Title: Dealing with crosstalk in electromagnetic fields measurements of portable devices

Running title: Correcting crosstalk in EMF measurements

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ABSTRACT

Portable devices measuring radiofrequency electromagnetic fields (RF-EMF) are affected by crosstalk: signals originating in one frequency band which are unintentionally registered in another. If this is not corrected, total exposure to RF-EMF is biased, particularly affecting closely spaced frequency bands such as GSM 1800 downlink (1805-1880 MHz), DECT (1880-1900 MHz), and UMTS uplink (1920-1980 MHz). This study presents an approach to detect and correct crosstalk in RF-EMF measurements, taking into account the real-life setting in which crosstalk is intermittently present, depending on the exact frequency of the signal. Personal measurements from 115 volunteers from Zurich canton, Switzerland were analyzed. Crosstalk-affected observations were identified by correlation analysis, and replaced by the median value of the unaffected observations, measured during the same activity. DECT is frequently a victim of crosstalk, and an average of 43% of observations was corrected, resulting in an average exposure reduction of 38%. GSM 1800 downlink and UMTS uplink were less often corrected (6.9% and 8.9%), resulting in minor reductions in exposure (7.1% and 0.92%). The contribution of DECT to total RF-EMF exposure is typically already low (3.2%), but is further reduced after correction (3.0%). Crosstalk corrections reduced the total exposure by 1.0% on average. Some individuals had a larger reduction of up to 16%. The code developed to make the corrections is provided for free as an R function which is easily applied to any time series of EMF measurements.

Keywords: Electromagnetic fields; personal monitoring; exposure measurements; crosstalk; ExpoM-RF; radiofrequency; mobile phone; DECT

Introduction

As mobile communication technologies became more present in our everyday environment, the concern about health effects resulting from exposure to radiofrequency electromagnetic fields (RF-EMF) grew [Schreier et al., 2006]. Consequently, there was a growing demand for characterizing the level and variability of personal exposure to RF-EMF using portable measurement devices which allowed the measurement of personal exposure to RF-EMF in real-time[Bhatt et al., 2016; Röösli et al., 2010]. All these devices have the advantage that they can operate on a battery for up to one day and they are light enough to be carried, for example by volunteers or study participants, to characterize their personal exposure levels for use in environmental epidemiology studies [Frei et al., 2009; Röösli et al., 2010; Roser et al., 2017].

These portable devices process both the strength and frequency of incoming wave signals by sweeping across different frequency bands sequentially, covering the full spectrum range within several seconds. The raw signal is subjected to a so-called “band pass filter,” which is defined by a continuous function, passing those signals which fall between the lower and higher ends of a frequency band, and attenuating all others (Fig. 1). Crosstalk occurs when a signal belonging to a certain frequency band, unintentionally produces a (often weaker, because of partial attenuation) signal in another frequency band. In the measurement of RF-EMF, this mainly occurs because the response of the band-pass filter is approximate, but never ideal: it does not fully attenuate all frequencies outside the intended frequency range nor does it pass the signals that fall within the intended range at full strength. Therefore, for each frequency band, there is a region just outside the lower and higher limits where signals belonging to neighboring bands are attenuated, but not completely rejected. All frequency bands are both aggressor and victim, but the issue particularly occurs where broader bands, such as GSM1800 downlink (1805-1880 MHz, global system for mobile communications downlink) and UMTS2100 uplink (1920-1980 MHz, universal mobile telecommunications service) are close to narrower bands, such as DECT (1880-1900 MHz, digital enhanced cordless telecommunications) [Lauer et al., 2012]. Crosstalk can also be caused by nonlinearities of the electronics (e.g., amplifiers), or if the harmonic of a strong signal falls in one of the other frequency bands. The level of crosstalk is not constant, but depends heavily on how close the sub-frequency of the band is, which might change during a mobile phone call (see Fig. 2 for an example). In telecommunications, crosstalk is a type of interference: any kind of unwanted signal which modifies or disturbs the signal whose capture was intended. Crosstalk in this context may also be referred to as out-of-band response or co-channel interference.

All portable RF-EMF measurement devices suffer from crosstalk to some extent, with the implication that -if not corrected- the total exposure to RF-EMF is overestimated due to some adjacent frequency bands getting double counted: an undesirable situation for exposure assessment intended to inform epidemiological research. This study presents a method to detect and correct for crosstalk in environmental RF-EMF measurements taking into account the real-life setting, where crosstalk is variable in time: sometimes present, sometimes absent. Rather than evaluating the entire time-series of the measurement at once, the authors propose an approach which allows for this variability. Crosstalk may happen between the DECT and GSM1800 downlink, and between DECT and UMTS uplink, and that either frequency can be aggressor or victim. Moreover, whereas a previously suggested correction method relies heavily on time-activity information for the decision whether to correct or not [Bolte, 2016; Frei et al., 2009], the method presented here relies on the correlation between the bands. It is presented and optimized for the ExpoM-RF, but the issue of crosstalk is not specific to this instrument, affecting all portable RF-EMF exposimeters which use multiband antennas and band filters.

Methods

Fieldwork

Personal exposure measurements

Personal measurements were taken by 117 volunteers from a range of rural and urban municipalities within the Swiss canton of Zurich. The same study population was used in the study report [Röösli et al., 2016], excluding one measurements lasting less than 23 h and one participant who did not fill out a questionnaire about their mobile phone use. This left a total of 115 participants: 30 young adults (aged 18-30), 43 adolescents aged 12-15, and 42 adults (the adolescents' parents). Each participant carried an ExpoM-RF measurement device for a total of 24 to 72 h, including at least one full workday (Monday to Friday). All sampling was done between February 2014 and November 2015 and took place during regular school weeks (not during holidays). The ExpoM-RF is a personal radiofrequency exposure meter originally developed at ETH Zurich (Zurich, Switzerland) and further developed and commercialized by the Spin-off company Fields at Work, Zurich, Switzerland.[Fields at Work, 2018] The ExpoM can sample 16 different frequency bands in the range of FM radio (87.5-108 MHz) to ISM 5.8 GHz / U-NII 1-2e (5150-5875 MHz), allowing a detailed specification of the exposure from all major wireless communication and broadcasting services (see Appendix 1 Table S1. for details). ExpoM-RF devices were previously used in the Swiss HERMES study[Roser et al., 2017] and were calibrated in an anechoic chamber every 6 months throughout the measurement campaign. During calibration, a 16-point calibration of known electromagnetic field levels between 0.016mV/m and 5V/m was performed for each frequency band, averaging the response across three repeated measurements in different orientations to account for the isotropy of the device. ExpoM-RF devices were set to sample at an interval of 4 s.

Time-activity diary

All participants kept a study smartphone based time-activity diary (developed by ETH Zurich), on which they could enter their activities and any self-initiated or received phone calls in real time. For the purpose of this study, the activities were re-classed as “home,” “indoor elsewhere”, and “outdoor”. Phone calls were reported for mobile phones and cordless landline phones. The study smartphone was locked into flight mode for the entire duration of the measurements, so that it did not affect the exposure.

Statistical analyses

Basic corrections

After the measurement files were imported from the ExpoM-RF, and merged with the time-activity information, they were corrected for discrepancies in the diary entries based on the GPS information recorded by the ExpoM-RF. This process is described in more detail elsewhere [Roser et al., 2017]. Furthermore, two basic corrections were performed:

1) Very low and very high signal strengths are not well-quantifiable. Therefore, values below the lower quantitation limit of the dynamic range were set to half of this value for all bands (reporting limit). Values above the upper quantitation limit of the dynamic range are set to this upper limit (Appendix 1, TableS1), following previous studies [Birks et al., 2018; Röösli et al., 2016; Roser et al., 2017]. Few measurement values were under the detection limit, resulting in a similar and negligible effect of this correction for the different frequency bands on all devices.
2) When the ExpoM-RF is charging, the charging cord acts as an antenna, making the device more sensitive to FM Radio band. The strength of the FM signal is therefore higher, and -if left uncorrected- would constitute a large part of total exposure. Since the strength of broadcast signals is rather constant in time and uniformly distributed (within e.g., the participant’s home), the FM-value when charging is replaced by the median FM-value at home while the device is not charging.

In the remainder of this paper, these “basic corrected” measurements will be used for all calculations.

Defining distinct exposure windows in the dataset

During periods of crosstalk, the two frequency bands involved show a correlated series of observations. The beginning and the end of such periods (hereafter named “clusters”) are easily spotted in a time series plot of an RF-EMF measurement: they coincide with a sudden change in the absolute value of the DECT band or the ratio between the DECT and GSM1800 downlink (hereafter called GSM1800DL), or the DECT and UMTS2100 uplink (hereafter called UMTS2100UL) bands. Accordingly, the start of a potential new cluster was automatically flagged whenever there was a distinct change which fulfilled any of the following conditions:

1) If the rate of change (ROC) in either of the frequency bands considered (calculated as the change in signal strength relative to its absolute value at discrete time t_n, see Equation 1) was higher than a threshold Y. The change in signal strength was calculated as the difference between the X observations preceding time t_n and the X observations following time t_n.

$$Equation1: \quad ROC(band1)_{t_n} = \left| \left(\frac{\sum_{i=t_{n-1}}^{t_n-X} band1_i}{X} - \frac{\sum_{i=t_{n+1}}^{t_n+X} band1_i}{X} \right) \Big/ band1_{t_n} \right|$$

2) If the rate of change (ROC) in the ratio of the frequency bands between the X observations preceding discrete time t_n and the X observations following time t_n was higher than a threshold Y (see equation 2). To allow for the signals to be treated equally, $band\_ratio_i$ was calculated as $\min\{band1_i/band2_i, band1_i/band2_i\}$ so the ratio between the signals was always between 0 and 1.

$$Equation2: \quad ROC(ratio)_{t_n} = \left| \left(\frac{\sum_{i=t_{n-1}}^{t_n-X} band\_ratio_i}{X} - \frac{\sum_{i=t_{n+1}}^{t_n+X} band\_ratio_i}{X} \right) \Big/ band\_ratio_{t_n} \right|$$

The sensitivity of the parameter X was chosen such that there was enough precision to separately detect both the beginning and the end of short phone calls as the start of a potential new cluster. Smoothing over more than four observations would result in the inability to detect both the beginning and the end of short clusters with high exposures. Yet, it was necessary to smooth the signals from the different bands enough that the inevitable jitter was not falsely detected as a moment of substantial change. The duration of a typical phonecall is 17 s or longer[De Melo et al., 2010], and considering our ExpoM-RF sampling rate of four s, a cluster could be as short as four observations. Hence, X=4 was chosen.

The ROC threshold was set to Y=10, corresponding to a 10-fold increase or decrease in either the DECT level or the ratio between DECT and GSM1800DL, or between DECT and UMTS2100UL. Whenever this occurred, the observation at time point t_n was flagged as the start of a potential new cluster (and thus, the end of the previous cluster). Placing the threshold lower would flag more potential clusters, but also result in fewer of those being truly relevant for identifying clusters. In Appendix 2, the impact of varying the ROC threshold between 2 and 20 is evaluated.

The start of a potential new cluster was sometimes flagged at several consecutive observations, and so there were several potential clusters of length 1. Potential cluster starts are indicated as yellow vertical lines in plots 1A and 1B. Clusters of length ≤2 are undesirable, since it is not possible to detect the presence or absence of crosstalk within such small clusters by using the correlation between the frequency bands. Whenever consecutive time points were flagged, the optimal starting point of a new cluster was identified as the time point where the ROC(ratio) was highest, so that any definitive cluster had a minimum length of 3 observations (see the black vertical lines in plots 1A and 1B).

Detecting the presence / absence of crosstalk

Within each cluster, the correlation between the logged exposures of DECT and GSM1800DL, and between the logged exposures of DECT and UMTS2100UL was calculated. The presence of crosstalk was detected whenever the correlation for that window was higher than a threshold Z. Since positive correlations were not expected to occur naturally because of behavior (e.g., exposure resulting from the use of a cordless phone is expected to be independent of base station exposure and UMTS uplink), a low threshold of 0.20 was chosen. In Appendix 3, the impact of the choice of correlation thresholds between 0.1 and 0.8 is evaluated.

Determining the direction of crosstalk

Since all frequency bands can either be aggressor or victim of the crosstalk, it was necessary to determine in which band the signal originated. Within each cluster, the average ratio between the DECT and GSM1800DL, and between the DECT and UMTS2100UL signals was calculated. The stronger signal was identified as the aggressor, the weaker signal as the victim.

Value substitution

Whenever crosstalk was detected, the signal of the aggressor frequency was left unchanged and the signal of the victim frequency was corrected unless the value was already lower than the substitute value. The substitute value was calculated as the most typical exposure level during each activity and for each frequency band: the median exposure to that frequency band whenever this band was not indicated as to-be-corrected, and while the person was engaged in the same activity. In this context, the median was identified as the most typical exposure level, whereas the mean (e.g., the mean DECT level at home) was found to be highly affected by peak exposures occurring during DECT phone calls, in which cases DECT was the aggressor and was therefore rightfully left uncorrected. Corrections only took place if the substituted value was lower than the original value, so that exposures were never corrected upward. In addition, an exclusively data-driven approach was evaluated which could be applied in situations where no activity information was available. Here, the substituted values were set equal to the reporting limit (which was set to half of the lower quantitation limit): 0.000017 mW/m² for DECT and GSM1800DL, 0.0000060 mW/m² for UMTS2100UL (Appendix 1, S1).

Aggregation of the data

Corrections were carried out for all 115 participants. Mean exposures to DECT, GSM1800DL, UMTS2100UL and total RF-EMF were calculated for each person before and after crosstalk correction. All data analyses were performed in R, version 3.2.2[R Core Team, 2015], but provided codes are compatible with later versions.

Sensitivity analyses

The impact of varying the value of the rate of change (ROC) threshold Y between 2 and 20 was evaluated, to see how this affected the ability to detect clusters. For each participant and each threshold Y, the number of potential clusters which were flagged initially was calculated, as well as the number of clusters remaining after resolving the consecutive ones.

Furthermore, values between 0.1 and 0.8 for the correlation threshold Z were evaluated. For each participant and each threshold, the number of GSM1800DL, DECT, and UMTS2100UL observations corrected for crosstalk were calculated. The effect of the correlation threshold Z on the mean exposure value after the correction was also evaluated.

Results

Visual inspection of the time series plots showed that the method was well able to distinguish different clusters in the time series data during which exposure levels and the ratios between them were relatively constant for DECT and for the ratios between DECT and GSM1800DL (Fig. 2A), or between DECT and UMTS2100UL (Fig. 2B). Figures 3A and 3B show both the uncorrected (dashed) and corrected (solid) signals, illustrating the downward correction to the median level observed during the specific activity in which the participant was engaged. More examples of crosstalk corrections are shown in Appendix 4. Both DECT (Fig. 2B) and mobile phone calls on the UMTS frequency were recognized as new clusters. Crosstalk was found to occur both from DECT to GSM1800DL (Fig. 3A), as well as from GSM1800DL to DECT (Fig. 2A), and from DECT to UMTS2100UL (Fig. 2B), as well as from UMTS2100UL to DECT (Fig. 3B). Whenever crosstalk was detected between DECT and GSM1800DL, the victim frequency was typically attenuated. Crosstalk between DECT and GSM1800DL was more common than between DECT and UMTS2100UL, affecting on average 43% versus 17% of observations, respectively. The reason for this is the small 20 MHz “gap” between the frequencies used for DECT (1880-1900 MHz) and those used for UMTS2100UL (1920-1980 MHz), whereas the GSM1800DL frequency band (1805-1880 MHz) borders on the DECT band directly.

Figure 1 shows an example of a typical filter response by frequency, showing the inevitably imperfect attenuation of the post-filter signals. Finally, 43% of DECT observations were corrected for crosstalk with either GSM1800DL or UMTS2100UL. In most cases where crosstalk was identified between DECT and GSM1800DL, GSM1800DL was the aggressor, resulting in only 6.9% of GSM1800DL observations getting corrected on average. Although this average seems high, the distribution was heavily skewed by a few individual experiencing high levels of DECT at the workplace and/or at home. The median percentage of corrected GSM1800DL observations was only 1.6%, corresponding to approximately 23 min per participant per day. UMTS2100UL observations were corrected for crosstalk 8.9% of the time on average (median 5.4%, corresponding to approximately 78 min per day).

Corrections for crosstalk resulted in a majorly reduced DECT exposure for the large majority of participants (Fig. 4). GSM1800DL was mostly affected by the correction in a few cases who experienced high levels of DECT exposure, and hence a lot of crosstalk into the GSM1800DL band. The difference in the UMTS2100UL and total exposures was much less pronounced (Fig. 4). Substitution of crosstalk-affected observations resulted in a reduction of GSM1800DL, DECT, UMTS2100UL, and total RF-EMF exposure with 7.1%, 38%, 0.92%, and 1.0% on average, respectively (Table 1). However selected individuals heavily affected by crosstalk had reductions of up to 72%, 99%, 31%, and 16% for GSM1800DL, DECT, UMTS2100UL, and total RF-EMF exposure. Reductions in GSM1800DL and DECT levels were more substantial if the substituted value was chosen as the lower reporting limit, than if the substituted value was the median exposure level during crosstalk-unaffected observations, which was typically higher than the reporting limit (table 1). In the case of UMTS2100UL, the median level during crosstalk-unaffected observations was almost without exception equal to the lower reporting limit, and thus there was no difference between the two corrections (Table 1). The contribution of DECT to the total exposure is typically already low (average 3.2%, median 0.91%), much lower than GSM1800DL (average 7.7%, median 5.9%), and UMTS2100UL (average 6.8%, median 2.6%) (Table 1). After correction, DECT contributes even less to the total (average 3.0%, median 0.44%), whereas GSM1800DL and UMTS2100UL are less affected. Corrections reduced the total overall exposure by just 1.0% on average, but in some individuals the crosstalk correction had a larger effect of up to 16% exposure reduction.

Sensitivity analyses

At an ROC threshold of Y=10, typically less than 1% of observations were initially flagged as potential cluster starts for both DECT-GSM1800DL (median 0.60%, interquartile range (IQR) 0.47-1.13%) and DECT-UMTS2100UL crosstalk (median 0.92%, IQR 0.56-1.66). After resolving the consecutive clusters, typically less than half of them remained for both DECT-GSM1800DL (median 0.25%, IQR 0.19-0.37%) and DECT-UMTS2100UL crosstalk (median 0.34%, IQR 0.21-0.59%). The lower the threshold, the higher the percentage of observations flagged as potential cluster starts (Appendix 2, Fig. S2A). However, regardless of the threshold, the number of resolved clusters stayed relatively stable (Appendix 2, Fig. S2A). The lower the threshold, the higher the number of false positives, thus the higher the risk of flagging consecutive cluster starts which were not ultimately relevant (Appendix 3, Fig. S2B.).

At a correlation threshold of Z=0.2 (chosen for the main analysis), 43% of DECT observations were corrected, against 46% at Z=0.1, and 26% at Z=0.5 (Appendix 3, Fig. S3A). Despite this large difference, the difference in the average percentage decrease in exposure was small: 38% for Z=0.2, 39% for Z=0.1, and 31% for Z=0.5. For GSM1800DL and UMTS2100UL, the percentage of observations corrected was much lower and the reduction in exposure appears almost unaffected by the choice of Z (Appendix 3, Fig. S3B). More observations were corrected for all Z's when replacing crosstalk-affected values with the quantitation limit instead of the median crosstalk-unaffected value, though this difference was again more pronounced for DECT.

Discussion

The occurrence of crosstalk in portable radiofrequency exposimeters is highly variable due to fluctuations within a band, and cannot be prevented completely by calibration. This study introduces a method to detect clusters of observations where high correlations are present between the DECT and GSM1800DL, or between the DECT and UMTS2100UL bands. The method is based on the observation that signal strengths are correlated whenever crosstalk occurs, that extent of crosstalk is temporally highly variable and that the signal of the aggressor is usually stronger than the signal of the victim band. The code to make the corrections was developed in the free programming language R and is provided as the function “correct_crosstalk” in the package “EMFtools” which can be downloaded.[Eeftens, 2017]. This function allows the user to change the parameters defined in the paper and apply them to their own data, as well as visualize the crosstalk and corrections through a sequence of graphs. Using personal measurement data from 115 individuals, this study shows that the correction minimally affects the total overall exposure, reducing it by just 1.0% on average. However, crosstalk affected the DECT band more substantially, reducing exposure 38%. Exposure to GSM1800DL and UMTS2100UL was reduced by 7.1%, and 0.92% on average, respectively.

While it is quite common for a new cluster to be defined in the time series data whenever a new activity is started (Fig. 2A), the method also allows for several clusters to be defined within a single activity period. This is necessary, because of the nature of the exposures: it is quite common for a GSM or UMTS call to change periodically to a different carrier frequency, even during a single call. This causes the frequency to “jump around” between different sub-bands within the broader GSM or UMTS bands, some of which result in substantial crosstalk with DECT, and others not.

For both the ROC threshold (Y) and the correlation threshold (Z), it was difficult to find a purely theoretical basis to determine the optimal value. Putting the thresholds too high will mean that you miss some important instances of change and correlation, while putting them too low will mean that many unimportant changes are flagged as new cluster starts, or that parts of the time series which are not affected by crosstalk are corrected. In this study, the authors have chosen to empirically find a balance by visually inspecting many time series plots similar to those in Figures 3A and 3B, adjusting the values of Y and Z if the method did not make the right corrections.

It is widely acknowledged that the multi-band antennae and band filters used in the ExpoM-RF (and other similar personal measurement devices) have a larger measurement uncertainty than reference instruments such as benchtop spectrum analyzers. These uncertainties, resulting mainly from antenna gain and imperfect isotropy have been quantified by the developers (Appendix 1, table S2). The limited ability of personal measurement instruments to filter out out-of-band responses (compared to e.g., benchtop spectrum analyzers) results in additional uncertainty. Yet, as a major advantage, their smaller size enables personal monitoring, enabling the objective characterization of variability of a person’s real-life exposure in time and space, which would have been impossible with a larger instrument.

Several previous personal measurement studies report a substantial percentage of RF-EMF exposure to be due to DECT, while some of the exposure measured as DECT likely originated in the neighboring GSM1800DL and UMTS2100UL bands, and vice versa [Frei et al., 2009; Thielens et al., 2015; Urbinello et al., 2014]. A previous study from Switzerland excluded the DECT band altogether during outdoor measurements [Urbinello et al., 2014], which may be valid for studies in the micro-environmental studies in outdoor environments, but this method relies heavily on the availability of activity data, and does not justify corrections for measurements taken in indoor environments. Another suggestion removes crosstalk by calculating a covariance matrix of all bands, calculating the matrix distance from an identity matrix of the same dimension, and using inversion to derive a completely orthogonal matrix without any residual positive or negative correlation between any of the bands [Thielens et al., 2015]. However, if applied to real-life studies, this method may result in negative exposure levels for some bands. Moreover, the method does not allow for any residual correlation to remain, which is unrealistic in epidemiological studies, because when moving into a different microenvironment (e.g., from outdoor to indoor), it is expected that downlink signals from mobile phone base stations go down, and both DECT and WiFi go up. Such correlation does not result from crosstalk, but from the presence or absence of sources in the specific microenvironment. Inevitably, the suggested approach also leaves room for some error, but a substantially larger error is introduced if the measurements are left uncorrected, if bands are entirely omitted, or if the corrected values no longer represent realistic (positive) exposures. The method has been applied in two studies now [Röösli et al., 2016; Roser et al., 2017], and will also be used in the European collaborative GERoNiMO and SCAMP projects.

Conclusion

Our method was able to detect distinct periods of crosstalk in personal measurements of radiofrequency EMF, by flagging series of observations for which two frequency bands were correlated in time. The method is freely available and can be applied to correct personal measurements for crosstalk in the future, and get a more realistic picture of the DECT levels that the public is exposed to. DECT exposure was typically substantially reduced by 38% by the new correction, but reductions were smaller for GSM1800DL (7.1%), UMTS2100UL (0.9%), and overall exposure (1.0%).

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Captions and Legends

Table 1: Exposure distribution among the 115 study participants for GSM1800DL, DECT, and UMTS2100UL and total exposure for each correction $[mW/m^2]$

(reduction in exposure relative to the uncorrected [%]).

Band	Correction	Mean $[\mu W/m^2]$ (reduction [%][a])	Min $[\mu W/m^2]$ (reduction [%][a])	25th percentile $[\mu W/m^2]$ (reduction [%][a])	Median $[\mu W/m^2]$ (reduction [%][a])	75th percentile $[\mu W/m^2]$ (reduction [%][a])	Max $[\mu W/m^2]$ (reduction [%][a])	Mean percentage contribution to total exposure (median)
DCSDL	Uncorrected	8.4 (0%)	0.083 (0%)	1.2 (0%)	2.9 (0%)	5.5 (0%)	160 (0%)	7.7% (5.9%)
	Correction 1 [b]	7.4 (7.1%)	0.061 (0%)	1.1 (0.2%)	2.6 (1.1%)	5.5 (4.9%)	160 (72%)	7.2% (5.6%)
	Correction 2 [c]	7.1 (7.9%)	0.061 (0%)	1.0 (0.26%)	2.6 (1.5%)	5.5 (5.6%)	160 (94%)	7.1% (5.5%)
DECT	Uncorrected	4.7 (0%)	0.020 (0%)	0.21 (0%)	0.42 (0%)	0.99 (0%)	370 (0%)	3.2% (0.91%)
	Correction 1 [b]	4.4 (38%)	0.017 (0.075%)	0.085 (9.9%)	0.19 (35%)	0.46 (61%)	370 (99%)	3.0% (0.44%)
	Correction 2 [c]	4.4 (45%)	0.017 (0.08%)	0.061 (18%)	0.15 (47%)	0.41 (73%)	370 (99%)	2.9% (0.36%)
UMTSUL	Uncorrected	5.4 (0%)	0.0061 (0%)	0.19 (0%)	1.8 (0%)	7.4 (0%)	42 (0%)	6.8% (2.6%)
	Correction 1 [b]	5.4 (0.92%)	0.0061 (0%)	0.18 (0.016%)	1.7 (0.064%)	7.4 (0.51%)	42 (31%)	6.8% (2.6%)
	Correction 2 [c]	5.4 (0.93%)	0.0061 (0%)	0.18 (0.019%)	1.7 (0.066%)	7.4 (0.51%)	42 (31%)	6.8% (2.6%)
Total	Uncorrected	86 (0%)	5 (0%)	31 (0%)	51 (0%)	100 (0%)	580 (0%)	
	Correction 1 [b]	85 (1.0%)	5 (0.0048%)	31 (0.17%)	51 (0.38%)	99 (0.81%)	570 (16%)	
	Correction 2 [c]	84 (1.2%)	5 (0.0051%)	31 (0.23%)	51 (0.45%)	97 (1.0%)	570 (21%)	

Table 1: Exposure distribution among the 115 study participants for DCSDL, DECT and UMTSUL and total exposure for each correction $[mW/m^2]$ (reduction in exposure relative to the uncorrected [%]).

[a] As compared to the uncorrected exposure

[b] Replacing crosstalk-affected values by the median of the exposure level while the subject reported that they were involved in the same activity.

[c] Replacing crosstalk-affected values by the lower reporting limit: 0.000017 mW/m^2 for DCSDL and DECT and 0.0000060 mW/m^2 for UMTSUL.

Fig. 1: Illustration of a crosstalk scenario from band A to band B based on a generalized filter response of a typical band pass filter as used in the ExpoM-RF device.

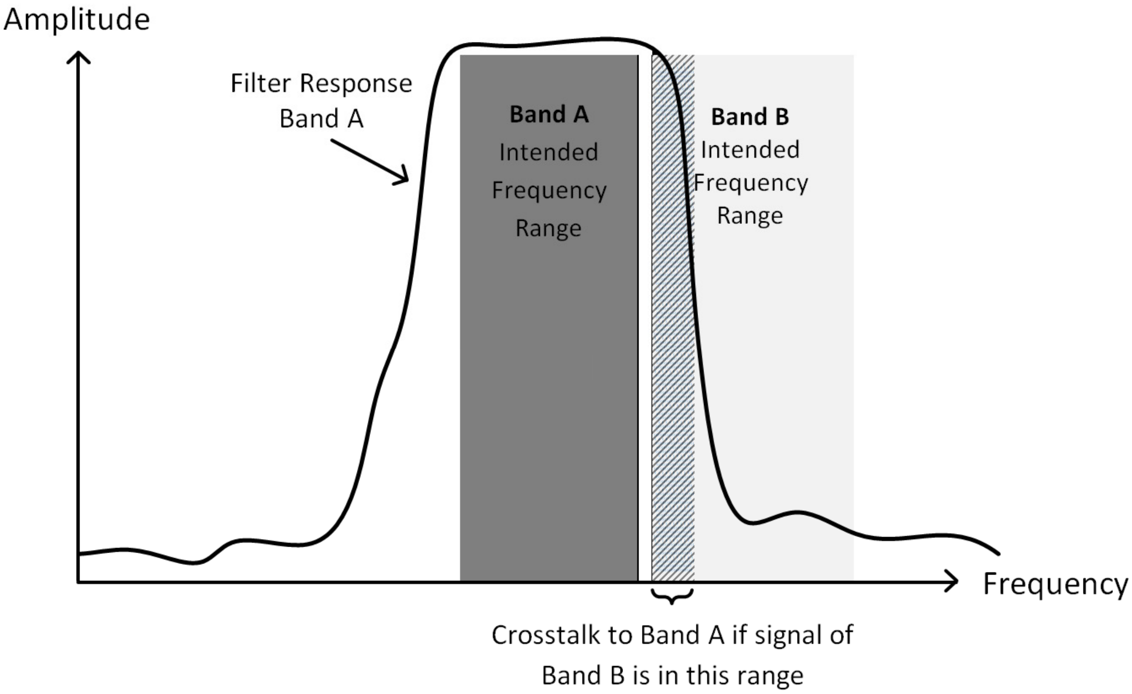

Fig. 2: Flagging of potential (yellow) and definitive (black) cluster starts:

A) Between DECT and GSM1800DL. A new cluster is flagged when the subject goes outdoor, and exposure to GSM1800DL increases, resulting in crosstalk into the DECT band.

B) Around several (attempted) DECT phone calls, which lead to crosstalk in the UMTS2100UL band. The third period of high DECT exposure (between 18:17 and 18:20) illustrates that even during a single phone call, the level of crosstalk measured in the UMTS2100UL band is not constant while the DECT level stays approximately the same.

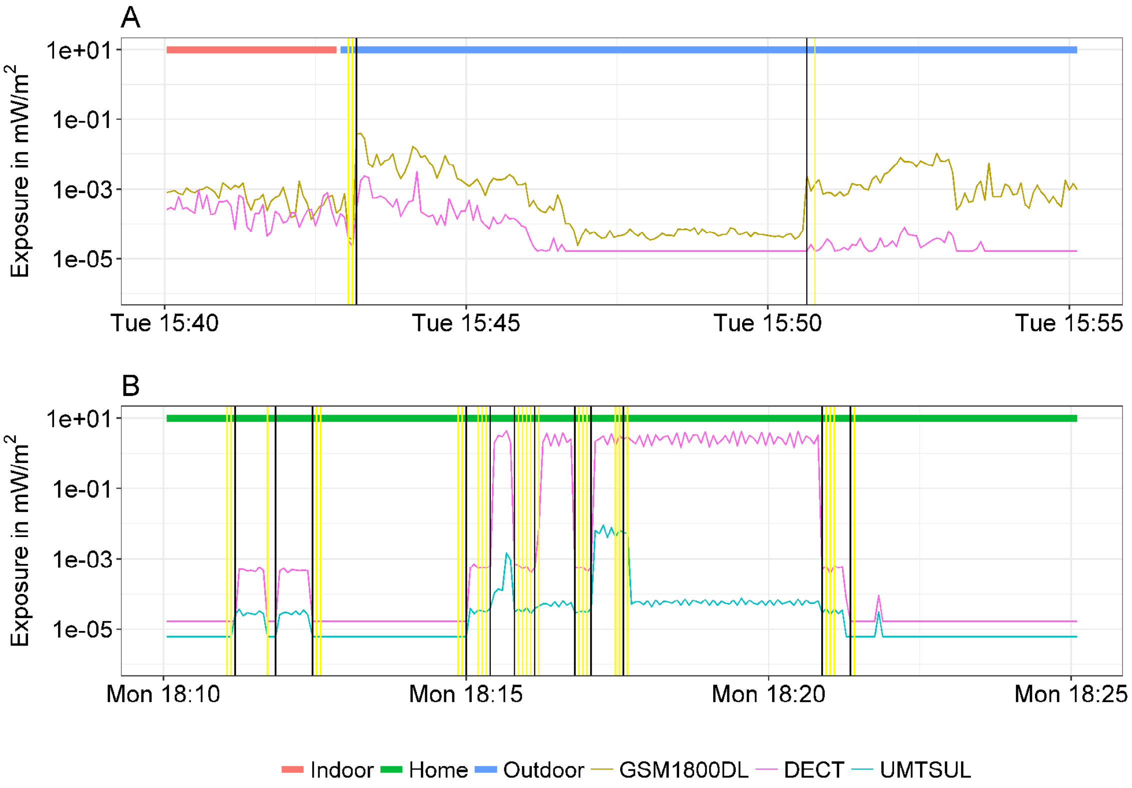

Fig. 3: Examples of the crosstalk correction applied to several different clusters in the time series, GSM1800DL and UMTS2100UL signals. The original measurements are shown as dotted lines, the corrected time series are shown as solid lines. The correlation (log) statistics apply to the cluster in the center of the time series plot.

A) An example of crosstalk from GSM1800DL to DECT while walking outdoors. The DECT signal is only corrected down to the median value for that activity, but no further. If the original signal (whether affected by minor crosstalk or not) was already below that, it will not be corrected.

B) An example of crosstalk from UMTS2100UL to DECT while at home. As shown, the levels measured in the (victim) DECT band are very low and the correction does not majorly affect the total levels.

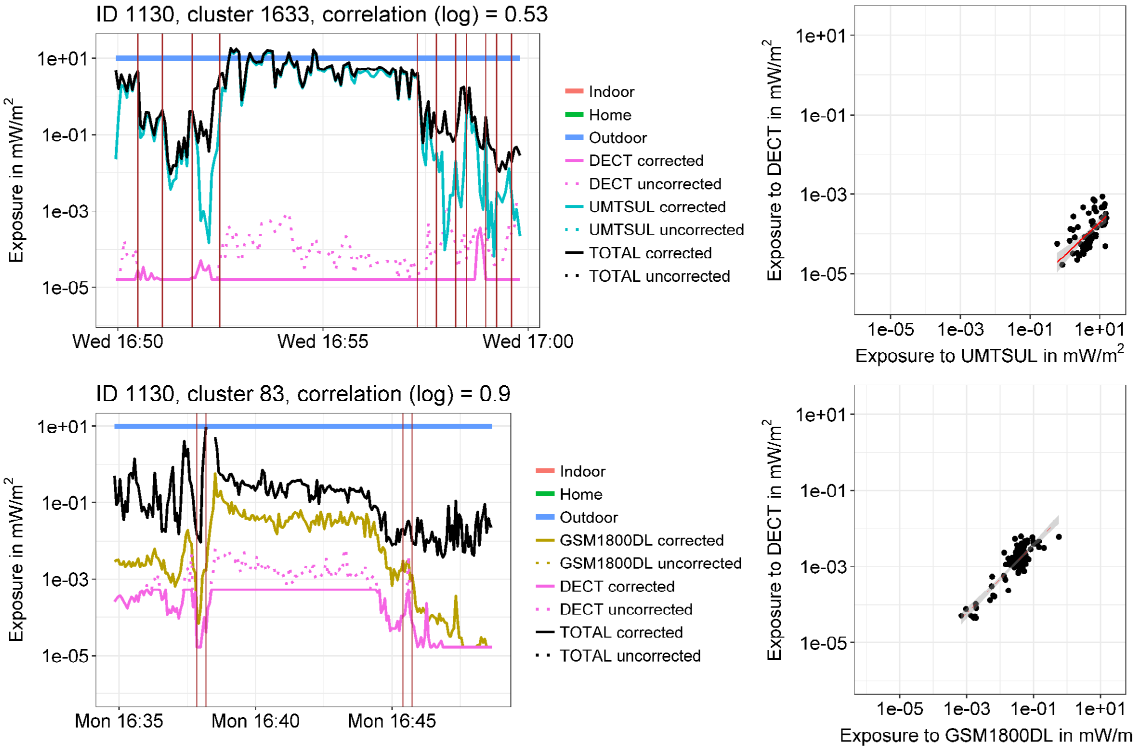

Fig. 4: The distribution of average exposure to GSM1800DL, DECT, UMTS2100UL, and total RF-EMF before correction, after correction replacing with the median crosstalk-unaffected exposure level, and after correction with the lower reporting limit for each of the 115 study participants (individually represented by the black lines). Widths of the colored areas are proportional to the number of observations.