EMI Shielding Effectiveness Study for Innovative Carbon Nanotube Materials in the 5G Frequency Region

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***Abstract*—It is crucial to extend the Electromagnetic Compatibility (EMC) studies to the new frequency regions where modern telecommunication systems operate, specifically those related to the fifth-generation technology standard for broadband cellular networks (5G). Electric Autonomous Vehicles (EAVs) are systems that feature 5G technology on board, for which it is essential to ensure the proper management of EMC to prevent malfunctions. Given the considerable development of the EAV-related sector, new materials and solutions for Electromagnetic Interferences (EMI) shielding with properties that reduce interference in the frequency regions of 5G technology are being investigated.**

Today, metal-based-on solutions are the most common EMI shielding materials used to mitigate EMC problems. Nevertheless, with the appearance of EAVs, it is needed the design of novel materials that provide a significant balance in terms of Shielding Effectiveness (SE) and mechanical properties. Thereby, Carbon Nanotubes (CNTs) are an attractive alternative to conventional EMI shielding materials due to their characteristics. The lightweight condition, flexibility, cost-effectiveness, easy processing, and resistance to corrosion made this new type of material perfect to be used in the field of EAVs. This contribution focuses on describing and characterizing three nanocomposite materials manufactured by loading a polymer matrix with 5%, 7%, and 10% CNT concentrations, respectively. The SE measurement is carried out with a Coaxial Sample Holder (CSH) based on the standard ASTM D4935-18. This measurement setup makes it possible to determine the performance of the three Materials Under Test (MUT) up to 18 GHz, covering part of the operation frequencies of 5G systems.

***Index Terms*— 5G technology, electromagnetic compatibility (EMC), electromagnetic interferences (EMI), shielding materials, carbon nanotubes (CNTs), ASTM D4935-18, shielding effectiveness (SE), coaxial sample holder (CSH).**

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I. Introduction

THE importance of EMI shielding relates to the high demand of today's society for the reliability of electronics and the rapid growth of the development of new telecommunications systems [1], [2] ,[3]. Nowadays, due to the ubiquitous presence of electronic circuits in all aspects of life, the study and modeling of EMC are more important than ever, especially in relation to extending these studies to the new frequencies.

The new 5G standard has a significant impact on the communication industry since a great variety of innovate technologies are derived from it. The main difference between 5G and previous generations is the operating frequency. The 5G spectrum is divided into two regions: FR1, also known as the sub-6 GHz frequency range and FR2, also called the millimeter-wave (mmWave) frequency range. Thereby, 5G technology faces the challenge of the environmental problems arising from the EM field generated by its antennas and how to prevent this from affecting other sensitive systems [4]. Therefore, one current challenge concerns the design of new EMI shields to promote the coexistence of 5G with other technologies.

One of the possible victim systems is the electric autonomous vehicle (EAV). The trend to develop a safe EAV is growing up, especially as the 5G network becomes more widespread worldwide. 5G, at least ten times faster than 4G, will improve communications between vehicles with innovative driving technologies [5]. Nevertheless, the massive number of electronic systems in new 5G operating vehicles will dramatically increase the demand for electromagnetic (EM) shielding materials with properties suitable to ensure low EMI in 5G radiation frequencies [6], as the use of devices for the attenuation of radiated emissions could affect car circuits, provoke interferences and resulting in traffic accidents [7].

EM shielding materials present the ability to obstruct and minimize the signal emitted through backward reflection of the field waves or by means of the absorption and dissipation of the radiation inside the material [8], [9]. Traditional metal shields can effectively attenuate EMI generated by 5G applications, but they have generally some drawbacks, such as lack of flexibility [8], bulkiness, weight, volume [10] or low corrosion resistance. Conductive polymer composites are a good alternative due to their properties, such as low density, good chemical stability, flexibility and easy-processing compared with metal-based materials [11]. This is why polymer-based materials are taking on a special relevance, showing a good performance when loaded with fillers that enhance their properties, such as carbon nanotubes (CNTs), thus eliminating the disadvantages of metal-based materials [11], [12].

In order to avoid the limitations of using metal shields in EAV systems and other applications with similar requirements on weight, significant scientific efforts have been devoted to study polymer-based EMI composite performance [13], [14], [15], [16], [17]. These alternative shields are generally based on polymeric materials loaded with additives in such a way as to enable them to absorb EM energy. The additives can be electrically conductive and/or can have dielectric/magnetic properties significantly different from those of the polymeric matrix.

Thereby, the incorporation of either conducting or ferromagnetic particles can modify the electrical conductivity/permeability of the composite to obtain an effective reflection/absorption shield. Depending on the nature of the filler, the material response to incident EM waves can be linked to a specific mechanism or to a combination of many [16]. Different types of additives such as metal flakes, silicon carbide, titanium dioxide, zinc oxide or talc particles have been reported in literature, showing the effect of their size, shape, concentration, electrical resistivity and dispersion degree in the host matrix on the EM properties. The investigation of lightweight EMI shielding materials will allow the possibility of increasing the safety of 5G communications in autonomous driving as well as improving the vehicle's consumption and autonomy [17].

Currently, there are many studies on the measurement and behavior of CNTs in which it is possible to see how the SE can vary depending on the frequency range and the selected material.

Several studies show measurements of about 13dB at 10wt% CNF loading [18]. Yang et al. [19] obtained a value of approximately 20 dB of MWCNT/PS (multi-walled carbon nanotubes/polystyrene) composites with a MWCNT loading of 7 wt%.

Other studies show the EMI SE of MWCNT/PP (multi-walled carbon nanotubes/polypropylene) composite as a function of MWCNT content and shielding plate thickness, where for a sample thickness of 1 mm and a MWCNT content of 5% and 7.5%, achieves an average SE value of 7.7 dB and 22.3 dB respectively. The latter shows an increase with frequency, reaching the value of 19.7 dB at a frequency of 10 GHz [20]. In another work from 2013, there is a comparison of MWCNT/portland cement (PC) composites as a function of the concentration of MWCNTs in the X-band. In it, an SE between 7-10 dB is achieved for a sample of 3 wt% and an SE greater than 27 dB is reported for a concentration of 15 wt% [21].

This contribution studies the shielding effectiveness (SE) provided by nanocomposites based on carbon nanotubes (CNTs), one of the most investigated additives in literature in the last few years. Thereby, the paper describes the manufacturing procedure used in order to obtain the best dispersion in the material under test (MUT) [22], [23], [24]. Moreover, how the CNTs concentration modifies the electrical conductivity of the MUT and how this is related to SE is also analyzed. In particular, the performance of three CNT samples with different particles concentration is investigated, considering a portion of the 5G frequency region (up to 18 GHz), including the FR1 and part of the FR2 spectrum. The measurement procedure consists on measuring the SE of the different planar material specimens with a coaxial sample holder (CSH) based on the standard ASTM D4935-18 [25], [26].

This manuscript is organized as follows. Firstly, Section II illustrates the selected shielding materials that are studied in this research. This section also describes the manufacturing process of the three samples. Section III defines the measurement setup used to determine the SE. Subsequently, the results obtained from the measurements are presented in Section IV. This section also analyses and discusses the performance of the three samples up to 18 GHz. Finally, the main conclusions of the research are summarized in Section V.

II. Shielding Materials characterization

The selected materials and their manufacturing procedure are described in this section. Carbon nanotube dispersion within the polymer matrix has a significant influence on the nanocomposite's final properties, including the electrical properties and the microwave susceptor capacity [27], [28]. Different processing parameters have been considered and which combination of them provides the best degree of dispersion in each sample. Finally, the electrical conductivity of the extruded samples is analyzed since higher electrical conductivity indicates a better ability to reduce interferences in the microwave frequency region [29], [30].

A. Definition of CNT Selected Materials

Graphene, graphite and carbon nanotubes are the main allotropic structures of carbon used for the absorption of electromagnetic radiation [31].

Carbon nanotube (CNT) is a unique form of carbon filament/fiber, conceivable as a two-dimensional hexagonal lattice of carbon atoms rolled up to form a tubular structure with diameter in the scale of nanometers. The introduction of CNTs into a polymeric matrix increases the electrical conductivity as well as the permittivity of the material [32], [33]. This, in turn, results in an increase in the number of conductive links and, thus, to an improvement of the shielding effectiveness.

Since their discovery [34], the exceptional mechanical, electrical, and thermal properties of CNTs [35], [36] have made them potential candidates for high-tech applications. These structures are divided into two groups: single-walled carbon nanotubes (SWCNT) with a diameter even less than 1 nanometer (nm) and multi-walled carbon nanotubes (MWCNT), consisting of nested SWCNT weakly bound together by van der Waals forces, having an external diameter increasing with the number of shells and even on the order of several tens of nanometers [30], [37], [38]. The latter type has been selected for the current study.

Notice that carbonaceous particles-based materials are excellent for absorbing electromagnetic radiation, and then converting that energy into thermal one. These materials can show high values of the imaginary part of complex permittivity (ε'') and, therefore, also high values of the loss tangent (tan δ). Carbonaceous particles absorb electromagnetic radiation due to the presence of delocalized π electrons, which can move freely [39], [40].

The samples manufactured for this research are based on polypropylene copolymer (coPP Moplen RP210G), properly selected due to its non-polar nature and microwave transparency. The CNT nanocomposites were prepared by melt mixing procedure using a co-rotative twin-screw extruder. The effectiveness of the heating process was tested by paying particular attention to the filler dispersion [29], [41], [42].

Table I lists the three different samples evaluated in this contribution.

TABLE I
LIST OF SAMPLES PRODUCED

Sample Code	Description
CNT5	Sheet of polymer matrix + 5% CNT
CNT7	Sheet of polymer matrix + 7% CNT
CNT10	Sheet of polymer matrix + 10% CNT

The intrinsic properties of the polymer nanocomposites depend directly on the number of microcapacitors and the polarization centers of the material.

An increase in CNT loading results in an increase in the relative permittivity and thus, in the number of these microcapacitors. In turn, the increase in CNTs increases the amount and mobility of charge carriers improving the electrical conductivity of the material, which is related to the improvement of the shielding effectiveness. Therefore, three samples with increasing CNT concentration have been chosen to observe how the amount of filler affects the SE [33], [43].

B. Sample manufacturing and processing parameters

The manufacturing procedure is based on microwave technology, a high-energy-efficient fabrication method for producing plastic materials. The use of CNT as processing additive has a double functionality as they act as mechanical reinforcement and electrically conductive fillers.

The nanocomposites were obtained in a co-rotative twin screw extruder COPERION W&P ZSK25 as is shown in Fig. 1. This extruder has a diameter of 25 mm and an L/D ratio of 40. Samples with different dispersion grades were produced by varying several processing parameters.

Carbon nanotube dispersion within the polymer matrix has a significant effect on the final properties of the nanocomposite. For this reason, it is essential to reduce the presence of agglomerates, which could decrease the performance of the final nanocomposite in terms of mechanical, electrical, and thermal properties. The dispersion of carbon nanotubes highly depends on the nature of the polymer matrix. In some polar polymers such as polycarbonate [44], polyvinyl alcohol [45], and polyamide [46] carbon nanotubes are easily dispersed. However, polyolefins are considered the less suitable matrices to disperse carbon nanotubes. Despite that, good properties can be achieved by optimizing the processing conditions.

All the samples are processed through the same technology, sheet extrusion and under the same conditions. Output parameters are differed due to the higher content of CNT, which increases the compound viscosity.

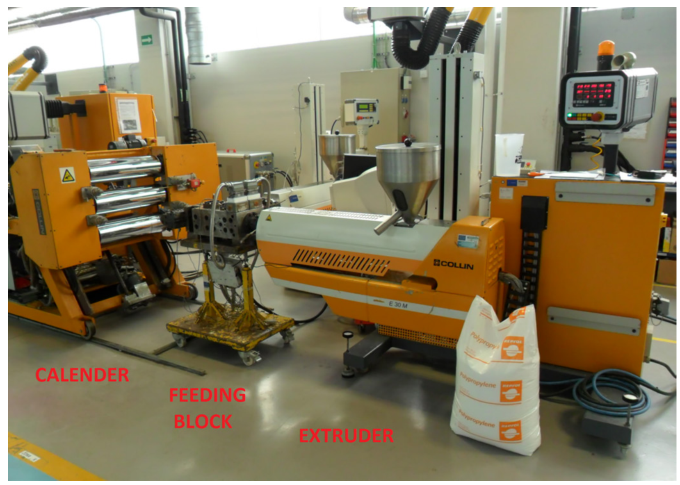

Fig. 1. Pilot plant cast-sheet co-extrusion line.

Table II summarizes the processing parameters of the extruder, optimized to maximize the degree of dispersion in the different CNT samples. The good quality of the resulting material based on CNT is observed in Fig. 2, where the sheet shows high homogeneity and a gleaming black piano surface.

TABLE II
PROCESSING PARAMETERS FOR CNT BASED FORMULATIONS

Sample code	CNT5	CNT7	CNT10
Melt T (ºC)	212	211	212
Pressure (bar)	72	82	100
rpm	85	90	90
Torque (N/m2)	4.9 – 25%	5.0 – 26%	5.3 – 26%
Drawing (%)	1.25	1.25	1.3
Die Gap (μm)	900	900	900
Rolls T (ºC)	80	80	80
Sheet thickness (μm)	900	950	950

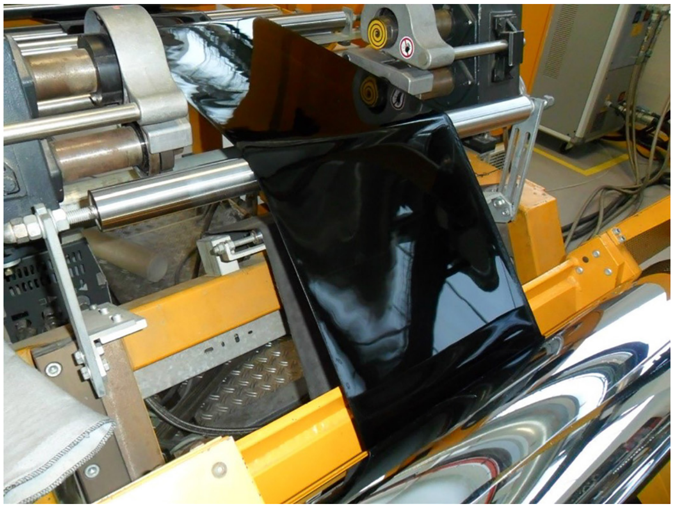

Fig. 2. Sheet production of coPP Moplen 210G + 7% CNT.

C. *Electrical conductivity of extruded sheets at pilot plant*

Nanocomposites characterized by a better filler dispersion generally exhibit more significant electrical properties than compounds in which MWCNT form bundles. The measurement of the dc electrical resistance is not only fundamental for evaluating the effect of the concentration of filler on the electrical properties of the material and therefore obtaining the percolation curve, but it is also useful for providing indications regarding the state of particle aggregation.

The manufactured sheets were cut to lower dimensions of 15 x 15 cm. The resistance between electrodes of all the sheets is studied in order to evaluate the relation between the electrical properties of the samples and their attenuation factor.

Tests on samples CNT5, CNT7 and CNT10 provided an electrical resistance of 540 Ω, 110 Ω and 20 Ω, respectively. Then, based on the standard ISO 3915, the resistivity (ρ) of the samples is calculated according to (1):

$$\rho = R\frac{b}{l} \quad (1)$$

where b is the width of the electrodes in centimeters and l is the distance between them. It follows that CNT5, CNT7 and CNT10 have a conductivity of 0.0018 S/sq, 0.009 S/sq and 0.05 S/sq, respectively.

III. SE MEASUREMENT SETUP

There are several methods to measure the SE of planar materials, among which are the shielded-room variations derived from the standard MIL-STD 285 [47] and de IEEE 299 [48], the coaxial transmission line based-on methods [49], [50], time-domain measurements [51], transverse electromagnetic (TEM), and dual TEM approaches [52], [53], [54]. Currently, all these methods have different limitations when it comes to the measurement of planar materials, especially in terms of frequency limitation, but one of the most widely used is that described by ASTM D4935-18 [25].

The measurement method employed in this study is based on the test method described in ASTM D4935-18 standard that defines a procedure for measuring the electromagnetic shielding effectiveness of a planar material for a plane, far-field EM wave. The frequency range limits are based on decreasing displacement current as a result of decreased capacitive coupling at lower frequencies and on excitation of modes other than the transverse electromagnetic mode (TEM) at higher frequencies for the size of the coaxial sample holder. This procedure applies to the measurement of SE of planar materials under normal incidence, far-field, plane-wave conditions, considering E and H tangential to the surface of the material. Therefore, according to the ASTM D4935-18 standard the measurement setup described in this contribution makes it possible to determine the net SE caused by reflection and absorption.

The method consists of measuring the insertion loss (IL) that results when introducing test samples in a coaxial two-conductor transmission line holder, supporting transverse electromagnetic (TEM) propagation mode. Test methods based on the use of coaxial TEM cells for evaluating the SE of a material are based on the mathematical equivalence between the ideal case of an infinite planar shield placed in free space and illuminated orthogonally by a plane wave, and the case of a material sample inserted in a transmission line [55].

The test fixture of the ASTM D4935-18 consists of a two-port flanged coaxial sample holder (CSH) with a characteristic impedance of 50 Ω. Notice that the major limit of the standard's CSH concerns its operating frequency range, as the method allows the characterization of planar samples in a narrow band from 30 MHz to 1.5 GHz. The frequency limits are based on the decrease in current displacement due to capacitive coupling at very low frequencies and overmodulation at higher frequencies where the wavelength becomes comparable to the sample size [25].

Smaller and modified versions of the CSH based on the measurement procedure described in ASTM D4935-18 have been manufactured and described in [56], [26] to extend the measurements up to 18 GHz. Therefore, the coaxial sample holder of [26] has been used to evaluate the performance of the materials sample of Table I in part of the frequency region employed by 5G technologies.

The two halves of the CSH have been connected through coaxial cables to the two-ports of a vector network analyzer (VNA) for the measurement of the scattering parameters (Fig. 3(a)). The used VNA (Anritsu VectorStar MS4647A, [57]) allows tests from 10 MHz up to 70 GHz with a dynamic range between 85 dB and 100 dB (depending on the frequency), but sufficient to measure the SE of the MUTs.

The sample holder is a coaxial probe with a characteristic impedance of 50 Ω. The diameter of the central conductor is 3 mm. The outer conductor has an inner diameter of 7 mm and an outer diameter of 15 mm, where it goes into contact with the MUT. The total contact area between the sample and the external conductor is only 138.23 mm^2.

The two cell sections are inserted into PVC supporting rings. To tighten the two halves together, either dielectric or metal screws can be used because being not electrically in contact with the cell's outer conductor [26].

The test requires two specimens of the same material and thickness, the reference and the load. In particular, the load specimen has a disk-like shape with a diameter equal to that of the outer CSH flange; the reference specimen has two parts: a washer and a disks-shaped sample, matching the dimensions of the outer and inner conductors, respectively. Their dimensions are reported in Fig.3(b). The use of two different specimens is justified because the reference one can partially compensate the effects of capacitive coupling by establishing a frequency-dependent reference level [15], [58].

The difference between the measurements of the load and the reference specimen provides the SE, caused by the reflection and absorption of the material sandwiched between the two flanges of the coaxial cell (Fig.3(c)). Hence, the SE in decibels can be expressed as:

$$SE = 20log_{10}\left|\frac{S_{21,R}}{S_{21,L}}\right| \quad (2)$$

where $S_{21,R}$ and $S_{21,L}$ are the measured transmission scattering parameter of the reference and load specimen respectively.

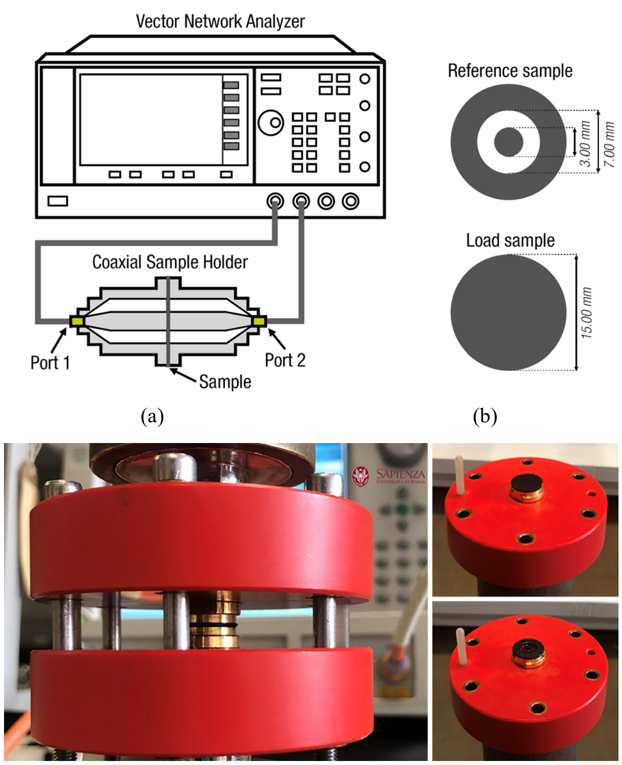

Fig. 3. Measurement procedure with the high-frequency CSH. (a) Sketch of the measurement test setup based on the ASTM D4935-18 procedure. (b) Shape and size of samples required for the SE measurement with the high-frequency CSH. (c) CSH with the MUT (load and reference specimens) for the SE measurements up to 18 GHz [26].

IV. Results and Discussion

This section is focused on showing the results and comparison of the SE measurements carried out for the three CNT-based samples having different filler percentage compositions.

The sample manufacturing process can result in samples with different dispersion grades and homogeneities. Several samples have been taken from the same sheet to check how the dispersion grade affects the SE. In this way, is possible to verify that the dispersion of the material is good if the traces are like each other. Note that it has not been possible to take the same number of samples from all of the sheets, given the complexity of the mechanization to prepare the samples with the required dimensions when the CNT loading is increased.

Firstly, Fig. 4 shows the SE provided by the CNT5 samples. It is observed that the traces are very close, indicating the good homogeneity of the composite and the reliability of the measurement system. The mean value obtained from the measurement of the CNT5 samples is 8.32 dB. At the frequency of 10 GHz, assumed from now on as a reference frequency, we have a SE value of 8.75 dB.

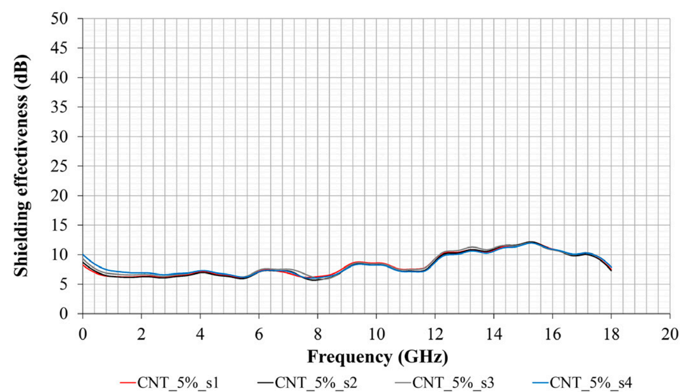

Fig. 4. SE results for different samples of the 5% CNT material under test.

Fig. 5 shows the results obtained by measuring three samples of the CNT7. As it can be observed, the responses of the different samples of this material are in good agreement with respect to each other. The most appreciable difference of about 6 dB can be observed in the low-frequency region. Above 8.50 GHz, the difference is negligible. In this case, the mean value is 19.29 dB; at the reference frequency of 10 GHz the SE value is 20.82 dB.

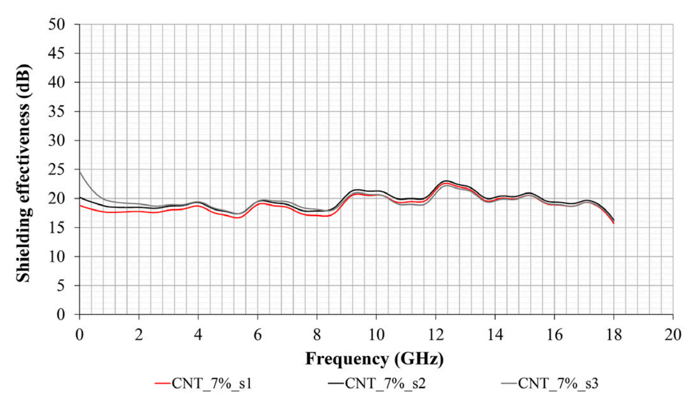

Fig. 5. SE results for different samples of the 7% CNT material under test.

Fig. 6 shows the CNT10 samples' shielding effectiveness results. Two samples are measured: the two traces are significantly coincident and do not present considerable variations throughout the entire frequency range. The most notorious difference is appreciated at the minimum frequency of 30 MHz, where the two traces differ by approximately 2 dB. The mean value obtained from the measurement of the CNT10 samples is 23.98 dB. A SE value of 25.60 dB is obtained at 10 GHz.

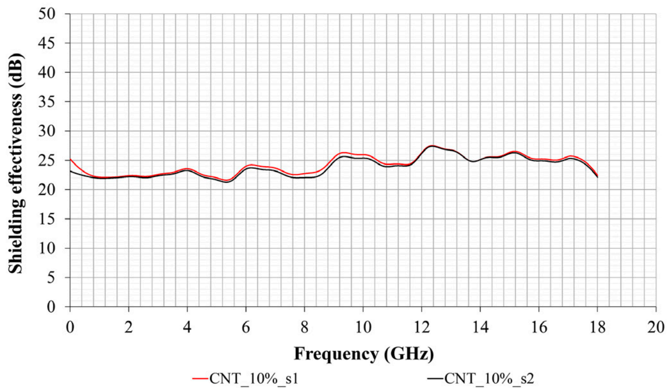

Fig. 6. SE results for different samples of the 10% CNT material under test.

Fig. 7 shows the average curves, calculated using the different samples' response, for each CNT concentration. It can be clearly observed that as the CNT loading increases also the SE provided by the material increases. Moreover, excluding the low frequency data (i.e., up to a few hundreds of MHz) where generally, as known in the literature, the reference sample is not able to perfectly correct the measurement, and those close to the cut-off frequency of the guide, the general trend of the curves shows that the SE increases with increasing frequency due to absorption phenomena. The mean value obtained for the CNT5 trace corresponds to 7.95 dB and the difference between the global extrema (the maximum and minimum values of the curve in the considered frequency range) is 5.99 dB. For CNT7 sample the mean value is 19.21 dB and 5.63 dB is the maximum SE variation, lower than the one obtained for CNT5 sample. The mean for the CNT10 sample is 23.88 dB, with a variation of 6.16 dB between the global extrema.

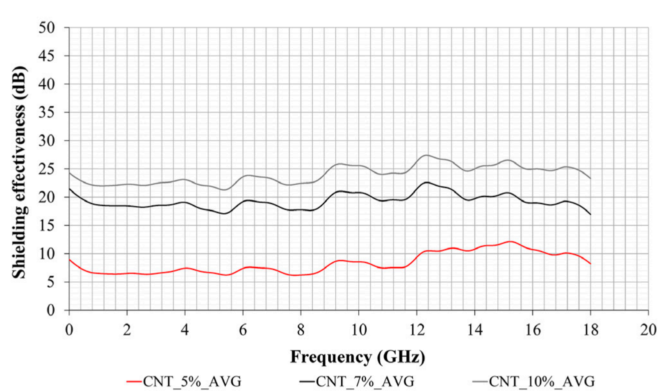

Fig. 7. Averaged SE results for CNT samples with the three different concentrations.

The difference in CNT concentration between the CNT5 and CNT7 nanocomposite samples, which is 2%, results in an average SE increase of 11.26 dB. Instead, although the difference in concentration between the CNT7 and CNT10 samples is more significant (3% of CNT), the difference in SE is only 4.67 dB. This means, as expected that the SE does not increase linearly with the increase in concentration of CNTs. Nevertheless, it is confirmed that with a higher filler loading (CNT10), the electrical conductivity is improved and, therefore, the shielding effectiveness of the material increases.

Martínez et al. [4] compared in the frequency range of 300 kHz – 8 GHz several samples of a carbon fiber (CF) reinforced composite, changing the type of the inner layer of the material. In particular, the comparison between a sample with a multi-walled carbon nanotube (MWCNT) based layer and a sample with a copper mesh layer is performed and the effects on the SE is analyzed. The samples were measured according to the ASTM D4935-18 standard. The results show that in the lower frequency range (up to 3 GHz), the MWCNT-based sample shows a better performance, resulting in a higher attenuation than that provided by the material with the copper mesh. At the frequency of 8 GHz, the latter sample provides an attenuation of 46.53 dB, whereas the one with MWCNT fillers shows a value of 55.55 dB. In the intermediate frequency range, the responses are very similar, and the values are comparable. Those results suggest that MWCNTs are a good alternative to copper in EM shielding applications. In this contribution, for the CNT10 sample it is obtained an SE of 22.44 dB at 8 GHz. Notice that, since in this paper only the CNT-based load has been characterized, and not the final CF reinforced material, which alone, without the contribution of nanocomposite layer provides a significant attenuation, the result here obtained can be considered important and significant for many applications in the field of shielding.

The values obtained in other previous studies on the EM behavior of CNT-based materials are very different because the manufacturing process, and then, the obtained properties of the samples, have a significant influence on the final SE measurement. For example, it has been demonstrated that for a final MWCNT/PS composite sample loaded with 7wt% of MWCNT, a SE of 20 dB @ 10 GHz is obtained [21], whereas for a MWCNT/PP material with a concentration of 7.5wt% of MWCNTs the SE is 22.3 dB at the same frequency [22]. Comparing those values with the mean SE of 23.98 dB @ 10 GHz measured in this study for the CNT10 sample, it confirms that the obtained results present a considerable EM attenuation for the coPP + 10% CNT material. This improvement demonstrates that the manufacturing process employed allows to increase the amount of CNT in the final material while providing a good dispersion.

V. Conclusions

The performance of three nanocomposites based on the dispersion of nanotubes within a polymer matrix has been analyzed in terms of EMI shielding effectiveness. The characterization has been carried out covering the frequency range up to 18 GHz with the aim of investigating the behavior of this kind of materials to reduce EMI in systems sensitive to 5G technologies. The materials studied have been manufactured by introducing three different concentrations of CNTs in order to evaluate their performance by using a measurement setup based on the ASTM D4935-18.

It has been concluded that the amount of carbon nanotubes dispersed significantly influences the effective electrical conductivity of the composite, and consequently the SE of the material. If the electrical conductivity results are compared with the results obtained in terms of SE, it is possible to observe that higher electrical conductivity results in higher attenuation. In particular, the CNT7 and CNT10 nanocomposites have demonstrated to provide a significant SE in a wide frequency range. Nevertheless, there is no proportional relationship between the increase of the concentration of CNTs and the electrical conductivity, and then the mean value of SE.

It was also shown that, given the values obtained from previous studies on the measurement of SE of CNT-based composites, significant SE results were obtained in this study, which makes these materials a suitable alternative to conventional solutions for the 5G frequency region in the EMC field.

Consequently, it should be noted that these types of characterizations are very relevant from a technological and industrial point of view. EMI shielding based on innovative nanocomposite materials has many advantages for automotive and related sectors, such as the manufacturing cost and weight reduction compared to traditional shielding.

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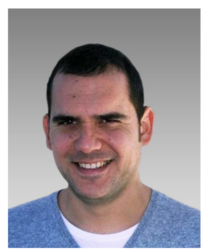

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