CHARACTERIZING AND MAPPING OF EXPOSURE TO RADIOFREQUENCY ELECTROMAGNETIC FIELDS (20–3,000 MHZ) IN CHENGDU, CHINA

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Abstract—**With radiofrequency exposure caused by electronic applications increasing, some members of the public are worrying about potential health risks. In this paper, methods of performing large-scale radiofrequency exposure evaluation are described. All studied sites were divided into three categories: commercial-area, residential-urban, and residential-rural. Then a series of site investigations were conducted on a car-mounted system in the years 2014 and 2015, aiming to characterize electric field exposure from 12 different radiofrequency sources. The results indicate that the studied environment is safe as indicated by exposure below guidelines and standards. The highest exposure measured in the 2 y of monitoring was from an FM source, 316.23 mV m^{-1}. Telecommunication sources dominate exposure, contributing the most power density (65–90%). Meanwhile, intergroup differences are discussed and summarized. The spatial distributions of FM and GSM1800 exposure are demonstrated on a map. This study describes an approach for the assessment of the spatiotemporal pattern of radiofrequency exposures in Chengdu and facilitates the identification of any sources causing exposure above relevant guidelines and standards.**
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Key words: electromagnetic fields; exposure, radiofrequency; International Commission on Non-Ionizing Radiation Protection; radiation monitors

INTRODUCTION

DURING THE past decades, radiofrequency (RF) communications such as GSM (Global System for Mobile Communication), CDMA (Code Division Multiple Access), WCDMA (Wideband Code Division Multiple Access, FDD-LTE (Frequency Division Duplex - Long Term Evolution), and WiFi (Wireless Fidelity) had increased significantly. Multiple RF sources contribute to exposure of populations. For instance, the power of FM and TV broadcasting transmitters can reach 500–2,000 kW (Seyfi 2013). As for cellular phones and wireless routers, although lower in energy output, they could cause higher exposure due to the large numbers of these devices. Therefore, several safety recommendations (ICNIRP 1998; IEEE 2005; FCC 2001) have been proposed to protect humans from effects of time-varying electromagnetic fields. Also China's Ministry of Environmental Protection (MEP) has published a national standard to control exposure to electromagnetic fields in 2014 (MEP 2014), which integrated previous separate standards into GB8702-2014. This standard also officially referred to ICNIRP and IEEE guidelines in limitations and evaluation methods. An additional guide for electromagnetic field instruments and methods for monitoring (MEP 1996) was published by the Chinese Environment Protection Authority in 1996 and named HJ/T 10.2-1996.

Researchers in Europe and the Middle East have been characterizing RF exposures in different environments (indoor, outdoor, city central, rural area, etc.) and typical sources. An example of RF exposure measurement is found in Ozen et al. (2007). The study evaluated exposure caused by FM and TV at an urban site in Turkey by measurements of the electric field (E-field) value and estimated Specific Absorption Rate (SAR). Joseph et al. (2008) investigated the relationship between E-field value and SAR in Ghent, Belgium. Joseph et al. (2009) investigated whether random short time measurements of maximal E-field could represent exposures over longer periods. As for spatial distribution of exposure, Giliberti et al. (2009) evaluated and mapped E-fields produced by 11 radio base stations in Italy. Site classifications were employed to assess exposure in different sizes of towns in Spain's Extremadura region (Rufo et al. 2011), and a study on RF sources is included in a review (Vermeeren et al. 2013) under the context of a survey of indoor exposure to children and adults conducted in Belgium and Greece.

Despite many studies of indoor or outdoor exposure, few have examined the spatiotemporal pattern of exposure to RF, which could be used to identify sources of higher exposure. Besides, some researchers rely on inaccurate data from

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personal exposure meters (Rösli et al. 2008) with a typical detection limit of 0.05 Vm^{-1} and restricted functions, which reduce measurement accuracy and disable continuous broadband monitoring. To address these problems, the authors built a car-mounted mobile measurement system (CMMS) and demonstrated its use in a comprehensive study of outdoor RF exposure on Chengdu, China.

In this paper, guidelines and investigation procedures are detailed first. Then the investigation results and site comparisons are presented, followed by a demonstration of an exposure map. Finally, successive works on continuous exposure monitoring are introduced.

MATERIALS AND METHODS

ICNIRP and Chinese GB8702-2014 guidelines introduced have provided safety recommendations for exposure investigation, and the survey methods are described.

Guidelines and standards

Aiming to protect humans from time-varying E-field effects, ICNIRP has proposed two classes of guidance (ICNIRP 1998). First is basic restrictions, which account for direct effects on health, including restrictions on current density, SAR and power density. However, only power density can be directly measured. The second class is reference levels, which provided for on-measure exposure assessment, including levels of magnetic flux density and electric field strength (E-field value). Generally, the reference levels (E-field values) are not equal to the basic restrictions (SAR), but further measures are essential. Moreover, E-field value is considered a good reference in the far-field region of the plain wave approximation on 10 MHz–10 GHz (ICNIRP 1998). Reference levels on the E-field value are shown in Table 1, listed with IEEE action levels and those of its Chinese counterpart.

Investigation overview

Investigations of outdoor RF exposure were launched on Chengdu, a Southwest Chinese metropolis, with an area of 3,679.9 km^2 and 5,816,300 inhabitants (2014) (Wiki 2016). The 2-y investigation conducted between September 2014 and October 2015 involved 100 and 60 sites, respectively, which are further divided into three categories (Jaekel 2009): residential-urban, residential-rural, and commercial-area, according to their location and expected population density.

Because it was proven feasible and cost-saving in ecological studies (Bolte et al. 2016), a car-mounted system (CMMS) was built for surveying and mapping exposure. CMMS consists of a spectrum monitoring receiver, an isotropic antenna, GPS and a laptop computer for data collection. The receiver equipped in 2015 was Rohde & Schwarz EB500 (R&S Inc., Munchen, Germany; http://www.rohde-schwarz.com) and in 2014 a QLR2A (DGBC Inc., Chengdu, China; http://dgbc.gotoip2.com) was used. Meanwhile, DG-A2103 (DGBC Inc., Chengdu, China) used an antenna that was specially designed for 20–3,600 MHz broadband radio spectrum scanning. The GPS location for each measurement was collected for spatial comparative analysis and exposure mapping by the National Administration of Surveying, Mapping and Geoinformation of China (NASG 2016). While CMMS provides flexibility from site to site, the system remains still during each measurement.

Table 1. Guidelines and Standards for general public exposure to time-varying E-field (10–3000 MHz) with f indicate the frequency ranges in MHz. (a) Reference levels (ICNIRP 1998) (b) Action levels (IEEE 1991) (c) GB 8702-014. (Ministry of Environmental Protection of the People's Republic of China, MEP, 2014).

(a)		
Frequencies(MHz)	E-field value ($V m^{-1}$)	Power density($W m^{-2}$)
10–400	28	2
400–2000	$1.357f^{0.5}$	$0.005f$
2000–3000	61	10
(b)		
Frequencies(MHz)	E-field value ($V m^{-1}$)	Power density($W m^{-2}$)
3–30	$823.8 f^{-1}$	$16.3 f^{-1}$
30–100	27.5	$158.3 f^{-1.668}$
100–400	27.5	0.0729
400–2000	–	–
2000–3000	–	–
(c)		
Frequencies(MHz)	E-field value ($V m^{-1}$)	Power density($W m^{-2}$)
3–30	$60f^{0.5}$	$12f^{-1}$
30–3000	12	0.4

Measurement deployment

The monitoring receivers provide the ability of 8 kHz–6 GHz continuous scanning with a sensitivity of 0.1 dB μV^{-1} for the received level (Rohde and Schwarz Co, 2016). Researchers in the study exposure intensity rather than its carrier or modulation. As for the receivers, the scan mode was set as "Panorama Scan," the filter span as 20 MHz, the Fast Fourier Transformation mode as "AVERAGE," the measurement time as "AUTO," the frequency increment as 25 kHz, and the sweep range from 20 MHz to 3,000 MHz (in 2014) or 3,600 MHz (in 2015).

Considering that a full-range sweep and calculations take a bit more than 1 min, the actual measurement time was 7 min to complete six round scans, although the recommended time is 6 min (Verloock et al. 2010). The antenna was fastened at a height of 1.5 m extending out the side windows to capture approximate maximum exposure of persons (Markakis and Samaras 2013). Moreover, to ensure no interference of the car with measurements, especially from the mounted inverter power supply, compatibility tests were performed inside and outside the car before launching the main study.

Measurements were carried out under mild weather ambient temperatures (17–25 °C) and relative humidity (55–75%). After a 7-min full-range scan and antenna calibrating, E-field values, E_{mdB} (dBμV m^{-1}) and E_{mVm} (V m^{-1}), were obtained as 7-min averaged RMS (root-mean-square) values with eqn (1) (Bechet et al. 2015):

$$E_{mdB}(f) = u_m(f) + g_a(f) + loss$$
$$E_{mVm}(f) = 10^{0.05\{[u_m(f)+g_a(f)+loss]-120}, \quad (1)$$

where f indicates sweeping frequencies and u_m, g_a, and $loss$ are the detected signal voltages, antenna gain factors, and cable loss, respectively.

Exposure presence rate or signal occupancy rate was calculated on each frequency increment and specific frequency ranges through eqn (2):

$$Occ(f) = T_s(f)/T_m(f)$$
$$Occ_{band} = \sum_{i=1}^{n} Occ(f_i)/n, \quad (2)$$

where T_s refers to, at a specific frequency, time received level higher than 5 dB μV^{-1}; T_m refers to the total measurement period; and n refers to intra-band (e.g., 88–108 MHz) increments. The intra-band Occ. or band-averaged Occ. enable exposure presence evaluation for various sources.

Power density was estimated through eqn (3):

$$I(f) = |E_{mVm}(f)|^2/Z_0, \quad (3)$$

where Z_0 (377 Ω) is the free-space impedance.

Each part of CMMS and manual operations contributes to measurement uncertainty, which is expected to be ±2.3 dB (International Telecommunication Union, 2011; CENELEC 2008) for a typical RF car monitor system.

After each site survey was finished, 119,201 (in 2014) or 143,201 (in 2015) data sets were obtained, corresponding to equivalent frequency increments scanned. Each set contains E-field values (dBμV m^{-1}), occupy rate (%) and received level standard deviation (dBμV) during six sweeps.

RESULTS

To characterize spatiotemporal distributions of exposure from various RF sources, statistical summaries of investigation results are presented along with the discussion.

Statistical summaries of results

The RF exposure ranges from 20–3,000 MHz included fields from 12 different RF sources as shown in Table 2: FM radio broadcasting, analogue TV broadcasting, various cellular phones, digital enhanced cordless (DECT) devices, and WiFi 2G emitters. Based on the classifications, Table 3 summarizes investigation results through the 99th percentile, 95th percentile maximal E-field values, occupancy rate and source presence, and is separated by source and site categories. For each value set, its range of value on the site's median value and standard deviation are provided to describe data distribution. The measured RF exposures are far below the guidelines and standards limits in Table 1. The 99th percentile max E-fields were 141.25 mV m^{-1} (2014) and 316.23 mV m^{-1} (2015), both in the FM band and measured at transmitter-nearby sites. Telecommunication sources such as GSM, CDMA and WCDMA make a significant contribution to exposure, which reached 135.56 mV m^{-1}, 25.11 mV m^{-1}, and 22.39 mV m^{-1}, respectively, and had a high occupy rate (83.4–98.8%). Aside from WiFi and DECT, the listed sources in Table 2 are common (source presence to 33–100% in 2015). The low presence of WiFi can be explained by indoor deployment, low output power, and short signal range. CDMA2000 sources emerged in 2015, and its presence increased from 0% (2014) to 57% (2015).

Table 2. Descriptions on 12 different RF sources and corresponding frequency ranges[‡].

Applications	Sources	Frequencies(MHz)[a]
FM broadcasting	FM	88–108
TV broadcasting	TV	48.5–92 167–223 470–798
2G telecommunication	CDMA	UL:825–830 DL:870–880
	GSM900	UL:885–915 DL:930–960
	GSM1800	UL:1710–1740 DL:1805–1835
3G telecommunication	CDMA2000	UL:1920–1935 DL:2110–2125
	WCDMA	UL:1940–1960 DL:2130–2150
	TD-SCDMA	2010–2025
4G telecommunication	FDD-LTE	UL:1745–1780 DL:1840–1875
	TD-LTE	1880–1900 2300–2390 2555–2655
DECT handset	DECT	1905–1920
Wireless fidelity(2G)	WiFi	2400–2483.5

[a]Note: 1. UL: uplink, from phone to base station. DL: downlink, from base station to phone.

[‡]Legislative Affairs Office of the State Council, People's Republic of China; 2016.

Influences of different RF sources

The gaps in sources' contributed exposure are significant, as indicated in Table 3. To further the discussion, 2-y sites are marked and classified in Fig. 1a and b. Moreover, the following sites belonging to different categories: commercial-area (sites 1, 5, 8) residential-urban (sites 3, 6, 4) and residential-rural (sites 2, 7, 9) are labeled on Fig. 1a as No. 1 to 9.

Fig. 2 illustrates the full-extent spectra (20–300 MHz) of two typical sites in logarithm unit dBμV m^{-1}, with corresponding RF sources labeled. The striking differences between various sources are visible in Fig. 2 and Table 3. Fig. 3 shows the exposure contributions of various sources in power density: telecommunication sources, including 2G, 3G, and 4G are of critical importance (65–90%), especially GSM and CDMA (35–70%), while other sources merely hold a

Table 3. Statistical summaries of 2-y investigation results for all sites.

Sources	Region[a]	99th-percentile-max[STD] (Median)/mV m^{-1} [b] 2014	99th-percentile-max[STD] (Median)/mV m^{-1} [b] 2015	95th-percentile-max[STD] (Median)/mV m^{-1} 2014	95th-percentile-max[STD] (Median)/mV m^{-1} 2015	Occ(STD) [Median]/% 2014	Occ(STD) [Median]/% 2015	Sources Presence 2014	Sources Presence 2015
FM	CA	2.79–141.25 [7.87] (37.11)[c]	4.97–316.23 [19.26] (43.67)	0.36–17.25 [0.99] (3.15)	0.79–25.14 [2.63] (7.14)	16.6–97.1 (18.2) [27.6]	28.5–97.9 (8.0) [42.4]	100%	100%
	RU	0.28–27.92 [1.95] (6.25)	0.38–58.13 [3.40] (12.50)	0.03–4.36 [0.37] (1.03)	0.21–3.47 [0.66] (0.81)	2.7–41.7 (10.3) [17.0]	10.4–71.2 (26.2) [47.8]	84%	100%
	RR	0.13–5.57 [1.17] (1.25)	0.36–7.74 [1.49] (2.06)	0.03–0.66 [0.16] (0.16)	0.12–1.98 [0.21] (0.43)	2.2–28.7 (6.1) [12.3]	6.9–57.1 (18.1) [42.2]	85%	100%
TV-DB5	CA	1.00–31.80 [3.58] (7.04)	0.64–12.59 [4.02] (5.24)	0.04–2.41 [0.07] (0.06)	0.07–1.26 [0.16] (0.05)	1.3–23.1 [2.8] (2.7)	1.6–24.9 (5.0) [14.2]	100%	100%
	RU	0.27–12.72 [2.54] (2.66)	0.30–3.19 [1.60] (1.14)	0.03–0.67 [0.03] (0.04)	0.07–0.20 [0.10] (0.03)	0.6–13.6 (2.4) [2.0]	0.9–19.3 (2.3) [4.1]	93%	90%
	RR	0.27–9.00 [1.13] (1.68)	0.28–9.00 [1.34] (2.21)	0.03–0.27 [0.01] (0.03)	0.01–0.20 [0.09] (0.03)	0.5–3.5 [0.8] [0.9]	0.8–11.5 (1.6) [4.4]	87%	100%
CDMA DL	CA	3.72–25.11 [7.51] (6.79)	0.49–14.13 [2.40] (3.82)	3.30–23.21 [6.58] (6.10)	0.45–12.20 [2.13] (3.56)	79.3–98.5 (7.0) [90.2]	78.7–87.4 (3.1) [81.6]	100%	100%
	RU	0.49–24.71 [3.92] (5.53)	0.30–13.48 [5.13] (3.91)	0.41–22.81 [3.61] (5.09)	0.27–11.98 [4.70] (3.51)	74.9–98.8 (7.3) [86.6]	79.1–90.6 (3.6) [80.7]	100%	100%
	RR	0.33–15.61 [2.49] (3.31)	0.56–12.03 [1.77] (2.91)	0.29–15.02 [2.27] (3.15)	0.50–11.43 [1.54] (2.68)	77.2–98.2 (5.6) [79.4]	77.6–90.4 (3.9) [80.2]	100%	100%
GSM900 DL	CA	3.43–112.20 [24.46] (31.16)	1.53–89.13 [20.64] (27.40)	0.58–16.77 [4.62] (4.54)	0.71–8.70 [1.49] (2.25)	70.5–87.1 (4.1) [79.2]	44.7–79.5 (8.4) [71.3]	100%	100%
	RU	1.71–85.47 [15.40] (18.68)	1.38–48.53 [9.68] (11.63)	0.61–14.93 [2.51] (2.67)	0.45–5.32 [2.18] (1.48)	67.4–80.7 (3.4) [77.4]	43.0–80.1 (10.4) [66.8]	100%	100%
	RR	1.41–86.49 [6.85] (18.57)	1.01–27.40 [8.66] (8.05)	0.52–6.17 [1.62] (1.41)	0.34–5.16 [0.81] (1.27)	67.6–80.7 (3.9) [75.2]	47.3–83.4 (10.5) [75.2]	100%	100%
GSM1800 DL	CA	3.46–135.56 [26.08] (35.50)	3.33–65.56 [33.70] (18.37)	0.96–13.72 [4.71] (3.56)	0.56–6.85 [1.71] (1.75)	42.9–90.3 (12.1) [73.1]	36.3–82.6 (15.2) [63.0]	100%	100%
	RU	0.72–52.50 [15.16] (14.17)	1.44–43.99 [11.42] (9.38)	0.37–8.23 [2.60] (1.92)	0.63–8.77 [1.92] (1.72)	27.2–83.6 (15.4) [64.9]	36.9–84.4 (14.8) [74.6]	100%	100%
	RR	0.50–81.05 [6.67] (18.83)	0.85–65.56 [3.71] (18.37)	0.30–4.84 [1.79] (1.27)	0.27–5.40 [1.05] (1.49)	27.2–82.5 (15.3) [57.4]	13.7–85.7 (17.3) [63.8]	100%	100%
WCDMA DL	CA	2.00–22.39 [5.62] (5.01)	0.55–12.59 [4.42] (1.18)	1.77–18.51 [4.94] (4.58)	0.51–3.90 [1.76] (1.05)	60.8–92.0 (10.4) [70.5]	64.8–92.5 (6.3) [67.5]	100%	100%
	RU	0.50–22.27 [3.18] (3.83)	0.12–12.45 [3.42] (2.52)	0.43–22.15 [2.97] (3.75)	0.12–12.39 [1.40] (2.50)	40.6–92.9 (15.7) [66.9]	45.5–69.2 (6.5) [67.1]	100%	100%
	RR	0.25–7.93 [2.52] (2.21)	0.25–3.91 [1.10] (0.99)	0.23–7.29 [2.44] (1.98)	0.22–3.53 [1.02] (0.87)	34.3–90.4 (13.0) [47.3]	42.1–69.7 (10.6) [56.4]	100%	100%
TD-SCDMA	CA	0.14–1.84 [0.36] (0.16)	0.06–0.92 [0.11] (0.17)	0.12–0.69 [0.30] (0.14)	0.05–0.26 [0.13] (0.05)	20.3–42.1 (5.5) [34.3]	11.9–46.9 [32.0] (10.8)	100%	100%
	RU	0.10–1.16 [0.37] (0.28)	0.05–0.52 [0.06] (0.10)	0.10–0.98 [0.32] (0.23)	0.05–0.44 [0.10] (0.09)	11.6–43.3 (7.3) [32.9]	15.4–49.1 (9.0) [31.0]	98%	95%
	RR	0.10–1.84 [0.21] (0.31)	0.05–0.29 [0.15] (0.06)	0.09–1.37 [0.17] (0.24)	0.04–0.57 [0.09] (0.11)	11.6–40.6 (7.8) [27.1]	12.8–44.4 (9.0) [26.2]	97%	91%
CDMA2000	CA	0.04–0.06 [0.00] (0.05)	0.12–0.81 [0.17] (0.22)	0.04–0.06 [0.05] (0.00)	0.04–0.29 [0.13] (0.08)	0.0 (0.0) [0.0]	0.5–77.8 (29.6) [49.9]	0%	76%
	RU	0.04–0.06 [0.00] (0.05)	0.03–0.75 [0.17] (0.19)	0.04–0.05 [0.05] (0.00)	0.03–0.14 [0.11] (0.14)	0.0 (0.0) [0.0]	0–77.7 (28.9) [51.2]	0%	71%
	RR	0.04–0.05 [0.00] (0.04)	0.03–0.81 [0.03] (0.22)	0.04–0.04 [0.04] (0.01)	0.03–0.11 [0.03] (0.17)	0.0 (0.0) [0.0]	0–71.0 (26.1) [30.1]	0%	27%
FDD-LTE DL	CA	0.59–12.59 [1.81] (6.59)	0.4–4.22 [0.67] (0.92)	0.55–8.82 [1.66] (1.04)	0.17–3.88 [0.61] (0.87)	57.9–87.5 (6.9) [67.4]	48.2–88.9 (10.3) [77.0]	100%	100%
	RU	0.47–12.39 [1.44] (2.3)	0.11–1.81 [0.71] (0.42)	0.45–8.67 [1.20] (1.59)	0.07–1.30 [0.61] (0.32)	35.6–79.2 (10.7) [61.2]	16.5–86.3 (10.4) [74.2]	100%	100%
	RR	0.23–7.34 [1.06] (1.17)	0.25–1.97 [0.89] (0.46)	0.18–4.53 [0.94] (0.78)	0.22–1.67 [0.64] (0.38)	41.6–67.3 (16.4) [47.9]	62.7–86.3 (5.8) [79.4]	100%	100%
TDD-LTE (2300)	CA	0.06–0.14 [0.02] (0.06)	0.06–0.08 [0.01] (0.07)	0.05–0.09 [0.06] (0.01)	0.04–0.06 [0.03] (0.01)	0–7.7 (1.0) [0.9]	0–9.7 (1.8) [0.1]	34%	40%
	RU	0.05–0.40 [0.05] (0.08)	0.04–0.06 [0.01] (0.05)	0.05–0.07 [0.06] (0.02)	0.03–0.07 [0.04] (0.01)	0–4.2 (0.8) [0.0]	0–1.6 (0.3) [0.0]	10%	15%
	RR	0.05–0.40 [0.06] (0.08)	0.03–0.04 [0.01] (0.03)	0.05–0.07 [0.05] (0.02)	0.03–0.05 [0.03] (0.00)	0–2.6 (0.4) [0.0]	0–2.1 (0.5) [0.0]	5%	9%
WiFi 2G	CA	0.07–0.25 [0.03] (0.11)	0.11–1.77 [0.24] (0.38)	0.07–0.19 [0.11] (0.02)	0.04–0.24 [0.10] (0.06)	0–11.9 (2.9) [0.3]	0.0–29.9 (5.1) [2.0]	9%	35%
	RU	0.05–0.18 [0.04] (0.10)	0.10–0.50 [0.09] (0.18)	0.05–0.18 [0.09] (0.03)	0.04–0.16 [0.07] (0.04)	0–3.5 (1.0) [0.1]	0.0–13.1 (5.4) [0.3]	0%	24%
	RR	0.05–0.20 [0.03] (0.07)	0.05–0.20 [0.04] (0.07)	0.06–0.13 [0.06] (0.02)	0.04–0.11 [0.05] (0.02)	0–3.4 (0.6) [0.1]	0–7.6 (2.0) [0.1]	0%	9%

[a]Note: CA refers to Commercial-area, RU refers to Residential-urban, and RR refers to Residential-rural.

[b]Note: STD refers to exposure value standard deviation among sites; Median indicates the site exposure value at an average level; Occ indicates band use; and Sources Presence refers to percentage of site with over 5% band utilization.

[c]Note: 20 dBμV m^{-1} = 10^{-5} V m^{-1}, 40 dBμV m^{-1} = 10^{-4} V m^{-1}, 60 dBμV m^{-1} = 10^{-3} V m^{-1} and 80 dBμV m^{-1} = 10^{-2} V m^{-1} according to eq (1).

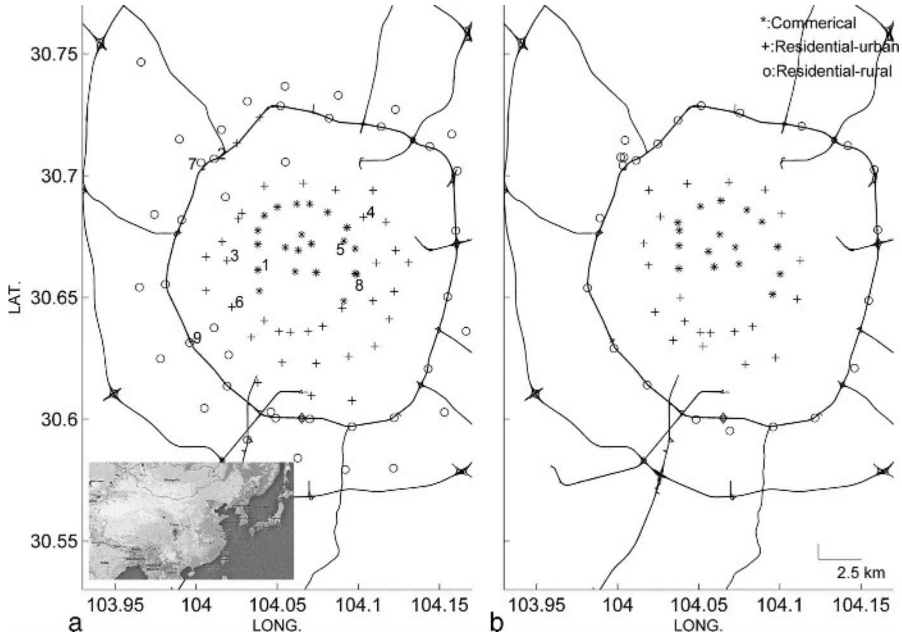

Fig. 1. Classified investigated sites on Chengdu map: (a) sites in 2014 with sites No. 1–9 labeled; (b) sites in 2015.

minority position, such as FM (1–10%), WiFi, and DECT (less than 1%). Particularly, exposure from FM and TV at sites 4 and 5 have a significant influence (weights over 15%) because they are the nearest to a known FM&TV transmitter tower.

Spatial and temporal distributions

It is interesting to discuss the exposure pattern since sites behave in similar ways in Table 3 and Fig. 3. Fig. 4 demonstrates empirical cumulative distribution functions of six sites. It is observed that exposures in commercial-areas (sites 1 and 5) are higher than in residential-rural areas (sites 7 and 9) with a visible difference (Joseph et al. 2012; Kutner et al. 2005).

Fig. 5 is a boxplot summary of measurements from GSM 900 DL and FM at eight sites. In Fig. 5a, a 20 dB $\mu V\ m^{-1}$ gap is viewed on maximal sample values between commercial-areas (site 1, 5, 8) and residential-rural areas (site 2, 7). Meanwhile, since sites have been arranged by their distance to the transmitter, the decay of FM exposure is also manifest

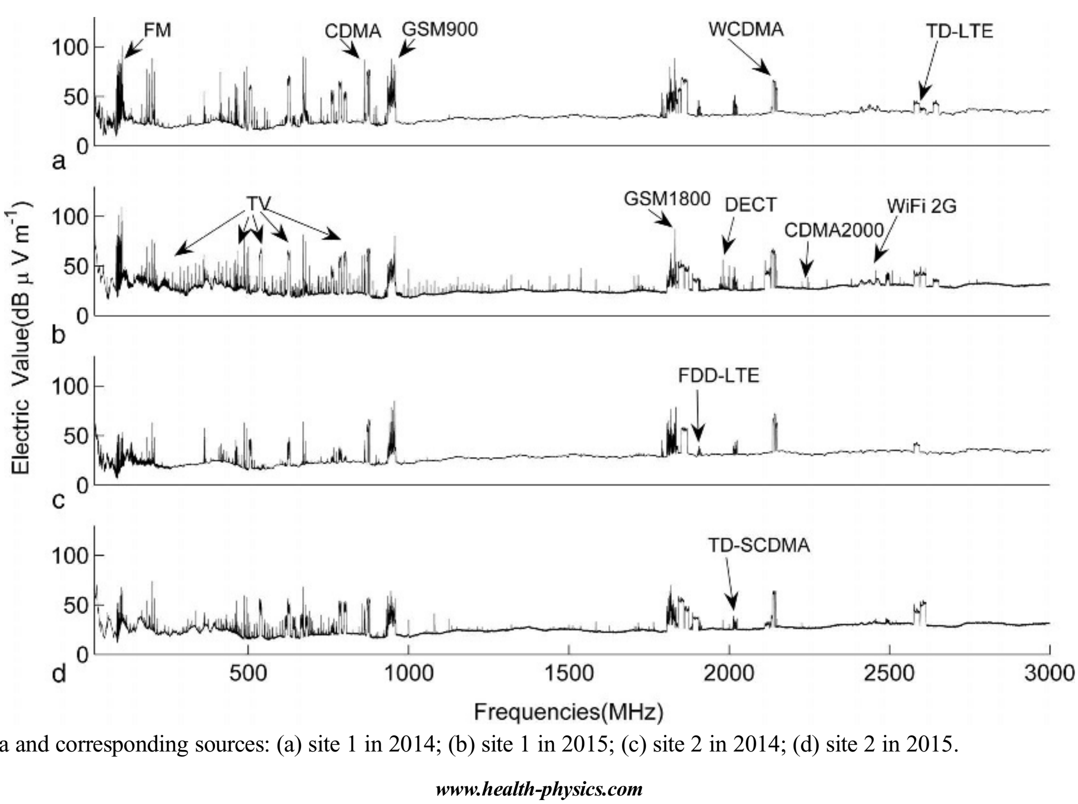

Fig. 2. Spectra and corresponding sources: (a) site 1 in 2014; (b) site 1 in 2015; (c) site 2 in 2014; (d) site 2 in 2015.

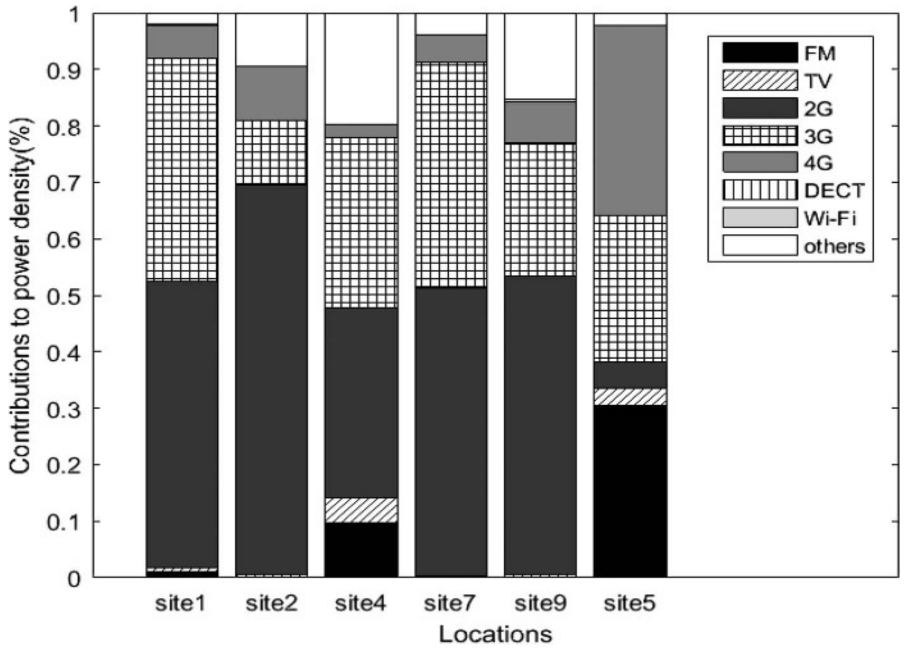

Fig. 3. Power density contributions (%) of various sources at five sites in 2015.

in Fig. 5b. The phenomenon in Fig. 5a is attributed to more radio base station and telecommunication services in densely populated commercial regions.

Apart from several emerging sources indicated in Table 3, temporal variations seem indistinctive as in Fig. 2. Therefore, in Fig. 6a–d the variations are studied with the comparison of 2 y band-averaged occupancy rate at four repeated measurement sites. A rise in 4G is observed, which likely results from deployment of 4G infrastructure and market launch of 4G devices between the 2 y. Meanwhile, other bands only have small fluctuations.

DISCUSSION

Interpolation and mapping

Mapping spatial data sets proved effective in demonstrating distribution of exposure and spatial trends (Oliver

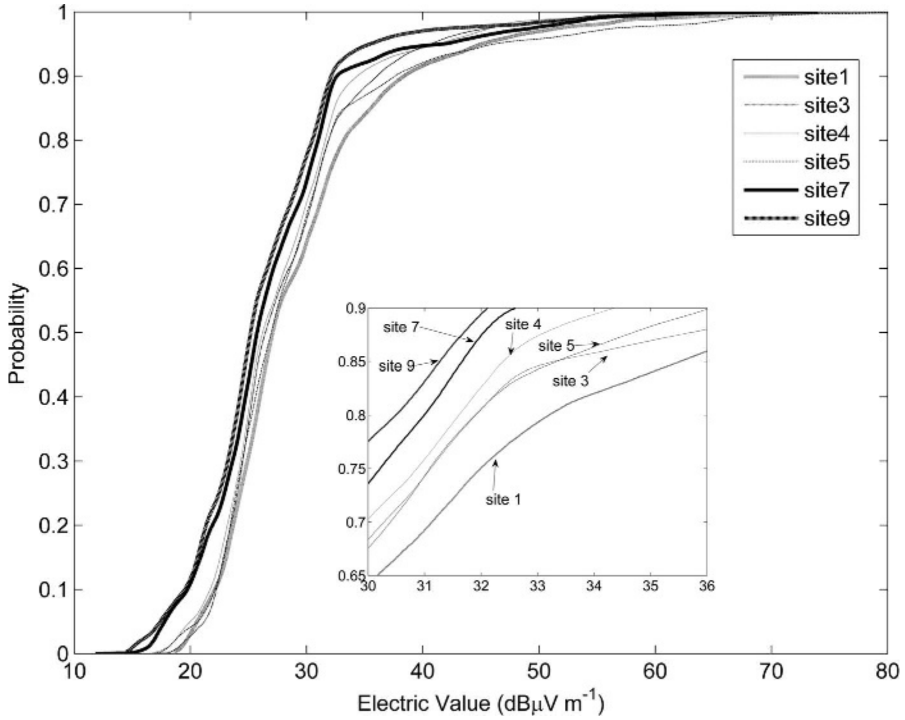

Fig. 4. Empirical cumulative distribution functions of 20–3,000 MHz exposure at six sites in 2015.

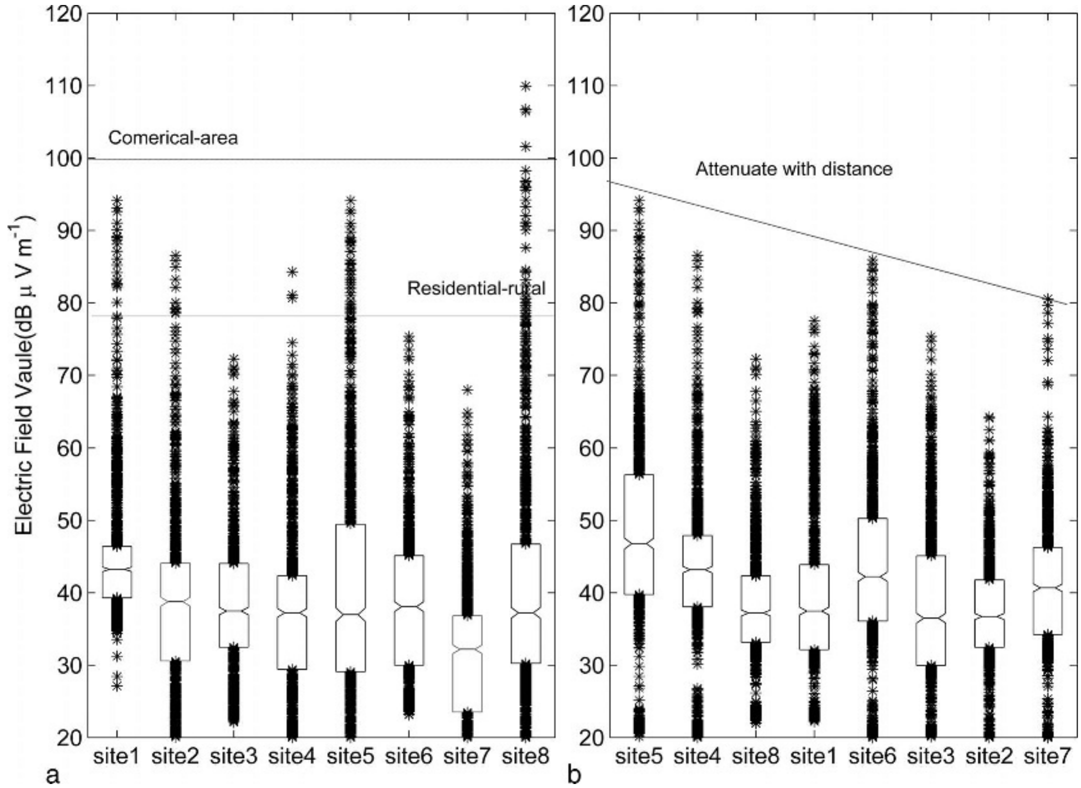

Fig. 5. Exposure samples from bands of specific sources: (a) GSM900 DL (930–960 MHz) in 2015; (b) FM (88–108 MHz) in 2015.

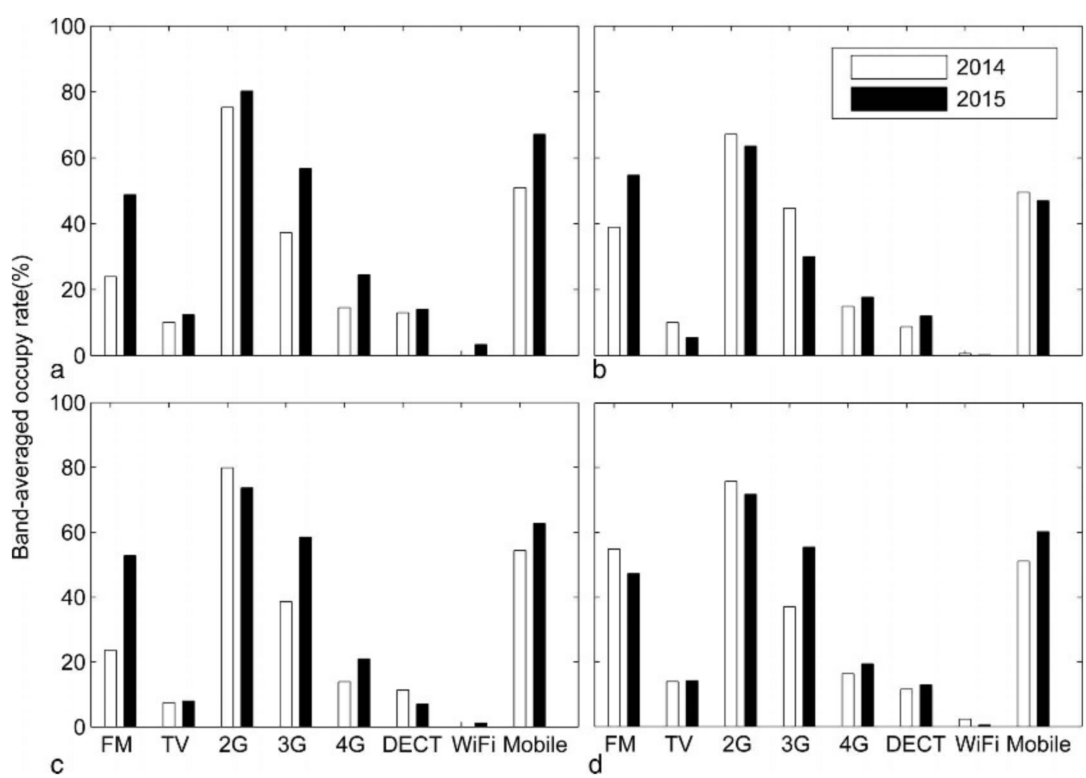

Fig. 6. Comparison of 2-y band-averaged occupancy rate: (a) site 1; (b) site 2; (c) site 3; (a) site 4.

and Webster 1990). However, since investigation results can hardly be sufficient to cover every corner of the region, mathematical methods for interpolation and extrapolation were applied. The Ordinary-Kriging and inverse distance weighted (IDW) (Shahbeik et al. 2013) methods were used. As a non-uniform interpolation method, kriging is widely used in geography to track sources and describe variations, which apply the principle that exposure comes from sources and attenuates with distance. IDW overcomes several limitations of ordinary-kriging by smoothing the outputs and correcting for abnormal values.

In this paper, the 99th maximal E-field values of FM and GSM1800 DL have been mapped on a simplified Chengdu street map as Fig. 7a and b. Fig. 7a demonstrates the attenuate of exposure from an FM transmitter, while Fig. 7b of GSM1800 DL reveals a characteristic of other telecommunication sources: In the majority of cases, densely-populated urban central area tend to have higher exposure.

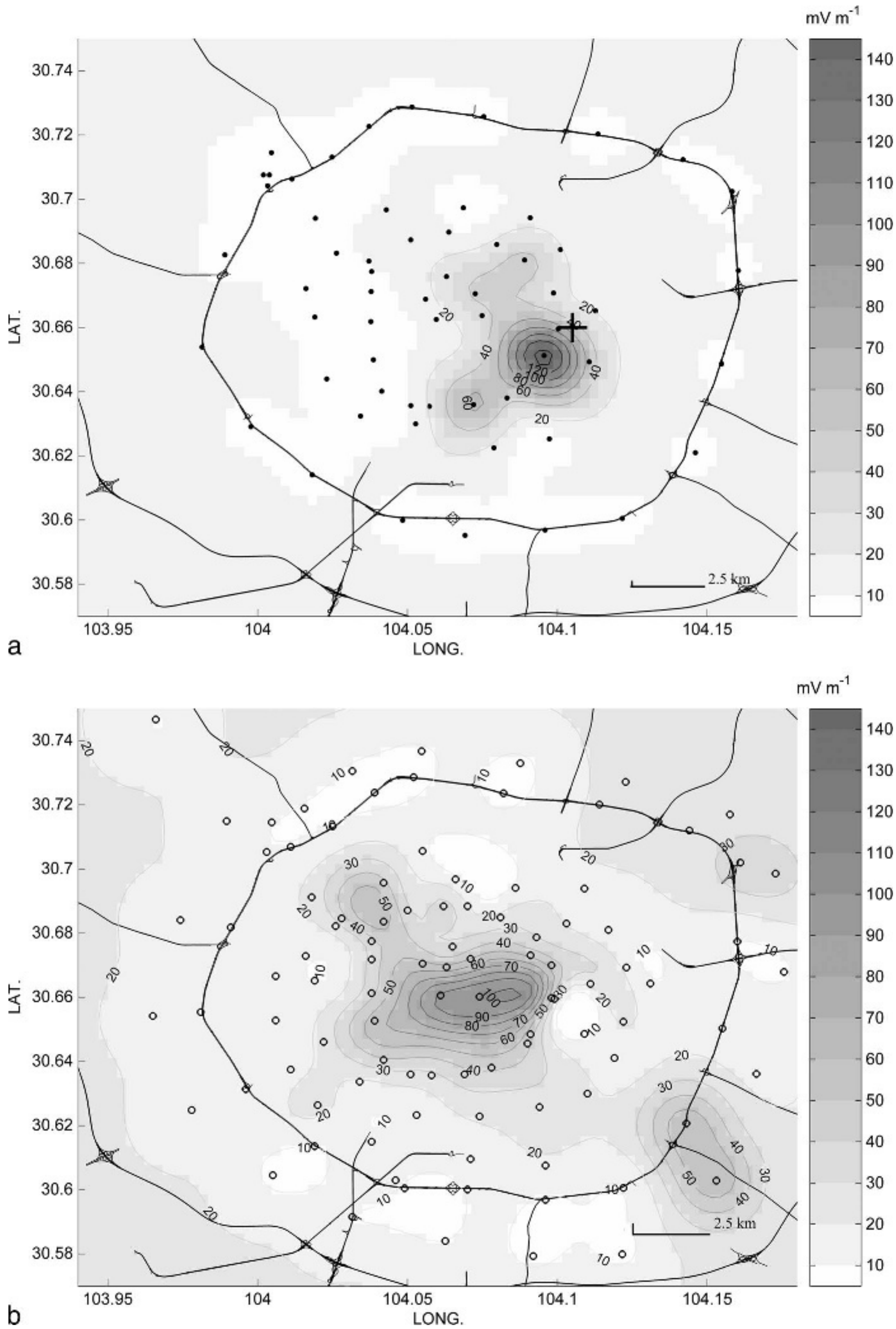

Fig. 7. Exposure map of 99th-percentile-max E-field value: (a) FM (88–108 MHz) in 2015, with investigated sites marked by "●" and transmitter by "+;" (b) GSM1800 DL (1,805–1,830 MHz) in 2014, with sites marked by "○".

Application and limits

Previous research on outdoor general public RF exposure provided results similar to those in this paper. The broadband E-field measurement results (Rufo et al. 2011) reached 0.12 V m^{-1} on FM at a medium-size town, with spectra dominated by FM, TV and GSM. In the research of Joseph et al. (2008), the maximal E-field was 0.57 V m^{-1} in GSM DL, followed by Digital Cellular System (0.30 V m^{-1}), FM (0.29 V m^{-1}), and TV (0.26 V m^{-1}) in the 99th percentile. In studies by Joseph et al. (2012), narrowband measurements on the wireless communication applications provided the highest median exposure of 0.74 V m^{-1} in an urban environment and 0.09 V m^{-1} in a rural environment, where GSM900 contributes over 60% of total exposure.

The spectrum receiver mounted on a car for this study provided a low-cost and time-saving approach for accurate and continuous exposure monitoring, especially efficient for a wide range area. For instance, using CMMS, researchers surveyed 100 sites within a week. Afterward, the research was expanded to a continuous exposure survey during December 2015 through a monitoring network in Tianjin, another metropolis on China's east coast. The survey lasted for a week, with 93 devices working simultaneously.

However, the proposed method did have drawbacks. For example, the measurement equipment is non-portable to locations not accessible by car and requires cooperation of several engineers. In addition, the massive data collected in the investigation raised demands for storage devices and high-performance algorithms.

CONCLUSION

RF exposures in Chengdu, China, were measured with car-mounted instruments. Exposure sources and spatiotemporal distributions were evaluated, and later continuous exposure monitoring was performed.

All measured levels of RF were below limits for public exposure in ICNIRP guidelines and GB 8702-014. The 99th maximal E-field value reached 316.23 mV m^{-1} in 2015. It was also found that telecommunication sources dominate the outdoor exposure with a contribution of 65–90%. Significant spatial differences in RF exposure were found between rural and urban areas and sites near and far from transmitters. The methods applied in the study may be useful for RF exposure of similar large regions.

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