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Assessment of the exposure of children to electromagnetic fields from wireless communication devices in home environments

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Abstract: Wireless technologies have transformed human lifestyles giving rise to research on electromagnetic (EM) field exposure assessment by prioritising what are considered as potentially the more vulnerable groups, such as children. The method presented in this study for assessing the exposure of children to EM fields from wireless communication devices consists of a statistical survey of families describing typical daily exposure to wireless devices followed by the estimation of the highest whole-body averaged specific absorption rate (SAR) between the vertical and horizontal polarisations (SAR_{WBmax}) for different devices according to the distance to the user using measured electric field data. Survey outputs, including daily exposure in hours and reported exposure distances, were used to identify spots for in situ experimental evaluation accomplished with a series of measurements of electric field strength of various wireless devices. Complementary to the results of the incident electric field strength, the SAR_{WBmax} values for 1–10 years old children during real-life exposure conditions to a few wireless communication devices are presented. The obtained results may contribute to derive recommendations on children exposure limits to specific wireless communication devices for far-field exposure scenarios.

1 Introduction

Rapid development of new wireless technologies and their pervasiveness in indoor and outdoor environments provide various benefits to individuals and society, but are also raising concerns regarding the electromagnetic (EM) field levels they produce and the possible biological and medical effects on humans as a result of exposure to EM fields.

In efforts to identify the vulnerable groups regarding exposure to EM fields from mobile devices, there is on-going research debate on whether children should be treated as a sensitive group [1, 2] and is being argued based on the fact that children have longer life time exposure to wireless communication devices, their morphological and physiological systems differ from adults, and human body permittivity and conductivity are age-dependent [3]. In addition, children are exposed to some age-specific devices such as baby surveillance devices, wireless toys and so on.

Actual international exposure limits and safety standards and guidelines [4–6] have been developed mostly for adults without taking in to consideration specific standards for children, although they do include safety margins considered to be conservative for all exposure conditions for all age groups.

The use of wireless communication devices within indoor environments is increasing, producing research of exposure levels emerging from new wireless technologies, specifically wireless technologies used for short-range indoor communications in homes and is also producing development of assessment methods for demonstrating compliance with existing safety limits of wireless devices used in home environments, as presented in studies [7–9].

Results of a population-based study assessing ownership and use of mobile phones and cordless phones among children and adolescents obtained from questionnaires answered by young people in the age groups from 7–14 years old and 15–19 years old are reported in studies [10, 11], respectively.

Among children aged 7–14 years old, 79.1% of the respondents reported mobile phone access and 26.7% of them talked for 2 min or more per day. Of those who reported mobile phone access, only 5.9% reported use of hands-free equipment. Use of cordless phones was reported by 83.8% of the respondents and 38.5% of them talked for 5 min or more per day, as reported in [10]. Some of the most frequently reported health complaints of the 15–19 years old age group were presented in [11]; these were tiredness, stress, headaches, anxiety, concentration difficulties and sleep disturbances. Regular users of wireless phones had more health symptoms and reported poorer perceived health than less-frequent users.

Pre-school age children, who also use mobile phones, were omitted from the above and other similar studies, and there are also very few studies assessing children's exposure to other wireless devices present in home and indoor environments such as: DECT (Digital Enhanced Cordless Telecommunication) handsets and base stations, WLAN (wireless local area network) devices, radio frequency peripherals, wireless toys and so on.

In the procedure of exposure assessment within home environments it is important to determine the most-used

wireless devices by children to evaluate field levels of each device separately and identify their contribution to overall EM field levels in the respective micro environments.

Crucial to the procedure of assessing the EM flux levels of indoor environments is the measurement of incident electric or magnetic field strength produced by wireless communication devices for far-field exposure scenarios, and comparison of obtained values with the exposure limits specified in [4] or to the maximum permissible exposure levels specified in [5, 6]. Compliance with these quantities implies compliance with the basic restriction limits of safety standards and guidelines.

To address the absorption of radio frequency EM energy on an exposed child's body, the induced specific absorption rate (SAR) values should be determined. Owing to difficulties presented by in vivo measurements for most bio tissues and the ethics of experiments on humans, especially regarding children, alternative approaches are necessary.

The method presented in this paper for assessing the exposure of children to EM fields from wireless communication devices in home environments comprises:

(a) Determination of usage patterns for wireless devices by children via statistical survey. Identification of most-used devices, daily exposure in hours and exposure distances for each specific device.
(b) Experimental evaluation of the electric and/or magnetic field strength at different distances from a device to a child's body. Measurement spots to be identified from survey outputs.
(c) Calculation of induced SAR values in a child's body as a result of exposure. Development of SAR algorithms based on child age, exposure distance and duration of exposure per day.
(d) Based on results obtained from the previous steps, derivation of recommendations for 'safe' limits of exposure to EM fields of wireless devices for children – Recommendations on precautionary measures.

Potentially this study will stimulate more sophisticated studies on experimental assessment of children's exposure to specific wireless communication devices preceded with inputs from surveys on exposure parameters with larger number of respondents.

The presented results in this paper may contribute to development of future algorithms for assessment of cumulative EM field levels of typical real life indoor environments.

2 Children's exposure to EM fields from wireless communication devices

2.1 Statistical survey on children's exposure to specific wireless devices

Considering the lack of studies on mobile phone usage for children younger than 7 years of age and very limited information on the assessment of children's exposure to other wireless devices present in home environments, the statistical survey presented here was conducted. The main goal of the survey was identification of real-life child exposure spots and parameters. The questionnaire comprising 16 questions was sent to parents of 1–10 years old boys and girls, asking which devices are being used by children, how many hours per day, and at what distances they are usually located from a child. The reasons why the questionnaire was sent to parents instead of interviewing children directly are that for some specific ages children are not entirely aware of exposure to wireless devices; as an example: exposure to baby surveillance devices. Also children that are so young are not normally able to report exact durations, distances, and types of exposure, therefore parents may contribute better data to derive more reliable conclusions.

The questionnaire was sent to 140 parents, male and female, residents of Kosovo, which were chosen from an age range of 25–45 years old, different educational backgrounds, and different socioeconomic levels. The response rate was greater than 90%. The results were processed with a SPSS-software package used for statistical analysis. Results are tabulated in Table 1.

The mobile phone remains among the most used devices by children, the differences between adult and children's exposure to mobile phone EM fields have been reported in various studies [12–19], so the focus of this paper is on children's exposure to EM fields produced by wireless communication devices other than mobile phones, although some general information regarding mobile phones was asked.

Table 1 Exposure of children to specific wireless devices

children exposure to wireless local area networks EM fields	exposure/day		%	
	no reply		1.9	
	<1 h		25.2	
	>1 h		30.1	
	no exposure/usage		42.7	
children exposure to DECT EM fields	exposure/day		%	
	no reply		1.9	
	<5 min		36.9	
	>10 min		19.4	
	no exposure/usage		41.7	
children exposure to mobile phone EM fields	exposure/day		%	
	no reply		4.9	
	<5 min		32.0	
	>10 min		29.1	
	no exposure/usage		34.0	
children exposure to Baby surveillance device EM fields	distance from baby surveillance device to baby head		exposure/day	
	no reply	18.4%	no reply	26.2%
	<50 cm	16.5%	3–5 h	47.6%
	50 cm–100 cm	47.6%	6–12 h	19.4%
	>100 cm	17.5%	>12 h	6.8%

Regarding DECT and mobile phones the questionnaire included the options: usage <5 min/day, usage >10 min/day and no usage. The main goal was to find out the percentage of exposed against non-exposed children while in further studies, other exposure duration intervals such as between 5 and 10 min, and even lager scopes of exposure duration will be included.

As reported in the survey, 57.3% of parents declared their children use wireless toys. The survey data indicate that 47.6% of parents are informed regarding levels of radiation their children are exposed to daily, while 86.4% of parents stated that they are concerned about the fact that their children use different wireless communication devices since an early age, confirming research efforts to evaluate children's exposure as a timely topic of concern in modern society.

2.2 Exposure assessment for a few wireless devices

A series of measurements of instant values of electric field strength have been conducted at different distances from a few wireless communication devices such as: baby surveillance devices, DECT handset and base stations, WLAN routers, Bluetooth devices and few radio frequency toys.

Measurements are conducted with calibrated measurement instruments: EMR-300 Narda E-field probe type 18C 2244/90.73 and Aaronia Spectran Radio Frequency Spectrum Analyzer HF-2025 E.

Measurements are performed in a furnished living room measuring 4 m × 5 m at a room temperature of 18°C and time of measurement between 10 and 11 a.m. Three adult persons were present in the room. Measurements were repeated a few times and confidence levels of the electric field values are ±15%.

To calculate the induced values of SAR inside a human body for different bio tissues software with FDTD – finite domain time difference code is commonly used.

A comparison between SAR values in child models derived from accurate anatomical scaling and those obtained using simple uniform scaling showed that the anatomical models are required only for accurate local SAR evaluation at the organ level, but are not necessary for compliance assessments, where whole-body averaged SAR (SAR_{WB}) is generally the limiting parameter, as pointed out in study [20]. Therefore if SAR values at specific parts of the body are not needed, whole body SAR algorithms may be sufficient. For compliance assessment purposes, among the most important factors for each frequency are the highest SAR_{WB} value between the vertical and horizontal polarisations and overall body dimensions.

In 2011, a study [20] proposed an empirical fitting formula to relate SAR_{WBmax} to a range of frequencies, as a function of exposed human height and weight and value of incident power density, described as follows

$$\mathrm{SAR}_{\mathrm{WBmax}} = (0.31 - 0.039f)\left(\frac{S}{M}\right)P_{\mathrm{inc}} \tag{1}$$

where f is the frequency in gigahertz, restricted to 900 MHz–3 GHz frequency range, P_{inc} is the incident power density in watts per square metre, the surface-to-mass ratio S/M is expressed in units of metres squared per kilogram and SAR_{WBmax} is obtained in watts per kilogram.

Formula validity is confirmed by comparing results obtained with the formula with measured results documented in [20]. For far field exposure the power density and field intensity are related by the following equation

$$P = \frac{E^2}{120\pi} \tag{2}$$

where E is the RMS value of the field in volts/metre, and 120π (Ω) is the characteristic impedance of free space.

The body surface area can be obtained by using one of several widely used formulas such as those proposed by Dubois and Dubois, Monsteller, Boyd, and Gehan and George, which give slightly different results. Haycock's formula is recommended for use in the general pediatric population [21]. The body surface area S according to Hayckok's formula [22] is given as

$$S(\mathrm{m}^2) = 0.024265 * \mathrm{height(cm)}^{0.3964} * \mathrm{weight(kg)}^{0.5378} \tag{3}$$

Haycock's formula was derived from the measured data of subjects ranging from premature infants to adults by multiple regression analysis, and provides a good fit for all values of S from greater than 0.2 m^2 to less than 2.0 m^2, where our group of interest (children 1–10 years old) belongs.

In results presented in this paper the height and weight of children are taken as the 50% percentile of child growth charts provided by the World Health Organization [23]. The methodology for extracting results for children growing at other percentiles remains the same. Also, for specific heights and weights of children, SAR_{WBmax} may be calculated according to the given methodology. All SAR_{WBmax} calculations presented in this paper are calculated according to the formulations described above.

2.2.1 Baby surveillance device: A series of measurements of electric field strength for three types of baby surveillance devices during continuous operation have been conducted.

Baby surveillance devices under test operate at the frequencies indicated below, with corresponding differences in transmitting power and range.

Baby surveillance device 1 – BP1 40.5 MHz	Baby surveillance device 2 – BP2 2.4 GHz	Baby surveillance device 3 – BP3 900 MHz

The maximum transmitting power for three types of baby surveillance devices under the test is <100 mW.

In Fig. 1, the results of the measurements of the electric field strength at survey-reported distances from the three types of devices are presented. Complementary to electric field strength results, the estimated SAR_{WBmax} values for 1–10 years old children exposed to BP 2 and BP 3 are given in Table 2.

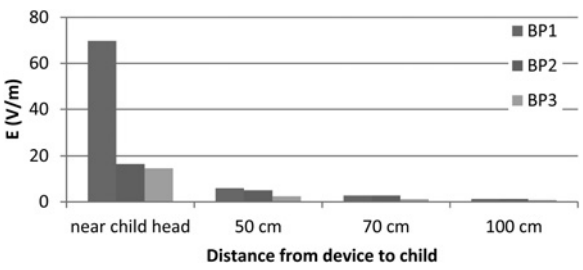

Fig. 1 *Electric field strength as a function of distance from device*

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Table 2 Estimated SAR_{WBmax} for 1–10 years old children exposed to baby surveillance devices

Child age	Baby surveillance device 2 – BP2			Baby surveillance device 3 – BP2		
	$d = 50$ cm; $E = 5.02$ V/m SAR_{WBmax}, mW/kg	$d = 70$ cm; $E = 2.73$ V/m SAR_{WBmax}, mW/kg	$d = 100$ cm; $E = 1.2$ V/m SAR_{WBmax}, mW/kg	$d = 50$ cm; $E = 2.43$ V/m SAR_{WBmax}, mW/kg	$d = 70$ cm; $E = 1.1$ V/m SAR_{WBmax}, mW/kg	$d = 100$ cm; $E = 0.8$ V/m SAR_{WBmax}, mW/kg
1	0.34	0.10	0.02	0.10	0.02	0.01
2	0.33	0.10	0.02	0.10	0.02	0.01
3	0.31	0.09	0.02	0.09	0.02	0.01
4	0.30	0.09	0.02	0.09	0.02	0.01
5	0.30	0.09	0.02	0.09	0.02	0.01
6	0.29	0.09	0.02	0.08	0.02	0.01
7	0.28	0.08	0.02	0.08	0.02	0.01
8	0.27	0.08	0.02	0.08	0.02	0.01
9	0.26	0.08	0.02	0.08	0.02	0.01
10	0.25	0.08	0.01	0.07	0.02	0.01

The results show similar trends of electric field strength and estimated SAR_{WBmax} values induced in children for all devices under test. The electric field strength decreases to 1.2 V/m (BP2) and 0.8 V/m (BP3) when the baby surveillance devices are placed 1 m from a child.

The ICNIRP recommended electric field level for general public is 61 V/m for devices operating at 2.4 GHz (such as BP2) and 42 V/m for devices operating at 900 MHz (such as BP3). Therefore, the electric field value at distance 50 cm from BP2 is 8.2%, at 70 cm is 4.47% and at 100 cm is 1.96% of reference level given by ICNIRP.

Electric field level at 50 cm from BP3 corresponds to 5.78%, at 70 cm to 2.61% and at 100 cm to 1.9% of ICNIRP reference levels.

The estimated induced SAR_{WBmax} values in 1–10 years old children exposed to the baby surveillance devices operating at frequencies between 900 MHz and 3 GHz decreases to 0.01–0.02 W/kg when the baby phone is placed at least 1 m away from child's head. Thus it is recommended to keep this type of device at least 1 m away from the child. With the proposed method it is not possible to derive the SAR_{WBmax} values for children exposed to BP1 since the formula is valid only for the frequency range 900 MHz–3 GHz. Owing to operating frequency the far-field conditions cannot be considered for BP1 at the paper considered distances therefore the assessment should be completed with magnetic field measurements and/or compliance with basic restriction should be conducted. The measured value of electric field of BP1 in location near child head is above reference level given by ICNIRP.

2.2.2 Digital Enhanced Cordless Telecommunication: For assessing child exposure to EM fields produced by a DECT device, the experimental setup comprising different exposure scenarios has been conducted; Table 3 shows the results of measurements of the electric field strength during call establishment and talk modes. The devices under test operate at a frequency 1.9 GHz. The maximum transmitting power of DECT base station and handset is 250 mW, while for base station normal time-averaged transmitting power is 10–66 mW with active call and 2 mW without call, in idle mode. The handset normal time-averaged transmitting power is 10 mW during call and 0 mW without call.

The highest value of electric field strength, as expected, occurs during the interval of call establishment, near the child's ear. The value decreases by approximately 50% when the handset is kept at a distance of 3 cm from the child's ear.

The ICNIRP reference level for electric field of the device operating at 1.9 GHz is 60 V/m. Electric field strength during call establishment mode at distance 3 cm is 19.76%, at distance 5 cm is 13.53%, at 10 cm is 5.56% of ICNIRP reference levels. During active call at distance 3 cm the electric field strength corresponds to 10.56% of ICNIRP reference level for general public exposure.

When children are in the same room/space with a DECT system, regardless of whether they are using it (passive exposure), they are exposed to a certain level of EM field.

The electric field values at distance 30 cm from DECT base station are 2.83%, at 50 cm 1.33% and at 100 cm 0.37% of ICNIRP reference levels.

The estimated SAR_{WBmax} values for 1–10 years old children from exposure to a DECT base station are presented in Table 4.

For example, if a child is 30 cm away from a DECT base station, the induced SAR_{WBmax} value for a 1–6 years old child will be 0.04 mW/kg, while if the child is 1 m away the induced SAR value will be < 0.01 mW/kg. Considering the time duration children spend in micro environments where a DECT is present, it is recommended they keep a distance of 1 m from the DECT base station.

The measurements should be re-confirmed with advanced settings instruments with a proper field probe, in connection to the various modulations of DECT signals.

Results should be completed with the induced SAR values for near-field exposure scenarios with a larger variety of devices under test. Also it is important to note that the use of the whole-body SAR (SAR_{WB}) to analyse DECT handset exposure is questionable since the device is placed very close to the head, therefore only SAR_{WBmax} analysis for a DECT base station is presented in this paper.

2.2.3 Wireless local area networks: Results of electric field strength measurements conducted at different distances

Table 3 Electric field strength as a function of distance during call establishment and call duration modes

Electric field strength from DECT			
Call establishment		Call duration	
Distance from ear, cm	*E*, V/m	Distance from ear, cm	*E*, V/m
3	11.86	3	6.34
5	8.12	5	5.10
10	3.34	10	3.27

Table 4 Estimated SAR_{WBmax} values for 1–10 years old children exposed to a DECT base station

Distance from DECT base station to child						
	30 cm		50 cm		100 cm	
Child age	*E*, V/m	SAR_{WBmax}, mW/kg	*E*, V/m	SAR_{WBmax}, mW/kg	*E*, V/m	SAR_{WBmax}, mW/kg
1–6 years old	1.7	0.04	0.8	0.01	0.3	<0.01
7–10 years old	1.7	0.03	0.8	0.01	0.3	<0.01

Table 5 SAR_{WBmax} values at 1–10 years old children exposed to WLAN router

WLAN router										
	30 cm		50 cm		100 cm		200 cm		> 200 cm	
Age	*E*, V/m	SAR_{WBmax}, mW/kg	*E*, V/m	SAR_{WBmax}, mW/kg	*E*, V/m	SAR_{WBmax}, mW/kg	*E*, V/m	SAR_{WBmax}, mW/kg	*E*, V/m	SAR_{WBmax}, mW/kg
1–10 years old	0.97	0.01	0.8	0.01	0.7	0.01	0.5	<0.01	0.2	<0.01

from a WLAN router, which is a key component in popular Wi-Fi technology, in scenarios without traffic, and serving 2 against 4 users using the network at the same time, are presented in Table 5 and Fig. 2. The device operates at frequency 2.4 GHz with maximum transmitting power of 100 mW. The receiving antenna should not be allowed to influence the measurement, since the settings of the instrument for the WLAN signal, which is stochastic-like, are very important for a proper result. The results of laboratory measurements carried out with examples of Wi-Fi devices used in other indoor environments such as schools to evaluate the radiofrequency power densities around them and their total emitted power are reported by the study in [24].Considerations related to human exposure to radio frequency energy from WLANs and other factors that determine exposure levels are described in detail in study [25]. According to the results of our research, one of the important exposure factors is the number of users on the network at the same time; there is a noticeable difference in exposure levels when a router is serving different number of users, in terms of the level of the EM field generated, as shown in Fig. 2. Without traffic the induced SAR_{WBmax} of 1–10 years old children for distances greater than 30 cm decreases to 0.01 mW/kg. The induced SAR_{WBmax} values increase when the number of WLAN users increases. Considering the possible lengthy periods of time children spend in wireless small indoor environments such as internet cafes, it is recommended that children do not stay in close proximity to a router that serves a network with many users.

The electric field values measured at distance 30 cm from WLAN device corresponds to 1.59%, at distance 50 cm to 1.31%, at distance 100 cm to 1.14% of ICNIRP reference levels, respectively, while at distances equal or greater than 200 cm values are less than 1% of ICNIRP reference levels.

2.2.4 Wireless peripherals and toys: Low levels of electric field strength and estimated SAR_{WBmax} values in children exposed to wireless toys and wireless peripheral devices such as Bluetooth, wireless mice and keyboards has been examined regarding far-field exposure scenarios. For illustration: the measured electric field strength from Bluetooth is 2.26 V/m, corresponding to 3.7% of ICNIRP reference levels. Electric field strength levels measured from

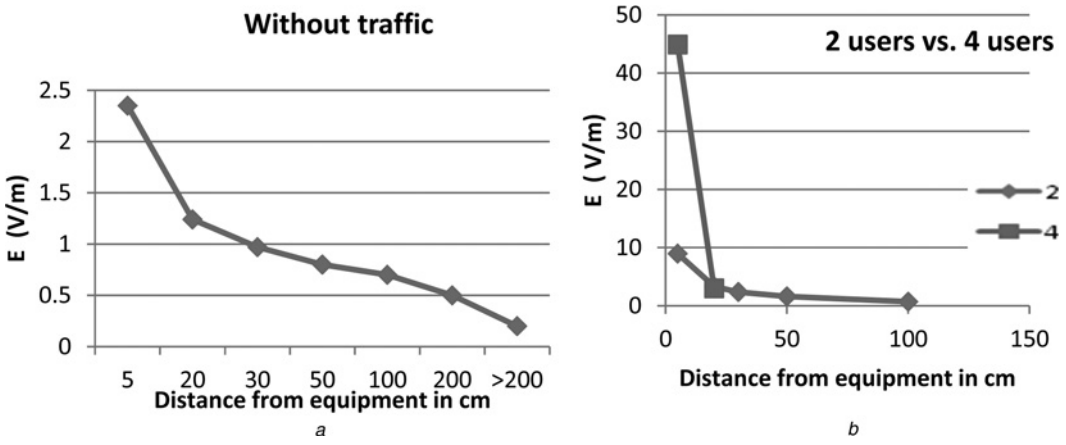

Fig. 2 *Electric field values in distances from router serving*

a No user
b 2 against 4 users

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Table 6 SAR_{WBmax} values for 1–10 years old children exposed to Bluetooth

Child age	*E*, V/m	SAR_{WBmax}, mW/kg
1–2 years old	2.26	0.07
3–7 years old	2.26	0.06
8–10 years old	2.26	0.05

wireless toys were lower, so only Bluetooth is evaluated. In Table 6, the values of induced SAR_{WBmax} for 1–10 years old children exposed to Bluetooth EM fields are provided.

3 Conclusions

Today's children are growing up in environments with a dense EM flux generated mostly by wireless communication devices. Survey data presented in this paper show that 86.4% of interviewed parents are concerned about the fact that their children have been using different wireless communication devices since an early age.

Determination of exposure parameters such as duration of exposure per day and distance from specific wireless devices to a child's body have been used as input for identification of locations and device types used in a home environment to conduct an experimental evaluation of electric and/or magnetic field strength followed with the estimation of induced SAR_{WBmax} values in children.

Survey results taken in Kosovo show that 47.6% of children are exposed to EM fields from baby surveillance devices 3–5 h a day and 19.4% of children are exposed 6–12 h a day out of which 16.5% of parents declared they keep a baby surveillance device <50 cm from the baby's head. The measured values of electric field strength show a notable decrease when the baby surveillance device is placed 1 m or further from a child, thus it is recommended to keep baby surveillance devices at least 1 m away from a child. Values of induced SAR_{WBmax} at a distance of 1 m from 1-years old children exposed to baby surveillance devices operating in a frequency range of 900 MHz–3 GHz was 0.01–0.02 mW/kg, depending on the type of baby surveillance device. Values of SAR_{WBmax} are significantly higher when the device is within 50 cm of the child.

A 36.9% of children use a DECT phone <5 min/day while 19.4% use a DECT phone >10 min/day. The highest value of electric field strength has been measured during the interval of call establishment, when the handset is near the child's ear. If a child is located 30 cm away from the DECT base station, the induced SAR_{WBmax} value for 1–6 years old children will be 0.04 mW/kg, while if they are located 1 m away, the induced SAR_{WBmax} value will be <0.01 mW/kg. Similar results apply for 7–10 years old children. With consideration to the time children spend in a room during the day and the possible effects of low level microwave chronic exposure, it is recommended they keep a safe distance (>1 m) from the DECT base station.

Survey results show that 30.1% of children 1–10 years old, both genders, are exposed to WLAN devices more than 1 h/day. For distances greater than 30 cm from WLAN router the induced SAR_{WBmax} value in 1–10 years old children decreases to 0.01 mW/kg. An increase in the number of users served by a WLAN router is followed with increased levels of EM fields and the respective induced SAR_{WBmax}; therefore it is recommended that children do not stay in close proximity to a router serving many users for extended periods of time.

All presented results, for far-field exposure scenarios, are below ICNIRP reference levels for general public exposure. ICNIRP limits are for short-term exposure based on thermal effects. There are ongoing researches on health effects and safety of RF long-term low-level exposure.

The presented results may contribute in development of algorithms for the assessment of cumulative effects of EM field levels in indoor environments and also to development of an exposure matrix based on a child's age and gender.

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