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Effect of Human Body Morphology on Measurement Uncertainty of A Multi-Band Body-Worn Distributed-Exposimeter

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SHORT ABSTRACT

For the first time, a multi-band body-worn distributed exposimeter (BWDM) calibrated for simultaneous measurement of the incident power density (S_{inc}) in 11 frequency bands, is proposed. The BDWM consists of 22 textile antennas integrated in a garment and is calibrated on five human subjects in an anechoic chamber to assess its measurement uncertainty in terms of 68% confidence interval (CI_{68}) of the on-body antenna aperture. The BWDM has a CI_{68} range of 2.7-8.8 dB for the five subjects participating in calibration measurements. The results show that using a combination of two antennas on the body leads to a maximum 0.1-3.2 dB difference in CI_{68} values for different body morphologies.

INTRODUCTION

Human exposure to radiofrequency (RF) electromagnetic fields is usually measured by Personal Exposimeters (PEMs) [1, 2]. These portable body-worn devices allow for continuous measurement of the electric fields strength in several frequency bands for which protocols have been developed [3]. The main disadvantage of these portable devices is that they are calibrated in free space while used on body. In other words, the measured values are compromised by the presence of the human body and thus have large measurement uncertainties [4]. Large variations in response of PEMs have been reported up to 35 dB [5]. A personal distributed exposimeter (PDE) with multiple antennas can be used to reduce this measurement uncertainty [6, 7]. In [6], a single band PDE was proposed using calibration measurements in an anechoic chamber but has not been used outside the lab. In [7, 8] a PDE was proposed for GSM 900 MHz downlink and WiFi 2 GHz bands. To the best of authors' knowledge to date, a multiband PDE has not been proposed to measure personal exposure to the present telecommunication signals including long term evolution (LTE) band.

In this study, for the first time, a multi-band body-worn distributed-exposimeter (BWDM) is proposed and the effect of human body morphology is investigated. The BWDM measures the incident power density (S_{inc}) using multiple antennas. Compared to PEMs used previously, the proposed BWDM has a lower measurement uncertainty. This device is useful for indoor and outdoor epidemiological studies - carried out mainly by volunteers - to relate health effects to incident field levels.

MATERIALS AND METHODS

The BWDM is designed and calibrated for measurements of actual S_{inc} for 11 frequency bands: LTE 800 and 2600 MHz, 900 MHz, 1800 MHs, 2100 MHz, DECT, Wi-Fi 2 GHz and 5 GHz including uplink (UL) and downlink (DL) bands. The BWDM consists of 22 nodes distributed in an optimal way on the front and back of the human torso as well as right and left hips. Selection of front and back and right/left is to avoid body shielding during the real measurements [7]. Each node consists of wearable elliptically polarized textile substrate-integrated-waveguide (SIW) antennas accompanied by a receiver circuit. The antennas are designed to have a power reflection coefficient of lower than -10 dB in the desired frequency bands. Each node has a sample interval of 1 Hz and a dynamic range of 80 dB. All the nodes are integrated into an outdoor garment and are synchronized with a master node via a custom bus protocol. Each node has an area of maximum 11×11 cm^2.

The location of antennas on body are optimized by calibrating the BWDM on a 28-year old male subject with a body mass index of 23.6 kg/m^2. A calibration procedure is proposed to concurrently determine an optimized location for each antenna per frequency band as well as an effective on-body antenna aperture (AA) for that location. Two nodes (RX) of the same frequency band are placed on a grid of $2 \times 2 \times 5$ (on torso) + 2 (on hips). For all frequency bands each pair of antenna is placed on diametrically opposite locations on body (considering right/left: 51 combinations) [9]. In order to examine all the locations for all bands 2244 measurements (11 bands × 4 polarizations × 51 combinations) would be needed. This was more feasible in a realistic time space. Therefore, a set of locations on body are selected randomly for each frequency band covering all the proposed locations on body and thus 120 measurements were performed.
First, the subject rotated 360° around his axis perpendicular to the ground floor of the anechoic chamber in the far field of a transmitting horn antenna (TX) with an input power of 20-60 mW (fixed in each frequency band). The rotation is repeated for both polarizations (V and H) of the TX resulting in the received powers on body $P_r^V(\varphi)$ and $P_r^H(\varphi)$. Second, the free-space incident power densities ($S_{inc}^{free,V}$, $S_{inc}^{free,H}$) are measured at the subject's place for both polarizations of the TX. Third, the on-body received powers $P_r^V(\varphi)$ and $P_r^H(\varphi)$ are averaged geometrically over the two nodes for each band. Both orientations of the RX are examined. Fourth, using the received powers on body are used to determine the geometric averaged AA of the BWDM for any realistic polarization:

$$AA(\varphi,\psi) = \frac{P_r^H}{S_{inc}^{free,H}} cos^2(\psi) + \frac{P_r^V}{S_{inc}^{free,V}} sin^2(\psi) \tag{1}$$

Where ψ is the polarization of an incident electric field. $AA(\varphi,\psi)$ is determined for 1000 ψ samples (drawn from a uniform distribution) in a loop with 100 repetitions to assess reproducibility of the distribution of $AA(\varphi,\psi)$. Finally, for each frequency band the combination (location and polarizations H/V for each node) with the minimal 68% confidence interval (CI_{68}) is chosen as the optimized arrangement of nodes on body as shown in Figure 1.

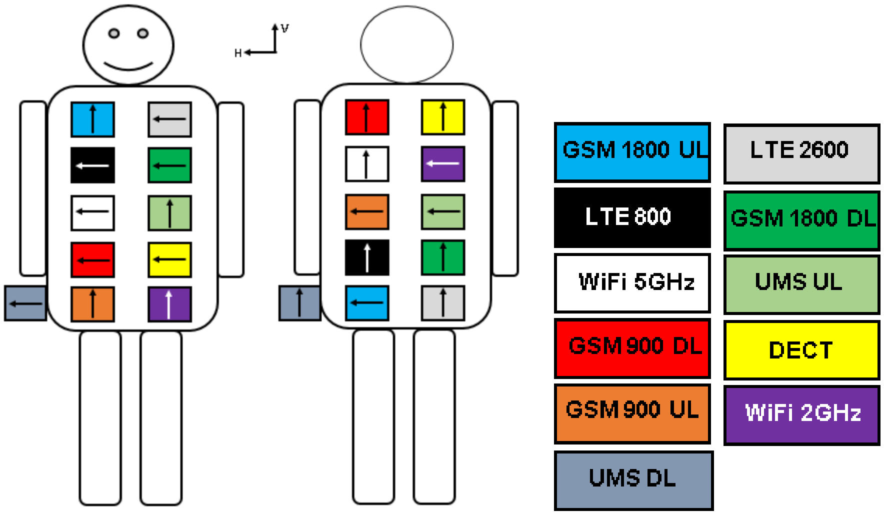

Figure 1.Optimized position and polarization of 22 nodes on body (28-year old male subject). The arrow indicates H/V polarization of each node.

Using the optimized location and polarization of the nodes, the BWDM is worn by 4 more people and the same on-body calibration setup is used to determine the on-body antenna aperture as well as the effect of body morphology on the BWDM's measurement uncertainty. Table 1 lists characteristics of the people participating in this study. It must be noticed that subject A is the male subject for whom the nodes are optimized.

Table 1. Characteristics of the subjects participated in calibration measurements.

Subject	Gender	Age	Height (m)	Weight (kg)	BMI (kg/m^2)
A	Male	28	1.83	79	23.6
B	Male	61	1.78	81	25.5
C	Male	39	1.69	95	33.2
D	Female	39	1.67	65	23.3
E	Male	43	1.78	76	23.9

RESULTS

Figure 2 shows the minimal 68% confidence interval (CI_{68}) of the on-body antenna aperture for 5 people per frequency band. Figures 2a and 2b show that the single exposimeter configuration on front and back have much larger uncertainties (up to 27 dB) than the uncertainty with 2 exposimeters configuration in Figure 2c (2.7-8.8 dB). For the optimized BWDM this is an improvement of up to 22 dB (with respect to front/back) for all subjects in the 11 studied frequency bands. Moreover, the calibration measurements show that the measurement uncertainty in different frequency bands, in terms of CI_{68}, can be reduced when 2 antennas are placed on body. These results are much lower than CI_{68} of a commercial exposimeter (ExpoM-RF 64), calibrated on the left hip of a male subject [10]. These results are consistent over all subjects.

The difference in CI_{68} is in the range of 0.1 to 3.2 dB for 5 different morphologies in all frequency bands. For example, subjects D and E have almost similar CI_{68} values for 5/11 bands: GSM 900 DL, GSM 1800 UL, DECT, WiFi 2 GHz and LTE 2600. This can be explained by their similar BMIs that can lead to a similar shielding effect. The different values for D and E in other frequency bands (3.2 dB at GSM 1800 DL) could be due to the different dielectric properties of body tissues for D (female) and E (male).

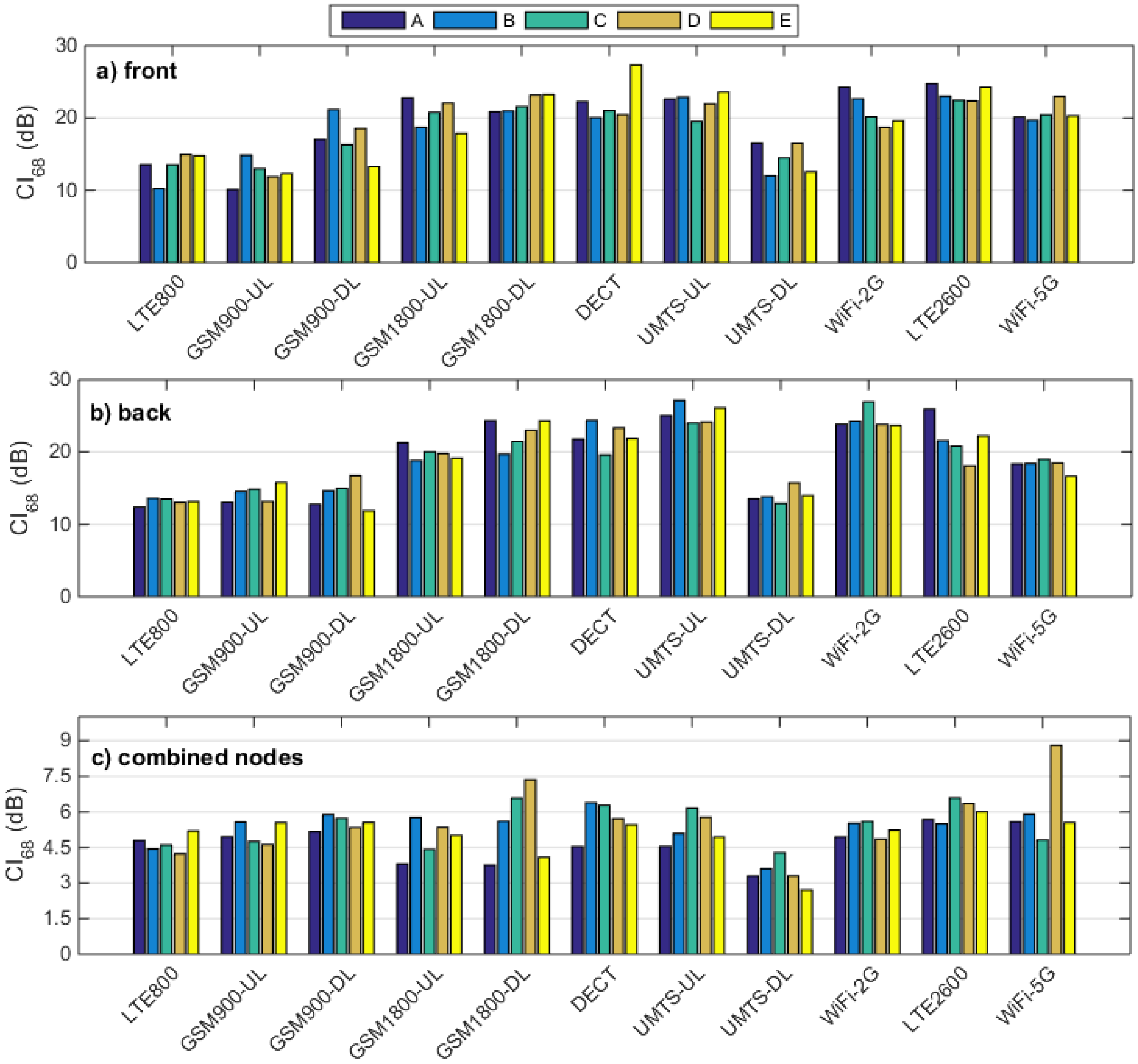

Figure 2. Minimal 68% confidence interval of the median on-body antenna aperture for each person per frequency band.

CONCLUSIONS

We propose a multi-band body-worn distributed-exposimeter (BWDM) for simultaneous on-body measurements of the incident power density in 11 telecommunication bands. The BWDM is designed and calibrated on-body in an anechoic chamber. An optimal placement of 22 antennas on body in the 11 frequency bands is determined. Once the BWDM is optimized, the calibration procedure is repeated for 4 people to study the effect of body morphology on the measurement uncertainty of the BWDM in terms of 68% confidence interval of the on-body antenna aperture. It is shown using multiple antennas on body for each frequency band reduces the measurement variation for all subjects. A combination of 2 antennas on diametrically opposite locations on body leads to 0.1-3.2 dB difference in combined CI_{68} values for various subjects with different body morphologies.

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