Assessment of Contribution of Other Users to Own Total Whole-Body RF Absorption in Train Environment

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Running title: Contribution of other users to own total absorption

Abstract- **For the first time, the contribution of radio-frequent radiation originating from other people's devices to the total own whole-body absorption is assessed in a simulation study. Absorption in a train environment due to the base station's downlink is compared with the absorption due to the uplink (UL) of the user's own mobile device and absorption due to the UL of 0, 1, 5, or 15 other nearby active users. In a Global System for Mobile Communications (GSM) macrocell connection scenario, the uplink of 15 other users can cause up to 19% of the total absorption when calling yourself and up to 100% when not calling yourself. In a Universal Mobile Telecommunications System (UMTS) femtocell connection scenario, the uplink of 15 other users contributes to the total absorption of a non-calling user for no more than 1.5%. For 5 other users in the train besides the considered person, median total whole-body Specific Absorption Rate is reduced by a factor of about 400,000 when deploying a UMTS femtocell base station instead of relying on the GSM macrocell.**

Key Words- general public exposure; SAR; simulation, train, uplink, downlink, RF, RF-EMF

Assessment of exposure to radio frequency (RF) radiation is important to study compliance with national and international guidelines such as ICNIRP [ICNIRP, 1998] and for quantifying potential health effects. Exposure is usually assessed through measurement campaigns using personal exposimeters [Neubauer et al., 2007; Joseph et al., 2008; Knafl et al., 2008; Roösli et al., 2008; Frei et al., 2009; Viel et al., 2009; Joseph et al., 2010b] or spectrum analyzers (SA) [Foster, 2007; Joseph et al., 2010a], or through simulations [Plets et al., 2013, 2015]. These studies quantify exposure originating from the base stations (BS) or from the user device, or even perform a global assessment of the exposure due to both BS and user device [Plets et al., 2015]. However, current research does not quantify the exposure originating from devices of other nearby users. This was also mentioned in Frei et al. [2009] and Joseph et al. [2010b]. In densely populated environments where wireless connection quality is bad, such as train wagons, it is expected that exposure originating from other users can make up a substantial part of the global exposure. For the first time, this exposure will be determined for different scenarios in a train environment, using simulations, path loss measurements, and actual in-train measurements. A comparison is made between a Global System for Mobile Communications (GSM) macrocell and a Universal Mobile Telecommunications System (UMTS) femtocell deployment scenario, since largely different device transmit powers are observed for these two configurations. A UMTS femtocell will reduce exposure more than a GSM femtocell, thanks to more advanced power control capabilities. Further, the influence of the number of other users (0-15) and their position relative to the considered user are investigated. To the authors' knowledge, this is the first study to compare the different contributions that make up the total RF exposure of a human. It allows making a fair and complete assessment of the exposure reduction when deploying a femtocell base station (FBS) in a train environment and checks compliance with the ICNRIP guidelines for general public exposure [ICNIRP, 1998].

Two train scenarios will be investigated, for which a 20 x 2.83 m train wagon (type M6, lower floor of double-decker, built by Bombardier (Montreal, Canada) and Alstom (Levallois-Perret, France)) with 66 passenger seats is considered (Fig. 1). The first scenario is a reference scenario, where persons in the train make a phone call and connect to a GSM macrocell base station at 900 MHz (GSM900), a typical current deployment. The second scenario considers a future deployment, in which persons on the train make a phone call and connect to an in-train UMTS FBS.

The considered user's whole-body Specific Absorption Rate (SAR) will be evaluated at 5 specific locations L in the wagon (L = A, B, C, D, E in Fig. 1) and as a median over all locations in Figure 1 without a number (1-15) indicated on it (51 out of 66 locations remaining). The 15 locations with a number (1-15) in Figure 1 indicate the locations where *other users* are possibly present. These other users will contribute to the considered person's absorption at L. The total personal absorption SAR_L of a user at location L then consists of a contribution due to (i) sources for which L is located in the far field (FF) and (ii) sources for which L is located in the near field (NF). The FF SAR contribution consists of SAR_{BS} due to all base stations (Macrocell Base Station (MBS) and/or FBS) in the area and SAR_{other} due to the UL of all other users (all other users are assumed to be in the FF of each considered user at L). The NF contribution consists of SAR_{own} due to the UL of the own mobile device. SAR_L [W/kg] can then be expressed as follows:

$$SAR_L = \underbrace{\underbrace{\sum_{BS=femto,macro} S_L^{BS} \cdot SAR_{FF\_ref}^{f_{DL}(BS)}}_{SAR_{BS}} + \underbrace{\sum_{j=1}^{J} S_L^{other\_j} \cdot SAR_{FF\_ref}^{f_{UL}(other\_j)}}_{SAR_{other}}}_{FF} + \underbrace{\underbrace{P_L^{own} \cdot SAR_{NF\_ref}^{f_{UL}(own)}}_{SAR_{own}}}_{NF}$$

where SAR_{BS} [W/kg] is determined by S_L^{BS} [W/m²] , the incident power density at L due to the considered base station (MBS or FBS), and by $SAR_{FF\_ref}^{f_{DL}(BS)}$ [W/kg per 1 W/m²], the far-field reference SAR at the frequency of the downlink (DL) traffic of the considered BS (i.e., the FF SAR for an incident power of 1W/m²). SAR_{other} [W/kg] is determined by $S_L^{other\_j}$ [W/m²], the incident power density at L due to the UL of another user device *other_j* (not located at L), and by $SAR_{FF\_ref}^{f_{UL}(other\_j)}$ [W/kg per 1 W/m²], the far-field reference SAR at the frequency of the UL traffic of user device *other_j*. J is the total number of other user devices accounted for in the calculation, and will in this study be 0, 1, 5, or 15. Other users become active in ascending order: for 1 other user, only other user 1 in Figure 1 is active, for 5 other users, other users 1 to 5 in Figure 1 are active, etc. The third contributing factor in SAR_L is SAR_{own} [W/kg] and is determined by P_L^{own} [W], the transmit power of the own user device at location L, and by $SAR_{NF\_ref}^{f_{UL}(own)}$ [W/kg per 1 W], the near-field reference SAR at the frequency of the UL traffic of the own user device (i.e., the NF SAR for a transmitted power of 1W).

The two considered deployment scenarios in the train wagon are discussed hereafter. For the reference deployment (*GSM900 macrocell scenario),* it is assumed that a uniform DL power density (MBS to L) and UL power (own device at L to MBS) are observed over the entire train wagon (single value irrespective of position inside wagon), given the relatively large distance of the wagon to the MBS compared to the wagon dimensions. SAR_{MBS} due to the MBS and SAR_{own} due to the own user device are thus assumed to be spatially invariant throughout the train wagon, so spatial absorption differences within the wagon are only caused by being located nearer or farther from active other users. The median transmit powers and incident power densities for train users connecting to a GSM900 MBS are obtained from measurements along an actual train trajectory in Belgium (Ghent–Eupen track, approximately 200 km) [Aerts et al., 2015] and equal 12 dBm or 15.85 mW (accounting for the GSM duty cycle of 1:8) and 7.134×10^{-3} μW/m² (or -72 dBm), respectively. The power received from the base stations along the trajectory, and the power transmitted by the mobile phone were recorded with the application Azenqos (Freewill FX Company Limited, Bangkok, Thailand), installed on a mobile phone. Given the large variations anticipated in both received and transmit power of a mobile phone along the train trajectory (average train speed of around 85 km/h), measurements were conducted continuously during the train ride. For this purpose, 159 voice calls were established to the "Speaking Clock" (a recorded voice service that gives the exact time), lasting on average 68.6 s (with a standard deviation of 5 s).

For the future deployment (*UMTS femtocell scenario)*, an FBS with an Equivalent Isotropically Radiated Power (EIRP) of -15 dBm is located inside the wagon as indicated with the purple dot in Figure 1. This low EIRP is sufficient to cover the entire train wagon. Each of the locations A-E is at a different distance to the FBS and will thus experience a different SAR_{FBS} and SAR_{own}. In-train users farther from the FBS will experience a lower SAR_{FBS} due to the decreasing FBS DL power density, but a higher SAR_{own} due to the increasing device transmit power towards the FBS (higher distance between FBS and device). Additionally, also an increasing SAR_{other} will be noticed for users farther from the FBS, since the other user devices surrounding the considered user will also be located farther from the FBS and will thus also transmit at a higher power and expose the considered user more. Although all in-train users are assumed to connect to the FBS in the second scenario, the MBS and SAR_{MBS} will still contribute to the user's total SAR. The transmit power of all user devices (own and other) towards the FBS is calculated according to Plets et al. [2013]. The transmit power of another user device is then used in combination with the relevant path loss model to calculate $S_L^{other\_j}$, the power density incident at L originating from the other user device. The reference SAR values required for the two scenarios are obtained from Lauer et al. [2013] and are listed in Table 1.

We will now discuss the results for the SAR values in the two considered deployment scenarios (GSM macrocell and UMTS femtocell).

Table 2 lists the results for the whole-body SAR values in the reference GSM900 macrocell scenario. As stated earlier, SAR_{MBS} due to the MBS and SAR_{own} due to the own user device at A-E are constant, irrespective of the considered location. The table lists SAR_{other} due to other users in the wagon for 0, 1, 5, and 15 other simultaneous users, evaluated at the 5 different locations A-E and for the median of all locations. An asterisk in a cell indicates that the considered SAR does not depend on the number of other users and the value can be retrieved from the corresponding cell in the same row for 0 other users. SAR_{MBS} (MBS DL) is always negligible compared to SAR_{own} (own device UL). Another user at a distance of 50 cm next to the considered user (other user 1 next to location C, see Fig. 1) has a contribution of 7.1% to the total SAR, compared to 92.9% due to the user's own device (at C). When the own device is located farther from the active other user (e.g., contribution of other user 1 evaluated for own device at locations B and D or even farther, at A and E), the other user's contribution reduces to less than 0.5%. As the number of other users increases, the contribution of SAR_{other} to the total exposure increases. For 5 other users, their contribution is between 2.9% and 10.4%, depending on the location of the other users relative to the considered location A-E. At location C and for 15 other simultaneously active users, SAR_{other} is 14.3 μW/kg, which is 23.6% of the value of SAR_{own} due to the own device (60.6 μW/kg), corresponding to a contribution of 19.1% to SAR_{total}. Median values for the 51 locations where no other users (users 1-15) are sitting, are comparable with the values obtained at locations B and D (see last line of Table 2). When the considered user is not calling (SAR_{own} = 0 W/kg), SAR_{other} is always dominant over SAR_{MBS} and has a contribution of almost 100% to SAR_{total}: e.g., only other user 1 already induces a SAR_{other} of 0.265 μW/kg at location E, which is 8,632 times higher than the SAR_{MBS} of 3.07×10^{-5} μW/kg. For the assumed median device transmit power (12 dBm when accounted for 1:8 duty cycle), SAR_{total} remains at least 1,068 times below the ICNIRP guidelines of 0.08 W/kg [ICNIRP, 1998].

Table 3 lists the whole-body SAR values in the UMTS femtocell scenario. SAR_{MBS} due to the macrocell base station still contributes to the total SAR and is constant for all considered locations and numbers of other users (3.07×10^{-5} μW/kg). For location A, right next to the femtocell, SAR_{FBS} (1.51×10^{-3} μW/kg) dominates over SAR_{own} (9.88×10^{-6} μW/kg) in the total SAR value (contribution of more than 97%). The contribution SAR_{other} of other users is negligible, even for 15 other users (0.06%), due to the very low transmit power of all users in the wagon and the high incident power density in A. As the considered location is chosen farther from the FBS, SAR_{FBS} decreases to 1.33×10^{-4} µW/kg for C and to 4.89×10^{-5} µW/kg for E, respectively, while SAR_{own} increases to 1.57×10^{-5} µW/kg for C (contribution around 8%) and to 4.07×10^{-5} µW/kg for E (contribution around 33%), respectively. This is due to the lower FBS incident power density and the higher transmit power needed to connect with the FBS, compared to locations closer to the FBS. SAR_{FBS} contributes to SAR_{total} for about 74% in C and about 40% in E, but remains the most dominant part of SAR_{total} (1.20×10^{-4} µW/kg). Hence, together with SAR_{FBS}, also SAR_{total} decreases between A and E, by almost a factor 13 (1.55×10^{-3} µW/kg at A vs. 1.20×10^{-4} µW/kg at E). SAR_{other}'s contribution is never more than 1.03% (at location C, 15 other users), even for locations farther from the FBS where the own device and devices of other nearby users will have the highest transmit powers to reach the FBS. Median values are found to be around those observed at location C (the middle of the wagon).

When comparing the SAR values for the reference macrocell scenario with those for the femtocell scenario, the following observations can be made. For the UMTS femtocell scenario, the maximal SAR_{total} value (1.55×10^{-3} µW/kg) is recorded at location A and for 15 other active users, but this value is more than 5×10^{7} times below the limit of 0.08 W/kg and 48,323 times below the maximal SAR_{total} value in the macrocell scenario (location C, 15 other users, 74.9 µW/kg). The minimal benefit of installing an FBS –assuming a phone call- is a reduction of SAR_{total} by a factor 39,097 (location A, 0 other users, 60.6 µW/kg for macrocell vs. 1.55×10^{-3} µW/kg for femtocell). For 5 other users, median SAR values are even reduced by a factor 393,250. Further, Tables 2 and 3 show that just one MBS-connected user (user 1) at even 6.1 m from another user (user at location A), causes a SAR of 0.305 µW/kg (see Table 2), which is 197 times higher than the total SAR at A (1.55×10^{-3} µW/kg, see Table 3) due to

MBS, FBS, own device, and 15 other active users when all are connected to a femtocell. Or also, from the perspective of a non-user, installing a femtocell is already beneficial when just one other user starts making a phone call: the SAR due to the MBS, the FBS, and the 1 other user equals 1.54×10^{-3} μW/kg in the femtocell scenario, whereas the SAR due to the MBS and the 1 other user equals 0.305 μW/kg for the macrocell scenario, an increase of a factor 198 compared to the femtocell scenario. This indicates the clear benefits of installing femtocell base stations in areas with a bad connection quality, also from an exposure point-of-view.

It can be concluded that for current deployments, the contribution of other in-train users is sometimes not negligible: 15 other users connected to a GSM900 macrocell base station can induce absorption rates up to 24% of the absorption rate induced by the own device. This corresponds for the considered scenario to a contribution of 19% to the total absorption rate when calling yourself and a contribution of 100% when not calling yourself. A UMTS femtocell deployment in this environment drastically reduces the total absorption (when calling, at least by a factor 39,097) and makes the other users' contributions to the total absorption negligible (at most 1.5% of the total absorption when not calling yourself). Future research will consist of considering the influence of the antenna orientation of the mobile device and of the assessment of 4G and 5G scenarios. In-train Long-Term Evolution (LTE) femtocell base stations will provide the user with high data rate traffic, while keeping exposure low, thanks to the power control mechanisms.

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FIGURE 1: Map of train environment (20m x 2.83 m, 66 seats) with indication of considered locations A-E for exposure calculation, location of other possibly active other users (1-15), and femtocell base station location (purple dot with EIRP of -15 dBm indicated inside). For median values, all 51 seats without a number (1-15) are considered.

TABLE 1: Reference SAR values (mW/kg) for different frequencies f for near-field (NF) due to the uplink of the own user device, and for far-field (FF) due to the downlink of a base station BS or the uplink of another user device other_j.

[1]: in NF, SAR values are expressed per W of transmitted power

[2]: in FF, SAR values are expressed per W/m² of observed power density

[3]: N/A= not applicable

TABLE 2: SAR_{MBS}, SAR_{own}, $SAR_{other'}$, and SAR_{total} values for 0, 1, 5, and 15 other active users and contribution of SAR_{other} to SAR_{total} in GSM900 macrocell scenario, at locations A-B-C-D-E (see Figure 1) and median values over all locations without other users. An asterisk (*) indicates that the SAR value is the same as the SAR value for 0 other users.

TABLE 3: SAR_{MBS}, SAR_{FBS}, SAR_{own}, SAR_{other}, and SAR_{total} values for 0, 1, 5, and 15 other active users and contribution to SAR_{total} in UMTS femtocell scenario, at locations A-C-E (see Figure 1) and median values over all locations without other users. An asterisk (*) indicates that the SAR value is the same as the SAR value for 0 other users.

Figure 1

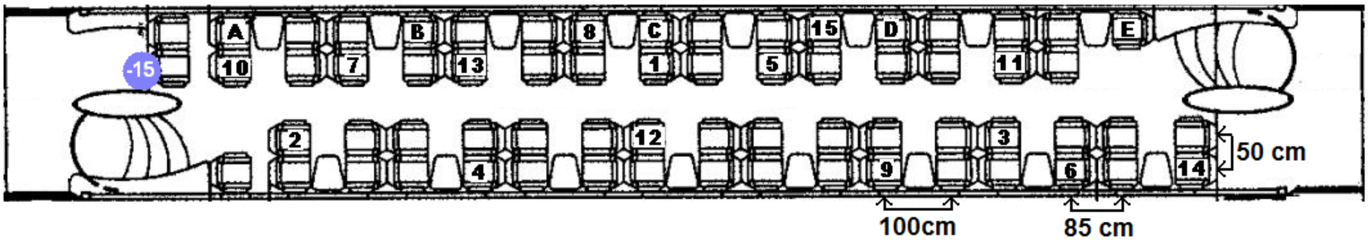

Table 1

SAR_{ref} [mW/kg]	frequency f_{DL}(BS)		frequency f_{UL}(own)		f_{UL}(other_j)
	900 MHz	2150 MHz	900 MHz	1950 MHz	1950 MHz
NF[1] (per W)	N/A[3]	N/A[3]	3.85	4.95	N/A[3]
FF[2] (per W/m²)	4.30	2.90	N/A[3]	N/A[3]	3.00

Table 2

#other users		0		1		5		15	
Location L		[µW /kg]	$\%_{total}$	[µW /kg]	$\%_{total}$	[µW /kg]	$\%_{total}$	[µW /kg]	$\%_{total}$
A	SAR_{MBS}	$3.07\text{x}10^{-5}$	0	*	0	*	0	*	0
	SAR_{own}	60.6	100	*	99.5	*	96.3	*	85.6
	SAR_{other}	0	0	0.305	0.5	2.33	3.7	10.2	14.4
	SAR_{total}	60.6	100	60.9	100	62.9	100	70.7	100
B	SAR_{MBS}	$3.07\text{x}10^{-5}$	0	*	0	*	0	*	0
	SAR_{own}	60.6	100	*	99.1	*	95.5	*	85.4
	SAR_{other}	0	0	0.553	0.9	2.88	4.5	10.4	14.6
	SAR_{total}	60.6	100	61.1	100	63.5	100	70.9	100
C	SAR_{MBS}	$3.07\text{x}10^{-5}$	0	*	0	*	0	*	0
	SAR_{own}	60.6	100	*	92.9	*	89.6	*	80.9
	SAR_{other}	0	0	4.61	7.1	7.00	10.4	14.3	19.1
	SAR_{total}	60.6	100	65.2	100	67.6	100	74.9	100
D	SAR_{MBS}	$3.07\text{x}10^{-5}$	0	*	0	*	0	*	0
	SAR_{own}	60.6	100	*	99.1	*	95.3	*	85.8
	SAR_{other}	0	0	0.553	0.9	3.10	4.7	10.0	14.2
	SAR_{total}	60.6	100	61.1	100	63.7	100	70.6	100
E	SAR_{MBS}	$3.07\text{x}10^{-5}$	0	*	0	*	0	*	0
	SAR_{own}	60.6	100	*	99.6	*	97.1	*	89.7

	SAR$_{\text{other}}$	0	0	0.265	0.4	1.82	2.9	6.96	10.3
	SAR$_{\text{total}}$	60.6	100	60.8	100	62.4	100	67.5	100
median	**SAR**$_{\text{MBS}}$	3.07x10^{-5}	0	*	0	*	0	*	0
	SAR$_{\text{own}}$	60.6	100	*	99.1	*	94.6	*	84.9
	SAR$_{\text{other}}$	0	0	0.541	0.9	3.49	5.4	10.8	15.1
	SAR$_{\text{total}}$	60.6	100	61.1	100	64.1	100	71.4	100

Table 3

#other users		**0**		**1**		**5**		**15**	
Location L		**[μW /kg]**	**%**$_{\text{total}}$	**[μW /kg]**	**%**$_{\text{total}}$	**[μW /kg]**	**%**$_{\text{total}}$	**[μW /kg]**	**%**$_{\text{total}}$
A	**SAR**$_{\text{MBS}}$	3.07x10^{-5}	1.97	*	1.97	*	1.97	*	1.97
	SAR$_{\text{FBS}}$	1.51x10^{-3}	97.39	*	97.39	*	97.38	*	97.33
	SAR$_{\text{own}}$	9.88x10^{-6}	0.64	*	0.64	*	0.64	*	0.64
	SAR$_{\text{other}}$	0	0	1.82x10^{-8}	0	1.49x10^{-7}	0.01	9.06x10^{-7}	0.06
	SAR$_{\text{total}}$	1.55x10^{-3}	100	1.55x10^{-3}	100	1.55x10^{-3}	100	1.55x10^{-3}	100
C	**SAR**$_{\text{MBS}}$	3.07x10^{-5}	17.10	*	17.01	*	16.99	*	16.92
	SAR$_{\text{FBS}}$	1.33x10^{-4}	74.17	*	73.82	*	73.72	*	73.40
	SAR$_{\text{own}}$	1.57x10^{-5}	8.74	*	8.70	*	8.69	*	8.65
	SAR$_{\text{other}}$	0	0	8.50x10^{-7}	0.47	1.10x10^{-6}	0.61	1.87x10^{-6}	1.03
	SAR$_{\text{total}}$	1.79x10^{-4}	100	1.80x10^{-4}	100	1.81x10^{-4}	100	1.81x10^{-4}	100
E	**SAR**$_{\text{MBS}}$	3.07x10^{-5}	25.50	*	25.50	*	25.45	*	25.25
	SAR$_{\text{FBS}}$	4.89x10^{-5}	40.63	*	40.62	*	40.55	*	40.23
	SAR$_{\text{own}}$	4.07x10^{-5}	33.87	*	33.87	*	33.81	*	33.54
	SAR$_{\text{other}}$	0	0	1.49x10^{-8}	0.01	2.30x10^{-7}	0.20	1.20x10^{-6}	0.99
	SAR$_{\text{total}}$	1.20x10^{-4}	100	1.20x10^{-4}	100	1.21x10^{-4}	100	1.21x10^{-4}	100
median	**SAR**$_{\text{MBS}}$	3.07x10^{-5}	18.89	*	18.84	*	18.78	*	18.69
	SAR$_{\text{FBS}}$	1.14x10^{-4}	69.88	*	69.71	*	69.49	*	69.16
	SAR$_{\text{own}}$	1.83x10^{-5}	11.24	*	11.21	*	11.17	*	11.12
	SAR$_{\text{other}}$	0	0	4.10x10^{-8}	0.02	4.02x10^{-7}	0.25	1.36x10^{-6}	0.84
	SAR$_{\text{total}}$	1.62x10^{-4}	100	1.63x10^{-4}	100	1.63x10^{-4}	100	1.64x10^{-4}	100