A Multi-Band Body-Worn Distributed Exposure Meter for Personal Radio-Frequency Dosimetry in Diffuse Indoor Environments

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Abstract—A multi-band body-worn distributed exposure meter (BWDM) is designed and calibrated for diffuse fields in a reverberation chamber (RC) for personal exposure assessment in indoor environments. The BWDM uses 22 nodes distributed over the torso and measures the incident power density (S_{inc}) on body for 11 telecommunication bands in the frequency range 790-5513 MHz. In order to calibrate the measurement device in diffuse fields, a protocol is proposed for on-body calibration of the BWDM. This protocol is applicable to wearable personal exposure meters in general. The BWDM and the proposed calibration protocol are validated in five indoor locations and five frequency bands (the downlink bands at 800, 900, 1800 and 2100 MHz and WiFi 2 GHz) using a tri-axial broadband antenna and a spectrum analyzer (SA). The calibration shows that the BWDM has a relatively low measurement uncertainty with a 68% confidence interval on its antenna apertures, in the range 3.4-5.5 dB. A maximum difference of 0.9 dB is obtained for the total exposure in the test areas between the measurements of the BWDM and SA, which is an excellent agreement.

Index Terms—Wearable, Radio-frequency, Personal exposure, Dosimetry, Indoor, Reverberation chamber

I. INTRODUCTION

This work was supported by the Research Foundation Flanders (FWO) under grant agreement No G003415N and the French National Research Program for Environmental and Occupational Health of ANSES (2015/2 RF/07) as part of project ACCEDERA. A.T. has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 665501 with the FWO. (Corresponding author: Reza Aminzadeh)

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CHARACTERIZATION of human exposure to radio-frequency (RF) electromagnetic fields (EMFs) is identified by the world health organization (WHO) as an important issue to be addressed by several countries [1]. Recently, potential adverse effects of mobile phone use on brain functions such as figural memory has been reported [2]. Additionally, thermal effects of RF-EMFs are well established [3]. In order to avoid these thermal effects of human exposure to RF-EMFs, the field strengths or alternatively power densities incident on the body (S_{inc}) are limited by adhering to reference levels such as those issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [3]. Personal exposure meters (PEMs) are commonly used to measure individual exposure to RF radiation [4]. These portable devices provide continuous monitoring of RF-EMFs in different frequency bands at the same location for the subject wearing the device. Measurement protocols have been proposed for the use of PEMs [5]–[7]. However, PEMs measurements are associated with large measurement uncertainties due to presence of wearer's body e.g. body shielding [8]. Thus, PEMs measure the electric fields on the body instead of the actual incident fields, which results in uncertainties on the estimation of the actual fields [9]–[11]. In order to address these issues, on-body calibration of PEMs and the use of multiple PEMs have been proposed in the literature [9], [11], [12]. Additionally, single-band [13]–[15] and a multi-band [16] body-worn distributed exposure meter (BWDM) have been proposed using on-body calibration in an anechoic chamber to increase the measurement accuracy of incident fields on-body. This calibration has proven effective for outdoor environments, where the incident RF-EMFs can be considered as specular components [17].

However, people spend more than 80% of their time indoors [18]. The increasing number of indoor wireless technologies such as smart home gadgets, makes it crucial to assess human exposure to RF-EMFs in indoor environments. The total power in an indoor environment is composed of specular and diffuse multi-path components (DMC) [19], [20]. The former is a result of coherent reflection (e.g. large surfaces like walls) whereas the latter results from non-coherent reflections (due to the presence of different objects) in an indoor area. In an indoor environment, DMC may contribute up to 95% to the total incident power density [21] and 88% to the whole-body averaged specific absorption rate [22]. In order

to assess human exposure to RF-EMFs in diffuse fields, an on-body calibration of PEMs in such fields was recommended in [12]. Reverberation chambers (RC) are environments in which diffuse fields can be generated in a controlled manner [23]. Previously, the response of two commercial PEMs has been determined using on-body calibration in a RC [12]. The correction factor of the calibrated (two) PEMs in the RC (diffuse fields) was found to be up to 4.8 times lower compared to when the PEMs are calibrated on-body in an anechoic chamber (specular fields) [12]. In other words, the calibrated PEMs in an anechoic chamber underestimate the diffuse exposure up to a factor larger than 4. This is a strong indication that a separate calibration of PEMs in a RC is necessary. However, on the one hand, a consistent on-body calibration protocol for PEMs/BWDM in diffuse fields is missing in the literature. On the other hand, to the best of authors' knowledge, no BWDM has been proposed or demonstrated in literature that is able to measure diffuse fields in indoor environments. It is expected that also in diffuse fields a BWDM will have a lower measurement uncertainty than commercial PEMs.

This paper presents, for the first time, the on-body calibration of the first BWDM for diffuse fields in a reverberation chamber (RC). The goal is to use the BWDM to simultaneously measure personal exposure to RF fields in indoor diffuse environments. First, the BWDM is designed and optimized based on the calibration measurements on a test person in an anechoic chamber. Second, the optimized BWDM is calibrated on the same person in a RC to determine its measurement uncertainty. In addition, a protocol is proposed for calibration of personal exposure meters (including conventional PEMs and personal distributed exposure meters) in a RC for measurement of personal exposure in diffuse indoor environments. The results are validated by performing a real measurement campaign in an indoor office environment.

II. MATERIALS AND METHODS

Section II-A describes the on-body setup and design of the BWDM. Section II-B introduces the used PEM, the Expom-RF. Section II-C presents the on-body calibration while Section II-D explains the cross-talk. The validation measurements are presented in Section II-E.

A. BWDM

The BWDM comprises 22 nodes connected to a common serial bus system. A portable master unit (see Fig. 1) controls the bus communication and can be connected to a laptop computer to read/erase measurement data. The master unit monitors the correct operation and synchronization of the nodes. The user can synchronously record time-stamps in all the 22 nodes by pressing a button on the master unit. The 22 nodes were placed on 22 locations (A to V) on the front and back of the body torso as well as the hips as shown in Fig. 1(a). The arms, the legs and the head were excluded for antenna deployment since their movements during the measurements would influence the performance of antennas [24]. Additionally, placing the used antennas on the head and limbs might impede the

subject's movements, which might negatively impact potential measurements done with the device. The BWDM covers 11 frequency bands allocated to legacy wireless communication systems from 800 MHz to 6 GHz as listed in Table I. For each frequency band, two nodes were considered on the front and back of the body to compensate for shielding of the body [11], [16]. The optimized location and polarization of the nodes (see Table I) were determined by on-body calibration of the BWDM on a test person (male; height: 183 cm) in an anechoic chamber [16]. At each center frequency, the term optimized was defined as the location and the polarization that provided the minimum measurement uncertainty. The polarizations in Table I are relative to the ground floor: vertical (V) polarization is orthogonal to the floor and horizontal (H) is parallel to the floor.

Fig. 1. (a) Location of the nodes on body (left) integrated into a garment (right). (b) Prototype of a node (left) and the master unit (bottom right).

1) *antennas*: The nodes are composed of linearly (Wi-Fi-5G) and elliptically (for the other bands) polarized textile-compatible substrate-integrated-waveguide (SIW) antennas and compact receiver electronics to register the incident EMFs. The design of the antennas is presented in [25]. The conductive parts and the antenna substrate were made from copper-coated nylon and closed-cell expanded rubber commonly found in garments of firefighters, respectively. A CO₂ laser with a spot size smaller than 0.1 μm was used to pattern the textile materials. The antennas have a power reflection coefficient lower than -10 dB in the desired frequency bands (cf. Table I). Compared to [15], the BWDM antennas have high-body antenna isolation and are more sensitive to radiation incident from directions away from the human body. The antennas have a gain in the 3-5 dBi range (along the direction away from the body). The antenna polarization is linear with an axial ratio

between 5 and 15 dB. The smallest and the largest antennas have a surface of $9 \times 10 \text{ cm}^2$ and $11 \times 11 \text{ cm}^2$, respectively.

2) *receiver nodes*: Figure 1(b) shows a prototype of the designed nodes for the BWDM. The receiving nodes are based on logarithmic radio-frequency (RF) detector chips, preceded by suitable band-pass filters for each band of interest. Ceramic Surface Acoustic Wave (SAW) filters are employed, providing a large out-of-band rejection in one small Surface Mounted Device (SMD). Concerning the detector chips, for the 5.8 GHz band the AD8318 is used, whereas for all the lower frequency bands, the ADL5513 is employed. Both detector chips are precision circuits manufactured by Analog Devices Inc. The ADL5513 provides a dynamic range of 80 dB, but its bandwidth is limited to 4 GHz. The AD8318 has an 8 GHz bandwidth but a more limited dynamic range of 55 dB. The temperature-dependent offset of the logarithmic power detector is compensated automatically using a Digital-to-analog-converter (AD5641, Analog Devices Inc) connected to the central micro-controller with a built-in temperature sensor. In the construction of the nodes on Printed Circuit Board (PCB), standard FR4 board is used for all bands up to 2.45 GHz. For the 5.8 GHz band, FR4 material causes too much signal loss and therefore the more expensive Rogers 0.5 mm thick Isola I-tera high frequency laminate was chosen.

The output of both detectors is a voltage proportional to the logarithm of the input power. This voltage is sampled by a 16-bit Analog-to-Digital Converter (ADC), connected to the central micro-controller via the Serial Peripheral Interface (SPI). The micro-controller performs a first processing of the measurements in order to determine the maximum, minimum and average power over (100 samples per second) each one-second measurement interval. Both the arithmetic and the geometric averages are calculated by the micro-controller, resulting in four measurement values to be stored in the 32 MBit local flash memory unit each second. The current consumption of each node and the BWDM (including 22 nodes and the master unit) in full operation are 39 mA and 1200 mA at 5 V, respectively. A 5V (13000 mAh) battery powers the BWDM. The minimum and maximum weight of the nodes are 15 g and 40 g, respectively.

TABLE I
LOCATION AND ORIENTATION OF THE NODES ON BODY AS WELL AS THEIR FREQUENCY BANDS.

Band name	Range (MHz)	F_c (MHz)	Location
800-DL	790 – 821	806	C^H, Q^V
900-UL	879 – 915	896	I^V, O^H
900-DL	921 – 960	941	G^H, K^V
1800-UL	1710 – 1785	1748	A^V, S^H
1800-DL	1805 – 1880	1843	D^H, R^V
DECT	1880 – 1900	1890	H^H, L^V
2100-UL	1900 – 1980	1940	F^V, P^H
2100-DL	2110 – 2170	2140	U^H, V^V
WiFi-2G	2400 – 2485	2443	J^V, N^H
2600-DL	2620 – 2690	2655	B^H, T^V
WiFi-5G	5150 – 5875	5513	E^H, M^V

F_c : center frequency; V: vertical polarization; H: Horizontal polarization.

Fig. 2. The setup for calibration measurements in the reverberation chamber (top view).

B. ExpoM-RF

A conventional PEM, ExpoM-RF (Fields at Work GmbH, Zürich, Switzerland) was used in this study and is denoted as Expom in this paper. The Expom has a detection limit of $0.024 \mu\text{W}/\text{m}^2$ for 2100-UL, 2100-DL and 2600-DL. The detection limit is $6.6 \mu\text{W}/\text{m}^2$ for Wireless Fidelity 5 GHz (WiFi-5G) and is $0.07 \mu\text{W}/\text{m}^2$ for other studied frequency bands (see Table I).

C. Calibration measurements

We present a procedure for on-body calibration of PEMs, including the BWDM, in a RC. The calibration measurements consist of two types of measurements: on body and in off-body. Figure 2 illustrates the setup for calibration measurements in the RC. The room dimensions are $5.7 \times 4.1 \times 2.8 \text{ m}^3$. The different electromagnetic modes in the RC were excited using a stirrer composed of four rotating metallic sheets. The RC has a total field standard deviation below 1.5 dB (below the 3 dB tolerance limit) in the range of 800-1000 MHz and decreases with increasing frequency. An SAS-571 horn antenna (TX) with vertical polarization, operating in the range of studied frequency bands was used. The TX emitted a constant power of 1 mW at each center frequency as listed in Table I. All the measurements were performed in the working area of the RC (dashed lines in Fig. 2) where fields had uniform distribution [26].

1) *Off-body measurements*: A broadband field meter NBM-550 in combination with EF 0391/EF 0691 probes (NARDA Safety Solutions) was placed in the working area of the RC (See Fig. 2). The goal was to measure the incident power density S_{inc}^{offb} in the RC. The NBM-550 broadband meter in combination with EF 0391 and EF 0691 probes has a combined standard uncertainty of 1.1 dB (including frequency sensitivity, linearity, thermal and isotropic responses) on the off-body measurements. S_{inc}^{offb} was measured for two scenarios: unloaded RC (in absence of the test person) and loaded RC (in presence of the test person).

To keep the variation of the RC's Q-factor to minimum [27], it was suggested to keep the subject in the chamber when performing the off-body measurements in a RC. This keeps the Q-factor of the RC and consequently the incident power density constant for all measurements including on-body and

in off-body. For off-body measurements, the test person stood in the working area but far away from the broadband field meter in order not to influence the measured power densities (probe's performance).

At each center frequency, the incident power density was measured at different heights in the range of 68.5-201 cm from the floor. During a full rotation of the stirrer (at a speed of 10°/s), 36 samples were measured at a sample rate of 1 Hz. The measurements were averaged over the height and the positions of the stirrer per frequency band. This was repeated for the unloaded (empty) and the loaded (with person) chamber.

2) *On-body calibration of BWDM*: The test person, for whom the BWDM was optimized (for details refer to [16]), was placed in the RC at the same location as the broadband field meter, in standing posture and wearing the BWDM. At each center frequency, the received power P_r was recorded simultaneously on two nodes (on the front and back), at a sample rate of 1 Hz, for a full rotation of the stirrer. The stirrer rotated at 2°/s resulting in 180 received P_r samples on each node as a function of the rotation angle φ of the stirrer. Compared to off-body measurements, the rotation speed decreased to register more samples to ensure that the number of samples are sufficient for correct estimation of the measurement uncertainty. These received powers P_r were first geometrically averaged over the two nodes on the front and back (in each frequency band i) $P_{r,i,geom}$ and then were averaged over φ , in order to determine the on-body geometrically averaged antenna aperture (AA) over front and back in diffuse fields:

$$AA_{geom,i} = \frac{\langle P_{r,i,geom} \rangle}{S_{inc,i}^{ofb}}, \quad (1)$$

where i is the center frequency of the eleven studied frequency bands and $\langle \rangle$ denotes the average over φ of the stirrer. During the measurements in a real environment, the BWDM registers $P_{r,i}^{meas}$ on each node. These data were then converted into measured power densities incident on body $S_{inc,i}^{meas}$ using geometrically averaged $AA_{geom,i}$:

$$S_{inc,i}^{meas} = \frac{P_{r,i,geom}^{meas}}{AA_{geom,i}}. \quad (2)$$

D. Cross-talk

Cross-talk is the fraction of power registered (P_r) in a specific frequency band j while the emission occurs in another frequency band i (misclassification). The ideal cross-talk is a unit matrix, of size n (n : number of frequency bands) with ones on the main diagonal and zeros else where. In this paper cross-talk C_{ij} for diffuse fields is defined as:

$$C_{ij} = \frac{\langle P_{r,j}(f_i) \rangle}{\langle P_{r,i}(f_i) \rangle}. \quad (3)$$

For the BWDM, nodes A to J and U (one node per frequency band) were placed on front of the body (see Fig. 1(a)). To compare the on-body cross-talk of BWDM with commercial PEMs, an Expom was worn simultaneously on the left hip

of the subject (above the location of node V) during the measurements in the RC. The received power P_r for each frequency band was averaged over all positions of the stirrer. For the Expom, P_r in Eq. 3 is replaced by $(E_r)^2$ where E_r is the electric field registered by the Expom.

E. Validation in a real indoor environment

The goal of this validation was to assess the applicability of the proposed calibration procedure for RF exposure measurements in real indoor environments. Therefore, using the AA values determined from unloaded and loaded RC, the measured S_{inc} values by the BWDM in an indoor office environment (see Fig. 3) were compared with the measured S_{inc} of an isotropic field probe at the same locations (the golden standard in RF-EMF exposure measurements [28]). This measurement setup has an uncertainty of ± 3 dB for the electric fields [28], [29]. Five measurement points including two office rooms and three spots in the corridor were considered as shown in Fig. 3.

Five downlink (DL) bands which are dominant (present) in indoor areas were considered here: 800, 900, 1800 and 2100 MHz as well as WiFi-2G. The S_{inc} was measured using an isotropic, tri-axial antenna and a spectrum analyzer (FSL, Rhode & Schwartz, Germany). The height of the antenna was 120 cm above the ground on each of the five locations. The spectrum analyzer (SA) measured in continuous sweep mode using a root-mean-squared (RMS) detector with a resolution bandwidth of 300 kHz. For each frequency band, 501 points were considered which resulted in a sweep time of 300 ms. Static measurements were chosen due to the lower measurement uncertainty compared to the dynamic measurements. Moreover, measurements of the isotropic antenna are not impeded by the operator's body that moves the antenna. Following the measurement at each location, the test person, who was wearing the BWDM, walked around in a square of 1×1 m² centered on each of the five points for 15 minutes. This is due to the fact that the on-body calibration considers a dynamic environment with changing incident fields. Therefore, static measurements using the BWDM do not make sense in this case.

III. RESULTS AND DISCUSSION

Section III-A presents the results of on-body calibrations. Validation measurements are discussed in Section III-C and the cross talk of BWDM is compared with the Expom in Section III-B.

A. On-body calibration of the BWDM

Figure 4 illustrates the 68% confidence interval (CI_{68}) of the on-body antenna aperture (AA) in diffuse fields for 22 nodes of the single body-worn (front and back) as well as the geometric average over each pair of nodes in 11 frequency bands. This figure shows that using two nodes on the front and back of the body reduces the CI_{68} in diffuse fields (black bars versus grey bars).

For the nodes on the front, the minimum and maximum CI_{68} are 8.8 dB (900-DL) and 4 dB (WiFi-5G), respectively. For the

Fig. 3. Locations of measurement points (black squares) used for validation measurements in an indoor office environment. The measurement setup with SA is shown on the right side.

nodes on the back, 900-DL and 2100-DL have the highest CI_{68} (9 dB) while WiFi-5G has the lowest CI_{68} (5 dB). The value of CI_{68} is 3.4 dB to 5.5 dB for the geometric average over two nodes on the front and back. This is an improvement of 3.3 dB for the nodes on the front (900-DL) and 3.5 dB for the nodes on the back (900-DL and 2100-DL) in comparison to single antennas. Similarly, a CI_{68} in the range of 3.3 dB (2100-DL) to 5.7 dB (2600-DL) was obtained for the BWDM calibrated on the same subject in anechoic chamber (subject #Sb-1 in [16]).

Fig. 4. The 68% confidence interval of the on-body antenna aperture in diffuse fields for 22 nodes in 11 frequency bands.

Figure 5 depicts the same 68% confidence interval (CI_{68}) of the on body antenna aperture (AA) in diffuse fields for different configurations of two antennas on the body in four frequency bands (900-DL, 900-UL, WiFi-2G and 2600-DL). All considered configurations are pairs of locations on the front and back of the body (or two-opposite hips). For 900-UL, 900-DL and WiFi-2G changing the locations of the nodes (see Fig. 1(a)) from IO to EK, GK to BN and JN to GM, changes CI_{68} by 0.1 dB, 0.5 dB and 0.2 dB, respectively. The CI_{68} remains constant for 2600-DL in Fig. 5 by changing the location of the nodes from BT to DL. This shows that the location of the two nodes on the body has little to no influence on the CI_{68} , if two locations on the front and back are chosen. Hence, the optimized locations of the nodes for the BWDM calibrated in anechoic chamber [16] can be used in the reverberation chamber. Since the polarization of the incident

waves in the RC has uniform distribution [19], changing the polarization of the nodes does not change the results.

Fig. 5. The 68% confidence interval of the on-body antenna aperture in diffuse fields for different positions on body. The results are obtained for the geometric average over two nodes on the front and back of the body per band/position (letters above the bars) in the RC. The polarization of the nodes (V/H) are those obtained from calibrations in the anechoic chamber [16].

Table II lists the AA values for each frequency band obtained from on-body calibrations in the RC. For the unloaded RC i.e. subject was not present in the RC during off-body measurements (section II-C1), an AA range of 0.05 cm² to 2.94 cm² is obtained for 2100-DL and 900-DL, respectively. For the loaded RC, i.e. subject was present during off-body measurements, the AA has a range of 0.21 cm² (2100-DL) to 15.44 cm² (900-DL). A ratio of 4.6 ± 0.53 ($\mu \pm \sigma$) is obtained by dividing the AA values for the loaded RC by those of unloaded RC. This ratio indicates that loading the RC with the subject increases the AA values and consequently decreases the actual measured incident fields in real indoor environment (equation 2) by a factor of up to 5. This is due to modification of the subject (the absence of the test person during the off-body measurements) that induces a random modification of the plane wave spectrum and results in variation of the RC's Q-factor [27]. In [12], using two PEMs calibrated in an unloaded RC resulted in higher measured S_{inc} (factor of 2.2) in an indoor environment compared to the measurements of the same PEMs calibrated in an anechoic chamber. Section III-C presents results of validation measurements of BWDM using both AA values in the unloaded and loaded RC. In this

paper only standing posture is considered for calibration and validation measurements. In [26], deviations of 6% and 10% on the absorption cross section have been reported for a human subject in sitting position and with stretched arms, respectively, compared to when the subject was standing in a RC. This implies that calibration of BWDM with a different posture could result in small deviation of AA values due to increased or decreased body surface area (BSA) of the subject as a result of increased or decreased absorption of the EMFs in the body. In addition, the BSA of a subject depends on its height and weight [30]. The influence of the posture and body mass index of different subjects on the measurement uncertainty of the BWDM will be investigated in future research.

TABLE II
ANTENNA APERTURES (AA) OF BWDM OBTAINED FROM ON-BODY CALIBRATION IN LOADED AND UNLOADED REVERBERATION CHAMBER.

Bands	$AA_{AN}^{\dagger}$ (cm ²)	AA_{RC} (cm ²)		Ratio $\frac{loaded}{unloaded}$
		unloaded	loaded	
800-DL	9.82	1.84	8.36	4.5
900-UL	12.40	2.2	10.55	4.8
900-DL	12.72	2.94	15.44	5.2
1800-UL	4.36	1.82	9.33	5.1
1800-DL	2.59	1.58	8.04	5
DECT	4.44	2.3	10.65	4.6
2100-UL	2.57	1.41	6.92	4.9
2100-DL	0.88	0.05	0.21	4.2
WiFi-2G	2.69	1.94	8.9	4.6
2600-DL	2.92	1.65	7.26	4.4
WiFi-5G	0.33	0.13	0.43	3.3

[†] AN: Anechoic chamber [16].

B. Cross-talk

Figure 6 depicts the on-body cross-talk (C_{ij}) of BWDM and Expom measured in the RC. For the BWDM (Fig.6(a)), the highest cross-talk occurs for DECT when 1800-DL is emitted (1 dB) and for 1800-DL when DECT is emitted (-4 dB). This has also been observed in literature [10], [11]. Since these are adjacent bands, selection of a narrow band filter is the design limitation of the BWDM. One solution could be the use of intermediate frequency (IF) filters to improve frequency selectivity. Additionally, in [31] post-hoc processing of the exposure data for detection and correction of cross-talk in three bands (1800-DL, DECT and 2100-UL) has been proposed.

When 2100-DL is emitted cross-talks of -6 dB (factor of 3.9), -7.6 dB (factor of 5.75) and -8 dB (factor of 6.3) are registered by 900-DL, 1800-UL and 800-DL, respectively. For the same emitted band, 1800-DL, DECT and 2100-UL registered a cross-talk of -11 dB (factor of 12.5) while the rest of the bands registered a cross-talk of lower than -14 dB (factor of 25.1). This is due to the wavelength at 2140 MHz (2100-DL), which is comparable to the traces on the PCB of the BWDM nodes. Although the mentioned cross-talk is not large (compared to DECT), node shielding is required in order to reduce it. This will be investigated in a part of the future work. For the rest of the bands the cross-talk is in the range of -20 dB to -35 dB which is larger than a factor of 100.

The on-body cross-talk of Expom is illustrated in Fig. 6(b). Similar to BWDM, the highest Expom cross-talk occurs for

DECT and 1800-DL. The 1800-DL registered a cross-talk of -3.9 dB (factor of 2.4) when DECT was emitted while DECT registered -14.7 dB (factor of 29.5) when 1800-DL was emitted. WiFi-5G registered cross-talks of -6 dB (factor of 3.9), -7.6 dB (factor of 5.7), -9 dB (factor of 7.9) and -11.2 dB (factor of 13.1), which corresponds to emitted 2100-UL/1800-DL, 1800-UL/DECT, 2600-DL/2600-UL and 2100-DL/WiFi-2G bands, respectively. In comparison, the BWDM has a larger cross-talk than the Expom when 2100-DL is emitted due to unshielded nodes: 15.6 dB difference for 900-UL and limited to maximum 11.6 dB difference for other bands. Except 2100-DL, for other bands, the BWDM has a 10 dB lower cross-talk than the Expom.

Fig. 6. On-body cross-talk (C_{ij}) of BWDM (a) and Expom (b) in the reverberation chamber.

C. Validation in a real indoor environment

Figure 7 shows the measured S_{inc} using the BWDM and SA (the SA provides the true incident field values here) in five locations for five frequency bands. For the BWDM, three calibrations including AA values from the anechoic chamber, unloaded RC and loaded RC are applied (see equation 2).

Using the BWDM calibrated in the anechoic chamber, the difference between the measured S_{inc} by BWDM and SA are in the range of 0.5-1.5 dB, 0.2-3 dB, 3.2-8.1 dB, 7.1-15.9 dB and 3.4-16.2 dB for 800-DL, 900-DL, 1800-DL, 2100-DL and WiFi-2G, respectively.

The BWDM calibrated in the unloaded RC measured S_{inc} values 5.7 dB to 8.1 dB higher than SA measurements for 800-

DL in five locations. For 900-DL the difference increases to 5.3 dB to 9.3 dB in different locations. Similar overestimation of S_{inc} up to 10.3 dB are observed for 1800-DL w.r.t. the values registered by the SA. For 2100-DL, the BWDM measured values up to 14.5 dB higher than the SA. For WiFi-2G, the BWDM underestimates S_{inc} values by 2 dB to 14.8 dB lower than the SA.

The measured S_{inc} values using the BWDM calibrated in the loaded RC are only 0.1 dB to 1.6 dB different than those of SA for 800-DL in five locations. This clearly indicates that the RC should be loaded for the calibration measurements. For 900-DL, this difference is limited to 0.1-2.1 dB in different locations. Similar differences between SA and BWDM calibrated in the loaded RC are observed for 1800-DL: 1.6 dB to 3.2 dB. For 2100-DL, the BWDM measured lower S_{inc} (0.7 dB) than SA for office 2 and 2.2 dB to 8 dB higher S_{inc} than SA for the other four locations. Although the difference between the SA and calibrated BWDM in loaded RC is up to 8 dB for 2100-DL, these differences are the lowest compared to the measured values using the BWDM calibrated in unloaded RC and anechoic chamber. For WiFi-2G, the BWDM calibrated in the loaded RC measured lower S_{inc} than SA in the range of 8.6 dB to 21.3 dB.

Figure 7 also demonstrates the underestimation of RMS values of incident fields in WiFi-2G band using three calibrations i.e. anechoic chamber, loaded and unloaded RC. However, it must be noted that the limitation for measuring WiFi-2G signals with the tri-axial antenna and SA is that the difference between DL and UL could not be distinguished. If during the measurements somebody had passed with a phone having an active WiFi connection (transmitting), the SA would measure the duty cycle in which the electric field was maximum. Therefore, for WiFi-2G, the calibration of BWDM in loaded RC is reprocessed with maximum value of AA_{geom} (41.18 cm²) instead of averaging the AA_{geom} values over all positions of the stirrer (8.9 cm²). Next, this maximum AA is applied to the *maximum registered powers* in WiFi-2G band by the BWDM during the validation measurements. For SA, maximum measured E-fields in WiFi-2G band is considered without applying the duty cycles. The results are shown in Fig. 7 (filled markers) and are compared in Table III.

Table III lists the difference of measured incident power densities (ΔS_{inc}) between the SA and BWDM calibrated in loaded RC. Considering the maximum AA in the loaded RC the maximum measured fields with the BWDM are in very good agreement with the maximum measured values of the SA in the WiFi-2G band. The difference between the two measurements is in the range of 0.6 dB to 2.37 dB. Except for 2100-DL, the maximum difference between measurements of the BWDM and SA is limited to 3.23 dB (1800-DL in corridor 3). Differences up to 8 dB are obtained for 2100-DL but this might be attributed to the larger cross-talk values as discussed previously. Consequently, the difference for the total exposure between SA and BWDM is below 0.9 dB (corridor 1), which is an excellent agreement.

The characteristics of the BWDM calibrated in loaded RC are listed in Table IV. An AA range of 0.21 cm² (2100-DL) to 41.18 cm² (WiFi-2G) results in an on-body limit of detection

TABLE III
THE DIFFERENCE OF MEASURED INCIDENT POWER DENSITIES IN DOWNLINK BANDS BY BWDM CALIBRATED IN LOADED RC AND SPECTRUM ANALYZER.

Locations	$\Delta S_{inc} = S_{inc,BWDM} - S_{inc,SA}$					
	800L	900	1800	2100	WiFi-2G*	Total*
Office 1	1.55	1.91	1.9	8.05	-1.51	-0.58
Corridor 1	-0.81	-1.89	2.3	4.97	-2.37	-0.92
Corridor 2	1.6	2.16	2.1	2.27	0.72	0.51
Corridor 3	-0.38	-1.09	3.23	6.12	-1.2	-0.35
Office 2	0.16	-0.10	-1.68	-0.74	0.6	0.18

* Maximum measured E-fields by spectrum analyzer (SA) vs. maximum AA in loaded RC applied to the maximum registered power by WiFi-2G nodes of the BWDM.

(LOD) in the range of 0.04 $\mu W/m^2$ to 1.5 $\mu W/m^2$ (WiFi-5G) for different frequency bands. The LODs of BWDM are compared by those of the Expom (see Section II-B) in the corresponding frequency bands. Except 2100-DL and 2600-DL, the BWDM has an LOD of 4.2 times (WiFi-5G) lower to 3.5 times (900-UL and DECT) higher w.r.t LOD of Expom. Although the BWDM has LOD values higher than those of a single Expom (for 9 bands), factors larger than 2 have been reported in literature [9], [11] for the underestimation of PEMs.

In [12], 50% confidence intervals (CI_{50}) of 2.2 dB to 3 dB have been reported for the average over two PEMs (EME Spy 140) on the front and back of the body calibrated in a RC. The calibrated BWDM in RC exhibits a similar CI_{50} in the range of 2.1 dB to 3.6 dB.

TABLE IV
CHARACTERISTICS OF BWDM CALIBRATED IN LOADED RC.

Bands	BWDM			2 PEMs†	
	AA (cm ²)	LOD ($\mu W/m^2$)	CI_{50} (dB)	CI_{50} (dB)	LOD ($\mu W/m^2$)
800-DL	8.36	0.11	3.2	-	0.07
900-UL	10.55	0.23	3.1	2.8	0.07
900-DL	15.44	0.11	3.4	3	0.07
1800-UL	9.33	0.12	3	2.7	0.07
1800-DL	8.04	0.11	3.5	2.6	0.07
DECT	10.65	0.23	3.6	3	0.07
2100-UL	6.92	0.07	3.3	2.8	0.02
2100-DL	0.21	0.21	3	2.5	0.02
WiFi-2G*	41.18	0.04	2.5	2.3	0.07
2600-DL	7.26	0.19	2.6	-	0.02
WiFi-5G	0.43	1.55	2.1	2.2	6.63

* Maximum AA in loaded RC.

† The average over two PEMs on the front and back of a subject [12].
LOD: limit of detection; CI_{50} : 50% confidence interval.

IV. CONCLUSION

In this paper we presented design and calibration of a multi-band body-worn distributed exposure meter (BWDM) in a reverberation chamber (RC) for personal exposure assessment in indoor diffuse environments. The proposed BWDM consists of 22 nodes for 11 frequency bands. Using the geometric average over two nodes, the BWDM has an uncertainty in terms of the 68% confidence interval (CI_{68}) of its antenna apertures in the range of 3.4 to 5.5 dB. The BWDM is less affected by the wearer's body and a maximum difference of 0.5 dB was obtained for the CI_{68} by changing the location of the nodes in the RC for four bands (900-UL and 900-DL, WiFi-2G and 2600-DL). The results showed that on-body

Fig. 7. Comparison of S_{inc} measured by BWDM calibrated in an anechoic chamber, an unloaded and loaded reverberation chamber (RC) with S_{inc} measured by spectrum analyzer (SA) in five locations for five frequency bands. For WiFi-2G, maximum measured S_{inc} by SA are shown vs. maximum AA in loaded RC applied to the maximum registered power by WiFi-2G nodes of the BWDM.

calibrations of the BWDM in an unloaded RC (i.e. subject was not present in the RC during off-body measurements) overestimated the incident fields up to a factor of 5. The results were validated using a tri-axial antenna and spectrum analyzer (SA) for five frequency bands in five indoor locations. The results of on-body calibration of the BWDM in the loaded RC (i.e. subject was present), were in very good agreement with SA measurements. Maximum differences up to 3.2 dB were obtained for the BWDM compared to the SA for four out of five bands in five locations. A maximum difference of 0.9 dB was obtained between measurements of the BWDM and SA for the total exposure in five locations which is an excellent agreement. Based on the results, the authors suggest on-body calibration of (commercial, distributed, wearable) PEMs to be performed in a loaded RC (e.g. in presence of a human-body phantom) instead of an empty RC. The on-body cross-talk was measured for the BWDM and an Expom in the RC. The results showed a high cross-talk for 1800-DL and DECT bands for both devices. One potential solution for the BWDM would be selection of narrow-band IF (intermediate frequency) filters for these bands to improve the frequency selectivity. In addition, compared to DECT, smaller cross-talk values were observed for the BWDM by other frequency bands (i.e. registering a small portion of 2100-DL band). This might be due to the comparable wavelength in 2100-DL band with the traces on the printed circuit board of the nodes. This could be reduced by shielding the nodes which is part of the future work. Except 2100-DL, for other bands, the BWDM has a 10 dB lower cross-talk than the Expom. The influence of subjects' posture as well as body mass index of different subjects on the measurement uncertainty of the BWDM will be studied in future research.

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plex environment. She is also involved in challenges of MIMO and Massive MIMO techniques, mainly dedicated for communication in rail and road transportation systems and industry 4.0.

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systems as well as sub-GHz long range wireless sensor networks.

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Roel Vermeulen photograph and biography not available at the time of submission.

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