoM. Consequently, C_c will be obtained from (2) since all parameters are known.

The coupling correction factor (C_c) of the SLT and STL antennas are 69.5% and 78.2% respectively. It indicates that the structure of STL antenna is farther from the masts on the average and therefore the masts have lower effects on its performance. The simulated radiation resistances of both antennas with and without masts and the calculated radiation resistances with and without the defined C_c are shown in Fig. 14a. Here we obtained C_c by matching the calculated and simulated radiation resistances. One can obtain R_r when C_c is given for a structure.

Finally a good approximation for (2) is

$$R_r \cong R_{r0}\left\{1 - N^{0.96}\left[0.00036\sqrt{C_c d} - \frac{131.82}{(C_c d)^2} - \frac{1.035}{\sqrt{C_c d}} + \frac{11.243}{C_c d} + 0.517\right]\right\} \tag{3}$$

for $50 < C_c d < 500$, and therefore the radiation resistance of an antenna with the masts and arbitrary radii r_m will be



(a)

(b)

Fig. 15. FEKO radiation resistances and reactances of STL antenna (a) without and (b) with the masts compared with NEC results.

$$R_r \cong R_{r0}\left\{1 - N^{0.96}\left[\sqrt{r_m}\left[0.00069\sqrt{C_c d} - \frac{235.06}{(C_c d)^2} + 0.986\right] - \frac{[-0.07(C_c d)^{1.5} + 71438 + 108(C_c d)^2]}{10000(C_c d)^2\sqrt{r_m}} - \frac{1.035}{\sqrt{C_c d}} + \frac{11.243}{C_c d} + 0.024\right]\right\} \quad (4)$$

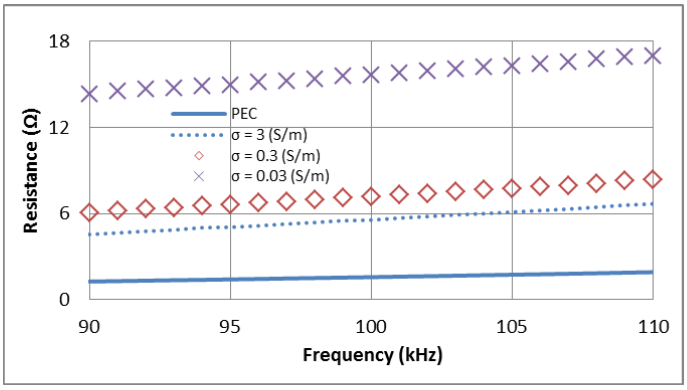
using the same method as for (1). The comparison with simulated results of a simple monopole is shown in Fig. 14b. The effect of C_c is similar to (2) and the distances of the masts are the same as the discussed SLT and STL antennas ($C_c d = 100\sqrt{2}$) which yield

$$R_r \cong R_{r0}\left[1 - N^{0.96}\left(0.374\sqrt{r_m} - \frac{0.00076}{\sqrt{r_m}} + 0.0332\right)\right]. \quad (5)$$

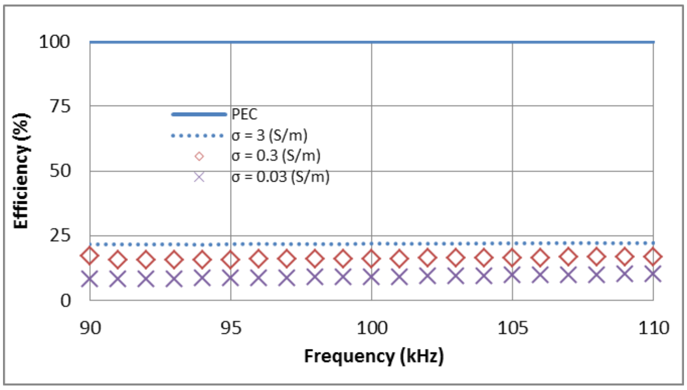
An example of the applications of calculating C_c is to obtain the radiation resistance of an antenna with the masts and arbitrary radii using (3) and the obtained C_c from one given radius.

D. Ground effect on STL antenna

The effect of lossy ground on the performance of the STL antenna is discussed in this part. FEKO is used for the simulations to provide another validation for the presented results from calculations and



(a)



(b)

Fig. 16. FEKO simulation results of STL antenna on lossy ground ($\epsilon_r = 5$ and $\sigma = \infty, 3, 0.3$ and 0.03 S/m) (a) antenna resistance (b) efficiency.

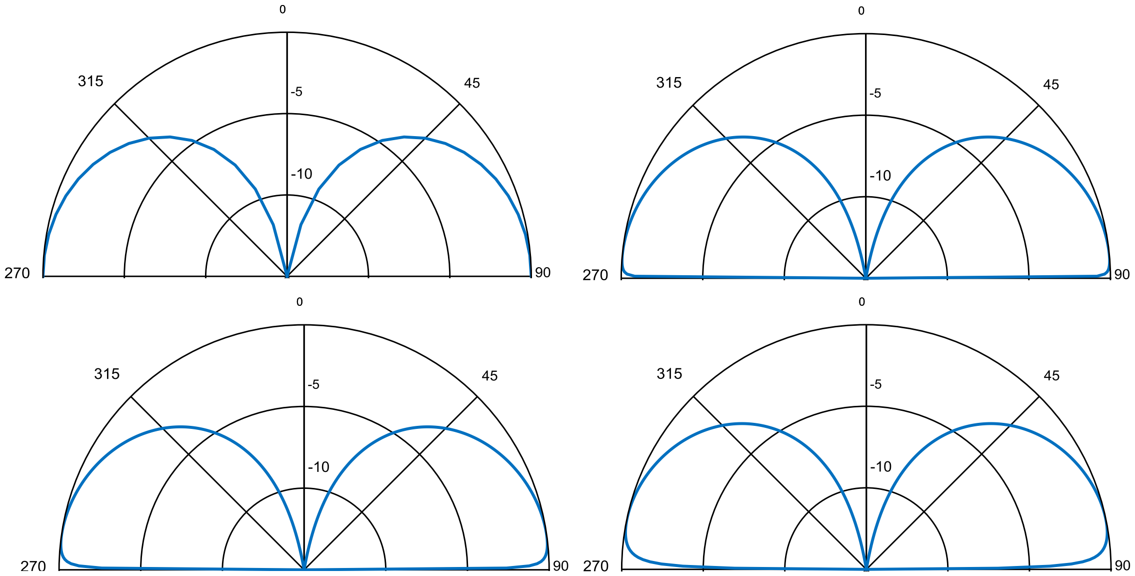


Fig. 17. FEKO radiation patterns of STL antenna on lossy ground with $\epsilon_r = 5$ and $\sigma = \infty, 3, 0.3$ and 0.03 S/m respectively.

NEC simulations. Radiation resistances and reactances of the STL antenna without and with the masts are indicated in Fig. 15. The results are in agreement with the NEC result in Fig. 13.

If we consider the ground loss the antenna resistance increases. For example, the antenna resistance on a ground with $\epsilon_r = 5$ and $\sigma = \infty, 3, 0.3$ and 0.03 S/m are indicated in Fig. 16 (a). As can be observed in Fig. 16 (a), the ground loss increases the resistance, significantly. Therefore the antenna efficiency reduces as indicated in Fig. 16 (b). However, the ground conductivity can be increased by placing a wire grid on the ground. A suitable wire grid can increase the efficiency almost up to the PEC ground. Finally, the effect of ground loss on the radiation pattern is indicated in Fig. 17. It can be observed that the ground loss decreases the low angle radiation that should be compensated by using the wire grid as well.

IV. CONCLUSION

In this paper some practical considerations are discussed for the Loran transmitter antennas. In particular, some new insights are achieved for this relatively old topic: 1) The coupling effects of one or multiple masts near a monopole antenna are discussed and illustrated in some plots; explicit equations are obtained for resistance and reactance of a monopole in the vicinity of conductive masts. 2) The effects of practical neighboring conductors near some types of Loran transmitter antennas are studied and it is shown that they affect the antenna performance significantly; some new methods are proposed for reducing the effect of conductors. 3) It is indicated that the masts decrease the performance of STL antenna less than SLT antenna. In addition, the effect of ground loss is studied on the antenna resistance, efficiency and radiation pattern.

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