Workshop on BAN Technology and Applications

WPI, Worcester, MA

CWINS

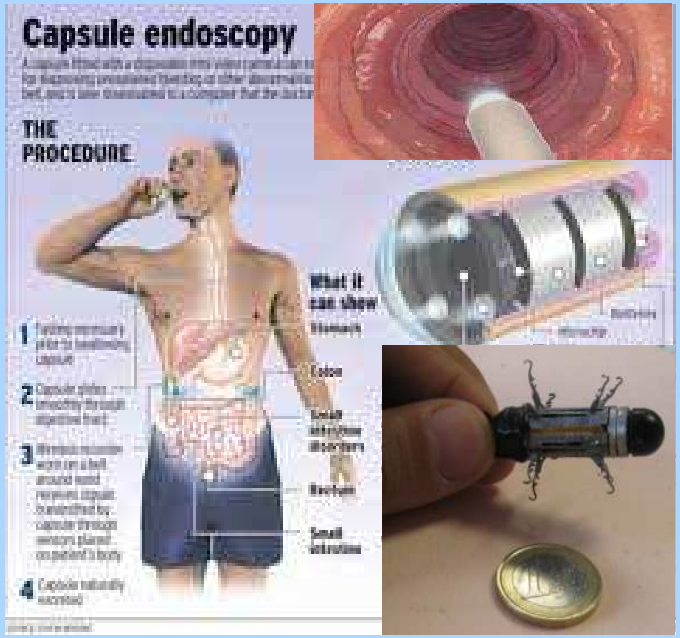
Channel Characterization for RF Localization Inside Human Body

Kaveh Pahlavan

Overview of CWINS Program on BAN

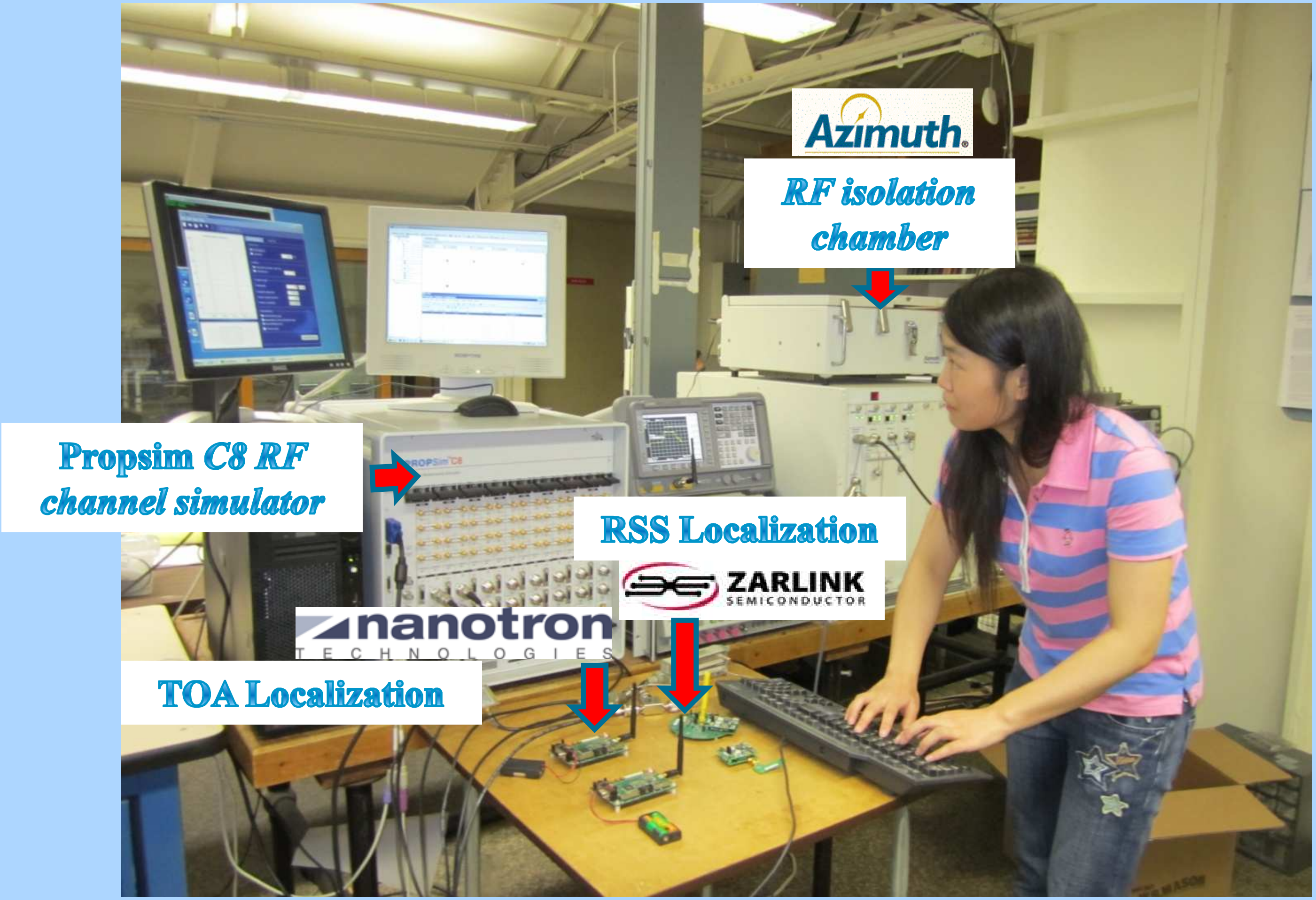
- **Current Project:** RF Propagation 1Measurement and Modeling for Wireless Body Area Networks – *Sponsored by NIST*
- Staff and Students at the CWINS Lab:
  - Kaveh Pahlavan
  - Allan H. Levesque (research scientist)
  - Kaveh Ghaboosi (Post Doc)
  - Reza Zekavat (visiting professor)
  - Ning Yang (affiliated research scientist)
  - Yunxing Ye, Fardad Askarzadeh (PhD)
  - Umair Khan, Ruijun Fu, Shen Li, Pranay Swary (MS)
  - Monir Islam (UG)
- Staff and Student at the Antenna Lab:
  - Sergey Makarov
  - Gregory M. Noetscher, Yang Xu (MS)
  - Ishrak Khair (UG)

Innovations starts with science fictions and a technical challenge!



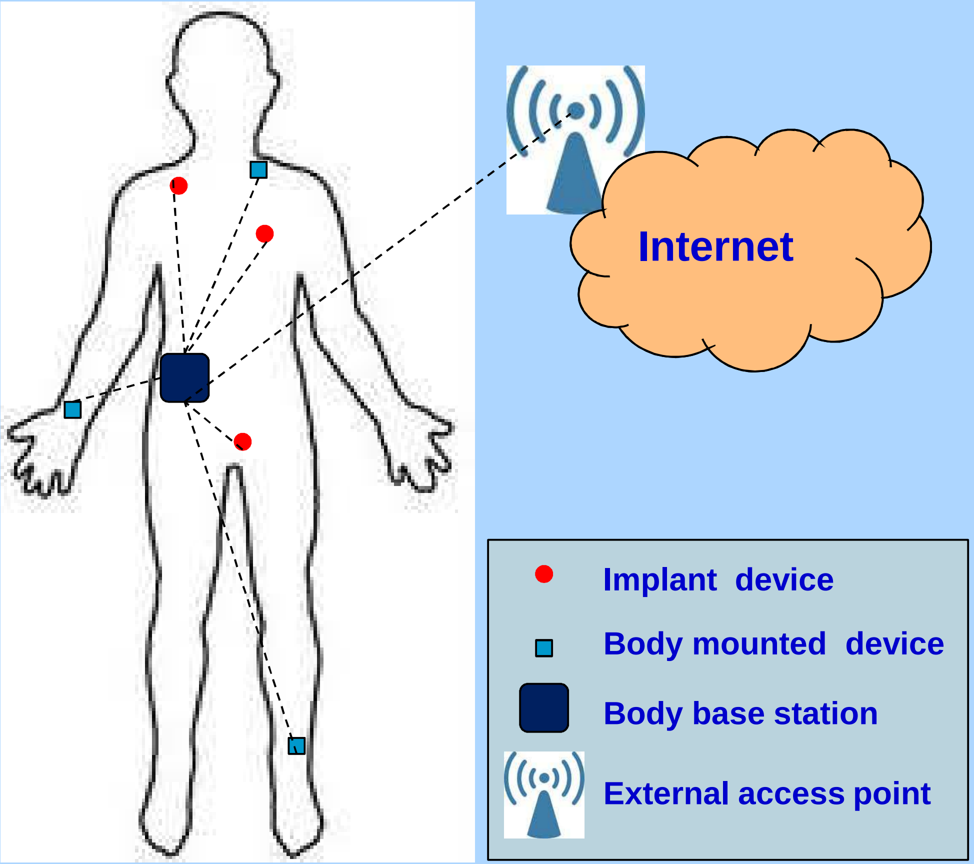
How can we localize the capsule using RF signal?

Performance evaluation needs channel models



[1] M. A. Assad, A Real-Time Laboratory Testbed for Evaluating Localization Performance of WIFI RFID Technologies, MS Thesis, CWINS, WPI, 2007
[2] L. T. Metreaud, An RF-Isolated Real-Time Multipath Testbed for Performance Analysis of WLANs, MS Thesis, CWINS, WPI, 2006
[3] M. Heidari, A Testbed for Real-time Performance Evaluation of Indoor Geolocation Systems in Laboratory Environment, MS Thesis, CWINS, WPI, 2005

Channel for in-body localization



Implant to implant

Implant to surface

Implant to external

Surface to surface LOS

Surface to surface NLOS

Surface to external LOS

Surface to external NLOS

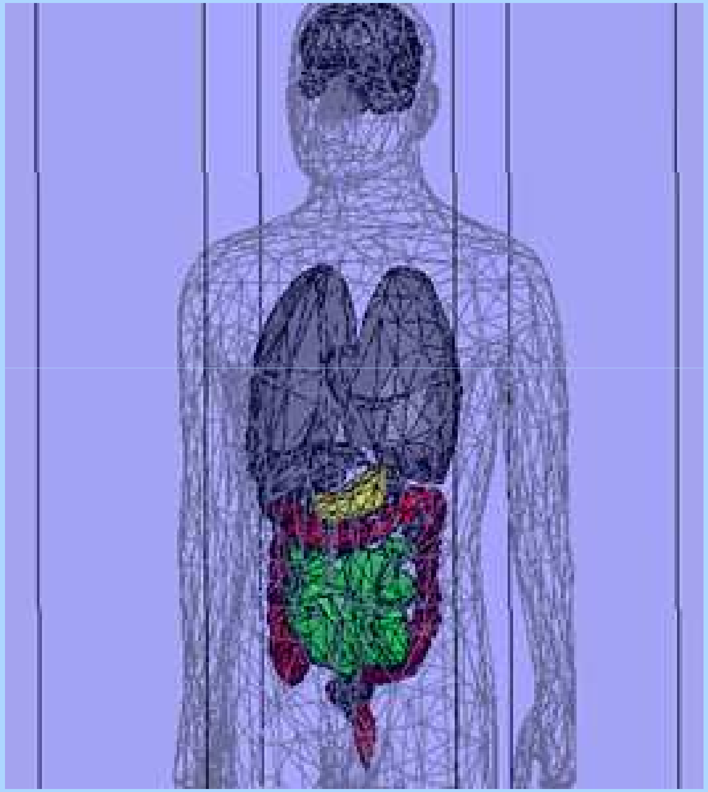
Channel Models for

- RSS-based systems [4]
- TOA-based systems [NA]

[4] Kamran Sayrafian-Pour,,Wen-Bin Yang, J. Hagedorn, J. Terrill, J. ; Kamya Yazdandoost, "A statistical path loss model for medical implant communication channels," *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on , vol.,* no., pp.2995-2999, 13-16 Sept. 2009.

Current research topics at CWINS

- What are the bounds on ranging error for RSS-based localization?
- What is the effect of non-homogeneousity of human body on TOA ranging?
- What are the effects of body motions?
- How can we measure inside human body?



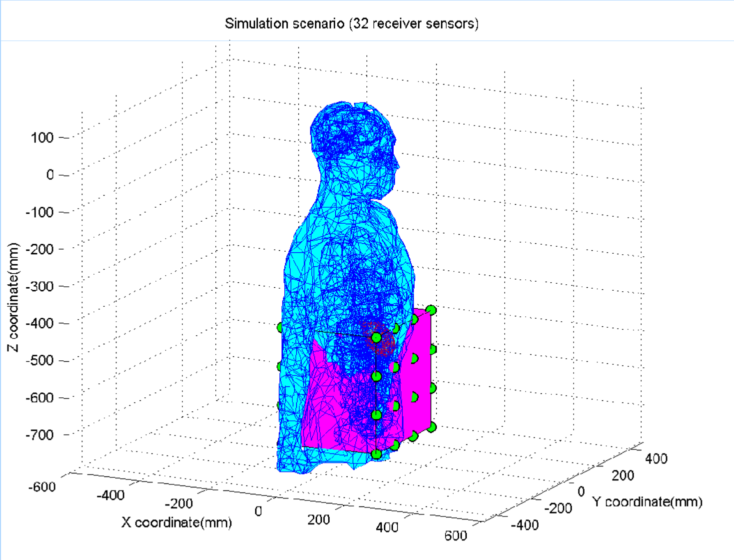
[5] Kaveh Pahlavan, Yunxing Ye, Umair Khan and Ruijun Fu “. RF Localization Inside Human Body Enabling micro-robotic navigation for medical applications,” International Conference on Localization and GNSS (ICL-GNSS2011), Tampere, Finland, June 29-30, 2011.

RSS-Based Localization for Capsule Endoscopy

Implant to Body Surface	$L_p(d_0)$	α	σ_{dB}
Deep Tissue	47.14	4.26	7.85
Near Surface	49.81	4.22	6.81

[4]

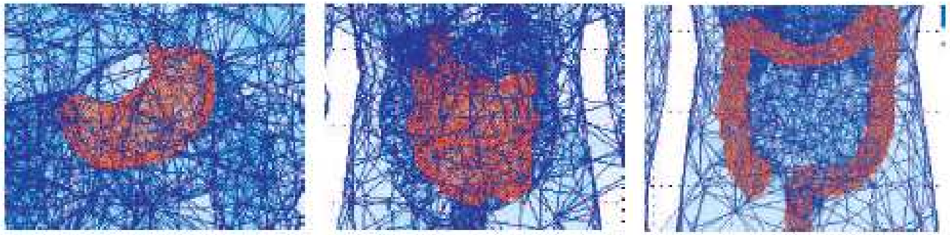
$$L_p(d) = L_p(d_0) + 10\alpha \log(d/d_0) + S \; (d > d_0)$$



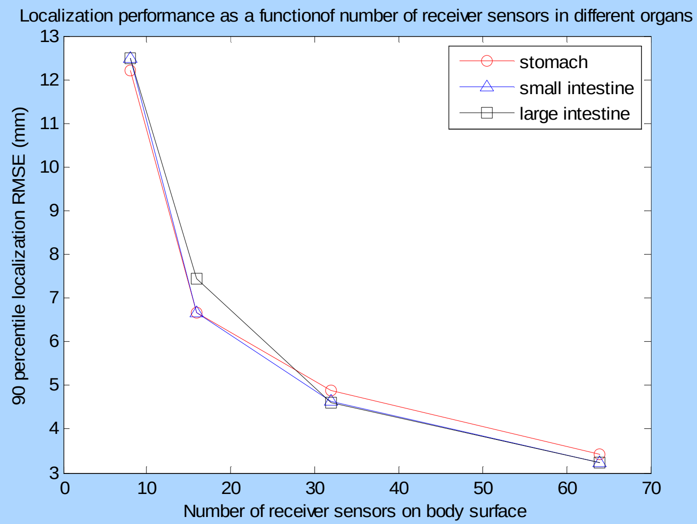
[6]

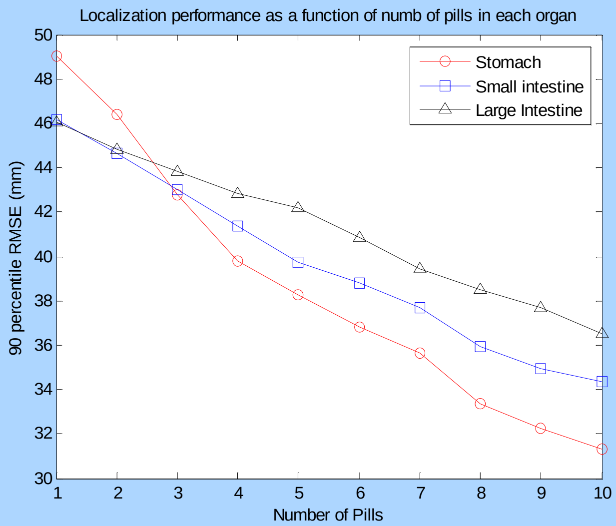
[6]Yunxing Ye, Umair Khan, Ruijun Fu and Kaveh Pahlavan. "On the accuracy of RF positioning in multi-capsule endoscopy" 22nd Annual IEEE international symposium on personal, indoor and mobile radio communications PIMRC 2011, 11-14 Septembre , Toronto, Canada.

Performance for capsule endoscopy



(a) Stomach (b) Small Intestine (c) Large Intestine



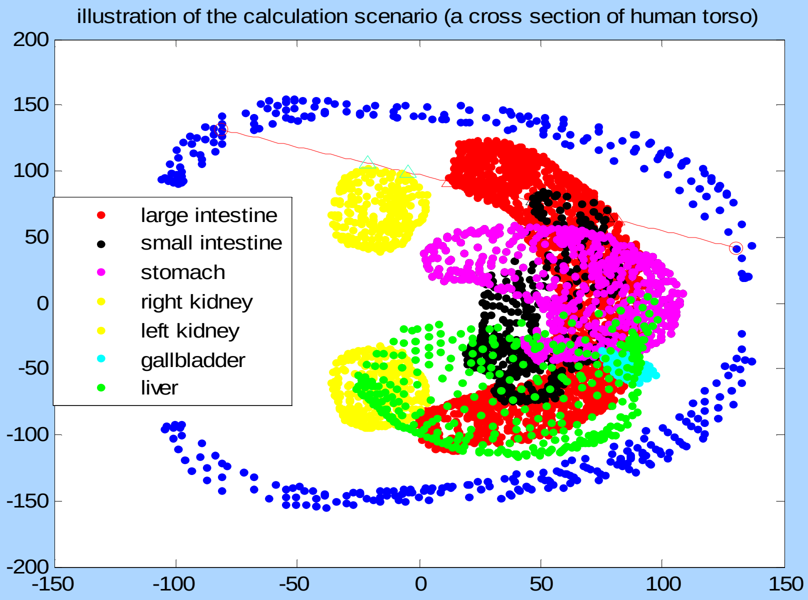


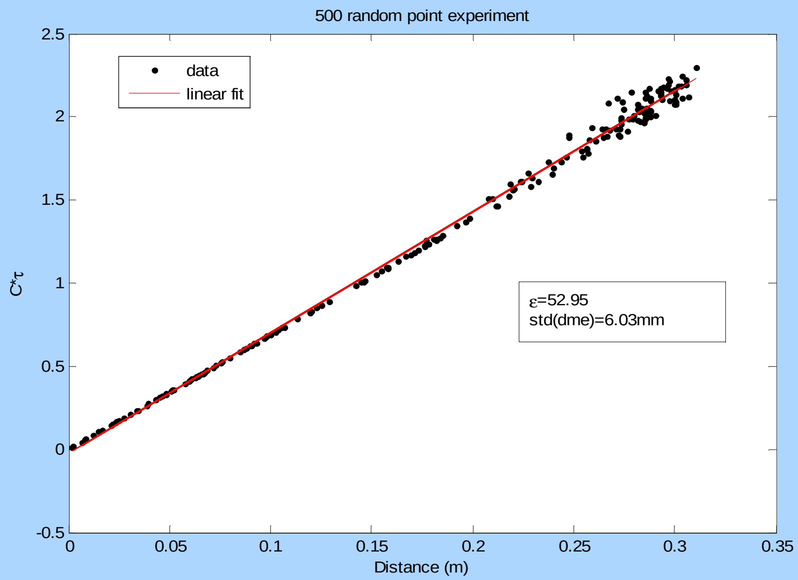
[6]Yunxing Ye, Umair Khan, Ruijun Fu and Kaveh Pahlavan. "On the accuracy of RF positioning in multi capsule endoscopy" 22nd Annual IEEE international symposium on personal, indoor and mobile radio communications PIMRC 2011, 11-14 September , Toronto, Canada.

Effects of non-homogeneousity

$$\hat{d} = c\tau = (\tau_1 + \tau_2 + \ldots + \tau_n)\frac{c}{\sqrt{\varepsilon_r}}$$

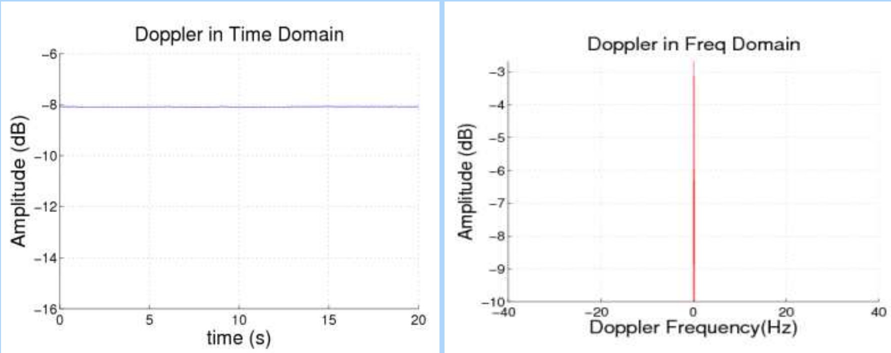
$$= \sum_{i=1}^{n}\frac{d_i}{v_i}\frac{c}{\varepsilon} = \left(\frac{d_1}{c/\sqrt{\varepsilon_1}} + \frac{d_2}{c/\sqrt{\varepsilon_2}} + \ldots + \frac{d_1}{c/\sqrt{\varepsilon_n}}\right)\frac{c}{\varepsilon}$$



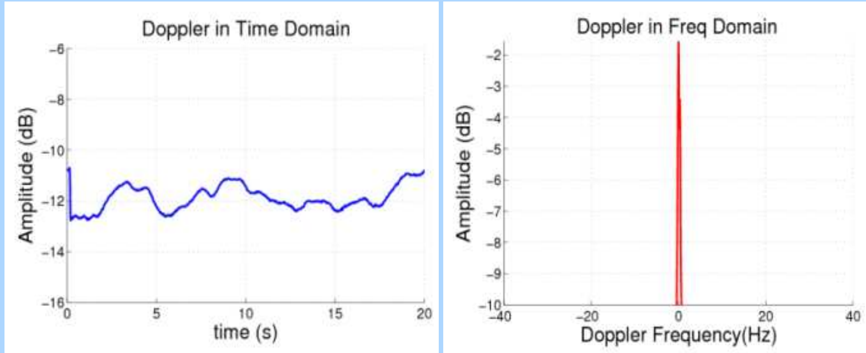


[7] Yunxing Ye, Umair Khan and Kaveh Pahlavan "Performance bounds for TOA based RF positioning for implant communication" 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC '11), Boston. August 30th – September 3rd 2011.

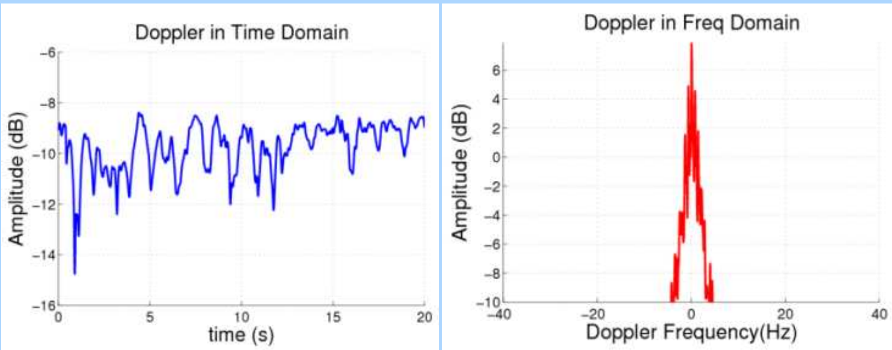
Effects of human motions



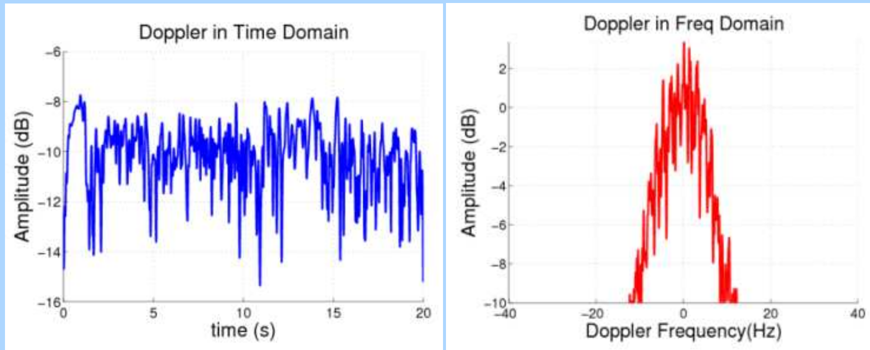
- (a) No motion



- (b) Stand Still



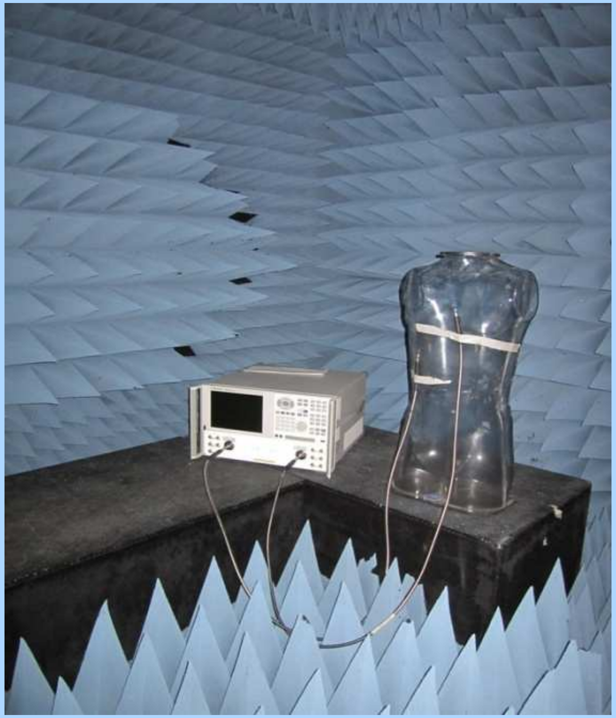
- (c) Walk



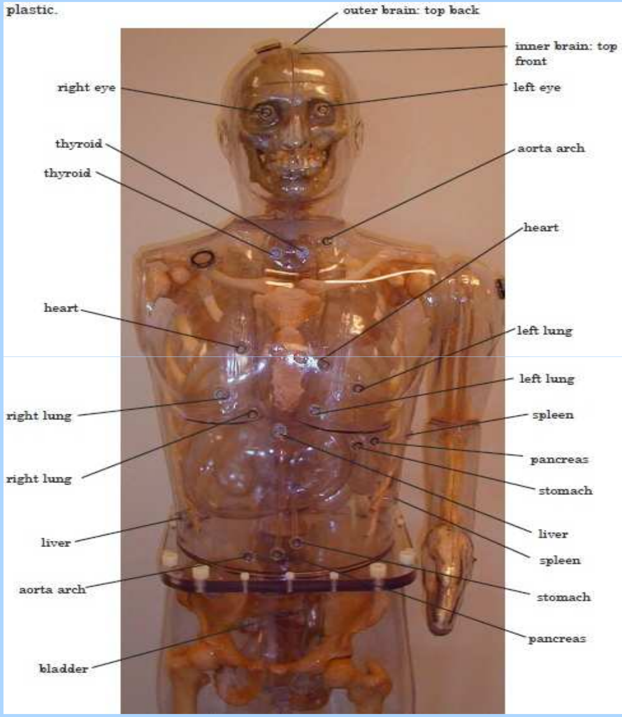
- (d) Jog

[8] Ruijun Fu, Yunxing Ye, Kaveh Pahlavan and Ning Yang , "Doppler Spread Analysis of Human Motions for Body Area Network Applications" 22nd Annual IEEE international symposium on personal, indoor and mobile radio communications PIMRC 2011, 11-14 September , Toronto, Canada.

Measurement program



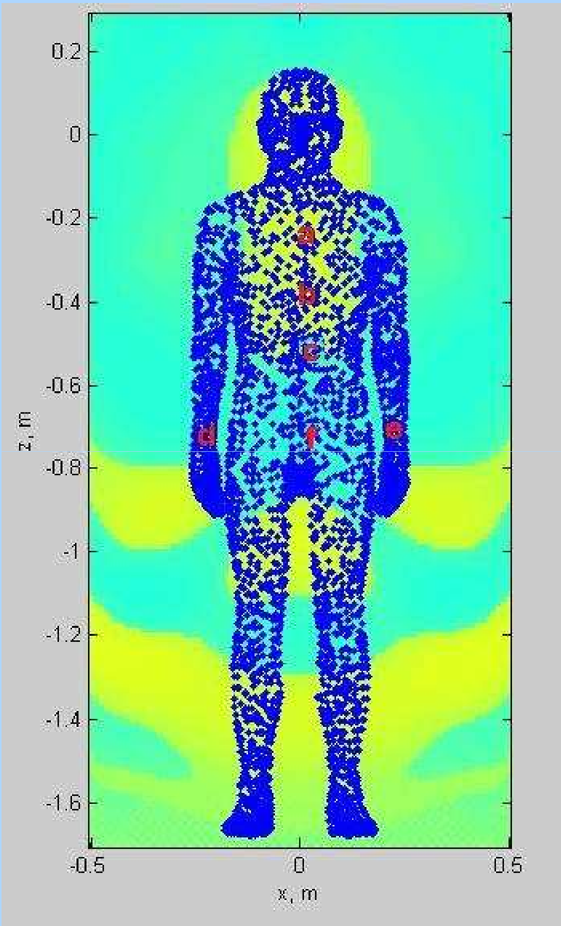
Hollow Phantom
in the Chamber

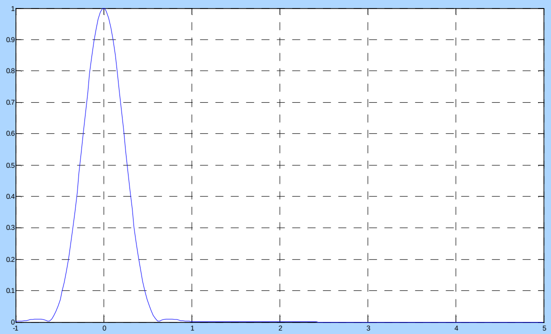


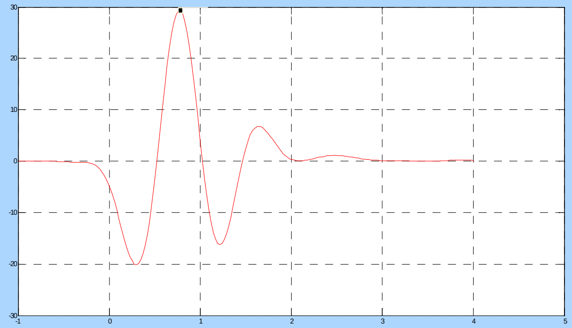
Phantom Phil with
Bones and Organs

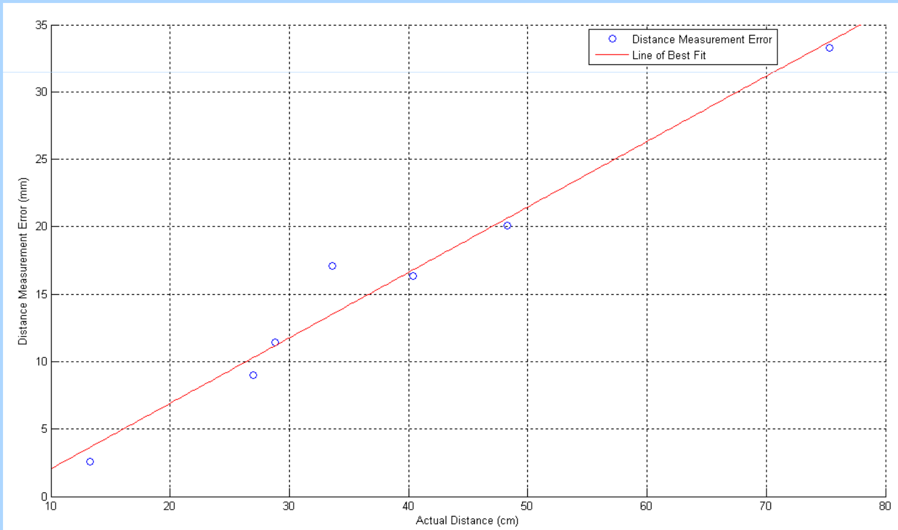
Using human
subject

Challenges in computer simulations









[9] Sergey N. Makarov, Umair I. Khan, Md. Monirul Islam, Reinhold Ludwig, Kaveh Pahlavan “On Accuracy of Simple FDTD Models for the Simulation of Human Body Path Loss”, presented at the 2011 IEEE Sensor Application Symposium, San Antonio, TX, February 22-24, 2011

[10] Umair I. Khan, Kaveh Pahlavan, Sergey Makarov “Comparison of TOA and RSS Based Techniques for RF Localization inside Human Tissue”, 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC '11), Boston. August 30th – September 3rd 2011.

Full Wave Modeling of Body Area Path Loss and Related Antenna Modeling

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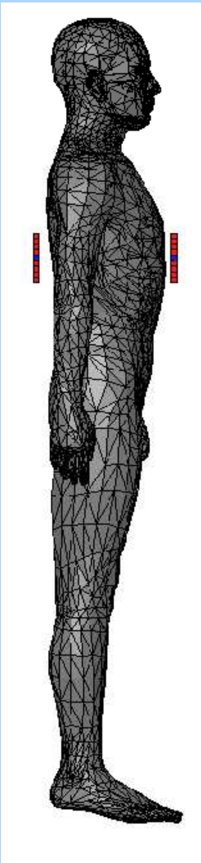
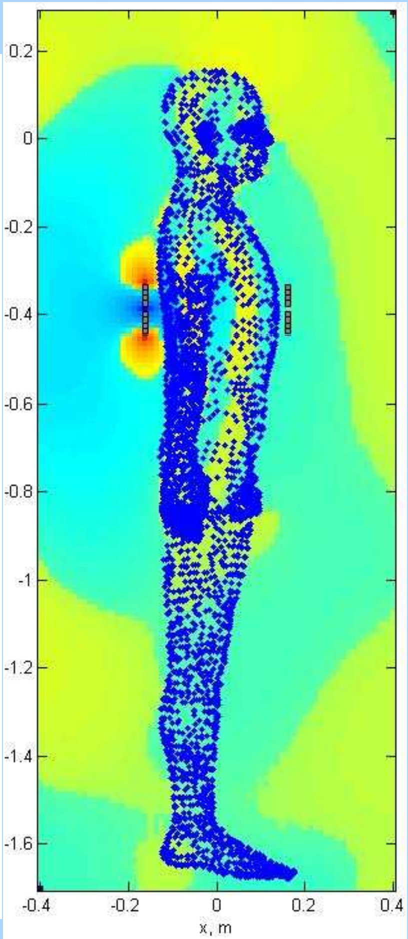
Task #1

- Compare performance of in-house MATLAB FDTD and FEM simulator Ansoft/ANSYS HFSS
- Establish how important the effect of internal body composition is on the performance of out-of-body wireless link
- Establish how important the effect of body shape variation is on the performance of out-of-body wireless link

Typical Simulation Results

Case 04_05:
Antenna position: X = 156.5mm, Z = -390.5mm.



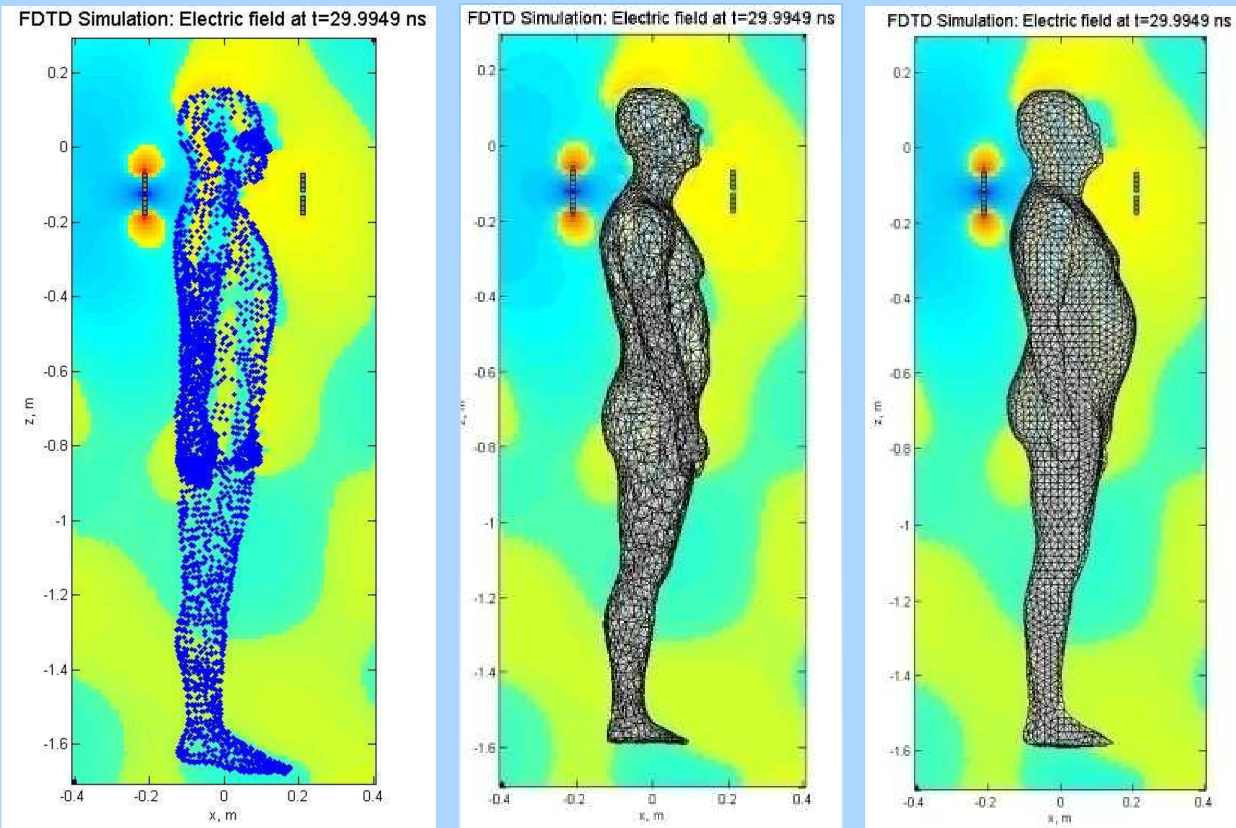


Adaptive Step Mesh Size (elements)	Z-matrix, Ω	S-Matrix	Received voltage amplitude, mV Ansoft/ANSYS (top) FDTD (bottom)	ANSOFT Runtime (HH:MM:SS)
1 400,193	Z_{11} = 165.8-88° Z_{22} = 226.3-88.2° Z_{21} = 0.171-29.3°	S_{11} = 0.981 -33.5° S_{22} = 0.9872-24.9° S_{21} = 4.187e-4 118°	**0.21** **0.035**	01:10:16
2 480,239	Z_{11} = 319.4-89° Z_{22} = 356.7-88.8° Z_{21} = 0.161-25°	S_{11} = 0.9947 -17.8° S_{22} = 0.9945-16° S_{21} = 1.378e-4 136°	**0.069** **0.035**	02:46:16
3 576,290	Z_{11} = 418.4-89.2° Z_{22} = 415.2-89° Z_{21} = 0.156-23.5°	S_{11} = 0.9969 -13.6° S_{22} = 0.996-13.7° S_{21} = 8.8249e-5 141°	**0.044** **0.035**	05:05:49
4 691,549	Z_{11} = 451.98-89.3° Z_{22} = 436.8-89.1° Z_{21} = 0.151-23.1°	S_{11} = 0.9974 -12.6° S_{22} = 0.9964-13.1° S_{21} = 7.5194e-5 143°	**0.038** **0.035**	08:19:50
5 829,863	Z_{11} = 465.7-89.4° Z_{22} = 446.2-89.1° Z_{21} = 0.148-23°	S_{11} = 0.9976 -12.3° S_{22} = 0.9966-12.8° S_{21} = 7.0322e-5 143°	**0.035** **0.035**	12:26:51
6 995,836	Z_{11} = 472.2-89.4° Z_{22} = 451.5-89.1° Z_{21} = 0.147-22.9°	S_{11} = 0.9977 -12.1° S_{22} = 0.9967-12.6° S_{21} = 6.7928e-5 143°	**0.034** **0.035**	17:21:15
7 1,134,472	Z_{11} = 475.5-89.4° Z_{22} = 454.2-89.1° Z_{21} = 0.146-22.9°	S_{11} = 0.9978 -12° S_{22} = 0.9968-12.6° S_{21} = 6.675e-5143°	**0.033** **0.035**	25:49:41
8 1,361,367	Z_{11} = 477.3-89.4° Z_{22} = 455.7-89.1° Z_{21} = 0.146-22.9°	S_{11} = 0.9978 -12° S_{22} = 0.9968-12.5° S_{21} = 6.6123e-5 143°	**0.033** **0.035**	27:57:15

Relative error comparison

Case Number	Estimated Relative Error of Received Voltage: FDTD vs. the finest FEM mesh $\delta = \frac{\lvert \upsilon_{HFSS} - \upsilon_{FDTD} \rvert}{\upsilon_{HFSS}} \times 100$	Ansoft/ANSYS HFSS Runtime (HH:MM:SS)	FDTD Runtime (MM:SS)
1	23%	23:29:10	10:57
2	21%	24:53:08	15:22
3	27%	27:55:01	28:01
4	6%	29:32:16	28:12
5	6%	27:57:15	27:51
6	14%	25:08:17	15:12
7	12%	25:47:53	27:45

Testing different body shapes



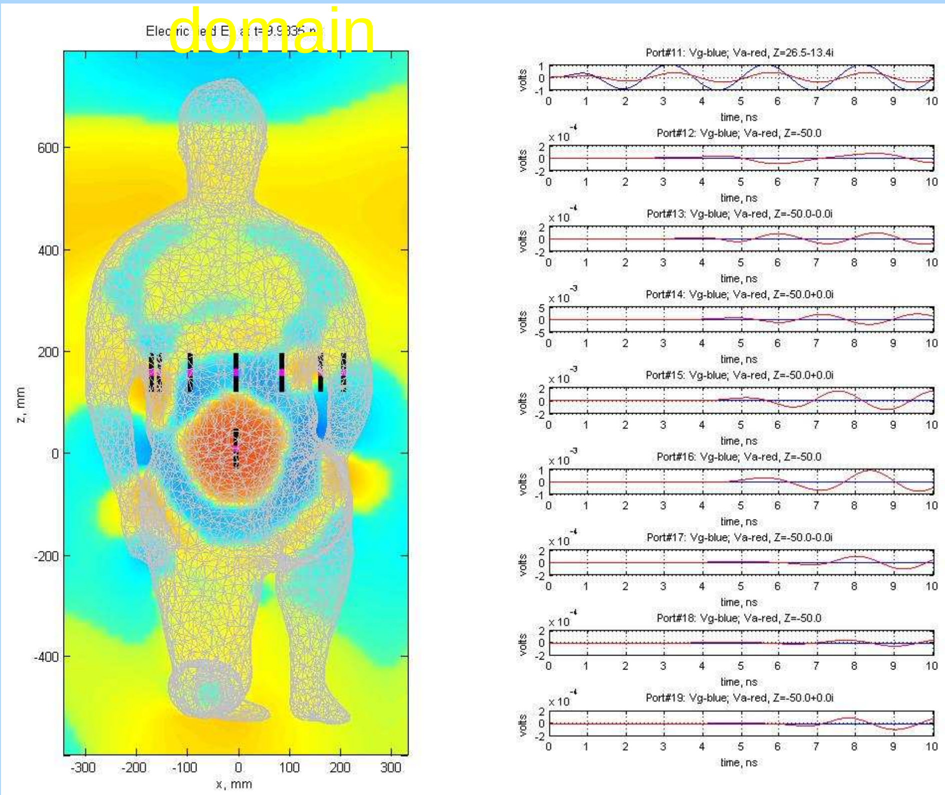
Case Designation	Received Voltage (mV)
WPI Male A	0.119
WPI Male B	0.119
Ansys Mesh	0.119

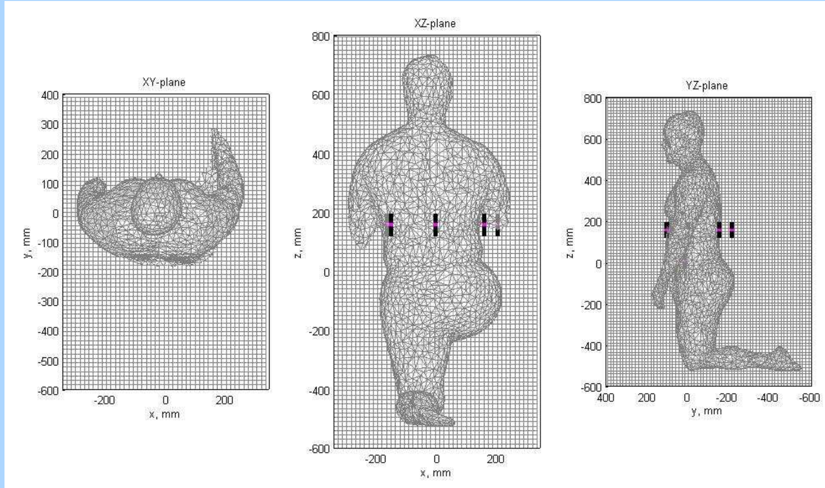
Conclusions:
out-of-body networks at 402 MHz

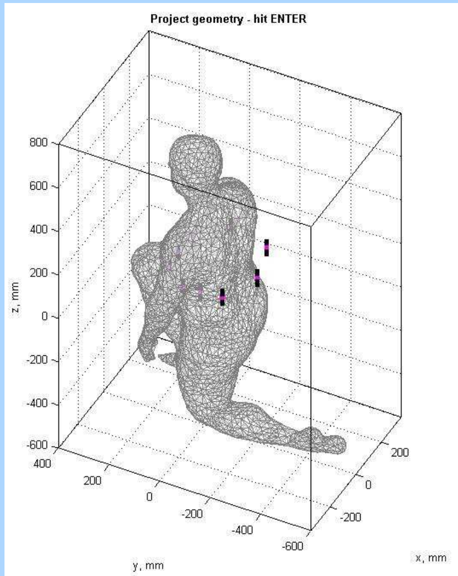
- Performed code-to-code validation
- Established that FDTD is superior to FEM w.r.t. CPU time
- Established that:
  - Out-of-body wireless link weakly depends on internal body composition
  - Out-of-body wireless link weakly depends on body shape
  - Critical diffraction parameters include path length and body area projected onto a plane perpendicular to path

Task #2-In-body to on-body link

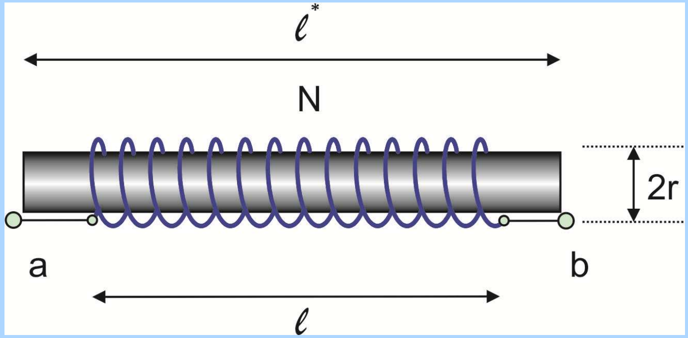
- 1x8 dipole array
- Homogeneous body
- Near-field scanning array task: ~2λ x 2λ x 2λ domain







Task#3-In-body Antenna Design



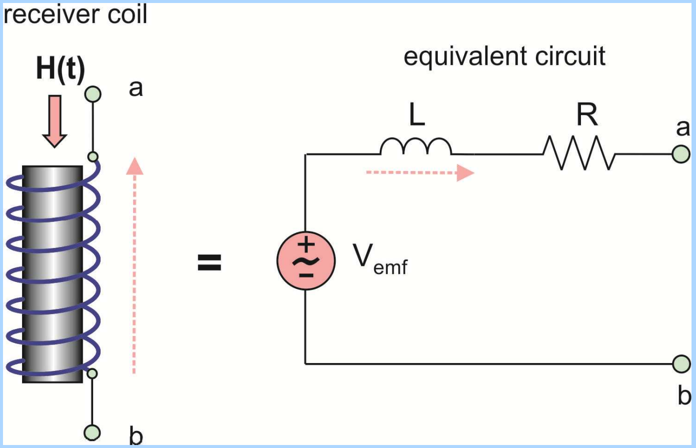
$$L = \frac{0.5\pi\mu_0 l^* N^2}{\ln\left[\frac{l^*}{r} - 1\right]}\left(1 - \frac{l}{2l^*}\right) \quad [H]$$

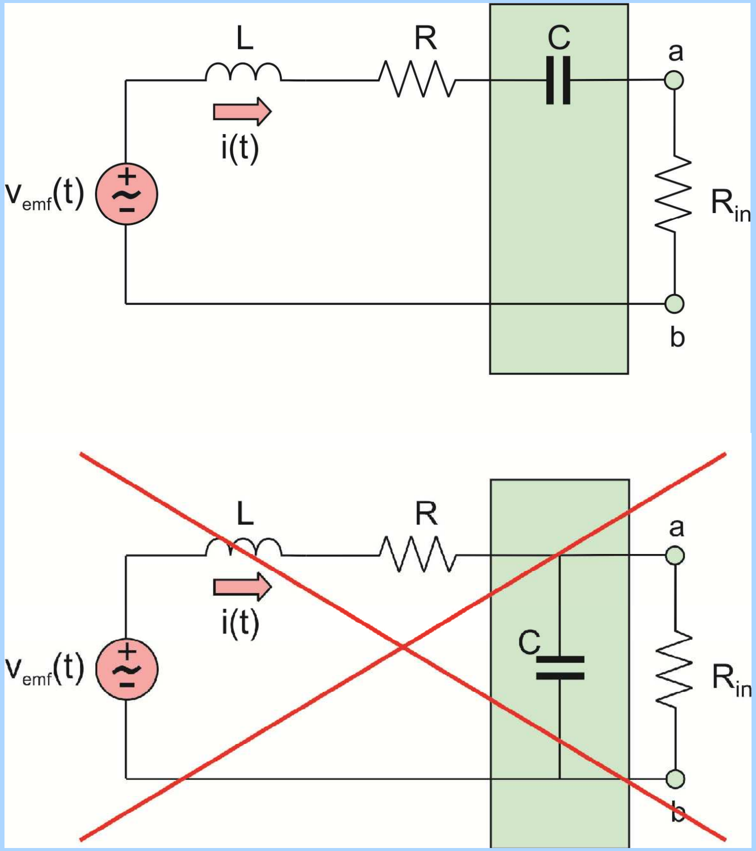
- Independent of μ_r as long as $\mu_r > 200$
- Induced voltage is found using Faraday's law (μ_{reff} >~10-20)

$$\mu_{eff} = \frac{0.5\mu_0 l^* l}{\ln\left[\frac{l^*}{r} - 1\right] r^2}\left(1 - \frac{l}{2l^*}\right)$$

$$V_{emf} = \left\{\frac{AN\mu_{eff}\,\omega E_0}{\eta_0}\right\}\cos(\omega t + \pi/2)$$

Antenna matching and tuning





- Series matching for low input impedance
- Input impedance is on the order of several ohms (loss resistance)

Antenna challenges

- Small impedance bandwidth: R/(2πL)
- High loss and low efficiency
- A 3D coil antenna is a must
- Direct measurements are difficult to perform
- Suggested: signal strength measurements with passive RFID SAW sensors and the calibrated reader antenna