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Characterization Study of Mutual Coupling between Monopole Antennas on Finite Ground Plane at Out of Band Resonant Frequencies

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Abstract—When multiple antennas, operating at different frequencies, are installed on a single platform where the typical inter antenna spacing is a few wavelengths at the lowest frequency, the mutual coupling between the antennas can be optimized by the suitable selection of frequencies and the separation of adjacent antennas. This paper characterizes the dependency of mutual coupling between monopoles on the frequency and separation of the radiating/interfering monopole as well as on the size and shape of the ground plane. The out of band (off-band) characteristics of the monopoles are studied, and the effect of frequency offset between the adjacent monopoles on off-band mutual coupling is summarized. The off-band mutual coupling is reduced by more than 15 dB when the adjacent antenna frequency is selected to be near the fourth harmonic. In the case of smaller ground planes, better isolation of more than 20 dB is possible at intermediate antenna spacing than at the edges. The effect on radiation pattern of an antenna by the proximity of nearby antennas is also studied. The operating frequency/resonant length of the nearby antenna and the inter antenna spacing are found to be the key factors causing variation in radiation pattern. Lower off-band interfering antenna of bigger size is found to have significant effect on radiation pattern at spacing less than 2λ. Analysis has been carried out using FEKO, whose findings are validated using another software HFSS and measurements.

1. INTRODUCTION

Mutual coupling between antennas has been one of the classical areas of research for decades. Initial days. The studies were focused on beam switching with parasitic elements, and more attention was given to how the antenna impedance and radiation pattern can be varied with position and termination of a nearby parasitic element [1–4]. With the widespread use of antenna arrays, studies on mutual impedance and mutual coupling between the antennas in an array, operating at same band got more focus [5–10]. However, all these studies were more into the in-band coupling, and almost no significant studies were done on the off-band mutual coupling between the antennas.

Presently, with the advancement in the wireless communication, the number of RF systems required to be integrated on a single platform has increased with a corresponding decrease in the inter antenna spacing. Vertically polarized monopoles are extensively used to meet the omnidirectional coverage requirements of RF systems especially for platforms like aircraft. During antenna siting, the key challenge is to minimize the mutual coupling between antennas to ensure that the Electromagnetic Interference (EMI) between the systems is within the acceptable limits. One of the practical methods to minimize the mutual coupling is to position antennas operating at different frequency bands adjacent to each other by following standard norms and practices [11], which necessitates a characterization of

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off-band mutual coupling. Additionally, because of the proximity, an out of band radiator also has an impact on the radiation pattern of the antennas [12, 13].

The out of band response of monopole antennas are studied by [14, 15]. Studies on mutual impedance between out of band dipole antennas are given in [16]. The off-band mutual coupling analysis between closely spaced antennas for mobile bands is provided in [17–20]. These studies indicate that the off-band coupling between antennas depends on the spacing between the antennas and the frequency offset between the mobile bands. However, these works are done for very small separations between the antennas of the order of fraction of a wavelength. The mutual coupling at these very short separations is governed mainly by coupling of reactive near field, and in these cases, the far field out of band gain of the antennas is a minor factor, as the main lobe of the radiation pattern is not formed at these short distances.

As monopole antennas have resonance at odd harmonics, mutual coupling levels are higher at some off-band frequency ranges, which are closer to the odd harmonics. The dependence of off-band gain and frequency offset is more prominent at higher inter antenna separations. In the case of antenna placement on vehicles, the inter antenna separation is of the order of a wavelength or more, and the off-band gain, which is again a function of frequency offset between the antennas, can be a major deciding factor of mutual coupling. Other factors that affect the mutual coupling are inter antenna separation and type and size of ground plane. An approximate method for calculating the mutual coupling between lines of sight antennas in vehicles is given in [21]. The work was mainly intended to derive a computationally efficient approximation for mutual coupling as the solution using numerical methods is time consuming and demands huge computational resources due to the very large electrical length of the platform.

This paper provides a characterization on the dependency of off-band gain of monopole antennas on the mutual coupling. The changes in far field gain of monopoles at out of band frequencies are discussed, and S_{21} variations at a reference frequency with changes in interfering antenna frequency are quantified. The impacts of inter antenna separation and ground plane size on surface currents and mutual coupling are discussed, and typical frequency offsets and separations to reduce the mutual coupling are brought out. The effect of adjacent antennas on radiation pattern of a monopole is also presented. The study has been carried out using FEKO, which is further validated using another simulator HFSS and measurements with reasonable agreement. Results of the present study are useful during the preliminary design of platforms with multiple antennas for different functionalities, as simulations are both time consuming and not feasible at the early stage of design due to lack of proper inputs.

2. OUT OF BAND GAIN OF MONOPOLES

The realized or absolute gain of the antenna is given in [22] as

$$G(\theta, \phi) = e_0 D(\theta, \phi) \tag{1}$$

where $D(\theta, \phi)$ is the directivity, and e_0 is the total efficiency, which comprises reflection efficiency (impedance mismatch) and radiation efficiency (conduction and dielectric losses). For wire antennas, at lower microwave frequency range, conduction and dielectric losses are negligible, whereas impedance mismatch becomes more significant at off-band. Hence, directivity and impedance matching are the key factors, which decide the out of band gain of the monopoles.

Monopole antennas designed at resonant frequencies of 1 GHz and 5 GHz are used for the analysis. The antennas are made of thin metal strips of width 3 mm and length 70.2 mm and 12.6 mm, respectively. The metal strips are fed with an SMA connector with the centre conductor elevated by 2 mm above the ground plane of size $\lambda \times \lambda$ (30 cm $\times$ 30 cm at 1 GHz and 6 cm $\times$ 6 cm at 5 GHz). The simulations are carried out using FEKO and HFSS.

2.1. Lower Off-Band Gain

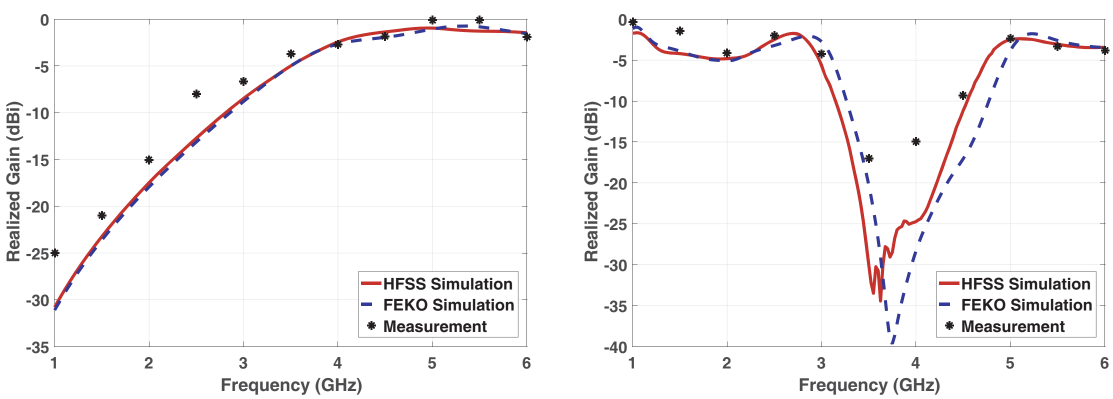
For the monopole antenna, as the operating frequency decreases, electrical length of the antenna decreases. This causes the antenna impedance to be more capacitive. The radiation resistance decreases with decrease in frequency from the ideal value of 36.5 ohm at the resonant frequency f_0 of a quarter wave monopole to less than 1 ohm at $f_0/5$. The directivity of a short dipole is given as 1.5 (1.76 dBi) whereas that of half wave dipole is 1.64 (2.15 dBi) [22]. Hence, the reduction in directivity of equivalent monopoles over an infinite ground plane, as the length decreases, is only marginal. However, the transmission efficiency and realized gain of the antennas at lower off-band decrease with frequency due to poor input impedance matching.

The lower off-band realized gain of 5 GHz monopole antenna with a ground plane of size $\lambda \times \lambda$ (6 cm) is shown in Fig. 1(a). The results indicate that the realized gain of a monopole falls rapidly in the lower off-band with a roll off rate of almost -40 dB/decade. There is reasonable agreement between three results; two simulated and a measured variations of gain with frequency.

2.2. Higher Off-Band Gain

The monopole antenna designed for fundamental frequency f_0 has multiple resonances at odd harmonics ($3f_0$, $5f_0$, etc.) where the radiation resistance is near 50 ohms. At even harmonics ($2f_0$, $4f_0$, etc.) the impedance matching is poor because of the large radiation resistance of a few hundred ohms. The azimuth directivity increases with frequency till slightly above $2f_0$. For linear antennas of length more than full wavelength, radiation pattern has more than one lobe [22]. This causes considerable variation in the azimuth directivity of the monopole at higher off-band.

The higher off-band realized gain of 1 GHz monopole antenna with a ground plane of size $\lambda \times \lambda$ (30 cm) is shown in Fig. 1(b). The results indicate that azimuth realized gain has multiple peaks at the odd resonances in the higher off-band. The increase in azimuth directivity at $2f_0$ compensates the poor impedance matching resulting in only a slight reduction around 5 dB in azimuth realized gain at $2f_0$. The radiation pattern is completely tilted up at $4f_0$ with almost no radiation in azimuth direction as one more lobe gets formed after $4f_0$. Therefore, the directivity is very poor at $4f_0$, $8f_0$, etc., and due to this reason, a considerable fall around 30 to 40 dB is observed in the realized azimuth gain at around $4f_0$. There is agreement between the three results.



(a) (b)

Figure 1. Comparison of simulated and measured off-band gain of monopole antennas. (a) Lower off-band gain of monopole antenna designed at 5 GHz. (b) Higher off-band gain of monopole antenna designed at 1 GHz.

2.3. Impact of Ground Plane Size

The effect of finite size of the ground plane on the antenna impedance at the designed resonant frequency was studied by Weiner [23]. The antenna impedance changes only slightly with the ground plane size, and the associated effect on antenna mismatch is minimal. However, the finite size of the ground plane tilts the beam away from the ground plane due to edge diffraction effects, which causes a reduction in gain at both in band and out of band frequencies in comparison with infinite ground plane.

The lower off-band and higher off-band azimuth gains of 1 GHz monopole antenna are simulated with infinite ground plane and with finite square ground planes of side dimensions 0.5λ, λ, and 1.5λ using full wave solvers of FEKO software, and the results are provided in Fig. 2(a) and Fig. 2(b). Though

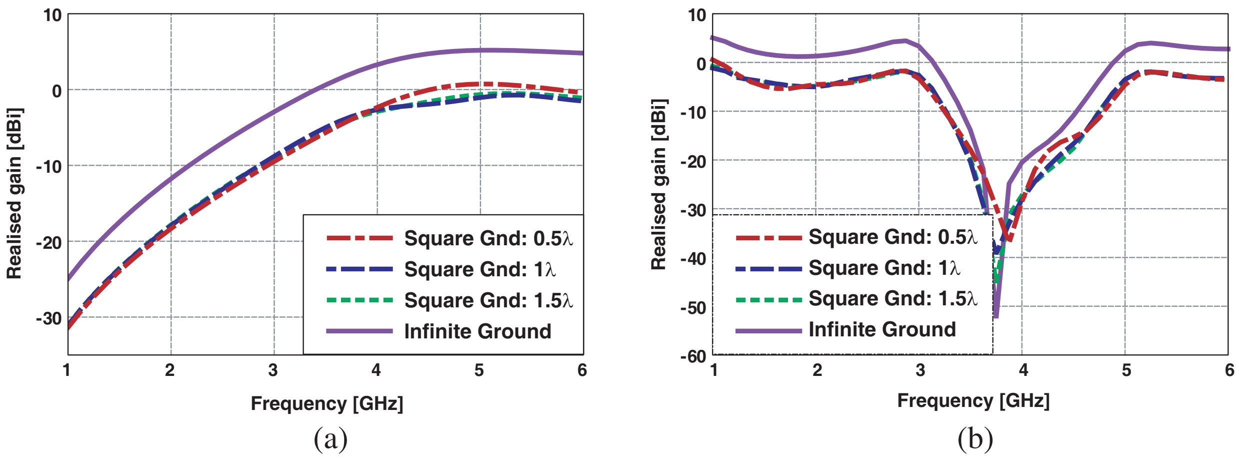


Figure 2. Comparison of off-band gain of monopole antennas on finite and infinite ground planes. (a) Lower off-band gain of 5 GHz monopole antenna. (b) Higher off-band gain of 1 GHz monopole antenna.

the variation of gain follows the same pattern as that of infinite ground plane, the realized azimuth gain of a monopole on a square ground plane of finite size is found around 6 dB less than infinite ground plane for in-band, lower and higher off-band frequencies.

3. OFF-BAND MUTUAL COUPLING BETWEEN MONOPOLES

For reciprocal antennas like monopoles, mutual coupling is the ratio of received power across a matched load to the transmit power from the antenna, which is given by $|S_{21}|^2 = |S_{12}|^2$. In this section, the factors affecting the off-band mutual coupling are explained, and the mutual coupling characterization with infinite ground plane using simulations and analytical methods is provided. The results are used as the reference for further characterization on finite planar ground planes.

3.1. S_{21} with Infinite Ground Plane

The mutual coupling between two monopoles over an infinite ground plane placed at a separation higher than the far field distance can be computed by using modified Friis transmission equation [24] and S_{21} is given by

$$S_{21}(\text{dB}) = Gt(\text{dB}) + Gr(\text{dB}) - FSPL(\text{dB}) - 6 \tag{2}$$

where Gt is the transmitting antenna gain, Gr the receiving antenna gain, and $FSPL$ the free space path loss given by

$$FSPL(\text{dB}) = -27.6 + 20\log(D) + 20\log(F) \tag{3}$$

where D is the distance in meter, and F is the frequency in MHz.

The Friis transmission equation is for free space conditions, and the correction factor of -6 dB is to nullify the effect of ground plane as it is already considered in transmitting and receiving antenna gains. As given in Eqs. (2) & (3), the off-band mutual coupling between monopoles depends on their off-band gains and is likely to decrease with increase in inter antenna separation and operational frequency. The applicability of the modified equation is verified with full wave numerical method using FEKO software.

3.2. Antenna Design

The monopole antennas of resonant frequencies 1 GHz, 1.4 GHz, 1.625 GHz, and 5 GHz are used for the analysis. The antennas are made of thin strips of 3 mm width and are of length 70.2 mm, 49.5 mm, 42.3 mm, and 12.6 mm, respectively, for the above four resonant frequencies. The metal strips are fed with SMA connector with centre conductor elevated by 2 mm above the ground plane.

3.3. S_{21} Dependence on Off-Band Gain

S_{21} between two monopole antennas of resonant frequencies at 1 GHz and 5 GHz is simulated over an infinite ground plane for the frequency range from 1 GHz to 6 GHz and compared with the calculated results using Eq. (2). Although the mutual coupling at either of the resonant frequencies is critical in practical cases, the S_{21} trends at other off-band frequencies are important in understanding the effects of off-band gain and frequency offsets in mutual coupling.

The inter antenna separations in this analysis are taken as 30 cm, 150 cm, and 750 cm which correspond to the electrical lengths of λ, 5λ, and 25λ at 1 GHz. The results are given in Fig. 3. The gradual increase on S_{21} from 1 GHz till 3 GHz is due to the increase in lower off-band gain of 5 GHz antenna. The fall in S_{21} between 3.5 GHz and 4 GHz is due to the fall in higher off-band azimuth gain of 1 GHz antenna and is more prominent at higher inter antenna separation where the near field interactions between the antennas are minimum. An increase in S_{21} at 5 GHz and a further reduction after 5 GHz is in par with 5 GHz antenna off-band gain performance.

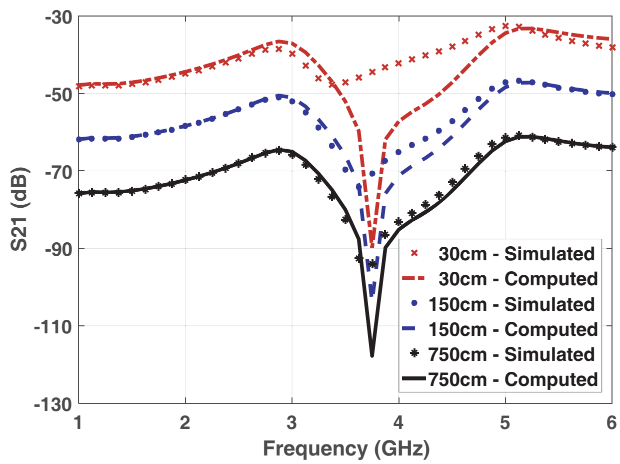


Figure 3. S_{21} between 1 GHz and 5 GHz monopole antennas at off-band frequencies with inter antenna spacing of 30 cm, 150 cm and 750 cm.

It is observed that the simulation results follow the calculated results exactly at higher separation of 750 cm where far field conditions get fully satisfied. At shorter separations, the analytical and simulated results follow the same pattern at all frequencies except near $4f_0$ where the azimuth gain drops due to the null (lobe separation) in radiation pattern. Even though the azimuth gain is very poor at this frequency range, higher S_{21} is observed at short inter antenna separation as sufficient portion of radiated energy from 1 GHz antenna falls on 5 GHz antenna. S_{21} is not dependent on azimuth gain at this frequency range especially at short inter antenna separation. The analytical and simulated results are exactly matching at other frequencies at 5λ and 25λ inter antenna spacing, whereas simulated results are slightly lower than analytical ones at 1λ inter antenna spacing. The difference at lower separations is due to reduction of gain from theoretical value at lower separations due to the interference from the other antenna.

3.4. S_{21} Variation with Resonant Frequency of Interfering Antenna

Comparison of simulated S_{21} on an infinite ground plane with 5 GHz monopole as reference (receiving) antenna and 1 GHz, 1.4 GHz, and 1.625 GHz monopoles as interfering (transmitting) antennas is provided in Fig. 4 for an inter antenna separation of 30 cm. 1.4 GHz monopole has its fourth harmonic gain drop around 5 GHz whereas 1.625 GHz antenna has the third harmonic resonance at 5 GHz. S_{21} at 5 GHz for 1.4 GHz interfering antenna is around 15 dB less than 1 GHz interfering antenna and 10 dB less than 1.625 GHz interfering antenna. This difference further increases at higher inter antenna spacing.

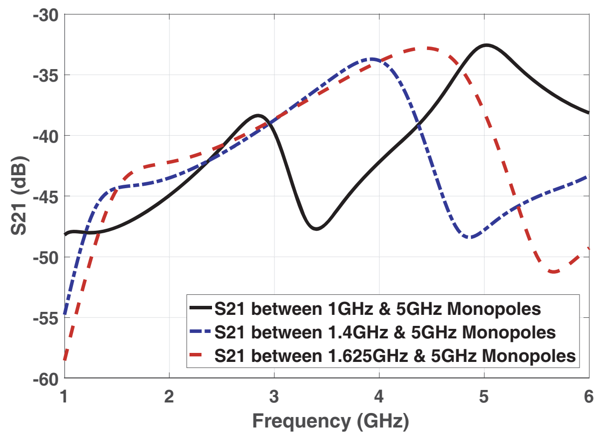


Figure 4. Comparison of S_{21} variation with resonant frequency of interfering antennas: 5 GHz monopole as reference antenna and monopoles of resonant frequencies 1 GHz, 1.4 GHz and 1.625 GHz as interfering antennas.

4. EFFECTS OF DIMENSION OF THE FINITE GROUND PLANE

The mutual coupling between monopoles is found to have a relationship with the inter antenna separation and resonant frequency of the interfering antenna on the ideal case of infinite ground plane. The extent of dependency of the finite ground plane on the above characteristics is studied with a set of planar ground planes of dimensions as given in Table 1. The antenna design is as mentioned in Section 3.2. The inter antenna separation is varied from 6 cm to 29 cm, and the simulated results are verified with measurements. The fabricated ground plane configuration 3 (as indicated in Table 1) with 1 GHz and 5 GHz antennas is shown in Fig. 5.

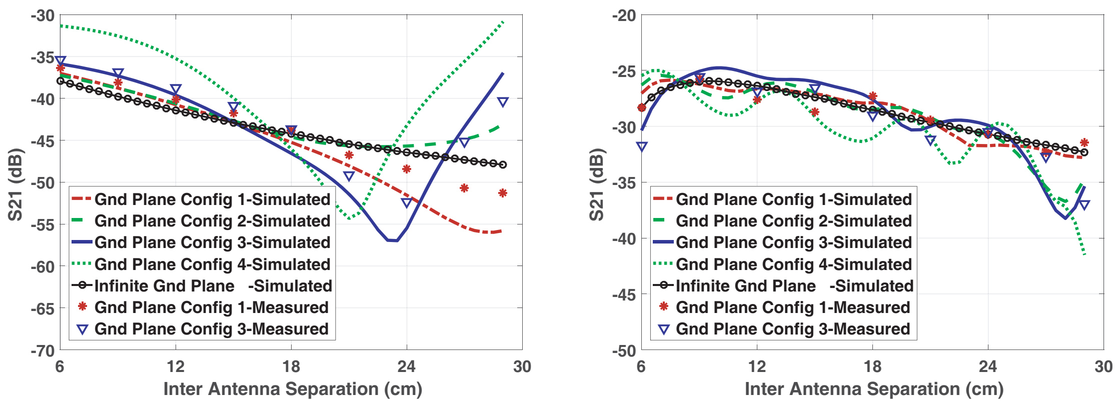
Table 1. Rectangular ground plane dimensions.

Ground plane configuration	Length (cm)	Width (cm)	Dimensions in λ at 5 GHz
1	60	30	10×5
2	30	30	5×5
3	30	12	5×2
4	30	6	5×1

Figure 5. Ground plane configuration 3 (30 cm $\times$ 12 cm) with 1 GHz and 5 GHz antennas.

4.1. S_{21} Comparison across Ground Planes

Monopoles designed at 1 GHz and 5 GHz resonance frequencies are considered in this analysis. The simulated and measured S_{21} comparison across ground planes as a function of inter antenna spacing is shown in Fig. 6(a) for 1 GHz frequency and in Fig. 6(b) for 5 GHz frequency. It is noted that the mutual



(a) (b)

Figure 6. Comparison of simulated and measured S_{21} across the ground planes. (a) S_{21} at 1 GHz. (b) S_{21} at 5 GHz.

coupling between the antennas on larger ground planes is similar to that of the infinite ground plane, whereas for ground plane configurations 3 and 4 of smaller width, there is a considerable variation in S_{21} in comparison with that of the infinite ground plane. Mutual coupling between the antennas at 1 GHz is found the least at 23 cm separation for ground plane configuration 3 and 21 cm separation for configuration 4. Higher mutual coupling is observed at 29 cm separation where the antennas are at the edge of ground plane. The variation in S_{21} with antenna spacing is up to 20 dB for ground plane configurations 3 and 4, and within 5 dB margin from infinite ground plane results for ground plane configurations 1 and 2. S_{21} values are found the same at 6 cm and 29 cm separation with ground plane configurations 3 and 4.

It can also be observed that S_{21} with finite ground plane can be easily computed using Eq. (2) intended for infinite ground plane, with an error limit of 2 dB, when the inter antenna separation is more than 1λ, and the antennas are kept more than $\lambda/2$ distance from the edge of the ground plane.

The simulated surface currents of 1 GHz antenna are shown in Fig. 7 for ground plane configuration 1 and ground plane configuration 3 with inter antenna spacing as 6 cm, 23 cm, and 29 cm. Fig. 8 provides the simulated surface currents of 5 GHz antenna for ground plane configurations 1 and 3. The surface current changes direction at every $\lambda/2$ distance, and its amplitude decreases with distance from the transmit antenna. The first minimum point is around $\lambda/4$ from the transmit antenna, and further minimum points are at every $\lambda/2$ distance from the antenna.

As antennas are moved towards the edge of ground plane, large surface currents are present at the edges, and the reflection from the discontinuity at edges results in modification of surface current pattern. The nulls in the surface current near the transmitting antenna or between the transmit antenna and the ground plane edge are found to be faded, and the surface current on other parts of the ground plane has increased. For the large ground plane, surface currents are reduced considerably at the edges, and the effect of edge reflection has less impact on the total surface current distribution. The peaks in surface current have a distorted shape in configuration 3 in comparison with that of configuration 1.

With ground plane configuration 3, antennas are at the edge of ground plane at inter antenna separation of 29 cm as shown in Fig. 7(f). A comparatively higher intensity surface current is observed at the 5 GHz antenna. At inter antenna separation 23 cm, the 5 GHz antenna is found at the position of least surface current, and at inter antenna separation 6 cm large surface currents are present at 5 GHz antenna. A similar trend is observed in S_{21} plot given in Fig. 6(a), where S_{21} is the least at 23 cm and higher at 6 cm and 29 cm.

The periodicity in surface current with distance causes a similar sinusoidal variation of the envelope of S_{21} when being plotted against the inter antenna spacing as can be seen in Fig. 6. The periodic variations in S_{21} with separation are the function of λ, and the length of a cycle corresponds to the wavelength. The amplitude of the oscillations is higher for lower frequency (1 GHz) and for smaller ground planes, as the amplitude of surface current reflecting at the ground plane edge is higher at these

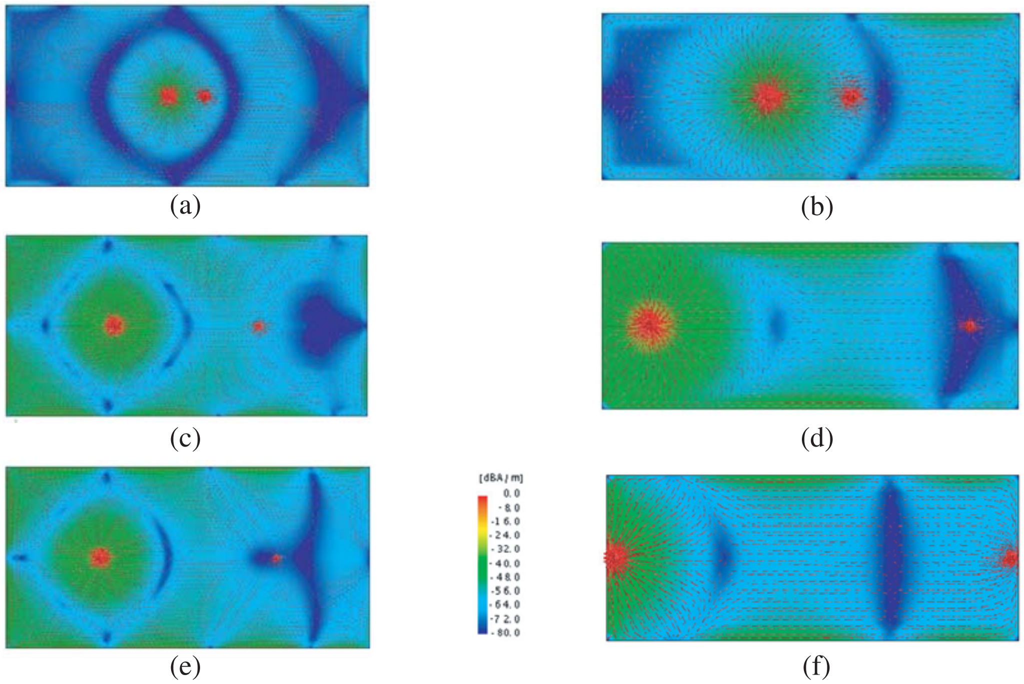


Figure 7. Surface Currents at 1 GHz. (a) Ground plane configuration 1, inter antenna separation 6 cm. (b) Ground plane configuration 3, inter antenna separation 6 cm. (c) Ground plane configuration 1, inter antenna separation 23 cm. (d) Ground plane configuration 3, inter antenna separation 23 cm. (e) Ground plane configuration 1, inter antenna separation 29 cm. (r) Ground plane configuration 3, inter antenna separation 29 cm.

cases resulting in more disturbances in total current distribution. It can also be seen that the sinusoidal variations in S_{21} are of higher amplitude towards the edge of the ground plane as surface currents vary considerably with slight variation in antenna position at edges.

4.2. S_{21} Variation with Resonant Frequency of Interfering Antenna

In this analysis, 5 GHz antenna is used as the reference (receiving) antenna, and 1 GHz, 1.4 GHz, and 1.625 GHz antennas are used as the interfering (transmitting) antennas. Simulated S_{21} at 5 GHz frequency are shown in Fig. 9(a) and Fig. 9(b) for ground plane configurations 1 and 3, respectively for all the interferer cases with inter antenna separation between 6 cm and 29 cm.

With ground plane configuration 1, a 6 dB fall is observed in S_{21} with 1 GHz and 1.625 GHz interfering antennas when the inter antenna separation is doubled whereas S_{21} fall rate is found to be much higher (around 12 dB) with 1.4 GHz interfering antenna. The higher fall rate is because S_{21} becomes more dependent on the far field gain of the antenna, which is again defined by the surface current distribution, as the inter antenna separation is increased. The off-band gain of 1.4 GHz antenna is very low at 5 GHz, and its more prominent effect on S_{21} at higher spacing causes the rapid fall. At lower inter antenna separation, the effect of near field interactions between the antennas dominates the mutual coupling compared with the far field gain. A 13 dB difference in S_{21} is found between 1 GHz and 1.4 GHz interferer cases at 24 cm separation, and it is further increased to 15 dB at the edges.

With ground plane configuration 3, a similar trend is observed till mid inter antenna separation, and the variations due to ground plane edge reflections are observed at higher inter antenna separation.

4.3. Effect of Interfering Antenna on Radiation Pattern

In the analysis to characterize the effect of lower off-band interfering antenna, 5 GHz monopole is considered as the reference (radiating) antenna, and 1 GHz, 1.4 GHz, and 1.625 GHz monopoles are considered as the interfering (receiving) antennas. In each case, 5 GHz antenna is excited, and the interfering antenna is terminated on load, with inter antenna spacing varying from 1 cm to 29 cm. The azimuth radiation pattern with 1 GHz antenna as interfering antenna on ground plane configuration 1 with inter antenna separation of 3 cm ($\lambda/2$), 6 cm (λ), and 29 cm ($\sim 5\lambda$) is shown in Fig. 10. The comparison of azimuth gains of 5 GHz antenna in the presence of each of the three interfering antennas, in the directions towards and away from interfering antenna, is shown in Fig. 11(a) for ground plane configuration 1 and in Fig. 11(b) for ground plane configuration 3.

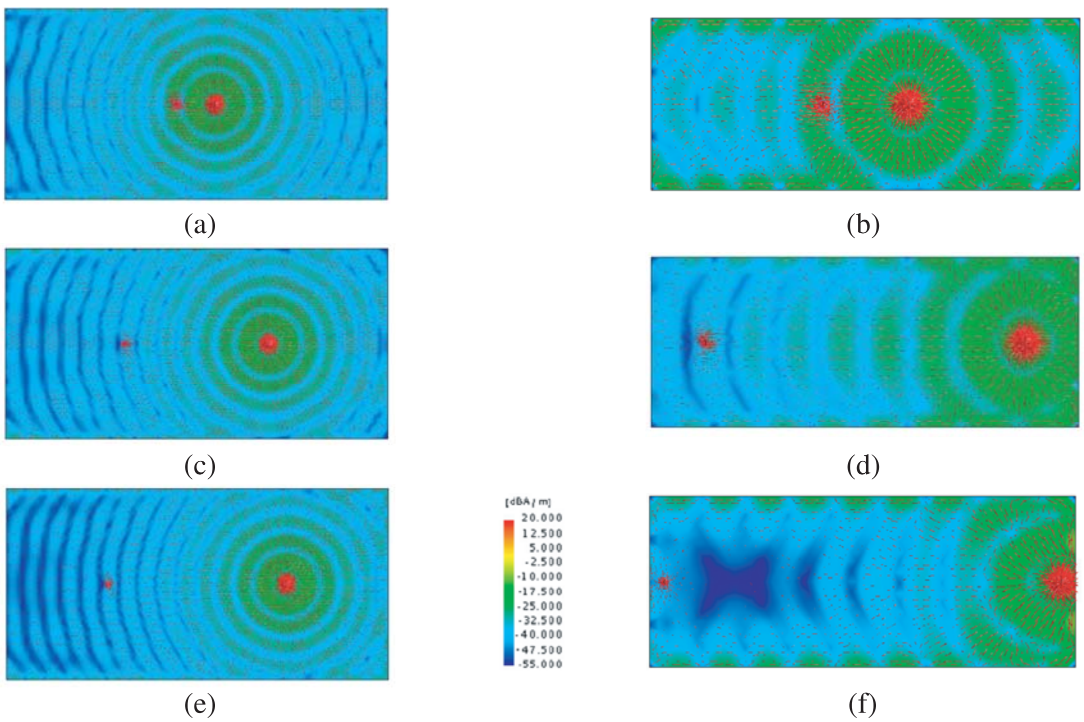


Figure 8. Surface Currents at 5 GHz. (a) Ground plane configuration 1, inter antenna separation 6 cm. (b) Ground plane configuration 3, inter antenna separation 6 cm. (c) Ground plane configuration 1, inter antenna separation 22.5 cm. (d) Ground plane configuration 3, inter antenna separation 22.5 cm. (e) Ground plane configuration 1, inter antenna separation 28 cm. (f) Ground plane configuration 3, inter antenna separation 28 cm.

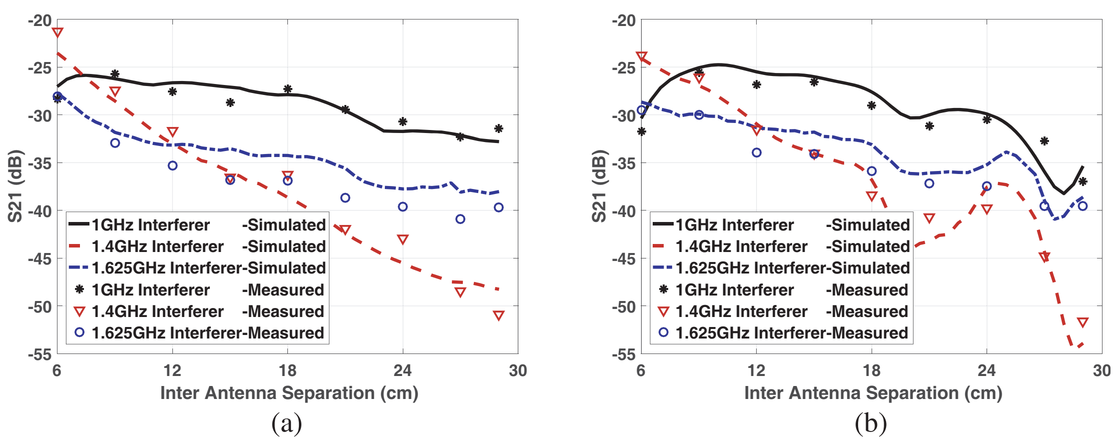


Figure 9. Comparison of simulated and measured S_{21} at 5 GHz across interfering antennas. (a) Ground plane configuration 1. (b) Ground plane configuration 3.

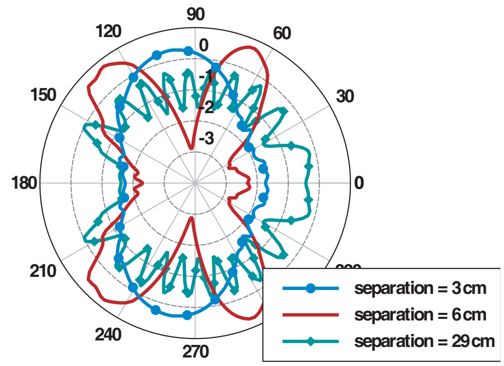


Figure 10. Variation of radiation pattern of 5 GHz monopole antenna with separation to 1 GHz interfering antenna.

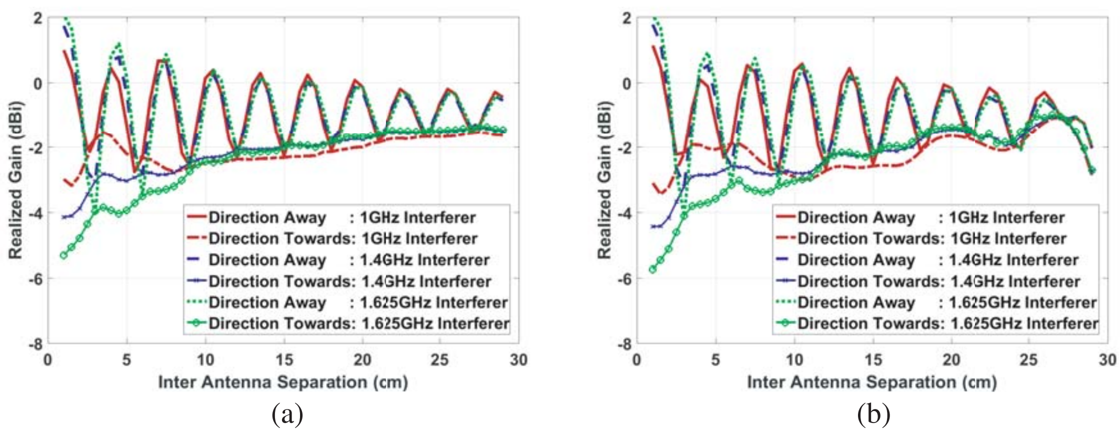


Figure 11. Comparison of azimuth gain variation of 5 GHz monopole antenna with separation to interfering antenna. (a) Ground plane configuration 1. (b) Ground plane configuration 3.

The observations on gain variation are summarized as

- The passive interfering antenna of lower off-band can cause a variation in the radiation pattern with ripple amplitude of 3 to 6 dB at shorter separations of less than λ (operating wavelength). The gain variations decrease to around 2 dB at 2λ separations and further decrease to around 1 dB at higher separations. The gain variations increase slightly at higher separation for smaller ground plane when the radiating antenna is at the edge of ground plane.
- The number of lobes in the radiation pattern increases with a reduction in ripple amplitude as the separation to the interfering antenna increases.
- The gain in the direction away from the interfering antenna has a variation similar to a damped sinusoid, when the inter antenna spacing increases. The gain towards the direction of interfering antenna follows the lower envelope of the damped sinusoid.
- The off-band gain and mutual coupling levels of the interfering antenna at operating frequency of the reference antenna do not have much effect on the radiation pattern.

Further, the 1 GHz antenna is excited and 5 GHz antenna terminated to study the effect of interfering antenna of higher off-band. The azimuth gain variation in the direction towards and away from 5 GHz antenna is shown in Fig. 12 for both ground plane configuration 1 and ground plane configuration 3. The passive interfering antenna of higher off-band does not affect the radiation pattern of a monopole, and the radiation pattern remains almost omnidirectional even at the shorter inter antenna separation. With the ground plane configuration 1, the pattern variation is less than 0.3 dB.

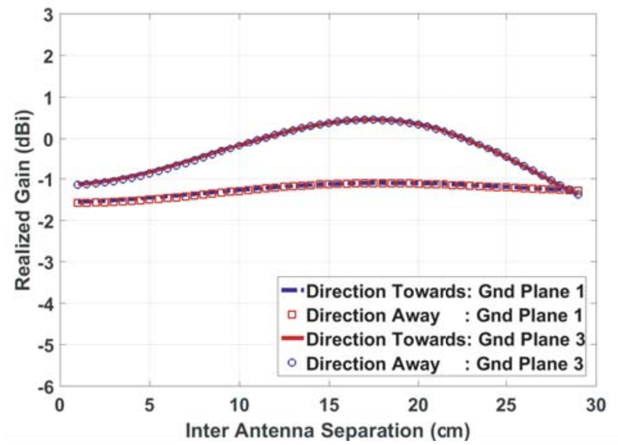


Figure 12. Comparison of azimuth gain variation of 1 GHz monopole antenna with separation to 5 GHz interfering antenna.

5. CONCLUSIONS

The far field gain variation of monopole antennas at out of band frequencies is discussed. The off-band azimuth gain is found to have a direct impact on mutual coupling at inter antenna separations higher than 4λ. For two monopole antennas, higher isolation can be obtained between the adjacent antennas, if the frequency pairs are selected corresponding to the fourth harmonic at which azimuth gain falls. S_{21} at the resonance frequency of a monopole can change by more than 15 dB due to variation in off-band gain of different interfering antennas kept at same separation. However, this dependence of S_{21} on off-band gain is found to be minimal at antenna spacing of less than 2λ.

The effect of ground plane on surface current distribution and mutual coupling is also presented. Finite size of ground plane has significant effects on mutual coupling if antennas are kept within $\lambda/2$ distance from the edge of the ground plane. An approximate method to calculate mutual coupling, when the inter antenna separation is more than 1λ, and the antennas are kept more than $\lambda/2$ distance from the edge of the ground plane, is presented, and errors between proposed method and simulated values are found within 2 dB. With smaller ground planes, better isolation is observed at intermediate spacing than placing the antenna towards the edge of ground plane. Out of band gain of the interfering antenna or S_{21} is found to have negligible effect on radiation pattern of a monopole antenna. The electrical length of the interfering antenna decides the ripple levels in the radiation pattern. Ripples of the level higher than 3 dB can get introduced in the radiation pattern by a lower off-band interfering antenna if inter antenna spacing is less than a λ. The effect of interfering antenna is negligible at antenna spacing higher than 2λ. The data presented in this paper provide insight for designing platforms with multiple monopole radiators operating at different frequencies for various functionalities especially in the preliminary design stage.

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