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Study of the isolation between VHF land mobile radio antennas in close proximity

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REPORT ITU-R M.2141*

Study of the isolation between VHF land mobile radio antennas in close proximity

(Question ITU-R 7/5)

(2009)

1 Introduction

This Report provides information on calculation and measurement techniques for isolation of VHF land mobile antennas located in close proximity. A major challenge is the management of co-site interference between various radio systems operating in close proximity. In this Report the isolation between antennas are investigated and quantified. The antenna isolation is theoretically analysed, numerically simulated and experimentally verified for the case of separation in the order of 1 to 7.6 m.

2 Scope

This Report provides information on the determination of isolation for mobile radio antennas separated horizontally less than a few wavelengths in the 30 to 108 MHz bands. The study presents analytical and experimental isolation results for two antennas. The impact of isolation to the operation of radio systems and effect of the physical characteristics of the antenna platform are not studied.

3 Related ITU-R Recommendations

Recommendation ITU-R SM.337 – Frequency and distance separations.

4 Abbreviations

NEC Numerical electromagnetics code

EZNEC The electromagnetics simulation program based on NEC

USUL Unmatched source-unmatched load model

MSUL Matched source-unmatched load model

AWG American wire gauge

VSWR Voltage standing wave ratio.

5 Approach used to compute antenna coupling

This study is specifically aimed at investigating the horizontal isolation between a two-vertical-antenna configuration. Of particular interest here is the canonical problem of two antennas separated by a specified distance and how the coupling between the two antennas varies with carrier frequency.

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* This Report should be brought to the attention of Radiocommunication Study Group 1.

Mutual impedance between antennas was evaluated on the basis of theoretical techniques used in electromagnetics and applied to the two antenna configuration. Coupled power was computed using standard circuit theory governing voltage, current and power. The theoretical predictions were validated against accepted theoretical results in the literature. Following this first order confirmation, independent calculations using an electromagnetic simulation package based on the numerical electromagnetics code (NEC) was employed to further confirm the validity of the theoretical results. The benefit of using the theoretical techniques over the NEC package is that:

– the expressions are in closed form; and
– relationships between electrical and physical parameters to impedance are seen clearly in the expressions.

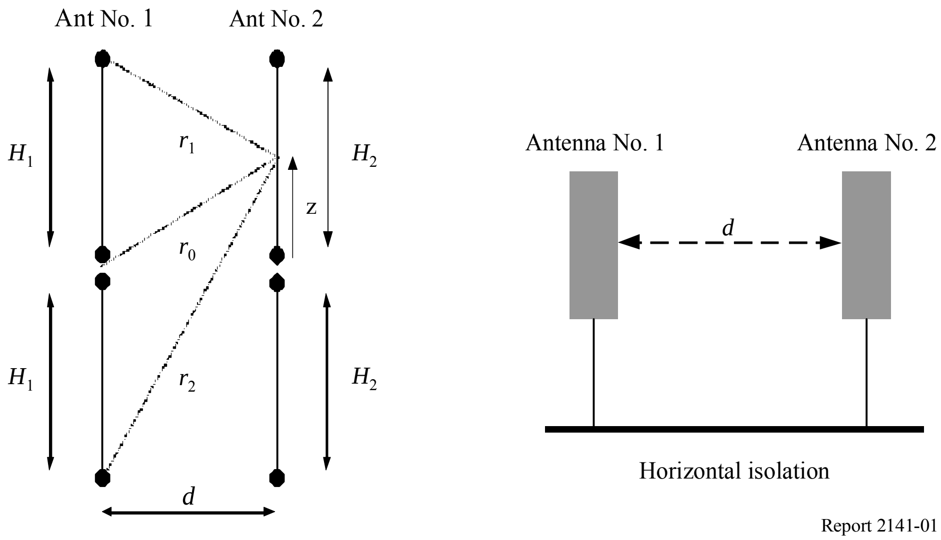
Based on the theoretical and simulation results, experiments were then devised to investigate predictions of coupled power levels.

6 Determination of self and mutual impedance

The problem under consideration is that of evaluating the power coupled between two antennas separated by a distance *d*, as illustrated in Fig. 1. Fortunately, this problem is addressed in books dealing with electromagnetics and antenna systems [Jordan and Balmain, 1968]. Closed form expressions and simulation of self mutual impedance between antennas are presented in this section.

FIGURE 1

Geometry for fields near the antennas

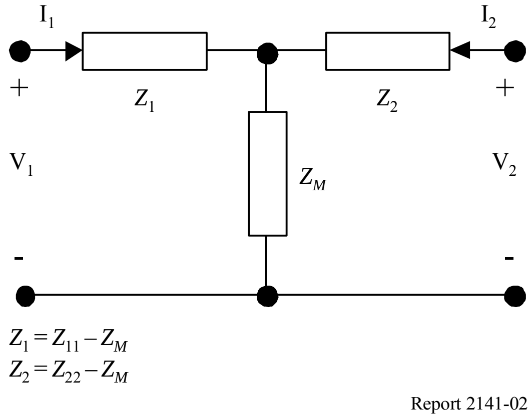


6.1 Theoretical expressions for mutual impedance

In Fig. 2, with the terminals at antenna 2 open circuit, the impedance seen looking into the terminals at antenna 1 is simply the self-impedance of antenna 1 in isolation, Z_{11}. Similarly, the impedance seen looking into the terminals of antenna 2 with the terminals of antenna 1 open circuit, the impedance seen is simply the self-impedance of antenna 2 in isolation, Z_{22}. By inspection:

FIGURE 2

Definitions of quantities used for derivation of self and mutual impedance



The mutual impedance of the pair $Z_M = Z_{12} = Z_{21}$ is computed by solving:

$$Z_M = \frac{Z_2(Z_{1,in} - Z_1)}{(Z_1 + Z_2 - Z_{1,in})}$$

iteratively for Z_M. Here $Z_{1,in}$ is the Norton equivalent impedance at the terminal of antenna 1 when antenna 2 is short circuited:

$$Z_{1,in} = \frac{Z_1 Z_2 + Z_1 Z_M + Z_2 Z_M}{Z_2 + Z_M}$$

and is a non-linear function of Z_M.

Finally, the notation used for resistance and reactance is:

$$Z_M = R_M + jX_M$$

Once these impedances are known, the quantities of interest such as the input impedance, VSWR, and isolation can be computed. What remains for analytical purposes is to determine Z_1, Z_2 and Z_M for a 2-element monopole antenna using the problem geometry in Fig. 1, which shows two element monopoles, with each element of height $H_1 = H_2 = H$. The general mutual impedance expressions for the two monopole antennas on a perfect reflecting plane and separated by distance d are taken from [Jordan and Balmain, 1968].

Mutual resistance is:

$$R_M = -30 \begin{pmatrix} \sin\beta H \cos\beta H \{Si(u_2) - Si(v_2) - 2Si(v_1) + 2Si(u_1)\} \\ -\dfrac{\cos 2\beta H}{2}\{2Ci(u_1) - 2Ci(u_0) + 2Ci(v_1) - Ci(u_2) - Ci(v_2)\} \\ -\{Ci(u_1) - 2Ci(u_0) + Ci(v_1)\} \end{pmatrix}$$

and mutual reactance is:

$$X_M = -30 \begin{pmatrix} \sin\beta H \cos\beta H \{2Ci(v_1) - 2Ci(u_1) + Ci(v2) - Ci(u_2)\} \\ -\dfrac{\cos\beta H}{2}\{2Si(u_1) - 2Si(u_0) + 2Si(v_1) - Si(u_2) - Si(v_2)\} \\ -\{Si(u_1) - 2Si(u_0) + Si(v_1)\} \end{pmatrix}$$

where:

d:	distance between antennas
H:	height of each antenna element, and half of the total antenna height
λ:	carrier wavelength
$\beta = \frac{2\pi}{\lambda}$:	wave number (or propagation constant).

Currents and voltages used in X_M are:

$$u_0 = \beta d$$

$$u_1 = \beta\left(\sqrt{d^2 + H^2} - H\right)$$

$$u_2 = \beta\left(\sqrt{d^2 + (2H)^2} + 2H\right)$$

$$v_1 = \beta\left(\sqrt{d^2 + H^2} - H\right)$$

$$v_2 = \beta\left(\sqrt{d^2 + (2H)^2} - 2H\right)$$

$Ci(x)$ is commonly defined as *cosine integral of* x, and has the property:

$$Ci(x) = \ln x + C - S_1(x)$$

where:

$$S_1(x) = \int_0^x \frac{1 - \cos v}{v}\,\mathrm{d}v$$

and

$C = 0.5772157$ is Euler's Constant.

The companion integral $Si\,(x)$ is $Si(x) = \int_0^x \frac{\sin v}{v}\,\mathrm{d}v$, and is known as *sine integral of* x. The *cosine integral of* x and *sine integral of* x are evaluated from 0 to H.

The self-impedance of a single antenna can be calculated using the formulas used for calculating Z_M, by evaluating the near-field on the surface of a single antenna and setting d equal to antenna radius to obtain Z_{11} and Z_{22}.

6.2 Mutual impedance through calculation

The results in Table 1 through Table 3 contain a comparison of mutual impedances for numerical calculations based on the expressions presented in § 6.1, as well as those obtained from Balmain and Jordan's [1968] (Mutual impedance between monopole antennas of equal height from page 541 Fig. 14-3).

TABLE 1

Antenna heights $H_1 = H_2 = \lambda/4$

d/λ	Z_M Ω (Jordan and Balmain)	Z_M Ω (Numerical)
1/8	33.3334 + *j* 0.0000	32.0911 – *j* 0.0364
1/4	21.0533 – *j* 14.9710	20.3929 – *j* 14.1745
3/8	3.79590 – *j* 19.6436	5.8804 – *j* 18.8891
1/2	–6.3781 – *j* 15.3981	–6.2660 – *j* 14.9643
5/8	–13.1658 – *j* 5.2304	–12.2781 – *j* 5.9581
3/4	–12.1648 + *j* 5.4586	–11.2484 + *j* 3.3161

TABLE 2

Antenna heights $H_1 = H_2 = \lambda/2$

d/λ	Z_M Ω (Jordan and Balmain)	Z_M Ω (Numerical)
1/8	86.6668 + *j* 0.0000	86.1492 – *j* 0.4936
1/4	53.6517 – *j* 38.1517	51.4186 – *j* 40.8743
3/8	10.0241 – *j* 52.3829	9.2218 – *j* 52.1955
1/2	–17.5396 – *j* 42.3447	–24.4226 – *j* 37.7734
5/8	–37.1739 – *j* 14.7682	–38.3842 – *j* 9.4549
3/4	–33.4533 + *j* 15.0111	–30.9104 + *j* 17.4653

TABLE 3

Antenna heights $H_1 = H_2 = 5\lambda/8$

d/λ	Z_M Ω (Jordan and Balmain)	Z_M Ω (Numerical)
1/8	41.5393 – *j* 19.3701	46.0515 – *j* 19.3203
1/4	25.2835 – *j* 24.2036	27.4183 – *j* 28.9481
3/8	3.1925 – *j* 27.3143	5.0070 – *j* 30.4951
1/2	–12.9055 – *j* 18.4310	–12.4704 – *j* 20.7838
5/8	–19.7446 – *j* 3.1861	–19.1637 – *j* 5.0009
3/4	–15.0940 + *j* 10.4062	–14.5008 + *j* 9.0260

6.3 Self and mutual impedance through simulation

The electromagnetics simulation program EZNEC is based on the numerical electromagnetics code (NEC), and is used in addition to the theoretical results to assess the overall behaviour of the system of coupled antennas. Two different models were studied: the unmatched source-unmatched load model (USUL) and the matched source-unmatched load model (MSUL).

7 Calculation of power coupling between antennas

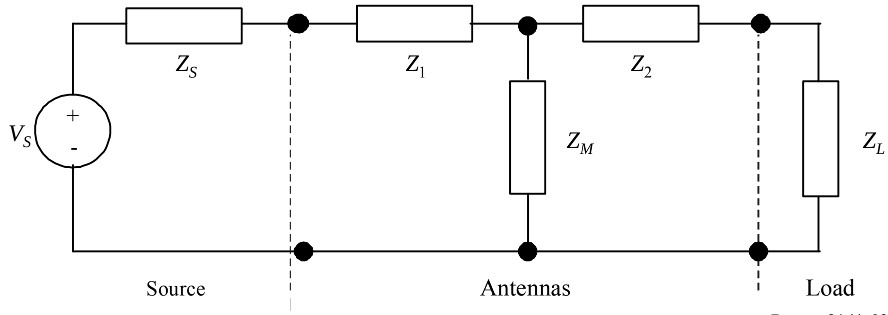
7.1 Unmatched source-unmatched load model (USUL)

7.1.1 Analytical expressions

With this model, no attempt has been made to match the impedance of the source or load to the antenna systems to which they are connected. Of importance here is to determine the power delivered to the load, Z_L, by the source. This ratio will be referred to here as the isolation, and is derived from the Thevenin equivalent circuit depicted in Fig. 3.

FIGURE 3

Thevenin equivalent circuit for unmatched source and unmatched load model



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Z_1, Z_2 and Z_M were defined in § 6.1. The source and the load impedances are Z_s and Z_L.

Define:

- V_s: source voltage that produces the source power when terminated with 50 Ω matched load
- Z_{in}: the impedance seen looking into the antenna terminals with the load impedance terminating the second antenna
- Z_{eq}: the Thevenin equivalent impedance seen looking into the antenna terminals with the source connected
- V_{in}: voltage across the input terminals to the network
- V_{oc}: the Thevenin equivalent source voltage (including antenna impedance)
- V_L: voltage across the load.

These quantities are used to calculate the power coupled to the antenna via the near field interactions using:

$$Z_{in} = \frac{Z_1 Z_M + Z_1 Z_2 + Z_1 Z_L + Z_M Z_2 + Z_M Z_L}{Z_M + Z_2 + Z_L}$$

$$Z_{eg} = \frac{Z_S Z_M + Z_S Z_2 + Z_1 Z_M + Z_1 Z_2 + Z_M Z_2}{Z_M + Z_1 + Z_S}$$

$$V_{OC} = \frac{Z_M V_S}{Z_S + Z_1 + Z_M}$$

$$V_L = \frac{V_{OC} Z_L}{Z_{eg} + Z_L}$$

$$V_{in} = \frac{V_S Z_{in}}{Z_S + Z_{in}}$$

and power expressions:

$$P_l = \frac{1}{2}\mathrm{Re}\left[V_l\left(\frac{V_l}{Z_l}\right)^*\right]$$

$$P_{in} = \frac{1}{2}\mathrm{Re}\left[V_{in}\left(\frac{V_{in}}{Z_{in}}\right)^*\right]$$

$$\text{Isolation} = 10\ \log_{10}\left(\frac{P_l}{P_{in}}\right) \qquad \text{dB}$$

where P_L is the average power delivered to Z_L and P_{in} is the average power delivered to the input of the network. *Isolation* is a measure of the proportion of power transferred from the co-site antenna into the receiver.

7.1.2 Simulation results (USUL)

Calculations were performed using theoretical values for the USUL model impedances and simulated values with EZNEC, and through direct calculation through EZNEC power measurements. The antenna parameters for the simulations are: for antenna spacing 1 m and length 3.5 m, wire diameter 2 mm (AWG No. 12) with 40 segments/wire simulating the system in Fig. 1. The load and source impedances are $Z_L = Z_s = 50\ \Omega$ and the source power is $P_s = 50$ W.

Figure 4 shows the isolation plots calculated and simulated for two 3.5 m antennas separated by 1 m. The peaks in the isolation curves give the maximum power transferred to the receiver from the co-site antenna. It was hypothesized that the peaks in the isolation curves could be related to the antenna length. Simple calculations show that the dipoles under consideration are approximately λ/2 in length at a frequency of 42.85 MHz. Then $\frac{\lambda}{2} = 3.5$ m giving $\lambda = 7.0$ m. The corresponding resonance frequency is:

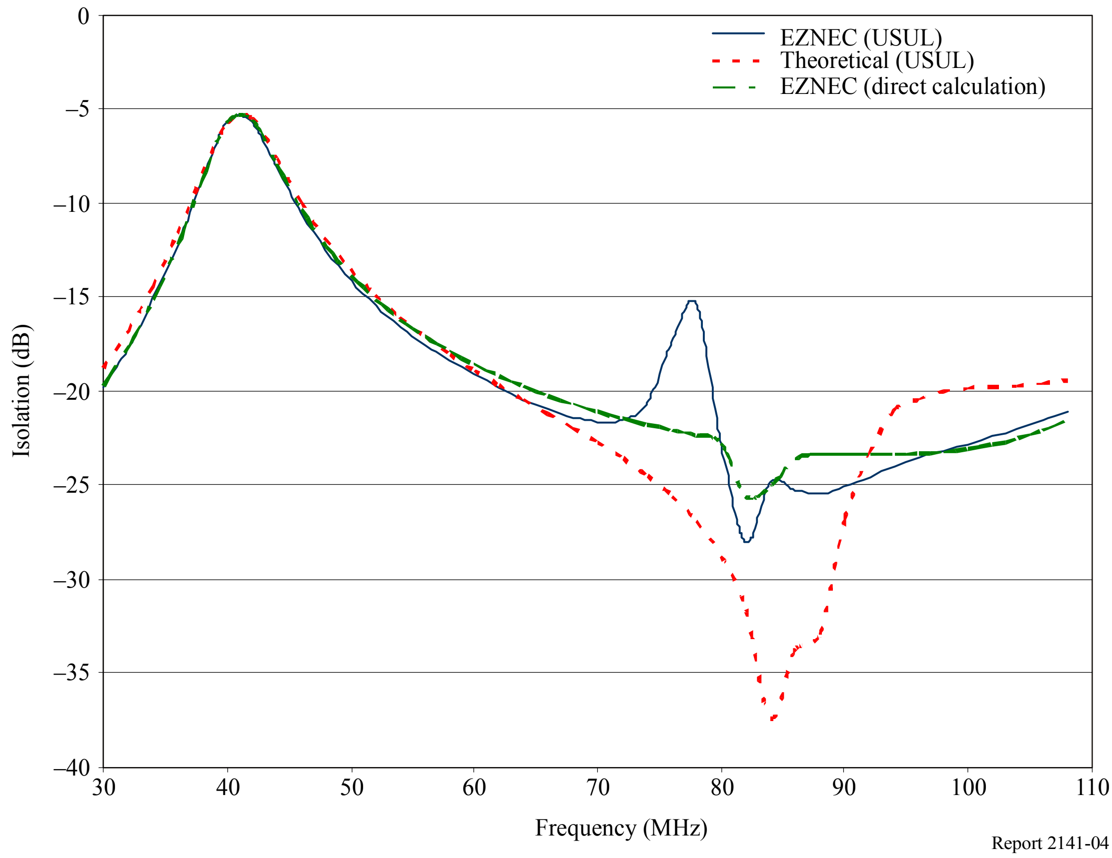
$$F = \frac{C}{\lambda} = \frac{2.998 \times 10^8}{7.0} = 42.85 \qquad \text{MHz}$$

The corresponding nulls in Fig. 4 appear to be at twice the resonance frequency according to the theoretical isolation calculations.

In Fig. 4 there is a discrepancy between the theoretical results, and those obtained numerically using EZNEC. The EZNEC results demonstrated a resonance at the same frequency as the theoretical results, however the null appears most vividly only in the theoretical results. The EZNEC results were obtained using 40 segments per wire, while the theoretical results treated the antennas as two wires each. It is hypothesized that the simplicity of the theoretical model failed to model the null correctly.

FIGURE 4

3.5 m dipole antenna 1.0 m separation − Unmatched source unmatched load (USUL) model

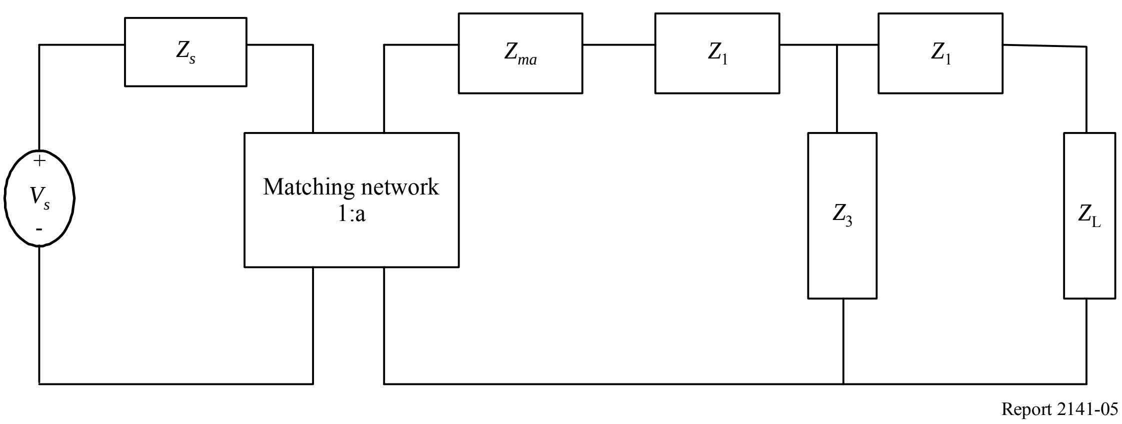


7.2 Matched source-unmatched load model (MSUL)

Calculations were performed using theoretical values for the MSUL Fig. 5 model impedances and simulated with EZNEC, and for a direct calculation of EZNEC power measurements. Results obtained using MSUL model are essentially the same as those obtained on the USUL case in Fig. 4.

FIGURE 5

Equivalent circuit for matched source and unmatched load model (MSUL)



and therefore will not be included. Matching parameters for the MSUL technique were varied at each frequency so that the transformation ratio and matching reactance provide a match for a single antenna, i.e. for matching to Z_{11} at each frequency.

8 Experimental evaluation of antenna coupling

To verify the theoretical and simulation results for antenna coupling, two 3.5 m VHF (30-108 MHz) vertically polarized centre-fed whip (dipole) antennas were placed at separation distances of 1 to 7.6 m. Two experimental set-ups have been used. The first method used direct power measurements and the second method used a network analyser for the isolation measurements.

8.1 Direct power measurement of antenna coupling

The power delivered to the transmitter antenna was measured with a directional power meter and the received power was recorded with a spectrum analyser, see Fig. 6. The cable losses and transmitter power delivered to the Tx antenna were accounted in the calculation of the antenna coupling loss measurements. Figures 7 and 8 show the transmit and receive experimental set-ups for direct power measurements. These measurements were repeated at frequencies over the 30-108 MHz frequency range for antenna separations of 1, 1.5 and 2 m, and isolation results have been shown in Fig. 10 through Fig. 12, respectively.

FIGURE 6

Power amplifier output for direct power isolation measurement into the power meter

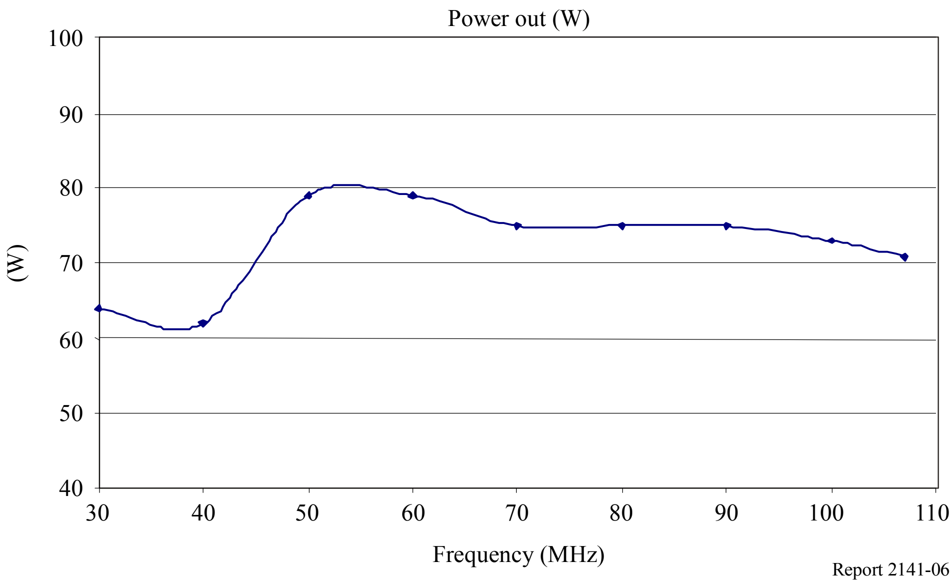


FIGURE 7

Direct power measurement (transmitter set-up)

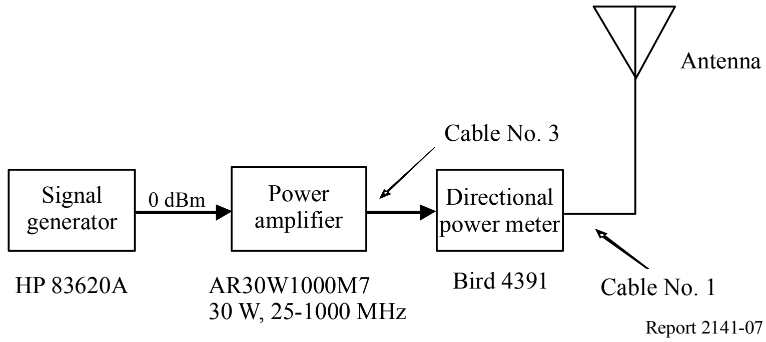
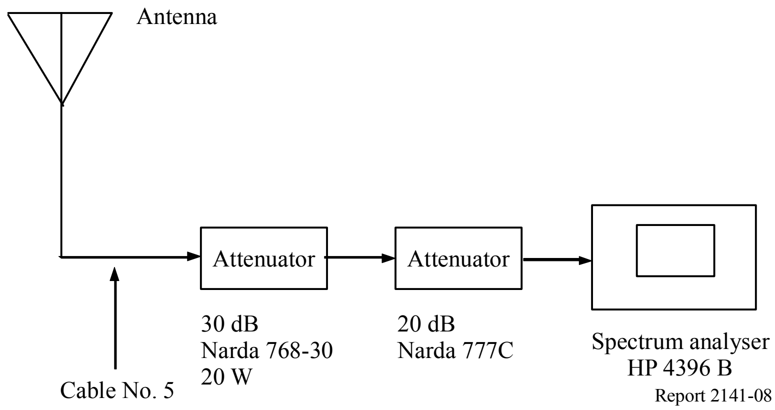


FIGURE 8

Direct power measurement (receiver set-up)



8.2 Antenna coupling isolation measurements using network analyser

The isolation measurements conducted as described in § 8.1 required individual power measurements to be taken at each frequency. In order to automate the measurement process and verify the direct measurement experiment with an alternate method, a network analyser approach was used. The measurement configuration is depicted in Fig. 9. The HP 4396B network analyser is calibrated to null the effect of cable No. 1 and cable No. 5 by connecting the cables back-to-back without antennas. Vertical monopole antennas are connected to measure the coupling losses at the 30-108 MHz frequency range at antenna separations of 1 to 7.6 m. The only drawback of this approach is that any strong signal on any frequency within the measurement band disturbs the coupling measurements. Strong interference from FM broadcast stations within the 88-106 MHz range have been observed in the antenna isolation plots in Fig. 10 through Fig. 19.

FIGURE 9

Antenna isolation measurement with a network analyser

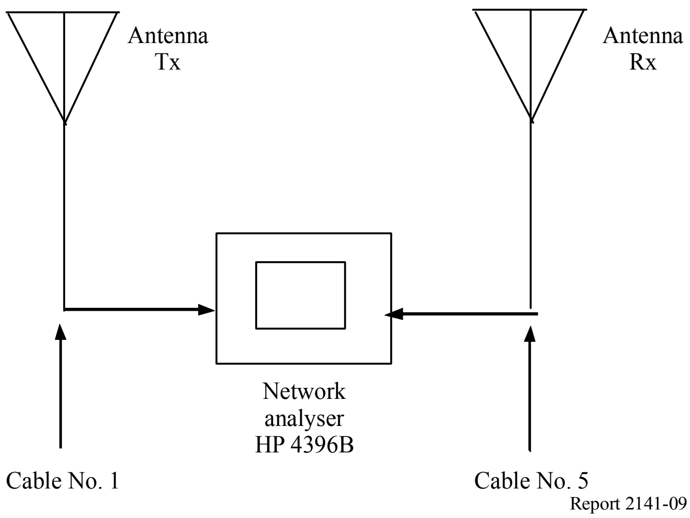


FIGURE 10

Isolation with direct power and a network analyser measurements at separation distance = 1 m

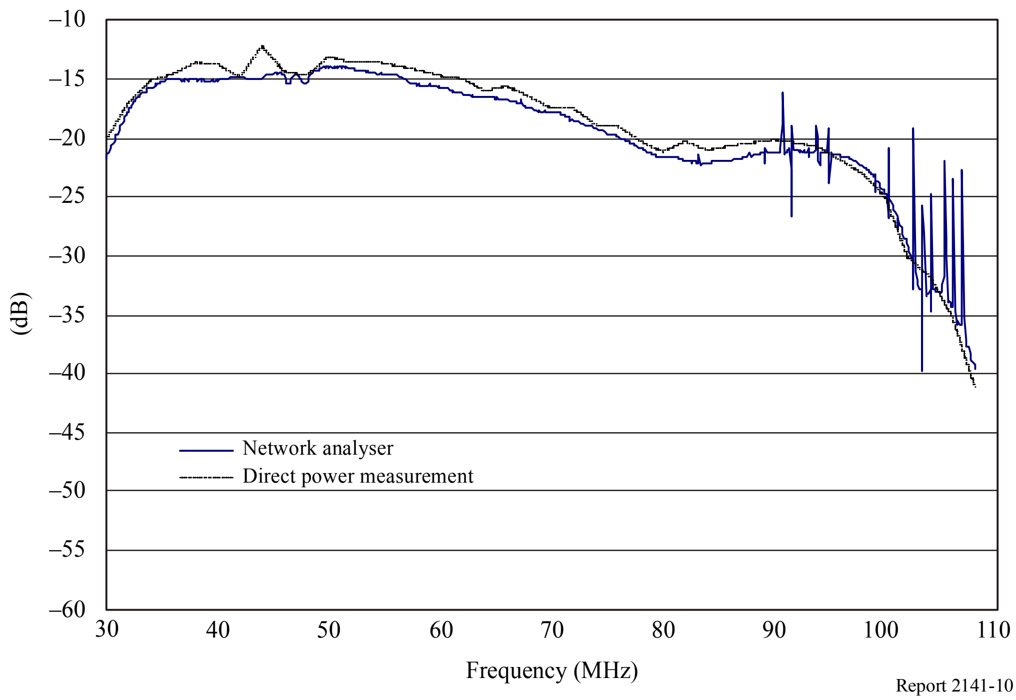


FIGURE 11

Isolation with direct power and a network analyser measurements at separation distance = 1.5 m

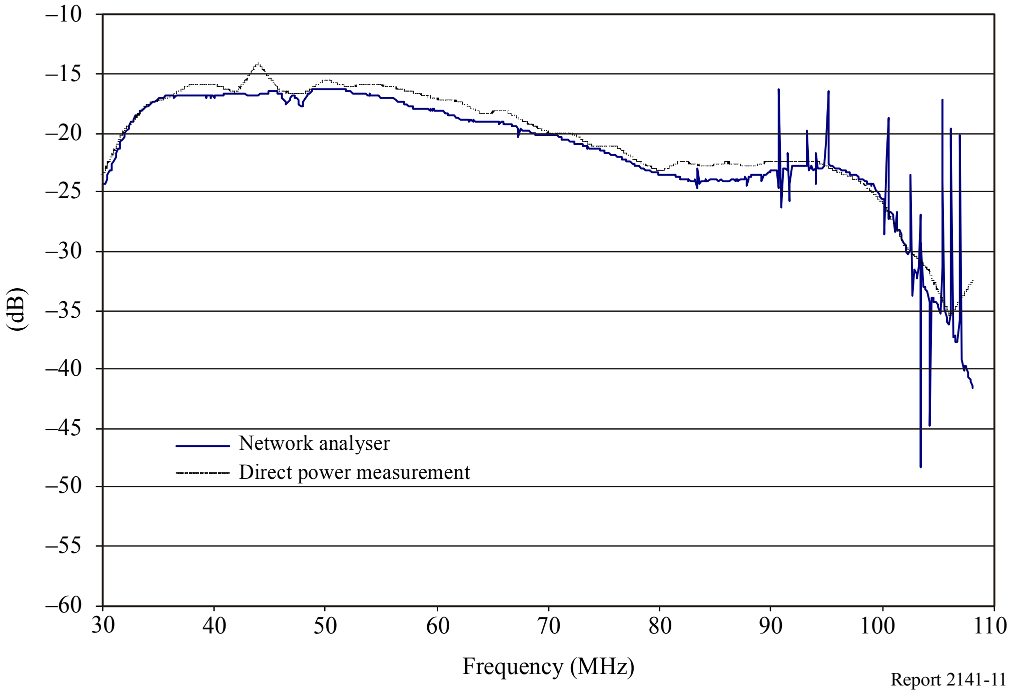


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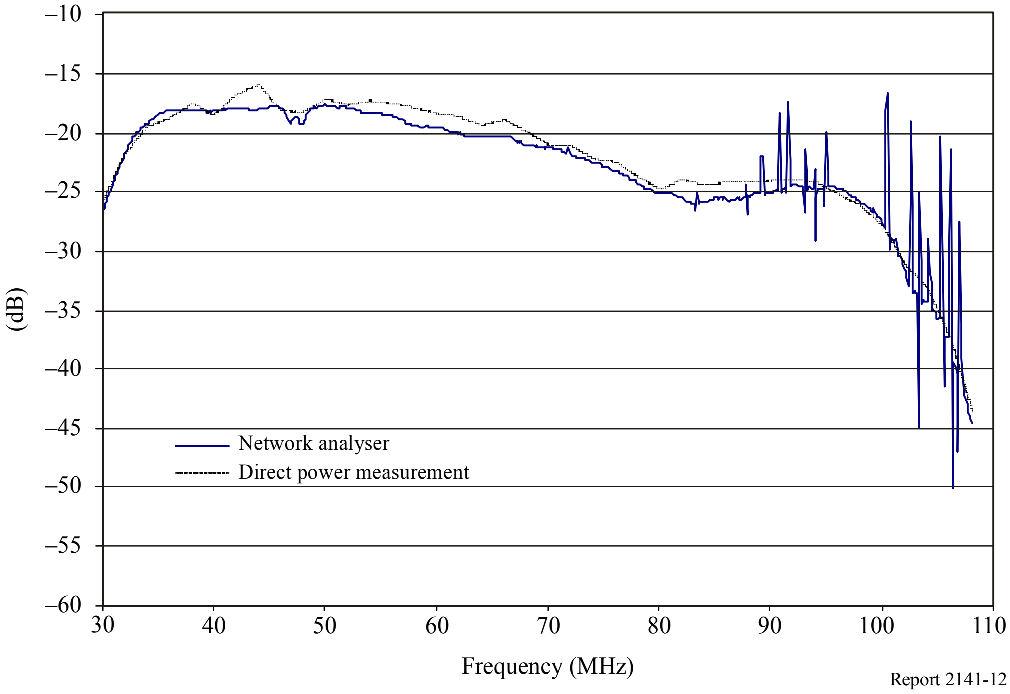
FIGURE 12

Isolation with direct power and a network analyser measurements at separation distance = 2.0 m



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The direct measurement and network analyser measurements had the same shape across the spectrum, while in general, the direct power measurements displayed lower isolation than the network analyser. This may be a result of limited calibration precision or network analyser measurement bandwidth. Figure 13 through Fig. 19 show the isolation results for 2.5 m to 7.6 m antenna separations measured with the network analyser only. It is observed that the theoretically predicted nulls, seen in Fig. 4 at approximately 84 MHz, appear much shallower in the measured network analyser results. This is attributed to unmodelled impedances in the measurement set-up. Differences have been observed between theoretically predicted isolation and experimental results can be attributed to broadband antenna matching network of the antennas.

The null frequencies also appear to be relatively independent of the antenna separation distance.

FIGURE 13

Isolation as measured with a network analyser at 2.5 m separation

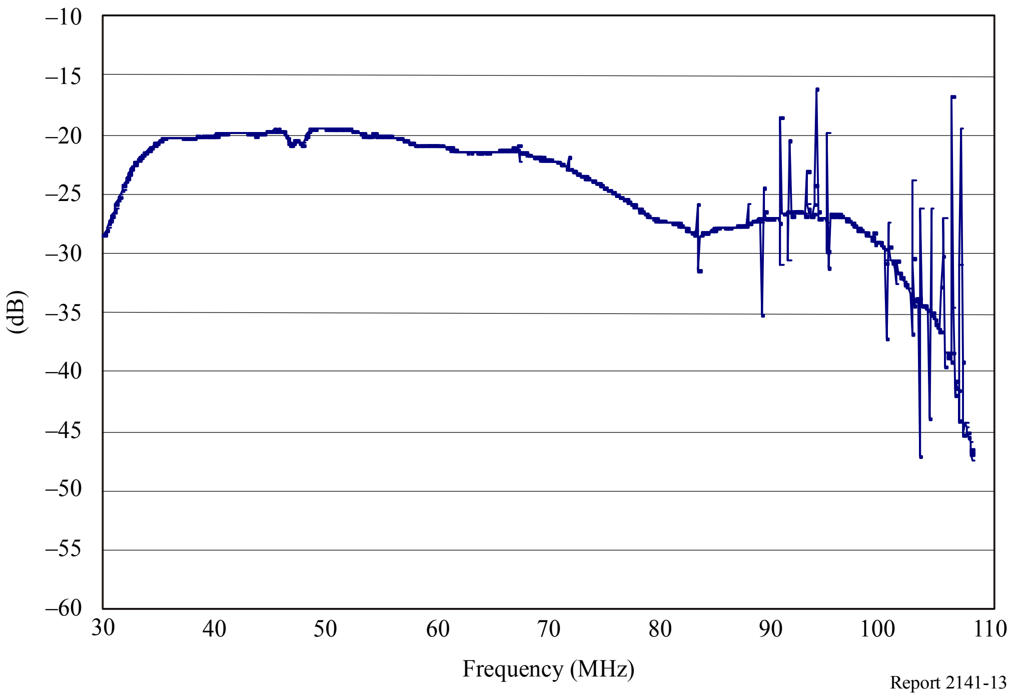

FIGURE 14

Isolation as measured with a network analyser at 3 m separation

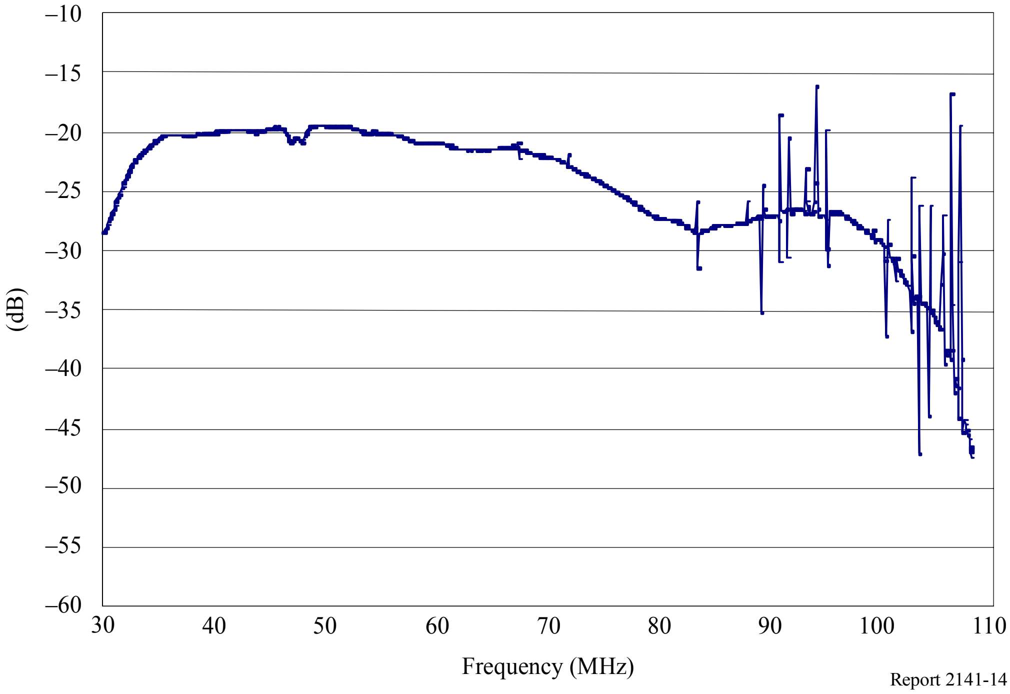

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FIGURE 15

Isolation as measured with a network analyser at 3.5 m separation

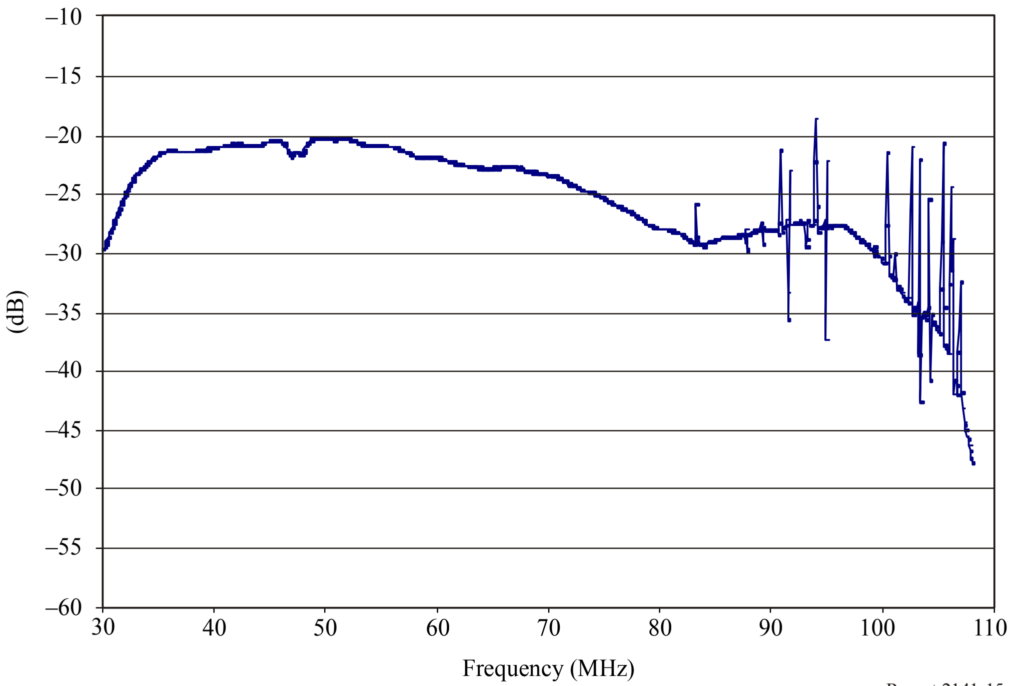

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FIGURE 16

Isolation as measured with a network analyser at 4 m separation

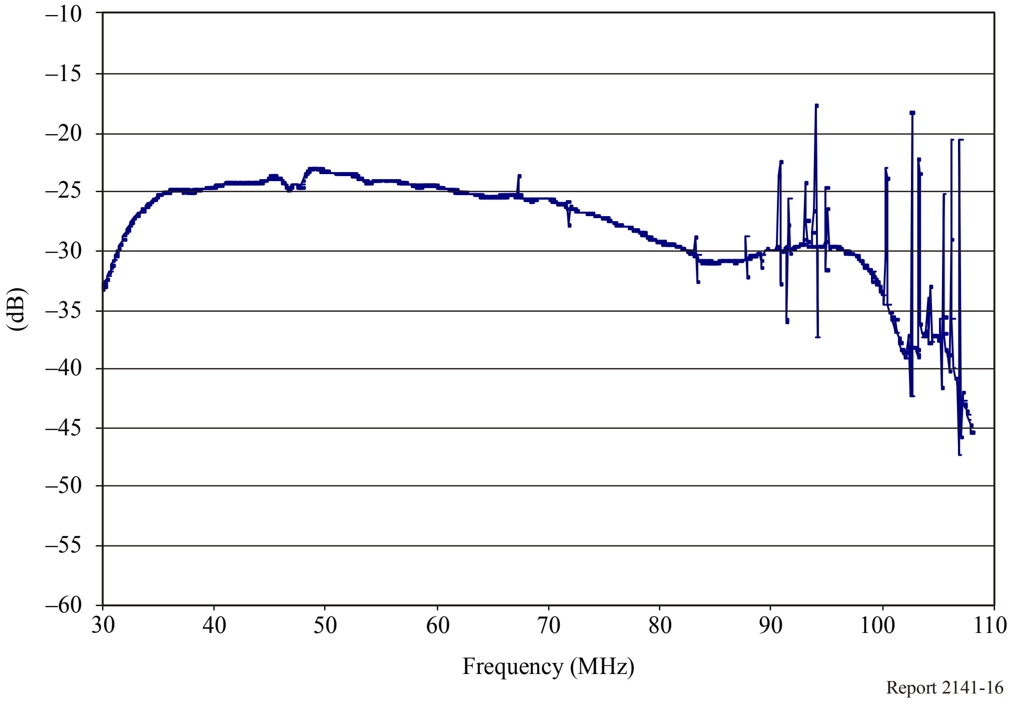

FIGURE 17

Isolation as measured with a network analyser at 4.5 m separation

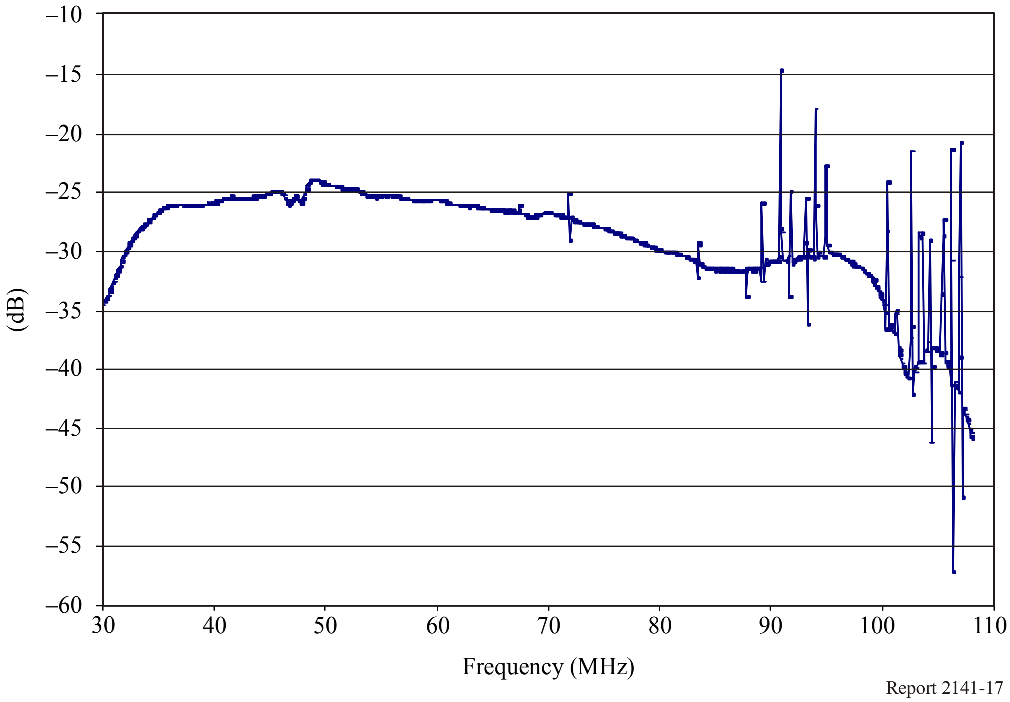

FIGURE 18

Achieving 20 dB isolation at 2.82 m separation

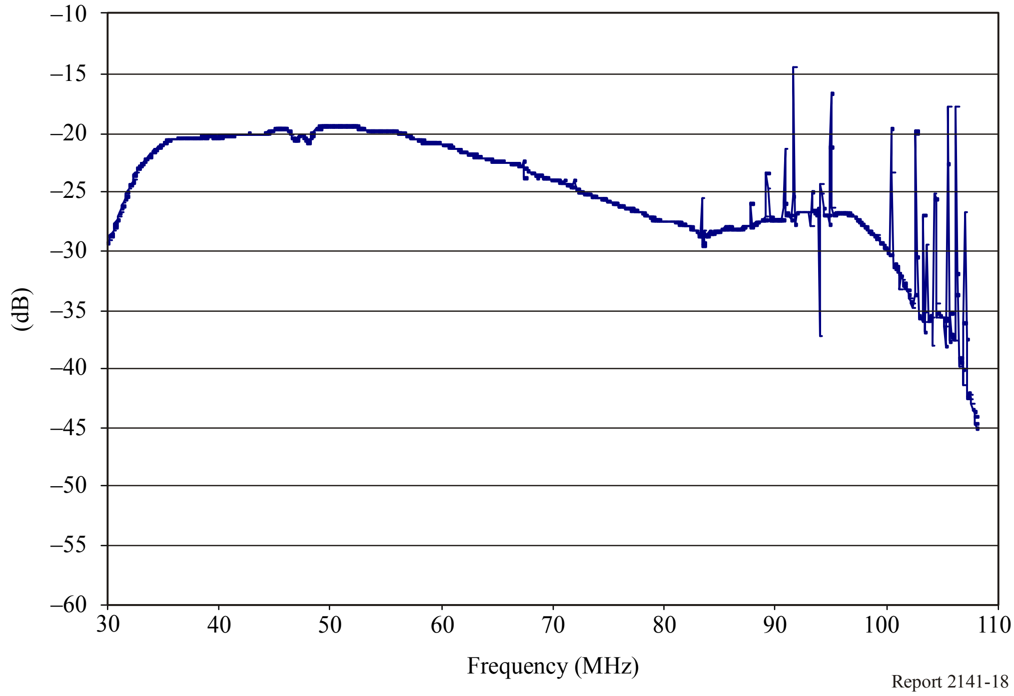

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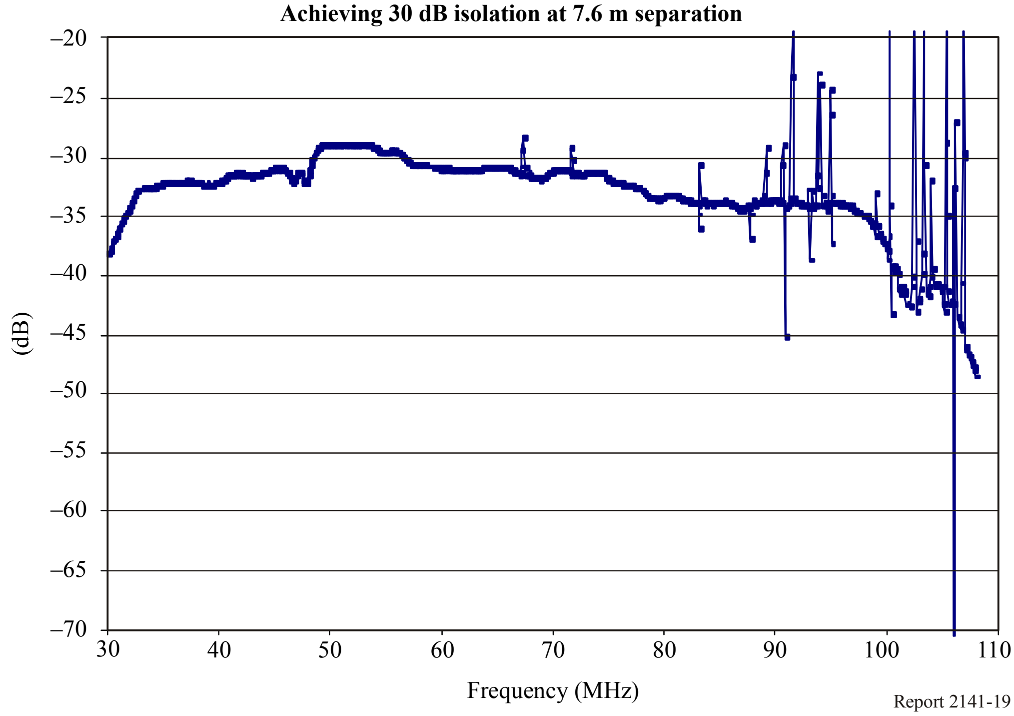
FIGURE 19

Achieving 30 dB isolation at 7.6 m separation



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In order to determine the antenna separation required for 20 dB and 30 dB isolation, the antenna spacing was increased until the required isolations were achieved. An isolation of 20 dB was achieved with 2.82 m spacing, and an isolation of 30 dB was obtained with 7.6 m spacing. These results are shown in Figs. 18 and 19, respectively. All the tests were conducted in a field, and the line-of-sight environment was an open grassy plain.

9 Conclusions

The isolation is theoretically analysed and numerically simulated. One administration experimentally verified the results for land mobile radio antenna separation in close proximity. The coupling between collocated radios is a function of many parameters. In particular, it is a function of antenna length, separation between antennas and operating frequency.

The values found for the isolation between two antennas in close proximity have confirmed that relatively high power can be induced into a nearby receiver and, not surprisingly, can negatively impact receiver/system performance. At a 1.0 m separation, isolation was measured to be 16 dB. Under these conditions, a 50 W transmitter operated at full output power will deliver approximately 1.23 W of RF power to the input of a victim receiver. The effects of this strong coupled signal on a receiver may desensitize and prevent reception of wanted signals. It should be noted that the findings of this experiment will likely reveal what corrective measures are required to overcome or at least limit the impact of co-site coupling effects.

References

JORDAN, E. and BALMAIN, K. [1968] *Electromagnetic Waves and Radiating Systems*. 2nd Edition, Prentice-Hall.