Proceedings Paper:
Parker, Sarah L, Flintoft, Ian D orcid.org/0000-0003-3153-8447, Marvin, Andy C orcid.org/0000-0003-2590-5335 et al. (6 more authors) (2016) Predicting Shielding Effectiveness of Populated Enclosures Using Absorption Cross Section of PCBs. In: Electromagnetic Compatibility (EMC EUROPE), 2016 International Symposium on. EMC Europe 2016, 05-09 Sep 2016 , POL , pp. 324-328.

https://doi.org/10.1109/EMCEurope.2016.7739305

Predicting Shielding Effectiveness of Populated Enclosures Using Absorption Cross Section of PCBs

S. L. Parker[1], I. D. Flintoft[1], A. C. Marvin[1], J. F. Dawson[1], S. J. Bale[1], M. P. Robinson[1], Ming Ye[2], Changyong Wan[3] and Mengze Zhang[3]

[1]*Department of Electronics, University of York, Heslington, York YO10 5DD, UK*
[2]*Research and Development Center, Huawei Technologies AB, Kista, Sweden*
[3]*Huawei Industrial Base, Huawei Technologies Co. Ltd, Shenzhen, P. R. China*

Published in the Proceedings of the International Symposium and Exhibition on Electromagnetic Compatibility, EMC Europe 2016, Wroclaw, Poland, pp. 324-328, 5-9 September 2016.

Accepted for publication: 21/04/2016

DOI: 10.1109/EMCEurope.2016.7739305

Predicting Shielding Effectiveness of Populated Enclosures Using Absorption Cross Section of PCBs

S. L. Parker, I. D. Flintoft,
A. C. Marvin, J. F. Dawson,
S. J. Bale, M. P. Robinson
Department of Electronics
University of York
York, UK
slp504@york.ac.uk

Ming Ye
Research and Development Center
Huawei Technologies AB
Kista, Sweden
ming.ye@huawei.com

Changyong Wan, Mengze Zhang
Huawei Industrial Base
Huawei Technologies Co. Ltd
Shenzhen, P. R. China
wanchangyong@huawei.com

***Abstract*—Shielding effectiveness (SE) is an important measure of how well an enclosure reduces the electromagnetic (EM) field incident upon it. Commonly, when the shielding effectiveness of an enclosure is stated it is for the case when the enclosure is empty. Including contents such as printed circuit boards (PCBs) in the enclosure will affect the shielding effectiveness as the PCB absorbs EM energy. One technique of determining how much energy a PCB absorbs is to measure its absorption cross section (ACS) using a reverberation chamber (RC). The measured ACS can be used to predict the shielding effectiveness of an enclosure when the PCB is inside it using power balance techniques. In this paper the ACS of a number of PCBs are measured both individually and in closely stacked groups. This information is then used to show how the ACS can be used to calculate shielding effectiveness and the results are compared to direct measurement of the SE of the enclosure containing a PCB. Knowledge of the ACS of typical or particular PCBs could be used by engineers to estimate the real shielding effectiveness of an enclosure with contents, when designing electronic systems.**

Keywords—Absorption cross section, printed circuit boards, enclosure shielding, reverberation chamber

I. Introduction

Shielding effectiveness measures an enclosures ability to reduce an electromagnetic (EM) field incident upon it. Commonly, the shielding effectiveness of an enclosure is given without including any contents, such as printed circuit boards (PCBs), in it. However, the contents in an enclosure will affect the shielding effectiveness as they will absorb some of the energy inside the enclosure [1]. This will reduce the internal EM field inside the enclosure thus increasing the shielding effectiveness. Average absorption cross section (ACS) is a measure of the energy absorbed by objects and was described by Carlberg [2]. This method has been previously used to measure the ACS of PCBs in a reverberation chamber (RC) [3]. Power balance techniques can be used to estimate the shielding effectiveness of a populated enclosure using the ACS of the objects [4].

Section II presents the shielding effectiveness and ACS calculations and theory used in this paper and shows how to predict shielding effectiveness of a populated enclosure using ACS. Section III describes the enclosure and PCBs used for this work and Section IV details the ACS measurement of the PCBs. Section V describes the shielding effectiveness measurement of an enclosure with and without a PCB inside it and shows how much the PCB affects the shielding effectiveness. Section VI compares measuring the shielding effectiveness of an enclosure with a PCB inside it to predicting it using the ACS of a PCB. Section VII is the conclusion.

II. Shielding Effectiveness and Absorption Cross Section

A. Shielding Effectiveness

One definition of enclosure "shielding effectiveness" for measurements made in a reverberation chamber is the ratio of the average power density outside the enclosure, $\langle S_{REF}\rangle$, to the average power density inside the enclosure, $\langle S_{ENC}\rangle$. It can most easily be determined by measuring the average power transmission between a transmitting antenna in the RC and both a reference antenna in the chamber outside the enclosure, $\langle |S_{21,REF}|^2\rangle$, and another antenna (identical to the reference antenna) located inside the enclosure, $\langle |S_{21,ENC}|^2\rangle$. The shielding effectiveness is then given by [7]:

$$SE = \frac{\langle S_{REF}\rangle}{\langle S_{ENC}\rangle} = \frac{\langle |S_{21,REF}|^2\rangle}{\langle |S_{21,ENC}|^2\rangle} \quad (1)$$

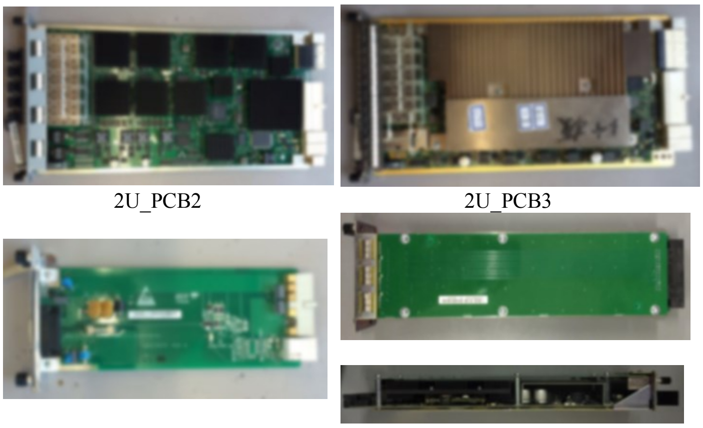
The scattering parameters are averaged over a number of stirrer positions and a range of frequencies to obtain an accurate average power density. Throughout this paper the brackets <…> indicate averaging over stirrer positions and over frequency.

B. Absorption Cross Section

Average ACS of an object as measured in a reverberation chamber, $\langle\sigma_a\rangle$, is defined as the ratio of the average power absorbed to the average power density of the incident field [2] and is given as:

$$\langle\sigma_a\rangle = \frac{\lambda^2}{8\pi}\left(\frac{1}{G_{wo}} - \frac{1}{G_{no}}\right) \quad (2)$$

where λ is wavelength, G_{wo} is the mean net power transfer function with the object in the reverberation chamber and G_{no}



2U_PCB2 2U_PCB3

6U_PCB12 2U_PCB9 from the top and side showing how it is a two PCB stack

Fig. 1. Photographs of one of each type of PCB (blurred to preserve design confidentiality).

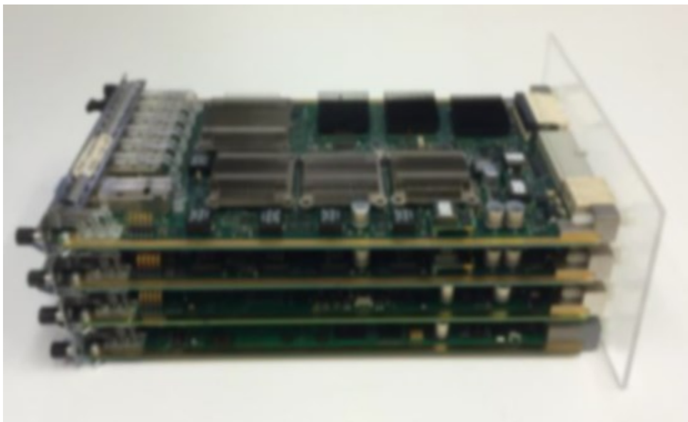


Fig. 2. Photograph of all four PCBs stacked together with the plastic backplane (blurred to preserve design confidentiality).

is the mean net power transfer function without the object in the chamber. The mean net power transfer function is given by

$$G = \frac{\langle |S_{21}|^2 \rangle}{(1-|\langle S_{11}\rangle|^2)(1-|\langle S_{22}\rangle|^2)} \quad (3)$$

where S_{21} is the transmission coefficient measured between two efficient antennas in the reverberation chamber and S_{11} and S_{22} are the reflection coefficients of the two antennas. [5] and [6] present methods to calculate the measurement uncertainty of ACS measurements in a reverberation chamber.

C. Prediction of Shielding Effectiveness using ACS

Flintoft et al [3] have previously described how to use the shielding effectiveness of an empty enclosure and ACS of a PCB to predict the shielding effectiveness of the enclosure with the PCB inside and shown that:

$$\langle SE_{populated} \rangle = \langle SE_{empty} \rangle + \frac{\langle \sigma_{PCB} \rangle}{\langle \sigma_t \rangle} \quad (4)$$

where <SE> is the shielding effectiveness of the populated or empty enclosure, calculated using (1), $<\sigma_{PCB}>$ is the ACS of the PCB, calculated using (2), and $<\sigma_t>$ is the total average transmission cross section of all the apertures allowing energy into the enclosure. A full explanation of the derivation of this

TABLE I. PCBs UNDER TEST

PCB Name	Dimensions	Notes
2U_PCB2, 2U_PCB5, 2U_PCB6, 2U_PCB7, 2U_PCB8	283 mm × 145 mm	High component density, low surface shielding amount
2U_PCB3	283 mm × 145 mm	High component density, high surface shielding amount
2U_PCB9	283 mm × 75 mm	Low component density, higher surface shielding, two PCB stack
6U_PCB12	210 mm × 85 mm	Low component density, lower surface shielding

equation and how to calculate $<\sigma_t>$ can be found in [3]. The high frequency geometric optics average transmission cross section is used, where $<\sigma_t>$ is a quarter of the area of the aperture [7].

III. ENCLOSURE AND PRINTED CIRCUIT BOARDS UNDER TEST

A. Enclosure Under Test

The enclosure used during these tests is shown in Fig. 4 inside the reverberation chamber. It was constructed from brass and had dimensions of 0.6 m × 0.5 m × 0.3 m. The enclosure had a rectangular aperture of 140 mm × 40 mm place centrally on the front (0.6 m × 0.3 m) face and a bulkhead connector on its top side attached to a 20 mm high monopole antenna in the roof of the enclosure 180 mm from the front face and 220 mm from the right side. The transmission cross section, $<\sigma_t>$, of the 140 mm × 40 mm aperture is 0.0014 m^2 using the approximation stated in Section IIc. The aperture cut off is approximately 1GHz so this approximation is valid for the frequency range presented here.

B. Printed Circuit Boards Under Test

The ACS of a selection of PCBs has been measured. The PCBs were taken from an ICT cabinet and are listed, grouped by type, in Table 1. One of each type of PCB is shown in Fig. 1. The PCBs had a range of components on them including heat sinks, integrated circuits, passive components and connectors. After measuring the ACS of the individual PCBs a number of measurements were also made with the PCBs in various different stacked positions. The configurations used were: two stacked PCBs together; three stacked together; and four stacked together. A plastic backplane was used to hold the PCBs together as they would be when installed in their enclosure. The spacing between the PCBs was 20 mm. A photo of all four PCBs stacked together is shown in Fig. 2.

IV. ABSORPTION CROSS SECTION MEASUREMENT OF PRINTED CIRCUIT BOARDS

The ACS of the PCBs were measured using the set up shown in Fig. 3 and the methodology is the same which has been previously described in [2] and [3]. The measurement was made inside a reverberation chamber with dimensions 0.6 m × 0.7 m × 0.8 m. A mechanical stirrer was used inside the chamber with 100 equally stepped positions and frequency stirring with a bandwidth of 50 MHz applied. A VNA was used to measure the S parameters between two monopole antennas

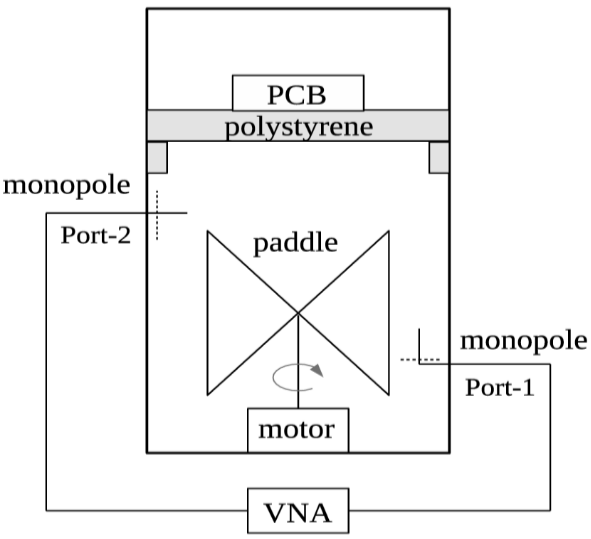


Fig. 3. Diagram of the ACS measurement set up.

from 2 GHz to 20 GHz using 10,001 measurement points and a sweep time of 4.5 seconds. A sheet of polystyrene was used to support the PCB under test in the working volume of the chamber. The ACS was calculated using (2) and (3) and requires two sets of measurements; one with the PCB in the chamber and a reference measurement without the PCB in the chamber.

Fig. 4 shows the measured ACS of the individual PCBs. For most PCBs the ACS ranges from 10^{-2} m^2 to 2×10^{-2} m^2. 6U_PCB12 is a much smaller PCB and so has a smaller ACS of between 3×10^{-2} m^2 to below $4\times10-4$ m^2. It also has a greater variation in ACS with frequency which could be due to its smaller size. The results show that the type of PCB, its components and dimensions greatly affect the ACS. The PCBs that have little shielding and those with a high component density have the highest ACSs. 2U_PCB3 has more shielding on its surface and has a slightly lower ACS than the other PCBs of the same size. The smallest PCBs have the lowest ACSs.

The ACS of the stacked PCBs is shown in Fig. 5. As expected the greater the number of PCBs in the stack the greater the ACS. When four PCBs are stacked together the ACS is between 10^{-2} m^2 and 2×10^{-2} m^2 and this reduces to between 3×10^{-3} m^2 and 1×10^{-2} m^2 when two PCBs are stacked together.

Fig. 6 shows the ACS of three individual PCBs, the ACS of these three PCBs summed together and the measured ACS of the three PCBs stacked together. There is a difference of approximately 5×10^{-3} m^2 (a reduction of roughly 20 %) between the summed and measured cases. This shows a 'shadowing' effect which reduces the expected ACS of stacked PCBs. The greater the number of stacked PCBs the more the ACS is reduced. For two PCBs 50% of its PCBs are shadowed for four PCBs stacked together it is 75%. These stacked results show that careful thought is needed when including the ACS of PCBs in a densely populated enclosure as 'shadowing' effects may also need to be included in any calculation.

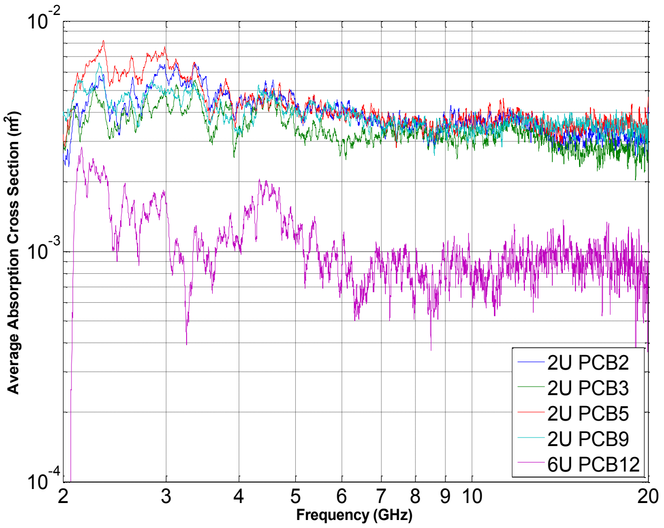


Fig. 4. Measured ACS of the individual PCBs under test.

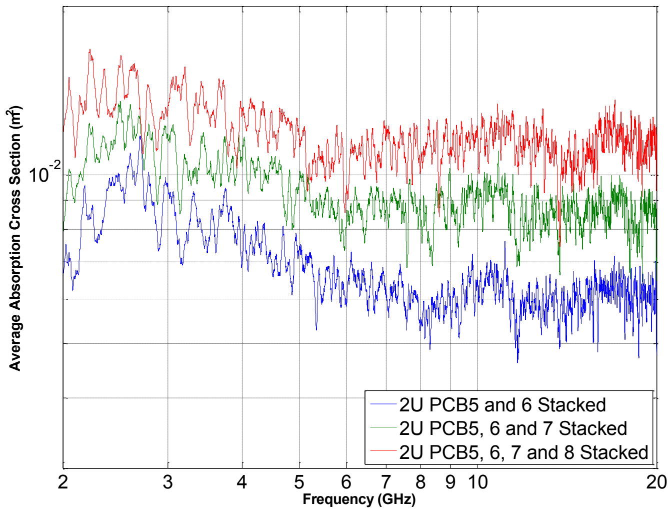


Fig. 5. Measured ACS of PCBs stacked in three different configurations.

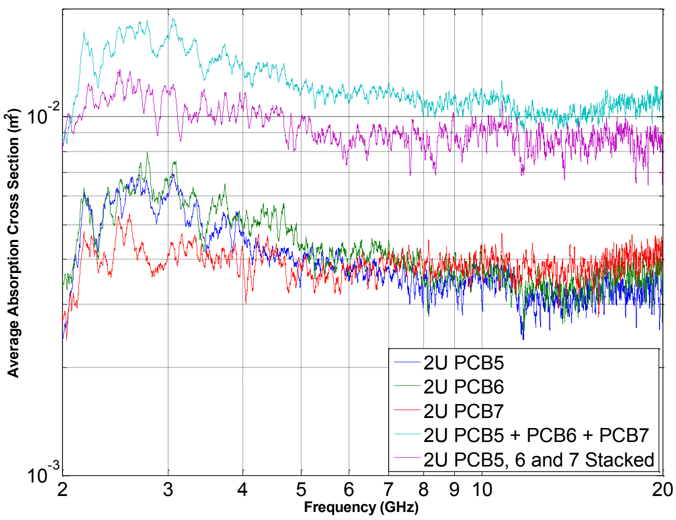


Fig. 6. Measured ACS of three stacked PCBs showing ACS of each individual PCB, the summation of these and the measured ACS of all PCBs when stacked together.

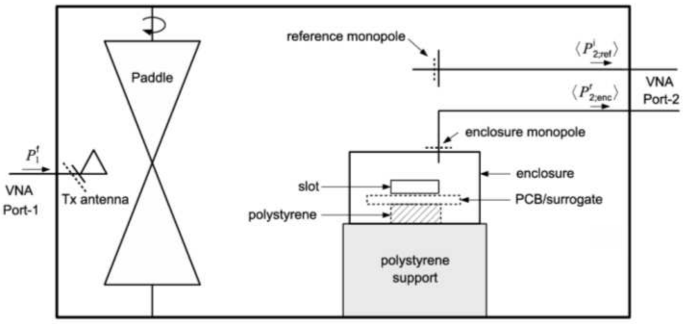


Fig. 7. Shielding effectiveness measurement set up.

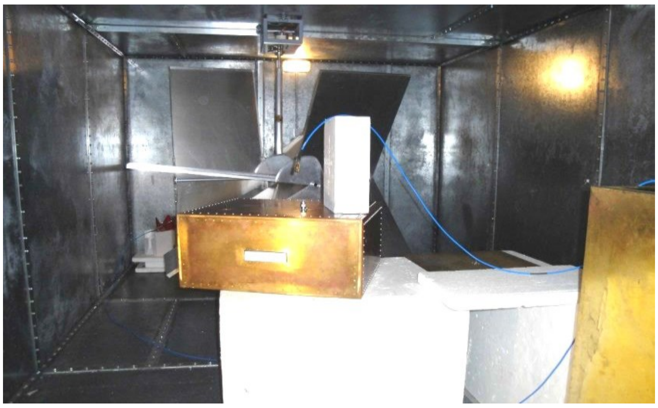


Fig. 8. Photograph of the shielding effectiveness measurement showing the brass enclosure in the centre and the reverberation chamber stirrer in the background.

V. Shielding Effectiveness of an Enclosure

The measurement of the shielding effectiveness for the brass enclosure described in Section III was carried out using the measurement set up shown in Fig. 7 and Fig. 8. The measurement was made in a reverberation chamber using a mechanical stirrer using 100 equally stepped positions over one rotation. Although no mechanical stirrer was used inside the enclosure under test, frequency stirring with a bandwidth of 100 MHz was applied to the data. The scattering parameters between a horn antenna outside the enclosure (port 1) and a monopole antenna inside the enclosure, or a reference monopole outside the enclosure (port 2) were measured using a vector network analyser (VNA) from 2 GHz to 20 GHz using 10,001 measurement points and a sweep time of 2.7 s. The shielding effectiveness was then calculated using (1). The measurement was carried out with and without the PCB inside the chamber. The PCB used was 2U_PCB5 as described in Table I and when measuring the shielding effectiveness with the PCB it was placed on a polystyrene block so that the board was component side up and centred horizontally in the enclosure.

The shielding effectiveness of the enclosure measured with and without the PCB inside is shown in Fig. 9. It is clear that including the PCB in the enclosure increases the shielding effectiveness. This is less obvious below approximately 4 GHz. Above 4 GHz the empty enclosure has a shielding effectiveness of between 1 dB and 4 dB and the enclosure with the PCB in has a shielding effectiveness of between 5 dB and

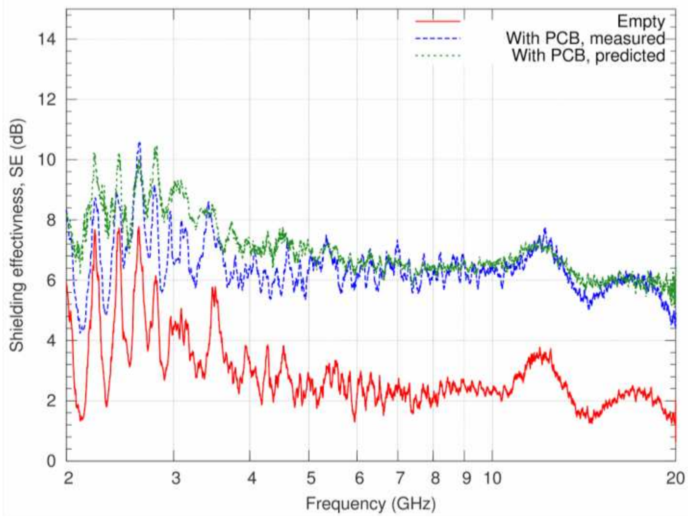


Fig. 9. Measured SE of the empty enclosure and the enclosure with a PCB in it and calculated shielding effectiveness using the ACS of the PCB.

8 dB. The shielding effectiveness of the enclosure with and without the PCB shows a difference of over 4 dB in some places. In both cases there are similar features in the results.

VI. Shielding Effectiveness Including Printed Circuit Boards in the Enclosure

This section compares the measured shielding ratio of an enclosure containing a PCB to the shielding effectiveness computed from the empty enclosure measurement and the measured ACS of a PCB. For this work only one PCB (2U PCB5) was used.

Fig. 9 shows the shielding effectiveness of the empty enclosure with no PCB inside, the measured shielding effectiveness with the PCB inside the enclosure and the predicted shielding effectiveness using the ACS of the PCB. The results show good agreement with the measured and calculated shielding effectiveness and the RMS error between the measured and predicted values is 0.77. Below 4 GHz the agreement is not as good as above this frequency. This is probably due to the limited number of modes inside the enclosure in this frequency range, compounded by the fact that there is no mode-stirring inside the enclosure. The Schroeder frequency of the enclosure, at which the mode bandwidth to mode spacing ratio is three, is about 4 GHz for the enclosure used and it is noted that this appears to correspond to the frequency at which the frequency stirring becomes effective at averaging out the mode structure. The results show that using the ACS of a PCB is a helpful method for estimating the shielding effectiveness of an enclosure with some contents.

VII. Conclusions

In this paper we have presented results showing how when PCBs are included in an enclosure the shielding effectiveness can be increased. The ACS of a number of different PCBs have been measured and then used to predict the shielding effectiveness of an enclosure with the PCB inside it. The predicted value of shielding effectiveness shows good agreement with the measured value.

Extensions to this work could include looking at predicting how other typical enclosure contents, such as cables, could affect the shielding effectiveness. Further investigation into how stacked PCBs in densely populated enclosures affect the shielding effectiveness would also be useful as well as how this changes with contents close to the reverberation chamber walls. The measured ACS of PCBs can be used to develop a set of representative contents which could be used during shielding measurements as described in [8]. Finally, the ACS of a set of PCBs could also be measured when they are powered on and active.

This work has shown why it is important to include enclosure contents when measuring shielding effectiveness and compares predicting the shielding effectiveness using ACS and measuring the shielding effectiveness with the PCB inside the chamber. Using the ACS showed good agreement with the measured shielding effectiveness showing that this could be a useful method for engineers to get an improved estimate of shielding effectiveness when designing electronic systems.

ACKNOWLEDGMENT

This work was supported by Huawei Technologies Co. Ltd., Shenzhen, P. R. China under Contract YB2014090010. Sarah Parker's PhD studentship is funded by York EMC Services Ltd and the Department of Electronics, University of York.

REFERENCES

[1] A. C. Marvin, J. F. Dawson, S. Ward, L. Dawson, J. Clegg and A. Weissenfeld, "A proposed new definition and measurement of the shielding effect of equipment enclosures" , *IEEE Transactions on Electromagnetic Compatibility , vol. 46, no. 3* , 459-468 , Aug. 2004.

[2] Carlberg, U., Kildal, P.-S., Wolfgang, A., Sotoudeh, O. and Orlenius, C., "Calculated and measured absorption cross sections of lossy objects in reverberation chamber," *IEEE Transactions on Electromagnetic Compatibiltiy*, vol. 46, no. 2, pp. 146-154, May 2004

[3] I. D. Flintoft, S. L. Parker, S. Bale, A. C. Marvin, J. F. Dawson and M. P. Robinson, "Measured average absorption cross-sections of printed circuit boards from 2 to 20 GHz", *IEEE Transactions on Electromagnetic Compatibility*, in press. DOI: 10.1109/TEMC.2016.2515658.

[4] A. Gifuni, "On the measurement of the absorption cross section and material reflectivity in a reverberation chamber," *IEEE Trans. Electromag. Compat.*, vol. 51, no. 4, pp. 1047–1050, Nov. 2009.

[5] A. Gifuni, G. Ferrara, A. Sorrentino and M. Migliaccio, "Analysis of the measurement uncertainty of the absorption cross section in a reverberation chamber", *IEEE Transactions on Electromagnetic Compatibility*, vol. 57, no. 5, pp. 1262-1265, October 2015.

[6] I. D. Flintoft, S. J. Bale, S. L. Parker, A. C. Marvin, J. F. Dawson and M. P. Robinson, "On the measureable range of absorption cross-section in a reverberation chamber", *IEEE Transactions on Electromagnetic Compatibility*, in press. DOI: 10.1109/TEMC.2015.2499841.

[7] D.A. Hill, M. T. Ma, A. R. Ondreika, B. F. Riddle, M. L. Crawford and R. T. Johnk, "Aperture excitation of electrically large, lossy cavities", IEEE Transactions on Electromagnetic Compatibility, vol. 36, no. 3, pp. 169-178, August 1994.

[8] *Standard Method for Measuring the Shielding Effectiveness of Enclosures and Boxes Having All Dimensions Between 0.1 m and 2 m*, IEEE-STD 299.1, Institute of Electrical and Electronics Engineers, Piscataway, NJ, USA, Oct. 2013.