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Review article

Public exposure to radiofrequency electromagnetic fields in everyday microenvironments: An updated systematic review for Europe

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ABSTRACT

Communication technologies are rapidly changing and this may affect public exposure to radiofrequency electromagnetic fields (RF-EMF). This systematic review of literature aims to update a previous review on public everyday RF-EMF exposure in Europe, which covered publications until 2015. From 144 eligible records identified by means of a systematic search in PubMed, Embase and Web of Knowledge databases, published between May 2015 and 1 July 2018, 26 records met the inclusion criteria. We extracted quantitative data on public exposure in different indoors, outdoors and transport environments. The data was descriptively analyzed with respect to the exposure patterns between different types of environments. Mean RF-EMF exposure in homes, schools and offices were between 0.04 and 0.76 V/m. Mean outdoor exposure values ranged from 0.07 to 1.27 V/m with downlink signals from mobile phone base stations being the most relevant contributor. RF-EMF levels tended to increase with increasing urbanity. Levels in public transport (bus, train and tram) and cars were between 0.14 and 0.69 V/m. The highest levels, up to 1.97 V/m, were measured in public transport stations with downlink as the most relevant contributor. In line with previous studies, RF-EMF exposure levels were highest in the transportation systems followed by outdoor and private indoor environments. This review does not indicate a noticeable increase in everyday RF-EMF exposure since 2012 despite increasing use of wireless communication devices.

1. Introduction

Communication technology has been rapidly changed over the last decade with the introduction of smart phones and new communication technologies such as Long-Term Evolution (4G). Recent data of European countries indicates that mobile-cellular telephone subscription rates were 91.7 per 100 inhabitants in 2005 and 118.2 per 100 inhabitants in 2017 (International telecommunication union, 2017). During the last 10 years, the number of radiofrequency electromagnetic fields (RF-EMF) transmitters such as mobile phone base stations and wireless local area networks (WLAN) has increased (International telecommunication union, 2017). There is considerable uncertainty about consequences of these developments for the RF-EMF exposure of the public (30 MHz–300 GHz) (Foerster et al., 2018, Röösli et al., 2010).

Since RF-EMF is mostly used for communication, occurs basically everywhere such as residential areas (Thielens et al., 2016), commercial areas (Aminzadeh et al., 2016), industrial areas (Bolte et al., 2016), educational environments (van Wel et al., 2017b), and transportation environments (Bhatt et al., 2016c; Hardell et al., 2016) in urban, suburban, and rural areas (Sagar et al., 2016). Most of the current RF-EMF literature has used four main methods to assess EMF exposure including (1) spot measurement, made with portable devices that can be set up temporarily at various places, (2) fixed site monitoring, where data is collected using measurement devices at fix locations usually in the framework of a routine monitoring, (3) personal measurement with volunteers carrying a device during their daily activities, and (4) mobile microenvironmental measurement with trained researcher walking, bicycling or driving through various microenvironments carrying a personal measurement device (Röösli and Vienneau, 2014).

The widespread EMF exposure has raised some concerns about adverse health effect in humans. RF-EMF has been suspected to be carcinogenic (IARC, 2013) or cause non-specific symptoms such as headache, fatigue- and dizziness-related problems (Röösli et al., 2010). However, there is insufficient evidence to meet a firm conclusion on the

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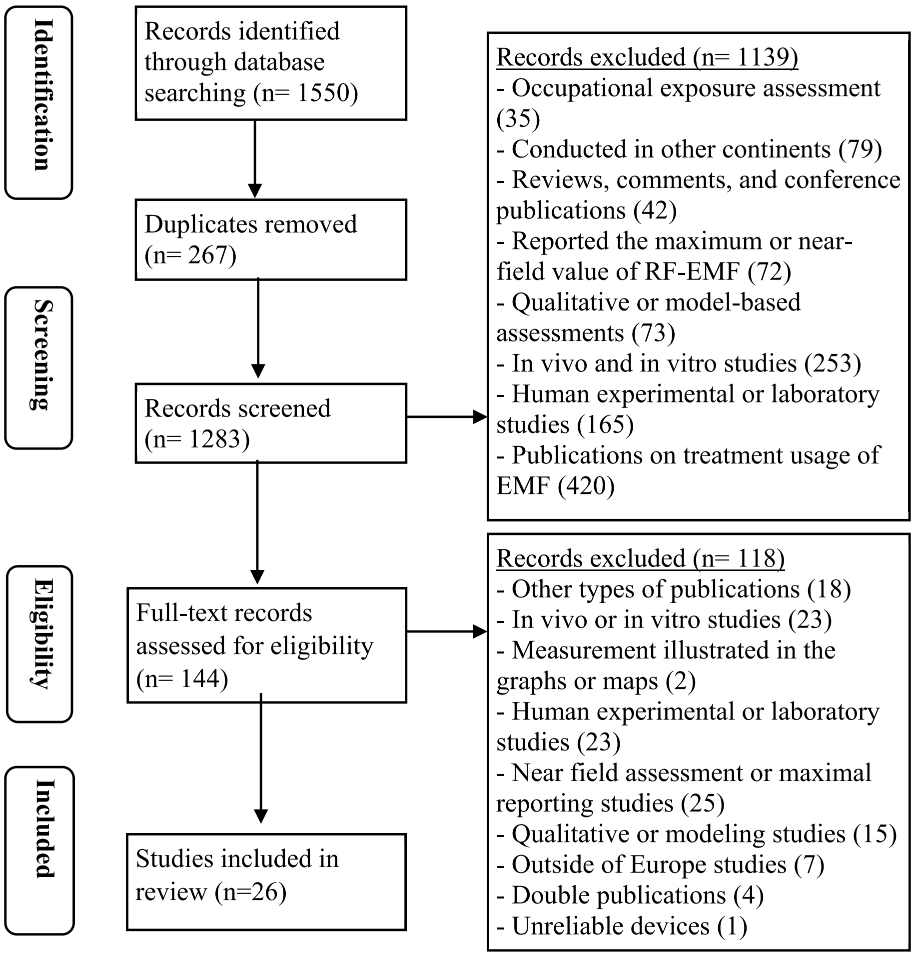

Fig. 1. PRISMA flow diagram of article selection and exclusion.

association between long-term low-level everyday environment RF-EMF exposure and adverse health effects (Baliatsas et al., 2012; Röösli, 2008; Röösli et al., 2010).

The health concerns have led to more investigations on the characterization of RF-EMF in different microenvironments. A narrative review on the European RF-EMF measurement studies concluded that the mean electric field strengths were between 0.08 V/m and 1.8 V/m with the overwhelming majority of measured values being below 1 V/m (Gajšek et al., 2015). A recent systematic review of studies, published between 1 January 2000 and 30 April 2015, which focused on exposure situations representative for the European populations, reported that the highest exposure levels occur in public transportation (~0.5–1.0 V/m), mainly due to uplink emitted from mobile phone handsets, followed by outdoor levels (~0.3–0.7 V/m) mainly due to downlink emitted from mobile phone base stations. Exposures at homes were typically in the range of 0.1–0.4 V/m with relevant contributions from the downlink, uplink and digital enhanced cordless telecommunication (DECT), whereas contribution from WLAN was relatively low (Sagar et al., 2018b).

Since the publication of this study, several new exposure assessment studies have been published. Thus, this paper aims at updating the recent review, by systematically reviewing recent literature on the characterization of public everyday exposures to RF-EMF in European countries.

2. Material and methods

2.1. Search strategy

We searched PubMed, Embase and Web of Knowledge for relevant records between 1 May 2015 and 1 July 2018 using four categories of keywords including exposure characteristics (thirteen keywords), study subject/area (23 keywords), exposure assessment/measurement (nine keywords) and radiation source (23 keywords) (Supplementary materials, Table S1). Moreover, we explored the technical/dosimetric RF-EMF studies in EMF-PORTAL site (www.emf-portal.org).

2.2. Study selection

HJ and MZ examined the title, abstract, and keywords of all publications. If the suitability of a record was unclear, its full text was evaluated. If no consensus was received on whether to include a particular study, MR made the final decision.

2.3. Eligibility criteria

Peer-reviewed records including letter to editor, brief communication and original articles, published in English language, were considered for inclusion in the current study. Moreover, following an

Table 1
Characteristics of 26 included studies, grouped by the type of measurement method.

ID†	Study	Country	sampling selection method	Place††	Microenvironment	Device	Date and time of measurement
				Spot measurement[a]			
1	van Wel et al. (2017a)	The Netherlands (Amsterdam)	Representative, not random	Urban	School (classrooms)	EME SPY 140	July 2011 and 2012, Weekday, 13:00–17:00
2	Djuric et al. (2015)	Serbia (Novi Sad)	Representative, not random	Urban	A university campus	Narda NBM 550	Not reported, Weekday, 10:00–14:00
3	Kottou et al. (2015)	Greece (Attica, Zakynthos, Lesvos-Agiasos and Mytilene-)	Random	Urban	Home (indoor)	Aaronia spectrum analyzer, Narda EMR-300	Not reported, Not reported, Not reported
4	Calvente et al. (2015)	Spain (Granada)	Representative, not random	Urban, suburban, and rural	Outdoor	TS/001/UB Taoma	2012 and 2013, Not reported, 14:00–16:00
				Fixed site monitoring studies[b]			
5	Sánchez-Montero et al. (2017)	Spain (Alcalá de Henares)	Random	Urban	Outdoor (city environment)	Narda EMR-300	October and December of 2006–2015, Not reported, 10:00–14:00
6	Rowley and Joyner (2016)	Italy (whole country)	Representative, not random	Not reported	homes, public places (including zones opened to the public like gardens, shops, etc.), hospitals, and schools (outdoor)	a monitoring system (EIT-EE4070 probe)	June 2002 and November 2006, whole week, Whole day
				Personal measurements with volunteers[c]			
7	Birks et al. (2018)	Multi country (Denmark, the Netherlands, Slovenia, Switzerland, and Spain)	Random	Urban and rural	Day, night, weekday, weekend, home, school, outdoor, traveling, bus, car, train, tram, metro	ExpoM-RF	August 2014 and February 2016 Whole week, Whole day
8	Hedendahl et al. (2017)	Sweden (Örebro)	Representative, not random	Urban	School	EME SPY 200	March and November 2016, Weekday, 8:00–16:00
9	van Wel et al. (2017b)	The Netherlands (Utrecht)	Random	Urban	Unspecified	ExpoM-RF	May and October 2015, Not reported, Whole day
10	Roser et al. (2017)	Switzerland	Representative, not random	Rural	Home, school, outdoors, train, bus, car, day, night, workdays, weekends	ExpoM-RF	May 2013 and April 2014, Whole week, Whole day
11	Valič et al. (2015)	Slovenia	Representative, not random	Urban and rural	Outdoor and indoor	EME SPY 121	February 2010 and March 2011, Not reported, Whole day
12	Martens et al. (2015)	The Netherlands (Amsterdam and Purmerend)	Random	Urban, suburban, rural	Indoor	EME SPY 121	2009 and 2010, Whole week, Whole day
				Mobile microenvironmental measurements with trained researcher[d]			
13	Sagar et al. (2018a)	Multi countries (including Switzerland)	Representative, not random	Urban and rural	City center, rural center, central residential area, industrial area, non-central residential area, rural residential, tourist areas, university areas	ExpoM-RF, EME SPY 201	March 2015 and April 2017 Not reported Daytime
14	Aminzadeh et al. (2018)	Belgium (Ghent)	Representative, not random	Urban	An urban residential outdoor	EME SPY 200, ExpoM-RF, A personal, distributed exposimeter	Not reported Not reported Not reported
15	Hardell et al. (2017)	Sweden (Stockholm Old Town)	Representative, not random	Urban	outdoor (Royal Castle, Supreme Court, Stortorget, Kornhamnstorg, Järntorget, Swedish Parliament)	EME SPY 200	April 2016, Weekday, Daytime
16	Thielens et al. (2016)	Belgium (Ghent)	Representative, not random	Urban	Outdoor (garden), home including living room, kitchen + toilet, stairs, bathroom, platform, bedrooms	A personal, distributed exposimeter	Not reported, Not reported, Not reported
17	Sagar et al. (2016)	Switzerland	Representative, not random	Urban, rural	City centers, centers of rural areas, central residential areas, non-central residential areas, rural residential areas, industrial areas, bus, tram, train	ExpoM-RF	March and July 2014, Weekday, Daytime
18	Hardell et al. (2016)	Sweden (Stockholm)	Representative, not random	Urban	Railway station (indoor)	EME SPY 200	November 2015, Whole week, Daytime

(*continued on next page*)

Table 1 (*continued*)

ID†	Study	Country	sampling selection method	Place††	Microenvironment	Device	Date and time of measurement
19	Gonzalez-Rubio et al. (2016)	Spain (Albacete)	Random	Urban	Outdoor	EME SPY 140	February.and April 2015, Whole week, avoiding Fridays and Saturdays, 20:30 and 23:30
20	Bolte et al. (2016) *	The Netherlands (Amersfoort) and United Kingdom (Cambridge)	Representative, not random	Urban	Industrial, residential, city office and city environment (outdoor)	EME SPY 120, EME SPY 121, EME SPY 140	May, October 2013, Not reported, Daytime
21	Bhatt et al. (2016b)	Australia and Belgium	Representative, not random	Urban, suburban, rural	19 microenvironments in Belgium	ExpoM-RF 64, ExpoM-RF 40	April, May, March 2015 Whole week, Daytime
22	Aminzadeh et al. (2016)	Belgium (Ghent)	Representative, not random	Urban	An office	EME SPY140	Not reported, Not reported, Not reported
23	Thielens et al. (2015)	Belgium (Ghent)	Random	urban	A suburban residential area	EME SPY 140	Not reported, Weekday, 12:00–16:00
24	Gryz and Karpowicz (2015)	Poland (Warszawa)	Representative, not random	Urban	underground infrastructure of the metro	EME SPY 121	summer and autumn of 2014, Not reported, Daytime
				Mixed method (spot measurement and personal measurement with volunteers)*			
25	Gallastegi et al. (2018)	Spain (Basque Country)	Representative, not random	Urban	Home (living room and child's bedroom), schools (playground and classroom) and park	ExpoM –RF	2014 and 2016 Whole week Whole day
26	Martens et al. (2016)	The Netherlands (Bunnik, Odijk, Zeist, de Bilt and Bilthoven)	Random	Urban and rural	Home, outdoor, bedroom (spot measurement)	EME SPY 140, ExpoM-RF	November 2013 and May 2014, Not reported, Whole day

† Identify document.

†† "And" indicates that the measurement has been reported independently for each place and "," indicates that the measurement has been reported mixed together for the places.

* The measurement type were car- and bike-mounted by the trained researchers.

** These studies have done spot measurement and personal measurements with volunteers.

[a] EMF assessment with portable devices that can be set up in individuals places provide an objective exposure surrogate at the place.

[b] EMF assessment with establishment of some measurement devices in some fix locations through an area.

[c] Measurement device carried by the participant and exposure data are collected as study participants go about their daily lives.

[d] Measurement device carried by a trained researcher walk/driving through some microenvironment to record RF-EMF.

earlier review by Sagar et al. (2018b), we considered publications which met additional following criteria: (1) carried out in European countries except Turkey, (2) reported the mean or median level (or enough data to allow calculation) of RF-EMF in at least one microenvironment, (3) measurement of RF-EMF carried out with a well-characterized meter such as a Narda device, EME Spy or Expom-RF (Bhatt et al., 2016a). In addition, in the case of duplication with multiple articles publishing data on the same results from a specific location or area, we used the most comprehensive record.

Studies with the following characteristics were excluded: (1) occupational exposure measurements, (2) applying a non-representative sampling strategy (i.e. only looking for worst case areas), (3) conducted in non-European countries, (4) reviews, comments and conference publications, (5) reported only maximum level of RF-EMF per environment (6) RF-EMF measurement in the near-field (i.e. measurement RF-EMF around a few meters of base stations), (7) publication with a qualitative or model-based assessment of RF-EMF, (8) data exclusively presented in the form of graphs or maps with no quantitative (numerical) information (9) in vivo and in vitro studies (10) human experimental (laboratory) or treatment studies.

2.4. Data extraction

Qualitative and quantitative data were extracted using a predefined form. This included study characteristics of the selected records including the name of the author(s), the publication year, the aim of investigation, study type, timing of measurement (i.e., calendar period, weekday, weekend, or whole week and the time of sampling), country, microenvironments, measurement instrument, and sample selection method. In the quantitative part, we extracted the following summarizing metrics from the results of electric field measurements from each study: mean, standard deviation (SD), minimum, 25th percentile (Q1), median (Q2), 75th percentile (Q3), and maximum. These values were extracted for six frequency bands grouped into the downlink (emitted radiation from base stations to the mobile cell phones), uplink (emitted radiation from mobile cell phones to the base stations), WLAN, broadcast (TV and radio frequencies), DECT, and total RF-EMF.

2.5. Data analysis

We descriptively analyzed all findings using Excel. In addition, GraphPad prism version 7 (GraphPad Software, San Diego, CA, USA) was applied to illustrate graphs.

3. Results

3.1. Selected studies

In the literature searches, 1550 records were identified. After screening the titles and abstracts, 144 publications remained. We excluded 118 records after examination of the full texts, and finally, 26 studies (Aminzadeh et al., 2016; Aminzadeh et al., 2018; Bhatt et al.,

Table 2
Mean and median (V/m) of total radiofrequency electromagnetic fields exposure form spot measurement and fixed site monitoring studies.

Study	Microenvironment/status	Mean (Median)	Sample*
	Spot measurement[a]		
Gallastegi et al. (2018)	Home (living room)	0.19 (0.11)	104 s
	Home (bedroom)	0.27 (0.14)	104 s
	School (classroom)	0.76 (0.18)	26 s
	School (classroom)	0.21 (0.17)	25 s
	School (playground)	0.31 (0.27)	26 s
	Park	0.48 (0.22)	79 s
van Wel et al. (2017a)	School (classroom)	0.16[†]	201 s
Martens et al. (2016)	Home (bedroom)	0.33 (0.07)**	47 s
Djuric et al. (2015)	A campus of the university	0.29	10 s
Kottou et al. (2015)	Home (Attica)	0.11	22 s
	Home (Agiasos)	0.19	739 s
	Home (Mytilene)	0.22	215 s
	Home (Zakynthos)	0.02[b]	46 s
Calvente et al. (2015)	Urban, sub urban and rural outdoor	0.12 (0.16)	123 s
	Population size (≤ 2031 inhabitants)	0.12 (0.15)	61 s
	Population size (> 2031 inhabitants)	0.13 (0.15)	51 s
	Fixed site monitoring[b]		
Sánchez-Montero et al. (2017)	outdoor (2006)	0.28	78 s
	outdoor (2010)	0.41	78 s
	outdoor (2015)	0.40	78 s
Rowley and Joyner (2016)	2002–2006 (all microenvironments combined)	0.54	50,662,433 m
	2002 (all microenvironments combined)	0.71	138,960 m
	2003 (all microenvironments combined)	0.97	2,549,156 m
	2004 (all microenvironments combined)	0.89	7,288,656 m
	2005 (all microenvironments combined)	0.62	13,129,898 m
	2006 (all microenvironments combined)	0.41	27,555,764 m
	Homes (outside)	0.73	27,369,656 m
	Public places (outside)	0.57	10,121,217 m
	Schools (outside)	0.28	12,275,279 m
	Hospitals (outside)	0.64	896,282 m

*m: #of measurement values; s: #of (fixed) sites.
** Mean of downlink.
†Included downlink (0.10 V/m), uplink (0.04 V/m), DECT (0.11 V/m), WLAN (0.03 V/m), broadcast (0.03 V/m), unspecified (0.02 V/m).
[a] Made with portable devices that can be set up in individuals places provide an objective exposure surrogate at the place.
[b] Made with establishment of measurement device in some fix locations through an area.

2016b; Birks et al., 2018; Bolte et al., 2016; Calvente et al., 2015; Djuric et al., 2015; Gallastegi et al., 2018; Gonzalez-Rubio et al., 2016; Gryz and Karpowicz, 2015; Hardell et al., 2016; Hardell et al., 2017; Hedendahl et al., 2017; Kottou et al., 2015; Martens et al., 2015; Martens et al., 2016; Roser et al., 2017; Rowley and Joyner, 2016; Sagar et al., 2016; Sagar et al., 2018a; Sánchez-Montero et al., 2017; Thielens et al., 2015; Thielens et al., 2016; Valič et al., 2015; van Wel et al., 2017a, 2017b) were included in the review (Fig. 1).

Table 1 shows the characteristics of included papers between 2015 and 2018. Studies were conducted in twelve European countries. In total, we included four spot measurement studies, two fixed site monitoring studies, six personal measurement with volunteers studies, twelve mobile microenvironmental measurement studies and two mixed method studies (spot measurement and personal measurement with volunteers). In total, 18 studies selected volunteers or sample sites to be representative for the study area. Eight studies selected sites or volunteers randomly from a comprehensive list of microenvironments or people. The RF-EMF was assessed in outdoors and indoor environments, and transportation systems of the urban, suburban, and rural areas using at least one of the following devices: EME SPY 120, 121, 140, and 200 (14 studies), Narda EMR-300 and NBM-550 (three studies), Aaronia spectrum analyzer (one study), TS/001/UB Taoma (one study), ExpoM-RF (nine studies), EMF Monitoring System (one study), and a recently developed distributed wearable personal exposimeter (one study) (Thielens et al., 2016). The measurements were conducted between 2000 and 2017 during weekday (six studies) and whole week (eight studies) in daytime (thirteen studies), nighttime (one study), and whole day (eight studies). Some studies did not report date (six studies), days (twelve studies), or time (four studies) of their measurements.

The mean and median RF-EMF exposure values from spot measurement and fixed site monitoring studies are presented in Table 2 (for percentiles see supplementary materials, Table S2), respectively. The exposure levels varied between 0.11 and 0.97 V/m).

Table 3 depicts the mean and median values of RF-EMF exposure in the different microenvironments, measured by personal measurement with volunteers studies. Percentile values are displayed in Table S3 (Supplementary materials). The highest mean total RF-EMF exposure was related to Switzerland's cars (0.56 V/m) and the lowest mean of exposure occurred in Swedish schools (0.09 V/m). Median personal total RF-EMF exposure of all environments combined was 0.20 V/m or lower in all countries.

In Table 4 the mean and median RF-EMF exposure values in different microenvironments, measured by mobile microenvironmental measurement studies are shown (for percentiles see Table S4 in Supplementary materials). The highest and the lowest mean total RF-EMF exposure were related to Swedish outdoor environments (1.27 V/m) and the rural/suburban Belgium residential indoors (0.04 V/m), respectively.

3.2. Microenvironments/status

3.2.1. Indoors

Fig. 2 illustrates public exposure to RF-EMF bands in indoor microenvironments. In total, four spot measurement studies, seven personal measurement with volunteers studies, and two mobile microenvironmental measurement studies reported the electric field strength of different RF-EMF bands in indoor microenvironments, mostly from schools and private homes and occasionally from some public microenvironments such as a library or an airport. Total RF-EMF exposure values were below 0.30 V/m in most circumstances.

Table 3
Mean and median (V/m) radiofrequency electromagnetic fields exposure: personal measurement with volunteers studies.

Study	Activity/status	Mean (Median)							Sample[*]
		Total[†]	Downlink	Uplink	DECT	WLAN	Broadcast	Unspecified	
Gallastegi et al. (2018)	All environments (Spain)	0.25 (0.14)							48
	Homes	0.26 (0.17)							48
	Bedroom	0.21 (0.10)							48
	living room	0.31 (0.14)			0.03 (0.005)	0.07 (0.03)			48
	classrooms					0.03 (0.02)			48
Birks et al. (2018)	all environments (5 countries)	0.26 (0.17)	0.17 (0.1)	0.09 (0.04)	0.03 (0.009)	0.04 (0.03)	0.17 (0.06)		529
	Day	(0.19)	(0.11)	((0.05)	(0.01)	(0.03)	(0.06)		529
	Night	(0.09)	(0.04)	((0.02)	(0.006)	(0.01)	(0.04)		529
	Weekday	(0.16)	(0.10)	((0.04)	(0.009)	(0.03)	(0.06)		529
	Weekend	(0.17)	(0.09)	((0.04)	(0.006)	(0.02)	(0.06)		529
	Home	(0.11)	(0.05)	(0.02)	(0.006)	(0.02)	(0.05)		529
	School	(0.11)	(0.05)	(0.02)	(< DL)	(0.01)	(0.04)		529
	Outdoor	(0.24)	(0.17)	(0.03)	(0.006)	(0.02)	(0.06)		529
	Traveling	(0.25)	(0.16)	(0.09)	(0.006)	(0.02)	(0.06)		511
	Bus	(0.28)	(0.19)	(0.10)	(< DL)	(0.02)	(0.07)		114
	Car	(0.23)	(0.15)	(0.07)	(< DL)	(0.02)	(0.05)		372
	Train	(0.38)	(0.21)	(0.20)	(< DL)	(0.02)	(0.03)		37
	Tram	(0.28)	(0.19)	(0.11)	(0.01)	(0.02)	(0.05)		18
	Metro	(0.45)	(0.31)	(0.2)	(0.006)	(0.02)	(0.13)		4
	Total Denmark	(0.18)	(0.11)	(0.06)	(0.009)	(0.03)	(0.06)		47
	Total the Netherlands	(0.16)	(0.12)	(0.03)	(0.02)	(0.03)	(0.05)		56
	Total Slovenia	(0.15)	(0.11)	(0.03)	(0.009)	(0.02)	(0.06)		54
	Total Switzerland	(0.12)	(0.06)	(0.05)	(0.006)	(0.02)	(0.04)		98
	Total Spain-Gipuzkoa	(0.14)	(0.07)	(0.03)	(0.09)	(0.02)	(0.09)		49
	Total Spain- Granada	(0.26)	(0.26)	(0.26)	(0.26)	(0.26)	(0.26)		30
	Total Spain- Menorca	(0.19)	(0.09)	(0.04)	(< DL)	(0.02)	(0.02)		53
	Total Spain- Sabadell	(0.20)	(0.13)	(0.03)	(0.02)	(0.03)	(0.08)		99
	Total Spain- Valencia	(0.17)	(0.10)	(0.05)	(0.006)	(0.02)	(0.07)		43
Hardell et al. (2017)	School	0.09 (0.04)	0.06	0.05	< DL (< DL)	0.05	0.02		18
van Wel et al. (2017b)	All environments (Utrecht)	0.26 (0.23)	0.17	0.14	0.04 (0.03)		0.12	0.06	34
Roser et al. (2017)	All environments (Switzerland)	0.15 (0.10)	0.07 (0.04)	0.13 (0.07)	0.02 (0.005)	0.03 (0.01)	0.04 (0.01)		90
	Outdoor	0.24 (0.14)	0.14 (0.07)	0.18 (0.06)	0.02 (0.004)	0.03 (0.01)	0.04 (0.02)	0.06	85
	Home	0.11 (0.06)	0.05 (0.02)	0.08 (0.02)	0.01 (0.002)	0.02 (0.009)	0.04 (0.01)	0.04	90
	School	0.15 (0.08)	0.04 (0.02)	0.14 (0.06)	0.01 (0.003)	0.03 (0.01)	0.01 (0.005)	0.02	87
	Train	0.45 (0.36)	0.18 (0.14)	0.40 (0.29)	0.04 (0.02)	0.02 (0.01)	0.05 (0.02)	0.08	20
	Bus	0.50 (0.26)	0.15 (0.07)	0.46 (0.20)	0.04 (0.005)	0.04 (0.01)	0.10 (0.04)	0.06	33
	Car	0.56 (0.15)	0.10 (0.07)	0.54 (0.09)	0.06 (0.004)	0.04 (0.01)	0.04 (0.02)	0.07	45
	Day	0.17 (0.11)	0.08 (0.05)	0.14 (0.07)	0.02 (0.006)	0.03 (0.02)	0.04 (0.02)	0.02	90
	Night	0.10 (0.06)	0.05 (0.02)	0.07 (0.01)	0.01 (0.001)	0.01 (0.007)	0.04 (0.02)	0.03	90
	Workdays	0.14 (0.08)	0.06 (0.03)	0.12 (0.04)	0.01 (0.003)	0.02 (0.01)	0.03 (0.02)	0.01	38
	Weekends	0.15 (0.08)	0.06 (0.04)	0.12 (0.04)	0.01 (0.003)	0.02 (0.01)	0.03 (0.01)	0.01	38
Martens et al. (2016)	All environments (Netherlands)		0.18 (0.10)						47
	Home		0.18 (0.08)						47
	Night		0.18 (0.08)						47
Valič et al. (2015)	All environments (Slovenia)		0.07 (GSM)		0.07	0.06			18
Martens et al. (2015)	Home and bedroom		0.09 (0.06)						93
	Home		0.08 (< 0.05)						93
	Bedroom		0.08 (< 0.05)						93

[*] #of volunteers who contributed to the mean/median levels.

In six studies (two spot measurement and four personal measurement with volunteers studies) from schools, the mean exposure levels ranged from 0.09 V/m to 0.76 V/m. In a spot measurement study, DECT (47%) and downlink (37%) contributed the most to the total RF-EMF in the 201 classrooms of Amsterdam, followed by uplink (6%), WLAN (3%), broadcasting (3%), and unspecified (4%) (van Wel et al., 2017b). The median values of personal volunteer measurements collected from 529 children's schools in five countries indicated that 56% of exposure was from downlink signals and broadcasting whereas the uplink, WLAN and DECT contributed only little (Birks et al., 2018). Hedendahl et al. (2017) observed higher contributions from uplink (27%) and WLAN (30%) in Swedish schools (Hedendahl et al., 2017). Roser et al. (2017) found the highest portion of signals for uplink (86%) followed by downlink (7%), DECT (4%), WLAN and broadcasting (each one 0.4%) as well as unspecified (2.2%) in personal measurements of adolescents during their stay at Swiss schools (Roser et al., 2017).

In private homes, the range of mean RF-EMF exposures was between 0.04 V/m and 0.24 V/m in eleven investigations including three spot measurement, seven personal measurement with volunteers, and one mobile microenvironmental measurement studies. Typically, the downlink was the most relevant exposure source except in a personal measurement with volunteers study conducted by Roser et al. (2017) in Swiss rural homes with uplink contributing 51%, followed by downlink (20%), broadcasting (13%), WLAN (3%), and DECT (0.07%).

3.2.2. Outdoors

Overall, outdoor RF-EMF exposure levels have been measured in rural and urban residential areas, city centers, and other outdoor areas by four spot measurement, one personal measurement with volunteers and nine mobile microenvironmental measurement studies. Mean RF-EMF exposure levels in the outdoor microenvironments ranged from 0.07 V/m in Ghent, Belgium rural and suburban residential outdoor to 1.27 V/m in the Old Town of Stockholm, Sweden, both of them assessed by mobile microenvironmental measurement (Fig. 3).

Fig. 3 illustrates that the range of mean exposure in rural/suburban residential outdoors (0.07–0.26 V/m) was lower than in urban areas

Table 4
Mean and median (V/m) radiofrequency electromagnetic fields exposure: mobile microenvironmental measurement studies.

Study	Microenvironment/status	Mean (Median)							Sample*
		Total	Downlink	Uplink	DECT	WLAN	Broadcast	Unspecified	
Sagar et al. (2018a)	City center	0.48 (0.48)	0.47 (0.46)	0.06		0.02	0.09		3
	Central residential areas	0.35 (0.38)	0.34 (0.37)	0.04		0.02	0.07		3
	Industrial areas	0.69 (0.63)	0.67 (0.61)	0.06		0.02	0.14		2
	Non central residential areas	0.23 (0.14)	0.18 (0.14)	0.02		0.01	0.14		3
	Rural centers	0.26 (0.27)	0.26 (0.26)	0.02		0.01	0.04		2
	Rural residential areas	0.22 (0.23)	0.21 (0.22)	0.02		< DL	0.05		2
	Bus	0.37	0.28	0.22		0.02	0.12		3
	Train	0.57	0.33	0.47		0.05	0.03		4
	Tram	0.38	0.3	0.21		0.03	0.08		3
Aminzadeh et al. (2018)	Urban residential outdoor		0.27**						
Hedendahl et al. (2017)	Outdoor (Old Town)	1.27 (0.45)	1.26	0.08	0.04 (< DL†)	0.01 (< DL)	0.08 (< DL)	0.12	1
Thielens et al. (2016)	Total EMF (Rooms + garden)		0.08 (0.08)						1
	Outdoor (garden)		0.03 (0.03)						1
	Home (indoor)		0.08						1
Sagar et al. (2016)	City Center	0.47 (0.43)	0.46 (0.41)	0.04 (0.02)	0.04	0.03	0.07 (0.03)	0.06	10
	Rural center	0.23 (0.17)	0.22 (0.14)	0.02 (0.009)	0.02	0.03	0.06 (0.03)		30
	Central residential area	0.32 (0.32)	0.29 (0.30)	0.02 (0.02)	0.03	0.03	0.13 (0.11)		9
	Non-central residential area	0.25 (0.21)	0.24 (0.21)	0.02 (0.01)	< DL	0.03	0.09 (0.04)		10
	Rural residential area	0.23 (0.19)	0.21 (0.15)	0.01 (0.007)	0.02	0.03	0.07 (0.03)	0.05	28
	Industrial area	0.53 (0.57)	0.51 (0.55)	0.01 (0.01)	0.04	0.03	0.12 (0.08)	0.06	10
	Bus	0.39	0.26	0.25	0.03	0.03	0.15		NR
	Train	0.46	0.26	0.37	0.02	0.04	0.04	0.06	NR
	Tram	0.69	0.57	0.36	0.04	0.05	0.07	0.12	NR
Hardell et al. (2016)	Railway station	1.21 (0.59)	1.20	0.05	0.08 (0.003)	0.02	0.10 (< DL)	0.06	1
Gonzalez-Rubio et al. (2016)	Outdoor		0.29		0.12				110
Bolte et al. (2016)	Residential (Cambridge)		0.15						1
	Industrial (Cambridge)		0.16						1
	City (Cambridge)		0.17						1
	Residential (Amersfoort)		0.18						1
	Office (Amersfoort-outdoor)		0.20						1
	inner city (Amersfoort)		0.43						1
Bhatt et al. (2016b)	Residential outdoor (urban)	0.92 (0.87)	0.91 (0.86)	0.01 (0.01)			0.11 (0.11)	0.06	1
	Residential indoor (urban)	0.24 (0.25)	0.23 (0.23)	0.05 (0.02)			0.07 (0.07)	0.01	1
	Office indoor (urban)	0.11 (0.10)	0.07 (0.06)	0.03 (0.02)			0.02 (0.01)	0.08	1
	Park (urban)	0.96 (0.90)	0.90 (0.85)	0.01 (0.01)			0.25 (0.26)	0.22	1
	City center	1.16 (0.95)	1.12 (0.93)	0.03 (0.02)			0.20 (0.20)	0.22	1
	Library (urban)	0.99 (0.77)	0.94 (0.74)	0.01 (0.01)			0.14 (0.14)	0.28	1
	Shopping center (urban)	0.14 (0.13)	0.08 (0.07)	0.07 (0.06)			0.06 (0.04)	0.07	1
	Train station (urban)	0.89 (0.30)	0.82 (0.11)	0.06 (0.09)			0.11 (0.12)	0.32	1
	Train	0.34 (0.24)	0.13 (0.11)	0.25 (0.09)			0.05 (0.01)	0.18	1
	Tram station (urban)	1.97 (1.95)	1.91 (1.91)	0.02 (0.01)			0.18 (0.17)	0.45	1
	Tram (urban)	0.53 (0.43)	0.45 (0.33)	0.04 (0.02)			0.17 (0.15)	0.22	1
	Bus (urban)	0.45 (0.41)	0.33 (0.26)	0.03 (0.02)			0.25 (0.19)	0.17	1
	Airport indoor	0.17 (0.16)	0.15 (0.14)	0.06 (0.05)			0.02 (0.01)	0.05	1
	Bicycle (urban)	0.78 (0.73)	0.74 (0.69)	0.01 (0.01)			0.02 (0.02)	0.25	1
	Bicycle (rural/suburban)	0.15 (0.12)	0.15 (0.11)	0.01 (0.01)			0.02 (0.01)		1
	Car (urban/suburban)	0.40 (0.31)	0.37 (0.29)	0.01 (0.01)			0.09 (0.08)	0.12	1
	Car (rural/suburban)	0.14 (0.11)	0.12 (0.09)	0.01 (0.01)			0.02 (0.01)	0.07	1
	Residential outdoor (rural/suburban)	0.07 (0.07)	0.07 (0.06)	0.01 (0.01)			0.01 (0.01)		1
	Residential indoor (rural/suburban)	0.04 (0.04)	0.02 (0.02)	0.01 (0.01)			0.01 (0.01)	0.03	1
Aminzadeh et al. (2016)	Office indoor (urban)					0.17 (0.07)			1
Thielens et al. (2015)	Suburban residential area	0.14 (0.14)	0.12	0.01	0.02 (0.02)	0.01 (0.01)			1

(continued on next page)

Table 4 (*continued*)

Study	Microenvironment/status	Mean (Median)							Sample*
		Total	Downlink	Uplink	DECT	WLAN	Broadcast	Unspecified	
Gryz and Karpowicz (2015)	Metro	(0.28)							1
	stations' platforms (Peak hours)	(0.29)							21
	stations' platforms (off-peak hours)	(0.26)							21
	Metro tubes (Peak hours)	(0.26)							1
	Metro tubes (off-peak hours)	(0.21)							1

* # of sites that contributed to the average; NR: not reported.
** Mean value of RF-EMF measured by three devices in a same place.
† Detection limit.

(0.23–0.92 V/m) and in city centers (0.47–1.27 V/m). In all mobile microenvironmental measurement studies, conducted in Belgium, Sweden and Switzerland, the downlink signals contributed between 61% and 99% to total RF-EMF exposure in the outdoor microenvironments. Uplink signals were negligible (< 1% of total exposure) in the mobile microenvironmental measurement studies but not in the personal measurement with volunteers study.

3.2.3. Transportation systems

RF-EMF levels during traveling have been examined in trains, buses, cars, and trams, on bicycles, and at transportation stations by two personal measurement with volunteers studies and four mobile microenvironmental measurement studies in Switzerland, Belgium, and Sweden as well as a multi country study. The range of mean RF-EMF exposure was between 0.14 V/m in Belgian cars in urban and suburban environments and 1.97 V/m at a tram station in the same country (Fig. 4). The exposure levels in cars ranged from 0.14 to 0.56 V/m, in buses from 0.28 to 0.50 V/m, in trains from 0.34 to 0.75 V/m, in trams from 0.28 to 0.69 V/m and in stations from 0.89 to 1.97 V/m. In trains, uplink was the predominant source, whereas downlink was more relevant in trams. In cars and buses, the contribution of uplink varied largely from an almost negligible contribution to almost exclusive constitution of uplink signals. Among all studied microenvironments, the highest RF-EMF exposure occurred at train and tram stations, with RF-EMF exposure levels of > 0.89 V/m, mostly from downlink signals.

3.2.4. Temporal variation

The results of Fig. 5 indicated that median RF-EMF exposure, examined by two personal measurement with volunteers studies, was < 0.20 V/m during day, night, weekday and weekend. People are exposed to higher RF-EMF level during daytime compared to nighttime. Levels were similar during weekdays and weekends.

4. Discussion

In this systematic review, 26 papers satisfied the inclusion criteria and were included. They were published between 2015 and 2018 and some general exposure patterns were identified for the everyday microenvironments. First, exposure to RF-EMF, predominantly downlink signals, was higher in urban compared to rural/suburban areas. Second, at outdoor sites especially in city centers, exposure levels were substantially higher than in private homes and schools. Third, the highest RF-EMF exposure levels occurred in public settings such as libraries, train and tram stations, with typical RF-EMF exposure levels of 0.5 V/m or higher. Exposure was typically higher in transport environments than in indoor or outdoor environments, with uplink exposure accounting for a higher proportion of the total in public transport, but not consistently in private transport modes. Contributions of different bands to the total RF-EMF exposure varied widely between studies, but in general uplink and downlink signals were the dominant sources.

4.1. Comparison to previous reviews

A recent analysis of RF-EMF exposure in European countries including research published until 2012, assessed that the overwhelming majority of measured mean electric field strengths were < 1 V/m (Gajšek et al., 2015). They found mean exposure values between 0.10 and 0.26 V/m in personal measurement with volunteers studies for the general population (Gajšek et al., 2015), similar to the personal measurement with volunteers studies in this paper.

In general, we could confirm the exposure pattern reported in a systematic review of Sagar et al. (2018b), preceding this paper and including studies published until 2015. They found that the average measured electric field strength per microenvironment in all spot measurement and personal measurement with volunteers studies was < 1 V/m but in 16 out of 151 microenvironments (11%), assessed

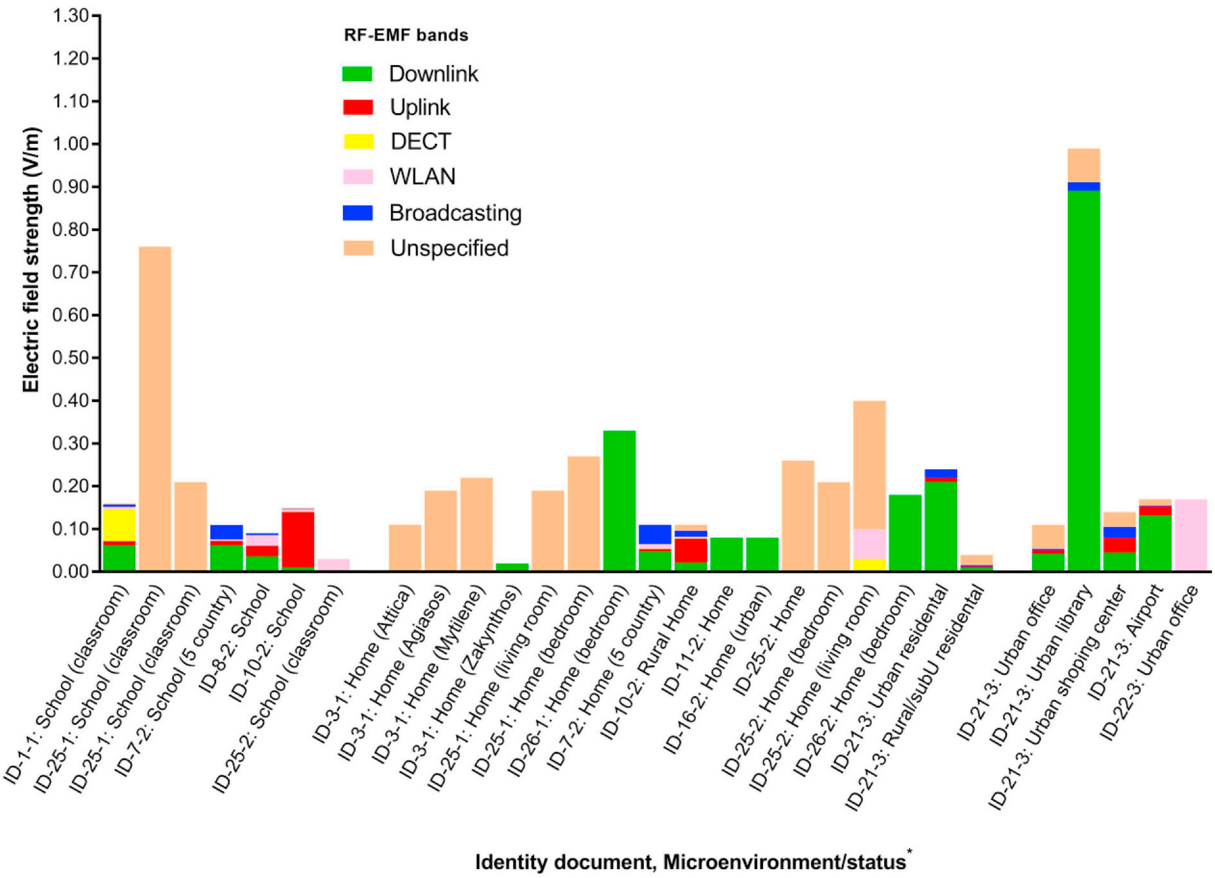

Fig. 2. Mean public exposure to different bands of RF-EMF in the indoors, arranged by the measurement method and type of microenvironments.* First number indicates the study ID (Table 1) and second number indicates measurement method (1: spot measurement; 2: volunteer participant; 3: trained researcher); median values are shown for ID-7.

by mobile microenvironmental measurement studies, measured electric field strengths were > 1 V/m. In line with Sagar et al. (2018b), we found that all of the spot measurement, fixed site monitoring, and personal measurement with volunteers studies reported mean exposure levels of less than 1 V/m. In the mobile microenvironmental measurement studies 14% of microenvironments had levels > 1 V/m. The current findings on exposure patterns in transport environments were also consistent with Sagar et al. (2018b): the uplink signals and downlink signals were found to be the strongest contributors to RF-EMF exposure, although there was a large variation between studies. In addition, we found that the highest public RF-EMF exposure might occur in public indoor settings like libraries or train stations, which were not considered by Sagar et al. (2018b). The findings of the current study indicated that public exposure to RF-EMF, mainly from mobile cell phones, was substantially below the suggested exposure threshold limits as recommended by International Commission on Non-Ionizing Radiation Protection for 900 MHz (41 V/m), 1800 MHz (58 V/m), 2100 MHz (61 V/m) as well as other frequencies (ICNIRP, 1998).

4.2. Bias and uncertainties among the publications

A direct comparison of the results from different studies applying different methods is difficult. Sampling strategy and measurement method affects the measured RF-EMF exposure levels (Roser et al., 2015). We did not consider study with a measurement strategy focusing on the maximum environmental exposure situations or studies that examined the near field situation (Buckus et al., 2017; Koprivica et al., 2016), as they do not reflect the typical RF-EMF exposure of the general population and thus their findings may overestimate typical exposure. For instance, public RF-EMF exposure level was reported up to 4.28 V/m in a Spanish study (2017), which considered maximum-hold mode in its measurements (Fernandez-Garcia and Gil, 2017). Note, that many implicit decisions have to be taken in RF-EMF measurement studies, which not all of them may be reported in the final paper. For instance, researchers may a priori known locations with high levels of RF-EMF and preferentially include such sites in their measurement protocol without being explicit about it. This may result in an overestimation of typical RF-EMF exposure values. On the other hand, some high-exposure sites may be avoided due to privacy or security restrictions (e.g. airports), which would lead to an underestimation of the population RF-EMF exposure.

Diurnal variation of RF-EMF (Aerts et al., 2016; Bürgi et al., 2014; Sánchez-Montero et al., 2017; Tomitsch and Dechant, 2015; van Wel et al., 2017b) is also an important uncertainty when comparing studies, which collected data at different times of the day. Bolte and Eikelboom (2012) showed that personal measurements with volunteers yielded three times higher values in the evening than in the night but this may mainly reflect different behaviors of the volunteers in their study using more communication devices in the evening. Diurnal variation of base station was found to be considerably less pronounced (Mahfouz et al., 2012). Bolte and Eikelboom (2012) also suggested that exposure level may be higher in autumn and summer, when trees carry leaves (Bolte and Eikelboom, 2012), although little empirical data is available for this hypothesis Thus, comparing studies with a different time of measurement might introduce some level of uncertainty in the conclusion of RF-EMF exposure in microenvironments (Eeftens et al. 2018a).

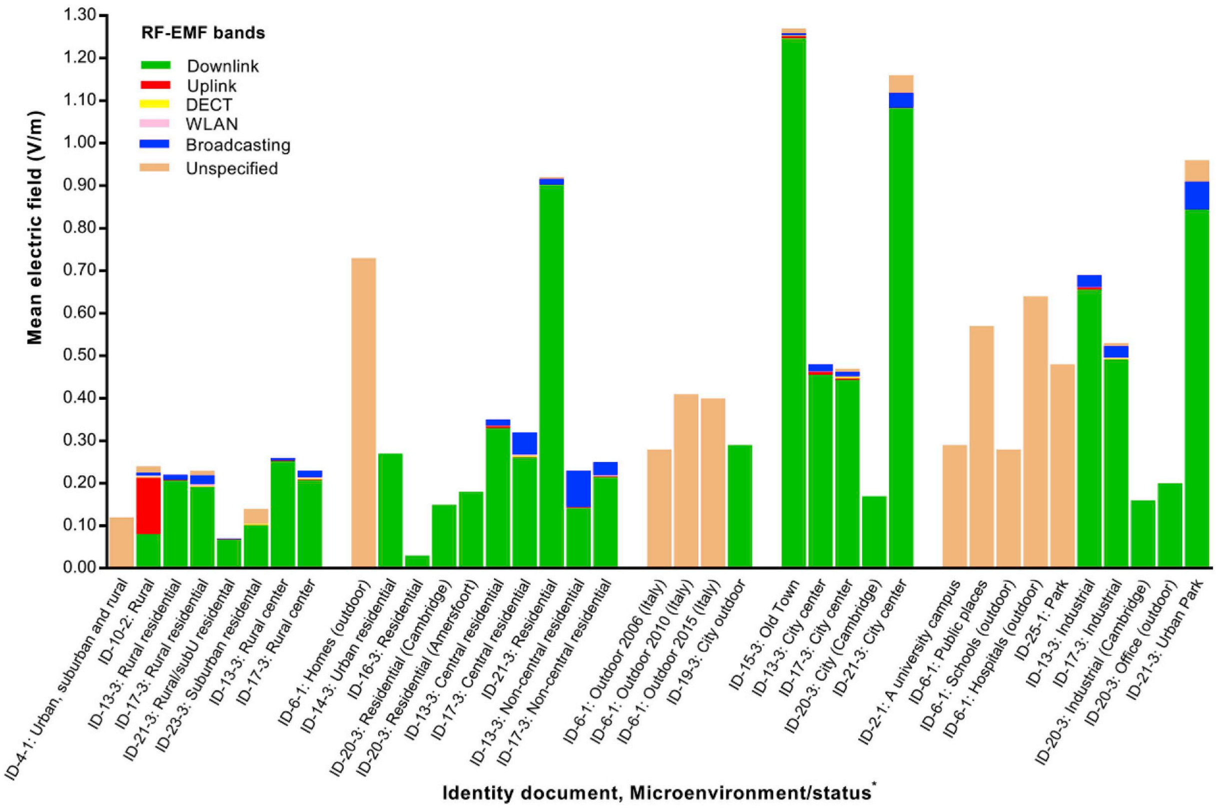

Fig. 3. Public exposure to different bands of RF-EMF in the outdoors, arranged by the measurement method and type of microenvironments. * First number indicates ID (Table 1) of the study and second number indicates measurement method (1: spot measurement/fixed site monitoring; 2: volunteer participant; 3: trained researcher); median values were illustrated for ID-7.

Another challenge is the comparison of different RF-EMF measurement devices. Various devices have been developed to measure RF-EMF (Bhatt et al., 2016a) and no systematic comparison of these devices has been made yet. For instance, it was shown that logarithmic detectors (e.g. EME SPY 121 and 140) might underestimate the electric field strength of phone signals by up to 75% (Bolte et al., 2016; Bolte, 2016). In addition, the extent of cross-talk between neighboring frequency bands may vary between different devices and various approaches have been used to correct for such cross-talk (Eeftens et al, 2018b). Another source of uncertainty relates to the fact that not all instruments measure exactly the same frequency bands. For example, ExpoM-RF (87.5–5875 MHz) (Fields at Work, 2015) measures a broader range of frequencies rather than EME SPY 120 (Microwave Vision Group, 2014b; Ramos et al., 2008). Another example is the updated instrument on which more bands has been considered compared to previous versions (EME SPY 120 vs 200) (Microwave Vision Group, 2014a). These uncertainties may introduce incomparability in the total measured exposure as well as band-specific values of electric field strength (Bolte, 2016). A broadening of the measured spectrum, or the measurement of additional bands, could result in an apparent increase of exposure over time.

Different study protocols also affect the outcomes of the studies. On the one hand, in personal measurement with volunteers studies, shadow effects and perturbations of electric field by the human body lead to exposure underestimation (Choi et al., 2018; Juan et al., 2007). On the other hand, volunteers carry and use their own phone while recording measurements. Thus, the own mobile phone, close to the measurement device, contributes to the uplink. In all other study types, the phone of the researcher taking the measurement is switched off and only ambient mobile phone signals are measured. Therefore, in all these types of studies RF-EMF levels represent environmental but not absorbed RF-EMF dose of individuals (Roser et al., 2015). Devices used close to the body result in considerably higher absorbed RF-EMF dose than what is measured in a free space environment. Even in personal measurement with volunteers absorbed dose from the own mobile phone is underestimated as the own device is usually operating closer to the body than to the personal measurement device. Several studies showed that for typical mobile phone users, the own devices contributes approximately 95% of the RF-EMF dose absorbed by the brain and approximately 90% of the RF-EMF dose absorbed by the whole body. Less than 10% originates from environmental exposure situations (Roser et al., 2015).

4.3. Conclusion

Despite all these caveats, a comparison of the RF-EMF exposure levels before and after 2012 indicates no major changes for the public transportation system or outdoor environments. In addition, personal measurement with volunteers studies do not indicate a notable increase in personal RF-EMF exposure, as mean levels are comparable to those reported in a previous review and still below 0.30 V/m. The reason for stable trends in exposure levels over time in the everyday environment, despite an increase in wireless communication technology use, may be explained by improvements in efficiency of these technologies and improved power controls of all emitters. It remains unclear, how well these everyday exposure studies represent absorbed RF-EMF dose of the population, which is mostly influenced by the own use of personal communication devices. There is thus an urgent need for a better quantification of absorbed RF-EMF dose from the own communication devices at the population level.

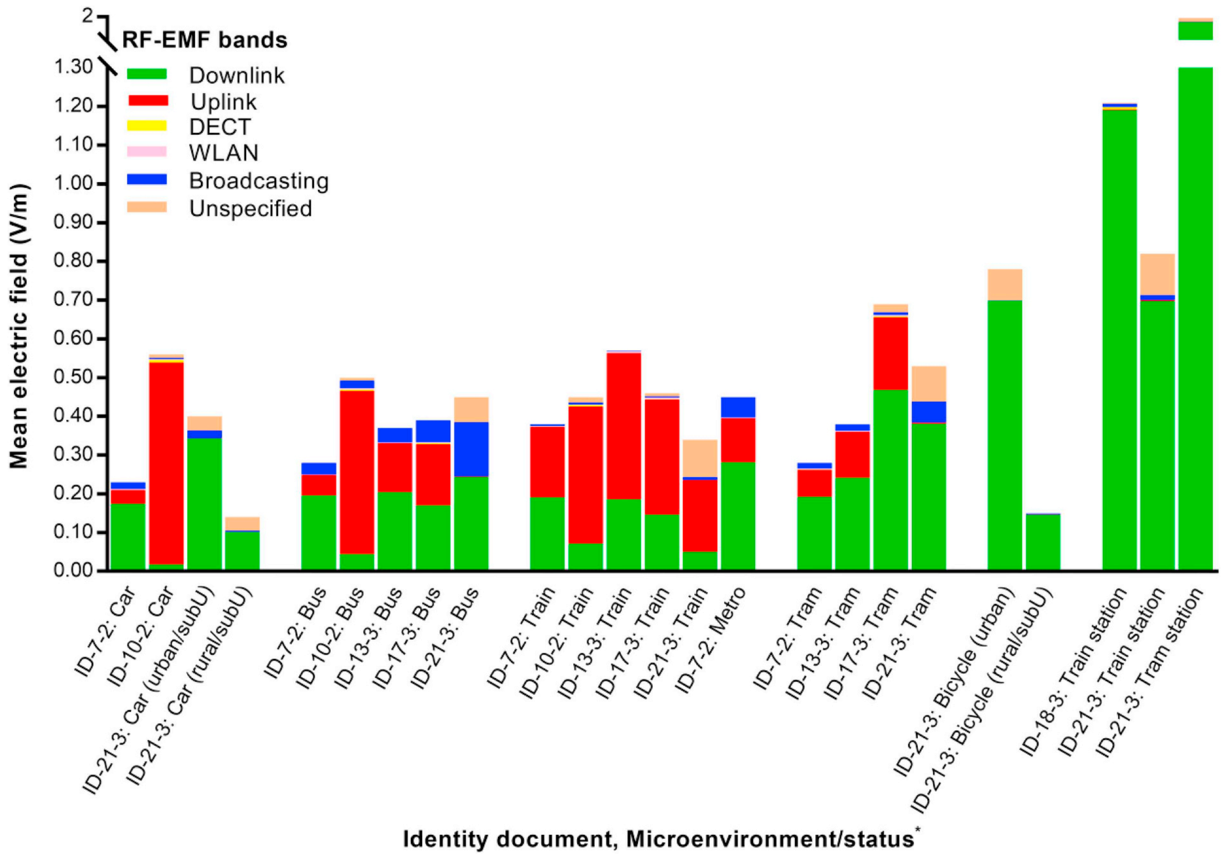

Fig. 4. Public exposure to different bands of RF-EMF in the transportation systems, arranged by the measurement method and type of microenvironments. * First number indicates ID (Table 1) of the study and second number indicates measurement method (2: volunteer participant; 3: trained researcher); median values were illustrated for ID-7.

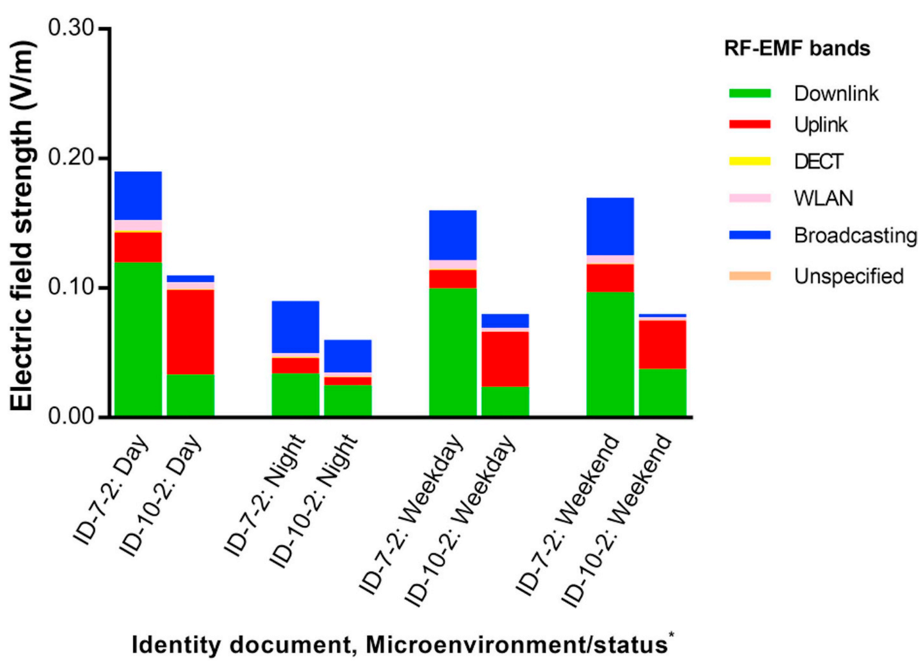

Fig. 5. Public exposure to different bands of RF-EMF regarding measuring time, arranged by the measurement method and times. * First number indicates ID (Table 1) of the study and second number indicates measurement method (volunteer participant).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2019.05.048.

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