RF & ELF Mobile Phone Exposure - Review and Newest Findings

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The Beginning

- early 80s
  - **Motorola:** developed first in-house SAR scanner
- late 80s
  - **IT'IS/ETH & Motorola:** published the absorption mechanism in the near-field of transmitter

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- late 80s
  - **IT'IS/ETH & Motorola:** published the absorption mechanism for the near-field of transmitters
- early 90s
  - **lawsuit:** no knowledge about the phone exposure (except Motorola)
  - **German Agency for Radiation Protection:** requested phone certification
  - **IT'IS/ETH:** received a contract to develop a prototype of certification system & procedures by German Ministry of Telecom, D-Telecom, Mannesmann, Swiss-PTT

Today

- each phone is certified to be compliant with the RF safety guidelines
- the maximum exposure (spSAR) is provided in the user manual
- lower values lead to a lower maximum exposure in the real world
- technology to assess the average real-world exposure of CNS and other tissues is ready
- each phone is intrinsically compliant with the ELF restrictions
- main unresolved details:
  - technical issues regarding measurement of latest technologies
  - hand effects on SAR
  - measurement distance for on-body testing

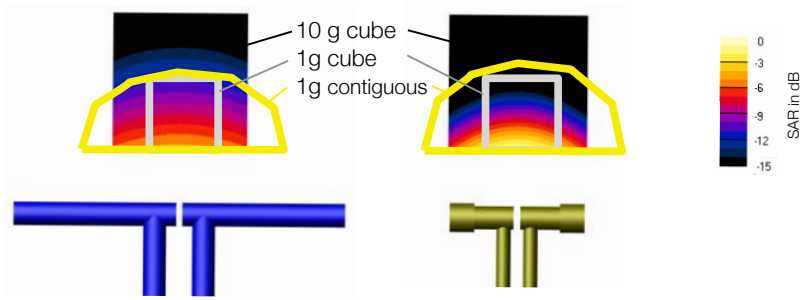
Radio-Frequency (RF) Fields from Mobile Phones

Basic Standard (>10 MHz)

	ICNIRP W/kg	FCC W/kg	IEEE 2006 W/kg	India W/kg
whole-body SAR limit	0.08	0.08	0.08	0.08
peak spatial SAR limit	2 **10g contiguous**	1.6 **1g cube**	2 **10g cube**	1 **10g cube**

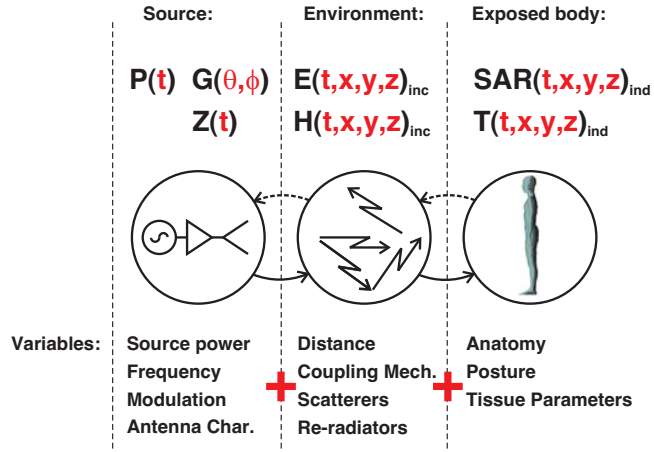
- whole-body limit: only relevant for vascular diseases
- spatial peak limit: relevant for local heating and potentially "athermal" effects

Dependence of Averaging Volume



2450 MHz 5500 MHz

Problem



Goal for Exposure Assessment (Compliance)

- the measured quantity must be conservative
  - >90th percentile of exposed population, i.e., all age groups
- simplified but not greatly overestimated exposure
  - i.e., w/o inhibiting technological progress
- low exposure in real life = low exposure in the test and vice versa
  - favors low exposure devices
- field distribution is greatly non-homogeneous
  - large gradients in 3D, multiple maximum
- mobile specific
  - highest absorption close to the surface
    - measurements closest to the surface
  - complex modulations
    - very large peak-to-average ratios

Research Effort of IT'IS/ETH

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majority of relevant references in the standard generated by IT'IS/ETH

1. Interaction Mechanism

$$\mathrm{SAR} = \frac{\sigma}{\rho}\,\frac{\mu\omega}{\rho\sqrt{\sigma^2+\varepsilon^2\omega^2}}\,(1+c_{\mathrm{corr}}\gamma_{\mathrm{pw}})^2 H_{t_{\mathrm{inc}}}^2 \qquad (1)$$

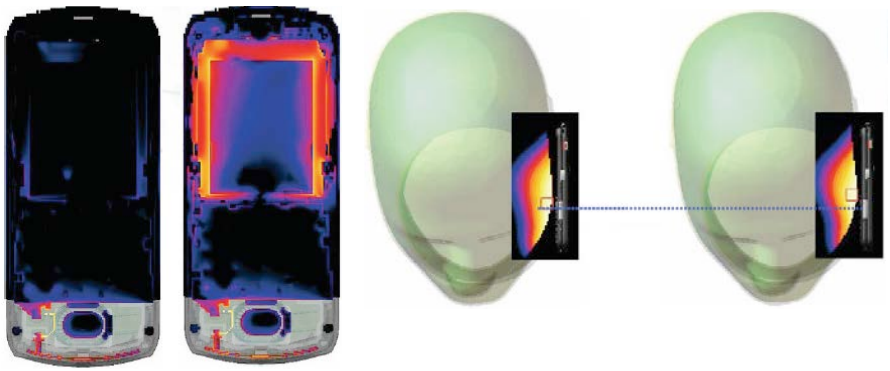
in which γ_{pw} is the plane-wave reflection coefficient for the H_t field

$$\gamma_{\mathrm{pw}} = \frac{2\left|\sqrt{\varepsilon'}\right|}{\left|\sqrt{\varepsilon'}+\sqrt{\varepsilon_0}\right|} - 1 \qquad (2)$$

$H^2 \sim j^2/d^2$

- SAR = $RF_{losses} \sim j^2/d^2$
- exposure is not directly related to the radiated power!
- strongly design dependent

1. Consequences of Interaction Mechanism



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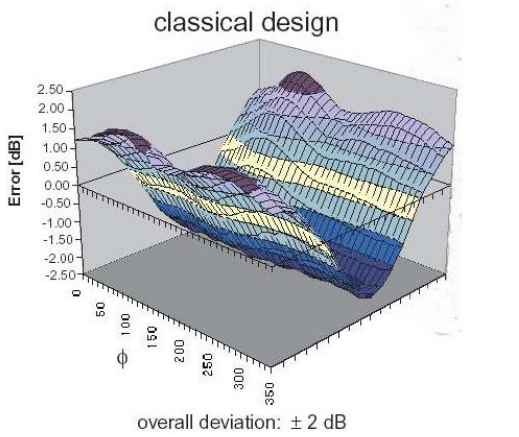
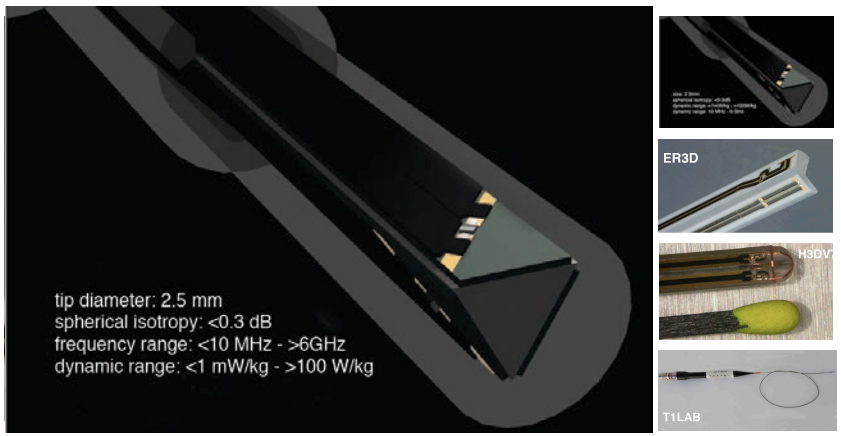
Historical Note



Smallest Isotropic Probes



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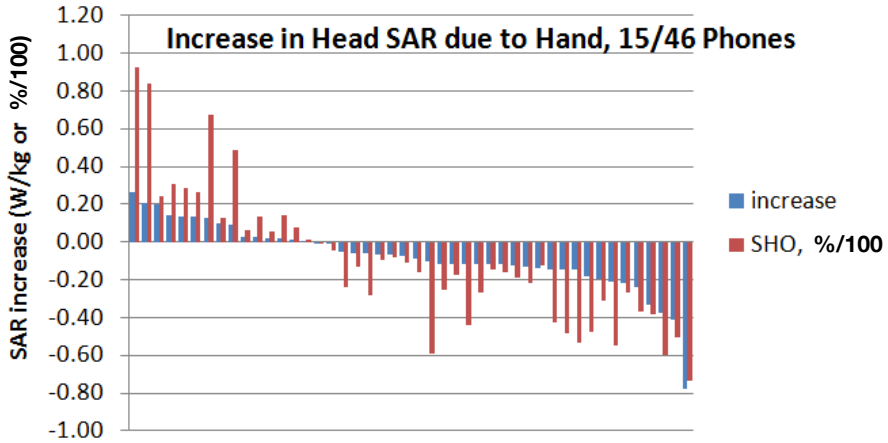
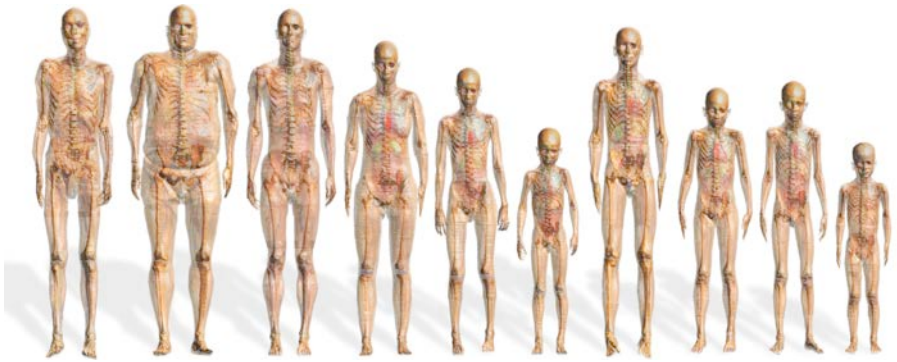
2. Phantom Shape + 3. Liquid + 4. Hand

- phone parts - close as possible
  - large head (90th percentile US army)
  - touch and tilt
- liquid representing worst-case tissue composition
  - liquid parameters derived from layered tissue model considering all tissue compositions
- hand
  - testing w/o hands since studies in the late 90s showed only reduction
  - currently under reconsideration

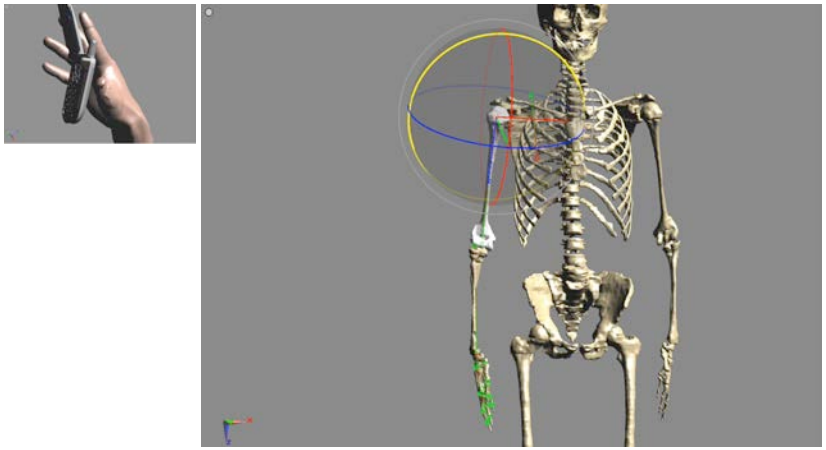
Hand Issue (Open)



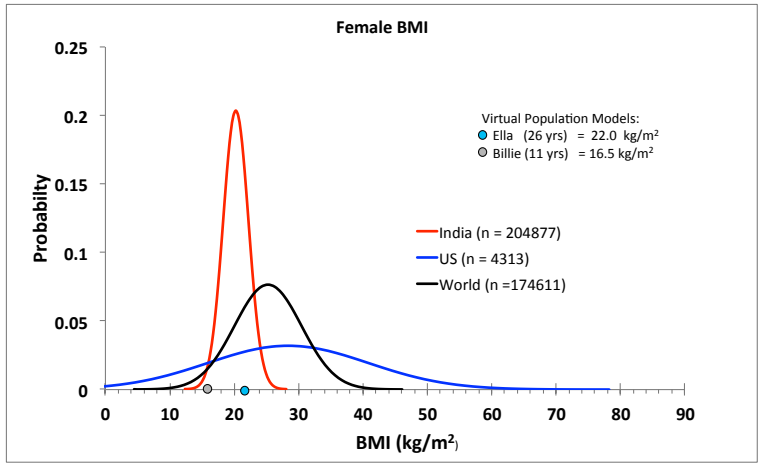
Virtual Population



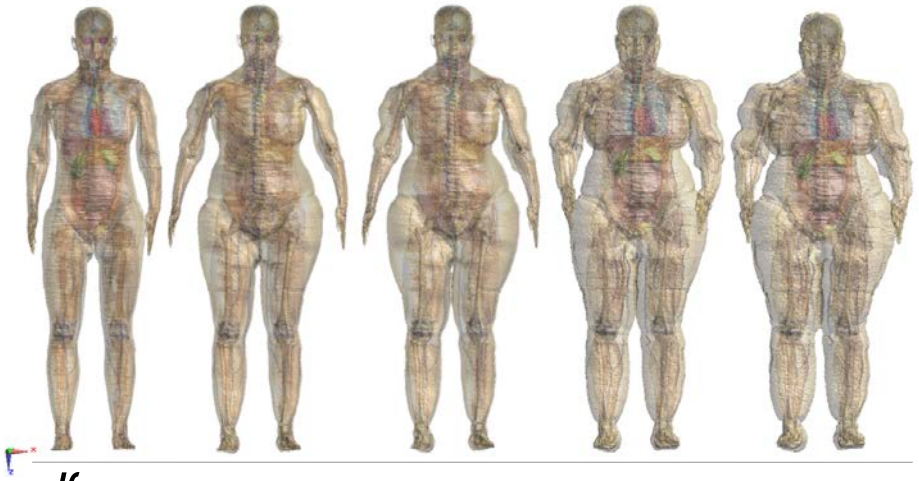
Poser



Anatomical Characteristics



Physics' Based Morphing



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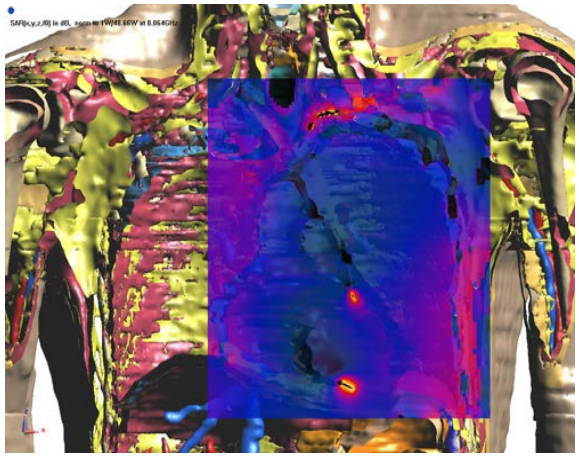
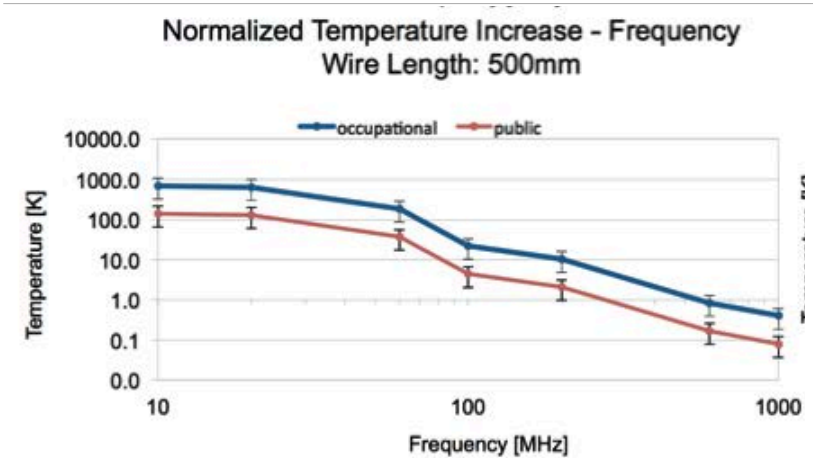
Implants - A Regulatory Gap



Evaluation at Basic Restriction Limit



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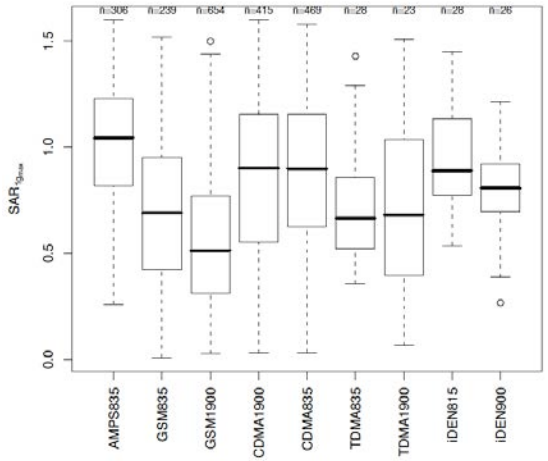
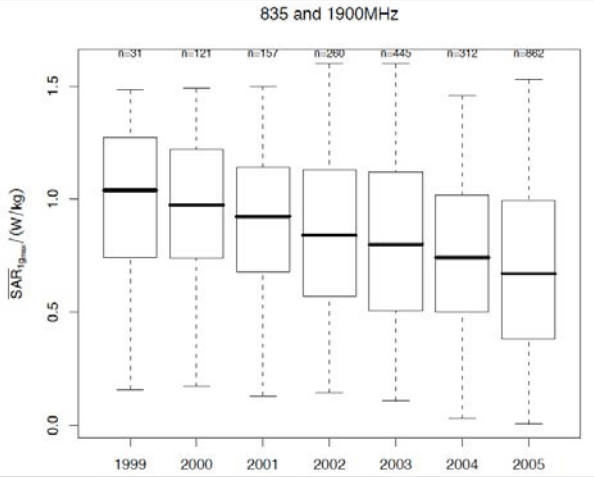
Latest Scanning System (DASY5 NEO)

Fast SAR Scanners

Spatial Peak SAR Values (System)

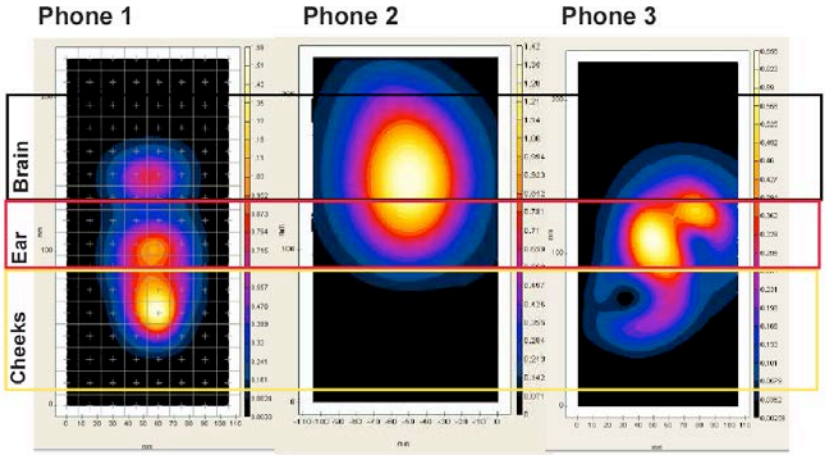


Spatial Peak SAR (t)

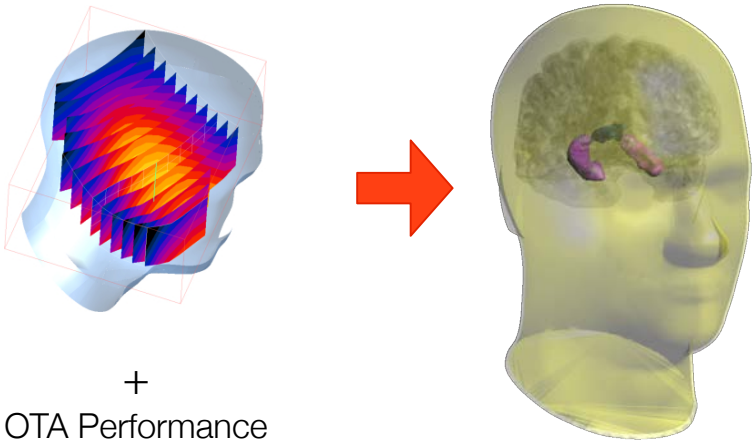


Brain Exposure as a Function of Anatomy

Brain Exposure (Phone Design)



Estimation of Avg Brain Exposure of Phone X



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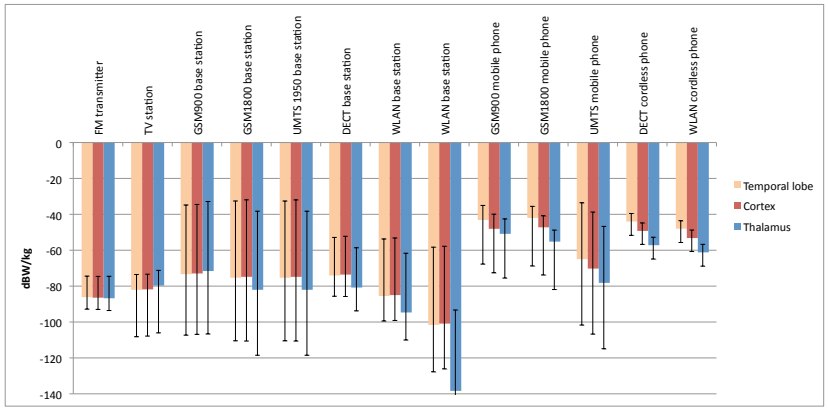
OTA Performance

Various Brain Regions Exposure by Sources

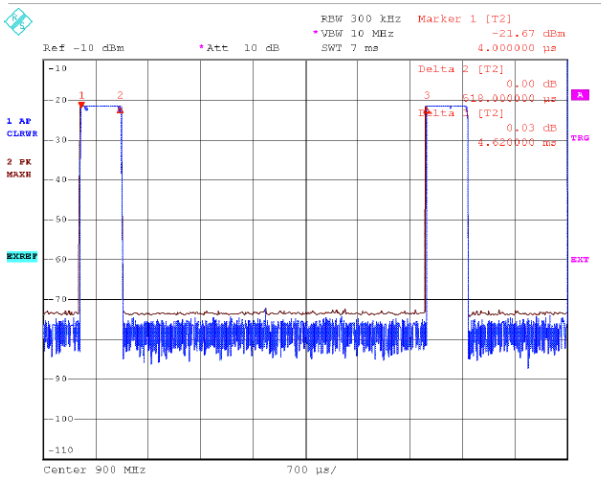
- Normal mobile/cordless phone user



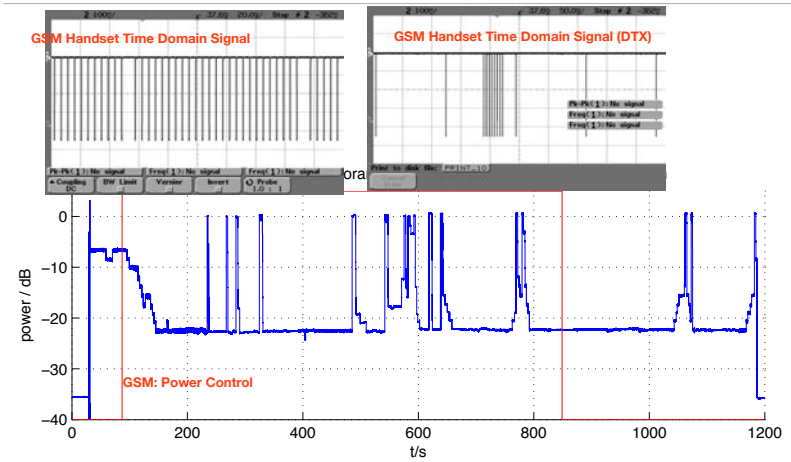
Mobile Phone Systems

	Bands (MHz)	System	max P_{rms} (mW)	avg P_{rms} (mW)	**maxpsSAR (W/kg)**	**avg psSAR (W/kg)**	remarks
NATEL/ NMT (1G)	450/900	FM/FFSK	1000	~500	**1 - 4**	**0.25 - 2**	
GSM/ EDGE (2G)	900/1800	TDMA, FDMA / GMSK	250/125	~50-100	**0.1 - 2**	**0.03 - 0.8**	
UMTS/ HSPA (3G)	1950	CDMA / QPSK	125	~1-5	**0.1 - 2**	**0.001 - 0.04**	
LTE (3.9G)	2600?	SC-FMDA / QPSK, 16QAM	<200	n.a.	**0.1 - 2**	**n.a**	avg. P in network still unknown
WiFi	2450/ 5200-5800	CSMA-CA / DxPSK, xQAM	100, 1000 (DFS, TPC)	usage dep: <1%	**0.05 - 1**	**0.0005 - 0.001**	
Bluetooth	2450	FHSS / GFSK, xDPSK	100/2.5/1	usage dep: <0.1%	**0.001 - 0.5**	**0.00001 - 0.005**	

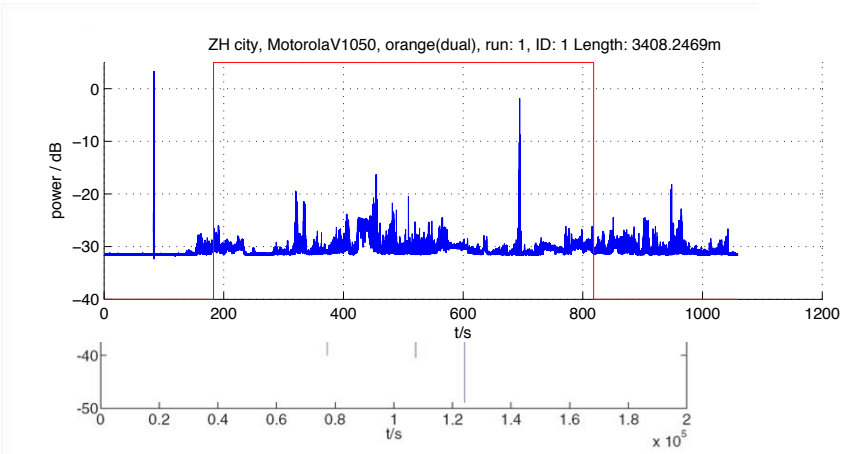
GSM: Time-Domain



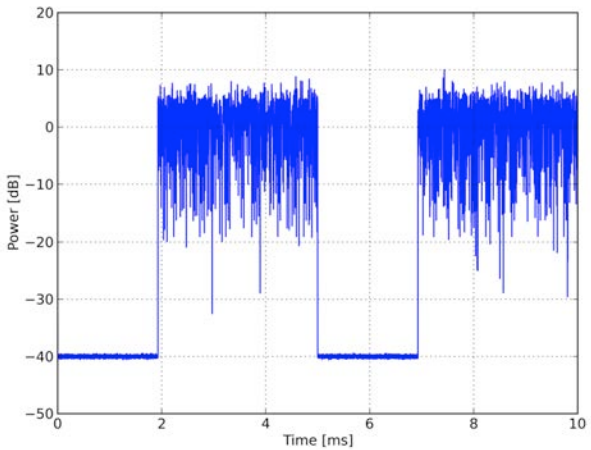
GSM Time Domain Signals



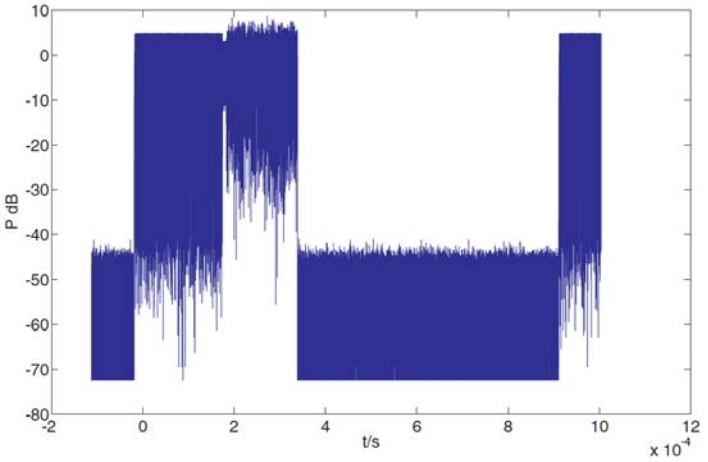
UMTS Time Domain Signals



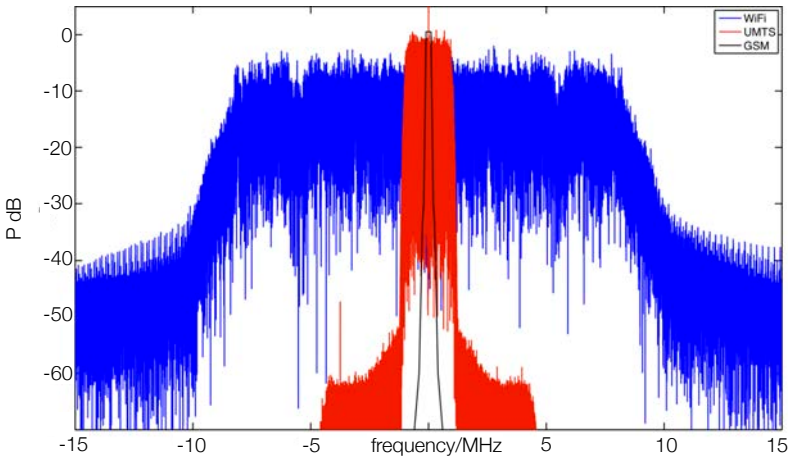
LTE: Time-Domain



WiFi: Time-Domain



Communication Systems: Frequency Domain



Low-Frequency (LF) Fields from Mobile Phones

- FSM Project

Absorption Mechanism (ELF)

- coupling with LF magnetic fields
  - induced electric fields by eddy currents
- exposure limited to prevent:
  - nerve and muscle stimulation
  - retinal phosphenes

ICNIRP Basic Restrictions (1998)

Table 4. Basic restrictions for time varying electric and magnetic fields for frequencies up to 10 GHz.[a]

Exposure characteristics	Frequency range	Current density for head and trunk (mA m^{-2}) (rms)	Whole-body average SAR (W kg^{-1})	Localized SAR (head and trunk) (W kg^{-1})	Localized SAR (limbs) (W kg^{-1})
Occupational exposure	up to 1 Hz	40	—	—	—
	1–4 Hz	40/*f*	—	—	—
	4 Hz–1 kHz	10	—	—	—
	1–100 kHz	*f*/100	—	—	—
	100 kHz–10 MHz	*f*/100	0.4	10	20
	10 MHz–10 GHz	—	0.4	10	20
General public exposure	up to 1 Hz	8	—	—	—
	1–4 Hz	8/*f*	—	—	—
	4 Hz–1 kHz	2	—	—	—
	1–100 kHz	*f*/500	—	—	—
	100 kHz–10 MHz	*f*/500	0.08	2	4
	10 MHz–10 GHz	—	0.08	2	4

$$\langle \mathbf{J}(\mathbf{r_0}) \rangle_A = \frac{1}{A} \int_A \mathbf{J}(\mathbf{r}) \cdot \hat{\mathbf{n}}\, da. \quad \text{A= 1cm}^2$$

ICNIRP Basic Restrictions (2010)

$$\langle \mathbf{E}(\mathbf{r_0}) \rangle_V = \frac{1}{V} \int_V \mathbf{E}(\mathbf{r})\, dv$$

V= 2x2x2mm^3

Table 2. Basic restrictions for human exposure to time-varying electric and magnetic fields.

Exposure characteristic	Frequency range	Internal electric field (V m^{-1})
Occupational exposure		
CNS tissue of the head	1–10 Hz	0.5/f
	10 Hz–25 Hz	0.05
	25 Hz–400 Hz	2×10^{-3}f
	400 Hz–3 kHz	0.8
	3 kHz–10 MHz	2.7×10^{-4}f
All tissues of head and body	1 Hz–3 kHz	0.8
	3 kHz–10 MHz	2.7×10^{-4}f
General public exposure		
CNS tissue of the head	1–10 Hz	0.1/f
	10 Hz–25 Hz	0.01
	25 Hz–1000 Hz	4×10^{-4}f
	1000 Hz–3 kHz	0.4
	3 kHz–10 MHz	1.35×10^{-4}f
All tissues of head and body	1 Hz–3 kHz	0.4
	3 kHz–10 MHz	1.35×10^{-4}f

IEEE Basic Restrictions (C95.6, 2002)

Table 1—Basic restrictions applying to various regions of the body[a, b]

Exposed tissue	f_e (Hz)	General public	Controlled environment
		E_0 - rms (V/m)	E_0 - rms (V/m)
Brain	20	5.89×10^{-3}	1.77×10^{-2}
Heart	167	0.943	0.943
Hands, wrists, feet and ankles	3350	2.10	2.10
Other tissue	3350	0.701	2.10

[a]Interpretation of table is as follows: $E_i = E_0$ for $f \le f_e$; $E_i = E_0 (f / f_e)$ for $f \ge f_e$.
[b]In addition to the listed restrictions, exposure of the head and torso to magnetic fields below 10 Hz shall be restricted to a peak value of 167 mT for the general public, and 500 mT in the controlled environment.

$$\langle \mathbf{E}(\mathbf{r_0}) \rangle_L = \frac{\hat{\mathbf{l}}_\mathbf{0}}{L} \int_L \mathbf{E}(\mathbf{r}) \cdot \hat{\mathbf{l}}_\mathbf{0}\, dl$$

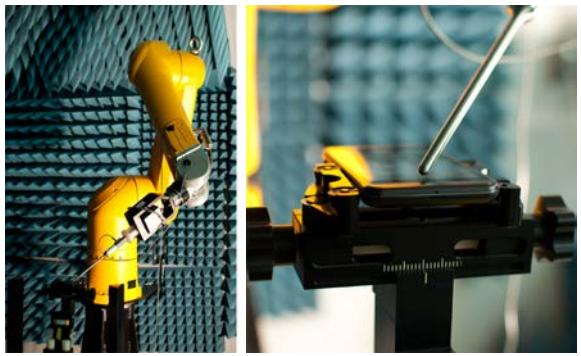
L= 5mm

LF Fields from Mobile Phones

- power of digital circuits
- power of PA including PCL
- audio signal

Measurement of Incident Fields

- 10 mobile phones
- GSM900, GSM1800, UMTS
- 3 PCLs
- front and back
- audio OFF/ON (1kHz)
- DASY52 NEO
- T-coil uniaxial probe
- time-domain via python implementation
- probe tip 1mm from phone surface (=4mm from sensor center)

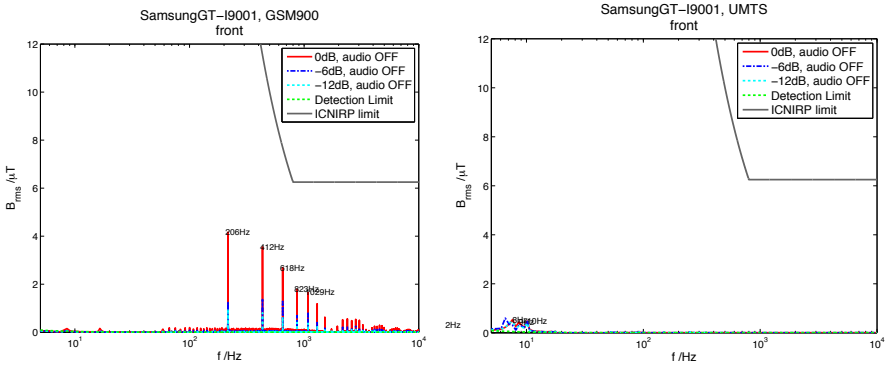


Measurement of Incident Fields - 10 DUTs

ID	Phone Model	Type	OS	Release Date
Nokia6120	Nokia 6120	bar		April 2007
SonyEricssonW910	Sony Ericsson W910i	slide		Oct 2007
SonyEricssonW760i	Sony Ericssion W760i	slide		May 2008
MotorolaV1050	Motorola V1050	flip		January 2005
HTCdiam100	HTC Diam100 Touch Diamond	smart	Windows Phone	May 2008
HTCtopa100	HTC Topa100 Touch Diamond2	smart	Windows Phone	April 2009
iPhone3g	Apple iPhone 3g	smart	iOS	July 2008
iPhone4	Apple iPhone 4	smart	iOS	June 2010
SamsungGT-I9001	Samsung Galaxy GT-I9001	smart	Android	June 2010
LG	LG P920 Optimus 3D	smart	Android	July 2011

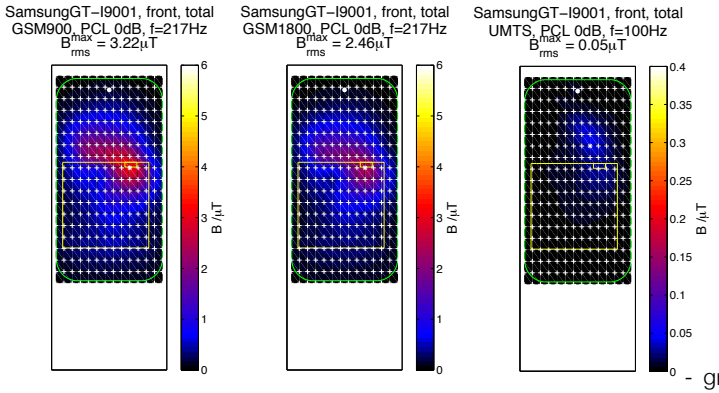
Measurement of Incident Fields - 10 DUTs

Results - Frequency Spectrum



- GSM: 217Hz and harmonics (B depend on PCL, confirms origin of field)
- UMTS: no significant

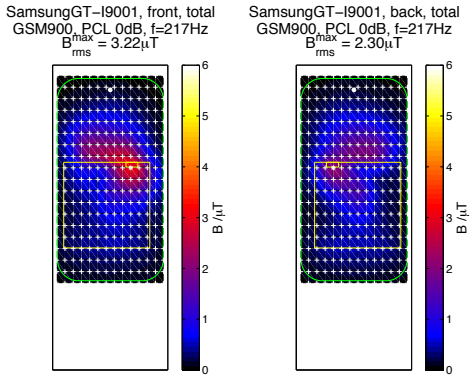
Results - Spatial Distribution



- GSM900, GSM1800 (217Hz)
- UMTS (100Hz)

- green: phone
- yellow: battery

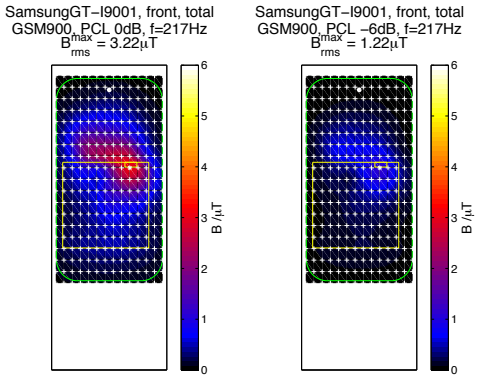
Results - Spatial Distribution



- GSM900
- front, back
- maximum is more often on back side, but depends on phone design

- green: phone
- yellow: battery

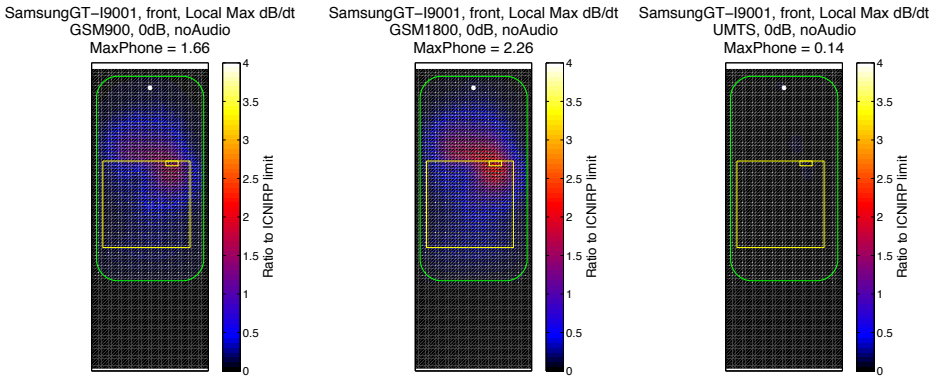
Results - Spatial Distribution



- GSM900
- max PCL vs -6dB
- B depend on PCL, confirms origin of fields

- green: phone
- yellow: battery

Results - Spatial Distribution (max dB/dt)



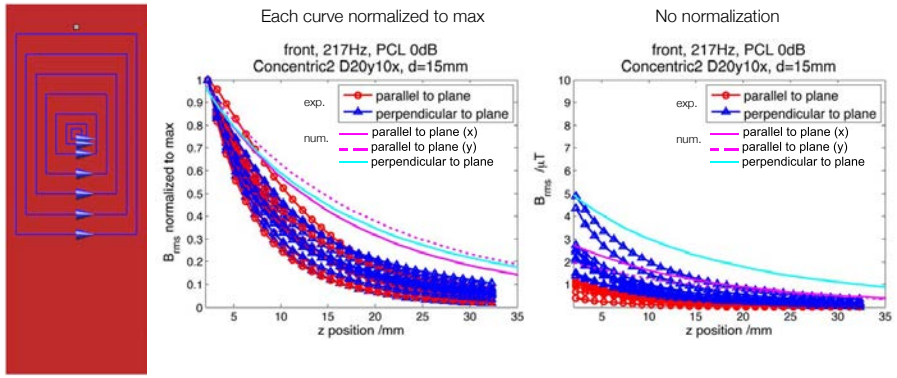
- GSM900, GSM1800, UMTS
- all frequencies
- maximum for each location

- green: phone
- yellow: battery

Results - Spatial Distribution (max dB/dt)

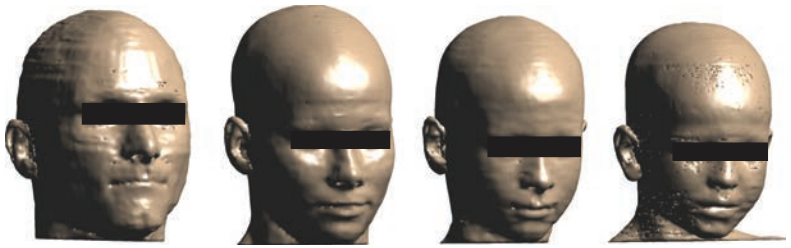
Phone	max ratio to dB/dt ICNIRP limits		
	GSM900	GSM1800	UMTS
HTCdiam100	4.49	3.13	0.44
HTCtopa100	4.50	2.08	0.49
iPhone3g	1.28	1.12	0.74
iPhone4	1.51	1.55	1.25
LG	2.49	1.64	0.68
MotorolaV1050	0.12	0.11	-
Nokia6120	2.88	2.22	0.49
SamsungGT-I9001	2.32	1.72	0.16
SonyEricssonW760i	0.97	0.88	0.55
SonyEricssonW910	2.64	1.52	0.37

Induced Fields - Model of Equivalent Source



Induced Fields - Anatomical Models

- anatomical heads from the Virtual Family
  - adults: Duke (34yo male), Ella (26yo female)
  - children: Billie (11yo girl), Thelonious (6yo boy)



Induced Fields - Frequency Spectrum

- for each quantity Q, the maximum ratio to the limits (ICNIRP, IEEE) is extracted using the spectrum for specific phones:

from simulation

frequency scaling

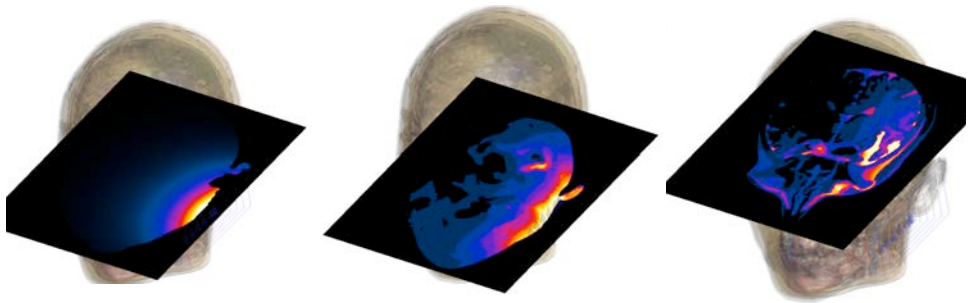
frequency spectrum (from experiment, per phone)

$$R_Q^{max} = \max\left(\mathrm{IFFT}\left\{\frac{Q_{sim}(f_0)}{Q_{lim}(f)}\,\frac{f}{f_0}\,\frac{B_{meas}(f)}{B_{sim}^{max}(f_0)}\right\}\right)$$

limit (ICNIRP, IEEE)

maximum field from simulation, in plane equivalent to measurements

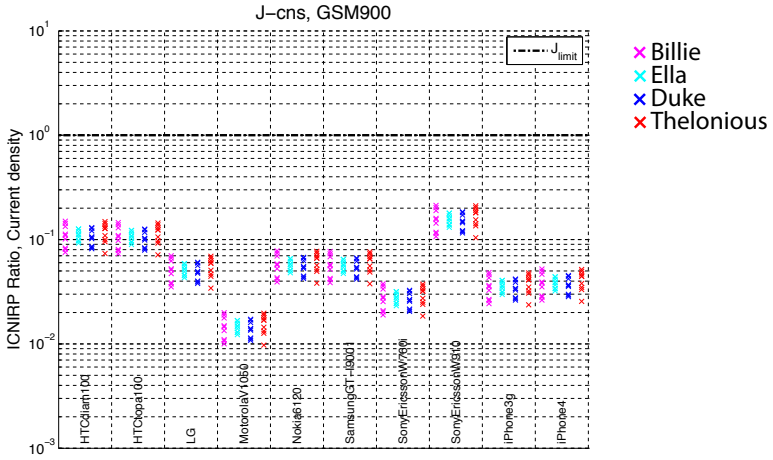
Induced Fields - Spatial Distribution



Brms Erms Jrms

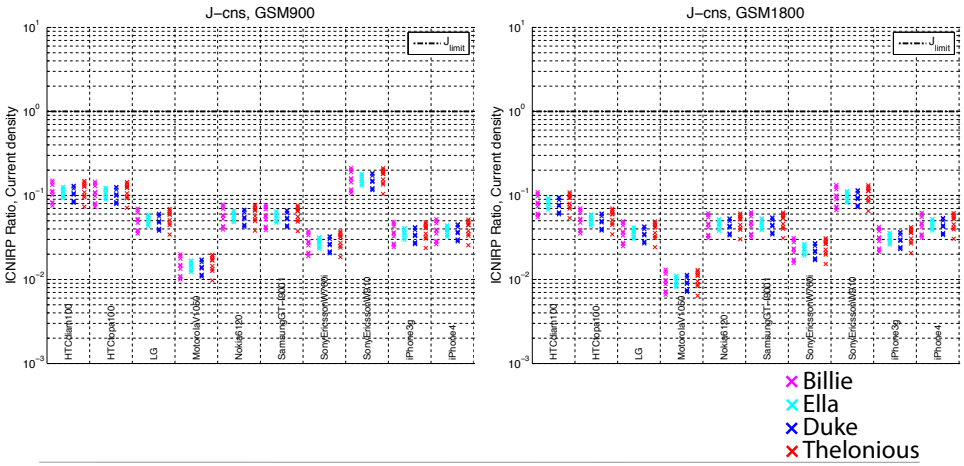
- plane through maximum

Induced Fields - J_{cns} vs all tissues



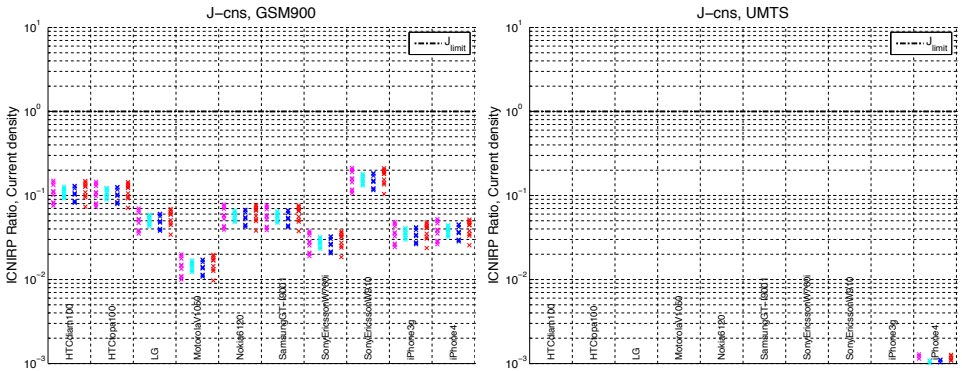
× Billie
× Ella
× Duke
× Thelonious

Induced Fields - J_{cns} GSM900 vs 1800



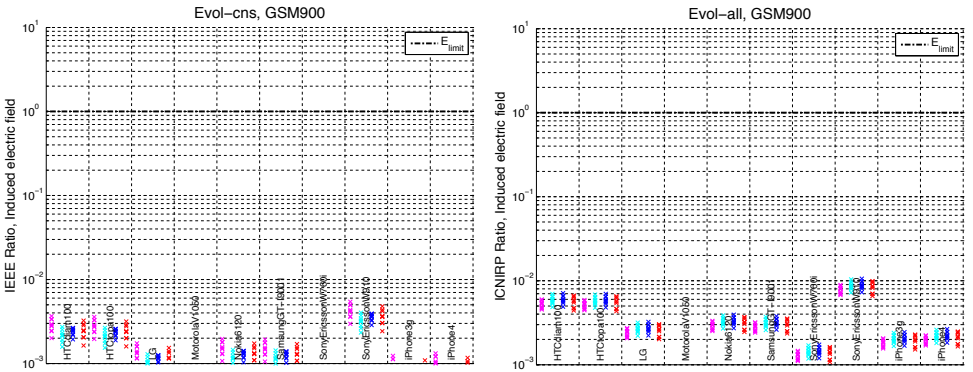
× Billie
× Ella
× Duke
× Thelonious

Induced Fields - J_{cns} GSM900 vs UMTS



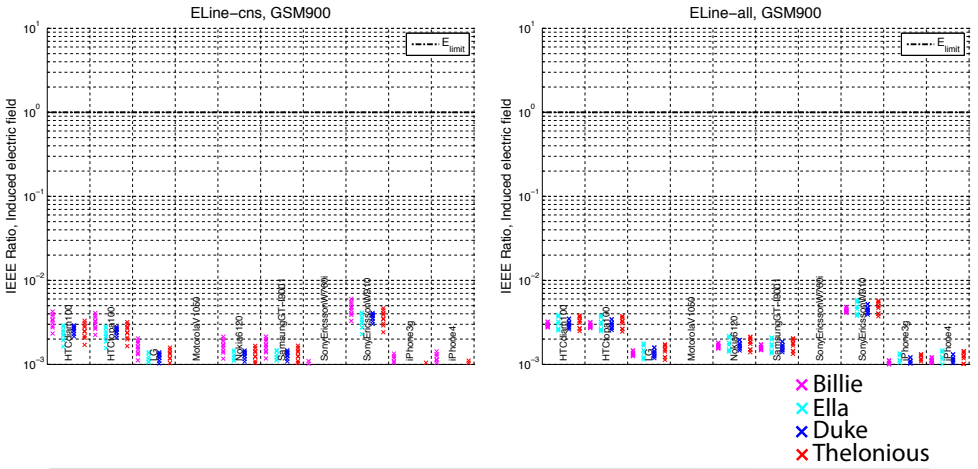
× Billie
× Ella
× Duke
× Thelonious

Induced Fields - E_{vol} CNS vs all tissues, GSM900

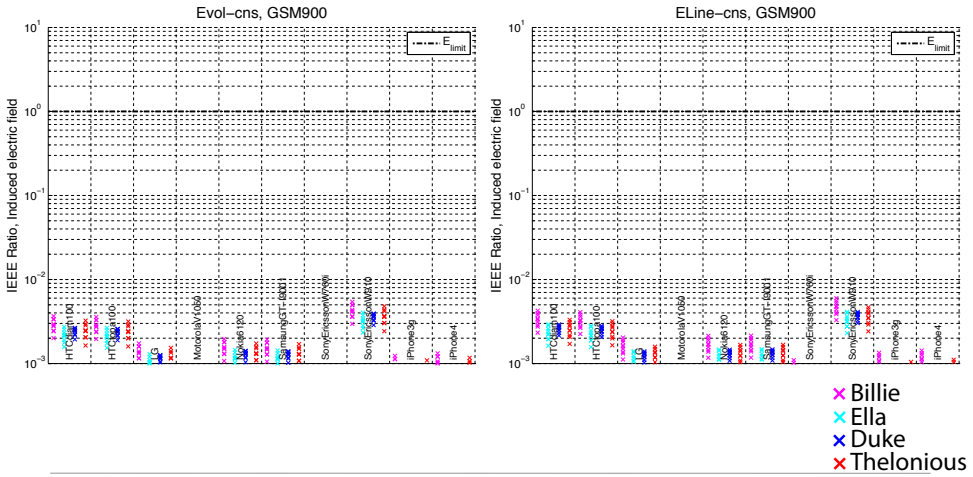


× Billie
× Ella
× Duke
× Thelonious

Induced Fields - E_{line} CNS vs all tissues, GSM900



Induced Fields - E_{vol} vs E_{line}, GSM900



Conclusions

- each phone is certified to be compliant with the RF safety guidelines
- the maximum exposure (spSAR) is provided in the user manual
- lower values lead to a lower maximum exposure in the real world
- technology to assess the average real-world exposure of CNS and other tissues is ready
- each phone is intrinsically compliant with the ELF restrictions
- main unresolved details:
  - technical issues regarding measurement of latest technologies
  - hand effects on SAR
  - measurement distance for on-body testing

Acknowledgements

- all PhD students, Post-Docs, colleagues, partners and sponsors who contributed and funded the RF research projects related to exposure assessment of wireless devices during the last 20 years
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