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Carbon Fiber Reinforced Polymer as Antenna Ground Plane Material Up to 10 GHz

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***Abstract*—Carbon Fiber Reinforced Polymer (CFRP) or generally Carbon Fiber Composites (CFC) are increasingly utilized in lightweight construction. Large CFRP parts such as chassis or fuselages are utilized as antenna ground planes. However, radiation characteristics of antennas designed for metal ground planes change when mounted on anisotropic composites. In this paper the influences of CFRP ground planes on the radiation characteristics of antennas in the range from 1 - 10 GHz are investigated with measurements of conical monopole antennas. Measurements show that ground planes from unidirectional CFRP severely distort radiation patterns, while the influence of woven plies is small.**

I. Introduction

Carbon Fiber Composites (CFC) consist of electrically conductive carbon fibers embedded in a matrix. Currently mainly non-conductive polymers are used as matrix, these materials are referred to as Carbon Fiber Reinforced Polymer (CFRP). Although a diversity of production techniques are currently in use, the majority of parts are manufactured from preimpregnated sheets of continuous fiber filaments (prepregs). Components are constructed as laminates from prepregs with woven or unidirectional plies.

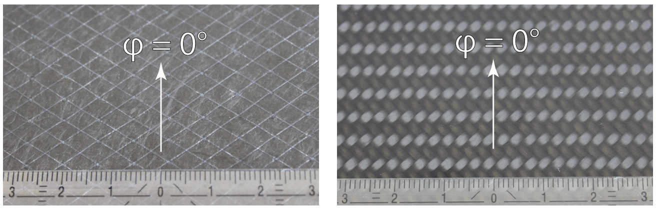
CFRP laminates are typically used in light weight construction. As high tensile strength is only available in fiber direction, laminates are designed for specific parts according to mechanical considerations. Either unidirectional fibers are used in the direction of expected stresses on the component, or woven fabrics are used to achieve a more uniform, but drastically decreased, tensile strength.

The electromagnetic shielding properties of CFRP allow their application as chassis material of electronic devices and vehicles [1], [2]. CFRP are already widely used in the production of airplanes, boats and cars. From an antenna viewpoint isotropic metallic ground planes are exchanged with a variety of anisotropic composites. In general conductivity, permittivity and permeability of CFRP are anisotropic and frequency dependent and vary with material composition: used fibers, matrix, fiber volume fraction, fabric weave, etc. [3] CFRP are diamagnetic with permeability varying with fiber orientation [4].

CFRP can be used to manufacture antennas, but metals are preferred in most applications. Metals still offer a larger, isotropic electrical conductivity and lightweight construction is not necessary in most antenna applications. CFRP antennas are resistant to corrosion as fibers are protected inside the polymer matrix. Patch antennas and slot antennas cut into unidirectional CFRP are investigated in [5], fiber orientation has a large influence on these antennas. A bow-tie antenna is presented in [6]. CFRP is used to manufacture lightweight reflectors [7], [8]. A millimeter wave CFRP reflector at W-band (75 - 100 GHz) in [9] shows the same performance as its chrome plated version. It is possible to use the anisotropy of CFRP as a design parameter. A mechanically reconfigurable patch antenna on carbon fiber nanocomposites is presented in [10], where the anisotropic conductivity acts as a mode filter.

Large conductive structures are utilized as antenna ground planes. Examples are car roofs as ground plane for monopole antennas in roof mounted antenna modules [11] or printed circuit boards (PCB) as ground plane for monopole antennas and inverted-F antennas in mobile phones, tablets and laptops [12]. The first measurement of the normalized pattern of a monopole antenna on a CFRP ground plane at 1 GHz is found in [13], but no detailed information of the material is given. [13] concludes that "The anisotropy effect of the composite material on the antenna patterns seems to be undetectable, at least within the system measuring accuracy." Monopole antennas for 2.45 GHz (ISM-band, WLAN, Bluetooth, etc.) and 5.9 GHz (intelligent transport systems, IEEE 802.11p) are mounted on two circular CFRP ground planes in [14]. It is found that the radiation patterns are not changed, but the CFRP ground plane results in an efficiency reduction of up to 23% relative to that achieved on an aluminium ground plane. In [15] a rectangular CFRP ground plane is measured, again no significant influence on the radiation pattern, but a 20% decrease in efficiency is found. Measurements of two IEEE 802.11p MIMO antennas in an automotive roof module on a CFRP car roof are discussed in [16]. A concealed antenna module manufactured as part of a CFRP sheet, is presented in [17]. [17] shows the feasibility to achieve near-omnidirectional radiation for Vehicle-to-Any communication (V2X) with antennas hidden inside CFRP cavities.

In this paper conical monopole antennas are measured on three different CFRP laminate ground planes: one from an industrial application, one with woven plies and a third composite consisting of unidirectional plies all oriented in the same direction. The rotationally symmetrical monopole antennas and ground planes reveal influences on the radiation characteristics of antennas due to material anisotropy of carbon fiber reinforced composites. This paper partially answers the question what a good CFRP for antenna ground planes is.



(a) industrial CFRP (b) twill CFRP

Fig. 1: Photographs of the twill and "industrial" CFRP with arbitrarily defined 0° directions.

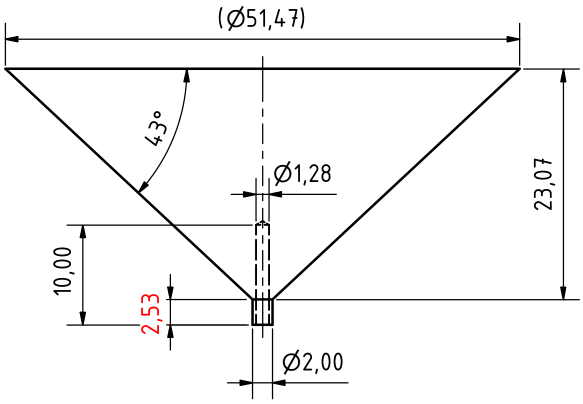


Fig. 2: Dimensions of the conical monopole antenna for the 1.6 mm thick CFRP ground plane. The length of the cylindrical extension on the bottom (red) is fit to the thickness of the ground plane. All dimensions in millimeter.

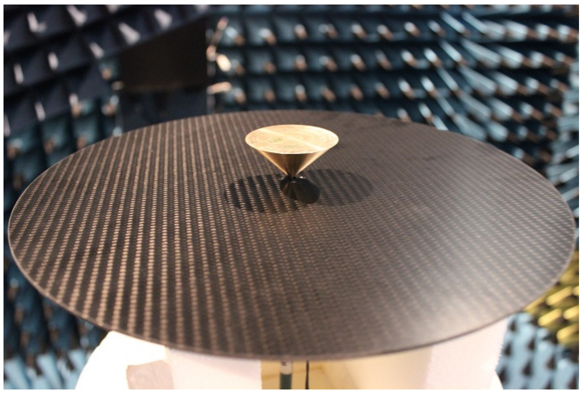


Fig. 3: Conical monopole antenna placed on twill weave CFRP ground plane. For measurements in the anechoic chamber it is placed atop a Rohacell pillar on the azimuth rotary stage.

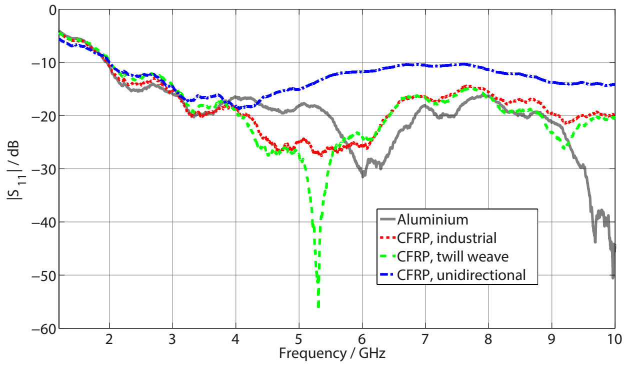


Fig. 4: Measured S-Parameters

II. CFRP Ground Planes

Three different CFRP are investigated in this paper. A CFRP made from unidirectional CFRP with fiber shreds on top is denoted as "industrial". The material is a 2.3 mm thick sample from the unpainted CFRP car roof used in [16]. Orientation $\varphi = 0°$ coincides with driving direction. The second CFRP is a 1.6 mm thick 2/2 twill weave stacked as $[0°/90°]$ from CG-TEC with a fiber volume fraction of 63% according to manufacturer. For the twill CFRP $\varphi = 0°$ was arbitrarily defined as depicted in Figure 1b. The third ground plane is a 4 mm thick sheet made from unidirectional (UD) carbon fiber plies all oriented 0°. For the unidirectional laminate $\varphi = 0°$ coincides with fiber direction. A 3 mm thick sheet of standard aluminium is used as reference material. Up to 10 GHz the fiber shreds on the industrial CFRP and the twill pattern are small compared to wavelength.

All ground planes were cut by waterjet to a diameter of 300 mm. For measurements coaxial cables are connected. The cables are attached to SMA flanges which are mounted in the center of the ground planes. The flanges are screwed to threaded holes in the ground planes. Drilling of CFRP with the wrong tools causes delamination, fraying and splintering [18]. Although threading of CFRP might not be industrially feasible, threaded metal inserts are avoided as they might influence antenna measurements. Note that while the metal flange of the SMA connector contacts the aluminium ground plane, this is not the case for CFRP as the conductive fibers are covered under epoxy.

III. Conical Monopole Antennas

For a characterization of the composites, the CFRP sheets are used as ground planes for conical monopole antennas. Conical monopole antennas are broadband antennas. They can be seen as a variant of biconical antennas, where one cone is mirrored on a conductive ground plane. A standard antenna design is used and parts are dimensioned according to [19]. Antenna dimensions are depicted in Figure 2. The antenna has a hole in the cylindrical extension on the bottom so that it can be tightly fit onto the inner conductor of the SMA connector, removing the need for soldering. For measurements this way of mounting the cone is common [20], of course in most applications the antennas need to be attached. The height of the cylindrical extensions is adjusted for each ground plane such that the tip of the cone is on the same level as the surface of the ground plane. For $[1.6\ 2.3\ 3\ 4]$ mm thick ground planes this leads to $[2.53\ 3.23\ 3.93\ 4.93]$ mm long cylindrical extensions. The cones were turned on a lathe from brass. A manufactured cone on the twill weave CFRP ground plane is depicted in Figure 3.

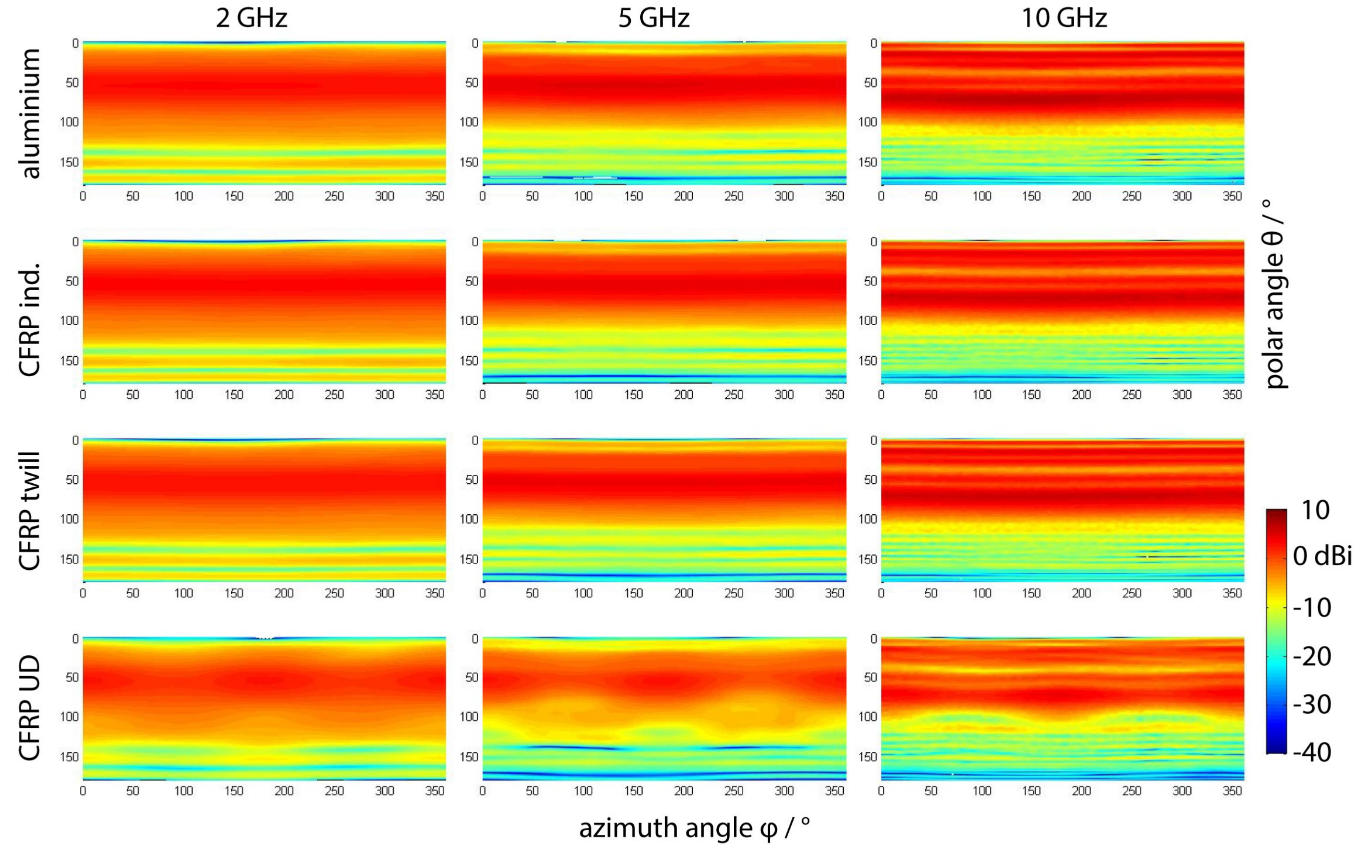
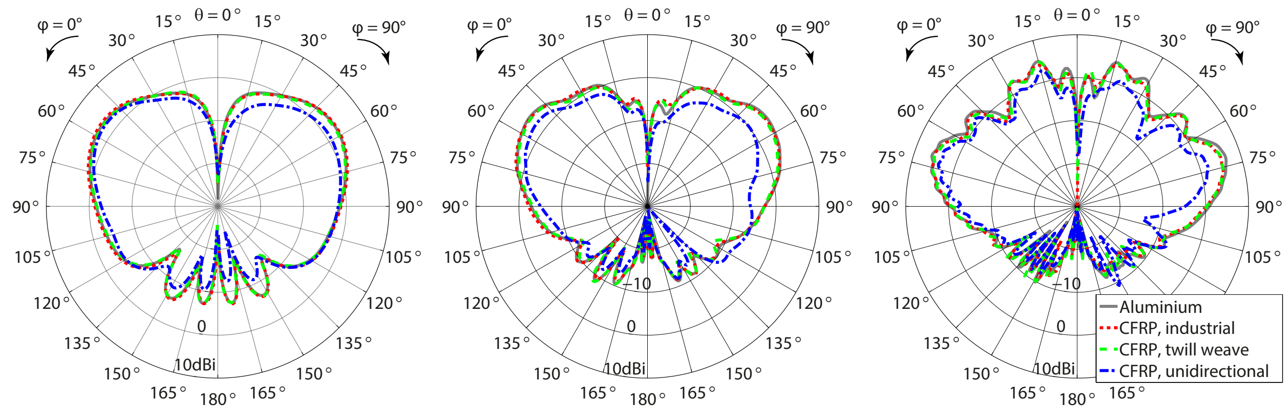


Fig. 5: Rectangular projections of the measured gain patterns at 2, 5 and 10 GHz on different ground plane materials. The patterns of the monopole antenna placed on the unidirectional CFRP significantly deviate from the isotropic aluminium ground plane, while the results on the other investigated CFRP are in good agreement with aluminium.



(a) 2 GHz (b) 5 GHz (c) 10 GHz

Fig. 6: Vertical cuts of the gain patterns. Cuts for azimuthal angle $\varphi = 0°$ and $\varphi = 90°$ are shown on the left and right side respectively.

IV. Measurement Results

Gain measurements were performed in the institutes' anechoic chamber. Antennas under test (AUT) were placed on a pedestal made from Rohacell (polymethacrylimide), a hard foam with air-like electromagnetic properties, on the azimuth angle φ rotary stage. Gain calibrations were performed with standard gain horns from NSI, leading to an absolute gain value accuracy of ± 0.5 dB according to manufacturer. Far-field results are obtained from a near-to-far-field transformation. This paper follows the IEEE definition of antenna gain obtained from accepted power. Gain values are calculated from

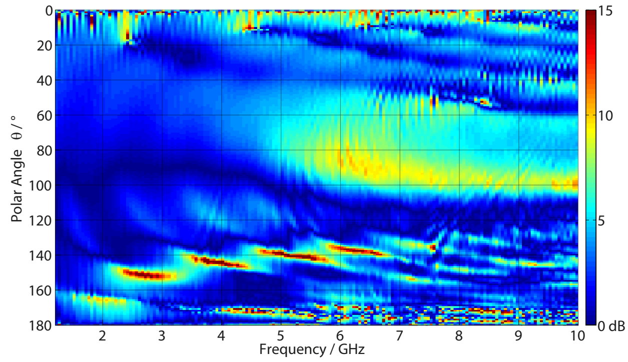


Fig. 7: Absolute difference between the vertical cuts of the gain patterns on aluminum and UD-CFRP for $\varphi = 90°$ (perpendicular to fiber direction) over frequency.

measurements of realized gain and separately measured S-parameters. For $f > 2\,\text{GHz}$ with $|S_{11}| < -10\,\text{dB}$ the factor $(1 - |S_{11}|^2)$ is close to 1, resulting in a maximum difference between gain and realized gain of $0.05\,\text{dB}$.

The S-Parameter measurements of the conical monopole antennas on the different ground plane materials are depicted in Figure 4. A return loss better than $10\,\text{dB}$ is achieved for frequencies larger $2\,\text{GHz}$ for all materials. The gain patterns of the conical monopole antennas on the four different ground plane materials for 2, 5 and $10\,\text{GHz}$ are displayed as rectangular projections in Figure 5. With increasing frequency the size of the ground plane relative to wavelength becomes larger, as expected this results in less radiation below the ground plane at higher frequencies. For an easier numerical comparison, vertical cuts of the patterns are shown in Figure 6. Cuts for $\varphi = 0°$ are shown on the left side of the plots, while $\varphi = 90°$ are shown on the right. In the investigated frequency range the industrial CFRP and the twill weave CFRP ground planes result in radiation patterns similar to that on aluminium. The patterns of aluminium, industrial and twill CFRP show only minor differences of about $1\,\text{dB}$. This is consistent with measurements at 2.45 and $5.9\,\text{GHz}$ in [14].

However, the gain pattern on the unidirectional CFRP deviates significantly. Distortions are largest perpendicular to fiber direction. For the UD-CFRP $\varphi = 0°$ coincides with fiber direction, $\varphi = 90°$ is perpendicular to fiber direction. In fiber direction the UD-CFRP causes a gain decrease of up to $3\,\text{dB}$ in the investigated frequency band $(1 - 10\,\text{GHz})$. As would be expected due to the decreased conductivity of UD-CFRP perpendicular to fiber direction, the gain reduction is larger perpendicular to fiber direction ($\varphi = 90°$). At $2\,\text{GHz}$ the reduction is about $2\,\text{dB}$ (Figure 6a), the gain gets further reduced with increasing frequency and around $6\,\text{GHz}$ the difference is as large as $10\,\text{dB}$.

To visualize the changes in gain pattern of the UD-CFRP further, in Figure 7 the absolute difference between the vertical cuts of the gain patterns on aluminium and UD-CFRP are drawn as a function of frequency. Several differences between the gain patterns on aluminium and UD-CFRP are apparent.

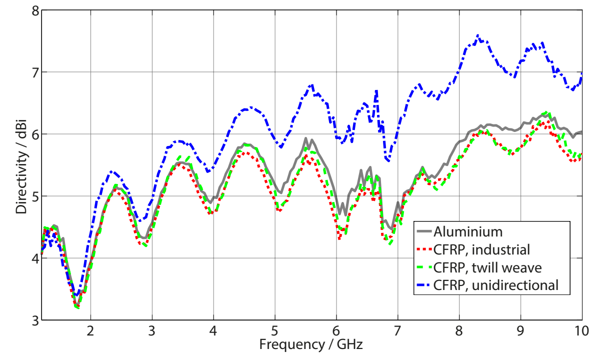


Fig. 8: Measured directivity

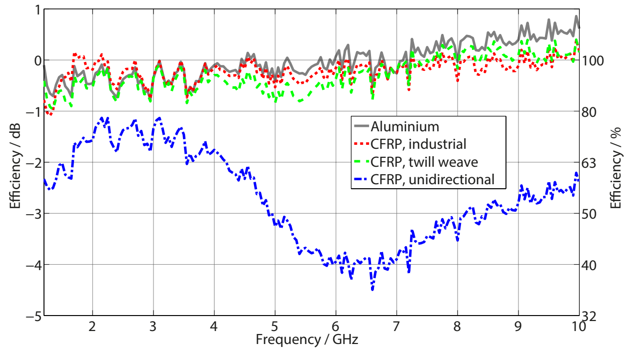


Fig. 9: Radiation efficiency, calculated from gain and directivity.

Deviations close to zenith ($\theta \approx 0°$) can be ignored as monopole antennas do not radiate towards zenith. Deviations close to nadir ($\theta \approx 180°$) are artifacts from the near-to-far-field transformation as the probe antenna can not be moved to angles $\theta > 160°$. Deviations in the back lobes around $\theta \approx 140°$ are typically of little interest as monopole antennas are used for their omnidirectional radiation pattern in the upper hemisphere. However, there are significant differences in the upper hemisphere across the whole investigated frequency band. At $6\,\text{GHz}$ the gain in the horizontal plane perpendicular to fiber direction is reduced by $10\,\text{dB}$. This is especially crucial as a frequency band for vehicle-to-vehicle communication in intelligent transport systems is located at $5.85 - 5.925\,\text{GHz}$.

As expected the derogation of the omnidirectional radiation pattern on the unidirectional CFRP ground plane results in a larger directivity, as can be seen in Figure 8. The radiation efficiency on the conical monopole antennas on the different ground plane materials is depicted in Figure 9. Efficiency is calculated from gain and directivity, both are subject to measurement inaccuracies. Relative values between the curves are more accurate, as all curves' absolute gain values are calibrated with the same reference horn antennas with $\pm 0.5\,\text{dB}$ variation. For radiation efficiency close to $100\,\%$ measurement inaccuracies might lead to values slightly above $100\,\%$. The efficiencies of the industrial and twill CFRP are close to that of aluminium. The efficiency on the UD-CFRP is decreased by 1 to $4.5\,\text{dB}$ compared to the efficiency on aluminium.

V. Conclusion

The choice of the CFRP ground plane has a tremendous influence on monopole antennas. From 2 to 10 GHz the gain of monopole antennas on CFRP laminate with unidirectional filament alignment decreases by up to 10 dB, while the gain on woven plies and fiber shreds is similar to aluminium. From an antenna perspective CFRP surfaces of planes, boats and cars can be used as ground plane in the GHz range, as long as a woven CFRP is used. The usage with antennas in mobile phones and laptop computers is also possible, in case the need for lightweight construction of electronic devices with CFRP arises. In many applications the CFRP laminate is designed to uphold the mechanical stability of a structure and can not be adopted to meet antenna requirements. However, due to the small skin depth of microwaves, it should be sufficient for antenna applications to form only the outer ply of a laminate from a material with properties favorable for antennas.

The influence of the ground plane material was measured with monopole antennas, as monopole antennas are used in a variety of applications where a large ground plane can be constructed or one is already present. It can be expected that the influence of CFRP ground planes on other ground plane antennas will be similar.

From a physical viewpoint unidirectional CFRP are more interesting, as the anisotropy of the material is more pronounced. Measurements of UD-CFRP show huge differences between conductivity in fiber direction and perpendicular to it [3], [4], [5] and indeed this anisotropy causes large changes in radiation patterns when UD-CFRP is used as ground plane material. However, the influence of the ground plane anisotropy on antennas is not visible for woven fabrics in the GHz-range. For simulations of antennas on woven CFRP, material properties obtained from measurements of UD-CFRP, do not adequately model the performance of the antenna. Measurements of the electromagnetic properties need to be repeated for CFRP laminates that are actually used in industry.

The result, that in the investigated frequency range woven CFRP is usable like a metallic antenna ground plane, is especially important, as many services for vehicles and electronic devices operate in this frequency range. Affected services include the Long Term Evolution of UMTS (LTE), Vehicle-to-Any communication (V2X) for Intelligent Transportation Systems (ITS), Global Navigation Satellite Systems (GNSS) such as Global Positioning System (GPS) or GLObal NAvigation Satellite System (GLONASS) and the Industrial, Scientific and Medical (ISM) bands at 2.45 GHz and 5.8 GHz with Bluetooth, Wi-Fi, etc.

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