Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Channel models for wearable and implantable WBANs]

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Re: [15-08-0033-00-0006-draft-of-channel-model-for-body-area-network]

Abstract: [This document shows a preliminary report on channel modeling for wearable and implantable WBANs. In order to design and evaluate specifications of PHY for BANs, suitable channel models are necessary. We hope this channel model will be referred as a common model to design and evaluate proposed systems.]

Purpose: [To evaluate PHY for IEEE 802.15.6 standard we prepare a preliminary version of a common channel model although a modified version will be reported after more propagation model are measured.]

Summary

- This presentation shows preliminary channel models for wearable and implantable WBAN.
- The models shown here are related to the CM2 and CM3 in 15-08-0033-00-0006-draft-of-channel-model-for-body-area-network.
- Updated results will be shown near future.

Channel models for wearable WBAN

Outline

1. Measurement setup
   - Frequency bands
     - 400 MHz, 600 MHz, 900 MHz, 2.4 GHz, and UWB band (3.1-5.1 GHz)
2. Measurement results
3. Preliminary channel models
   - Power profile model
     - only for UWB band
   - Path gain model (distance vs. path gain)
     - for all frequency bands
4. Concluding remarks

Measurement setup

- Measurements were conducted in the frequency-domain.
  - S21 of the channel were measured and stored.
  - Vector network analyzer
    - Agilent 8363B
    - # of points: 801
    - IF BW: 1 kHz
    - Sweep time: auto (740 ms)
    - Calibration: Full-2-Port (Tx power = 0 dBm)

Measurement setup

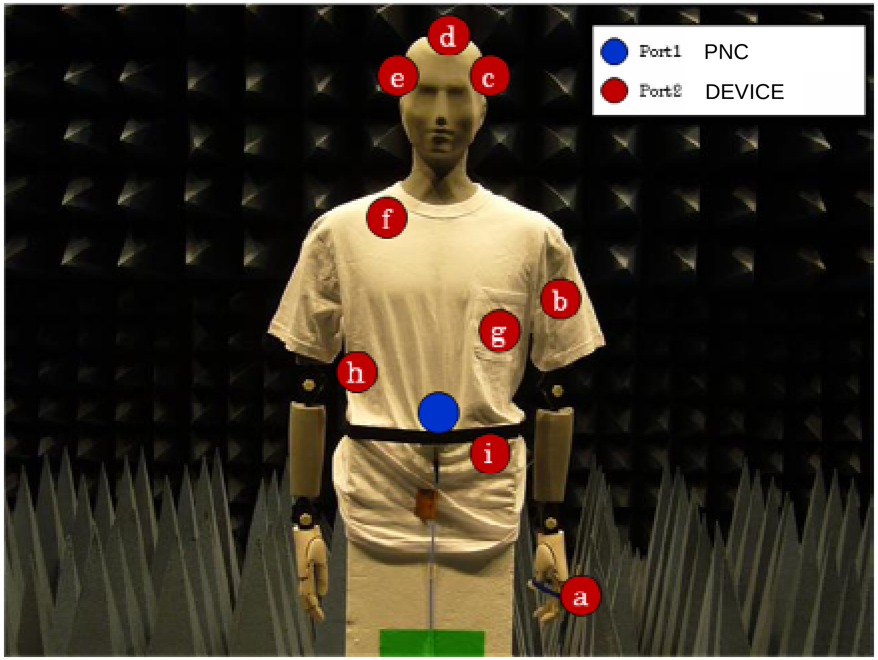
- Frequency bands and antennas

Bands	Range	Antenna
400 MHz	400 - 450 MHz	dipole
600 MHz	608 - 614 MHz	dipole
900 MHz	950 - 956 MHz	dipole
2.4 GHz	2.4 - 2.5 GHz	colinear
UWB	3.1 - 3.5 GHz	skycross

- Human body
  - male, height = 171 cm, weight = 63 kg

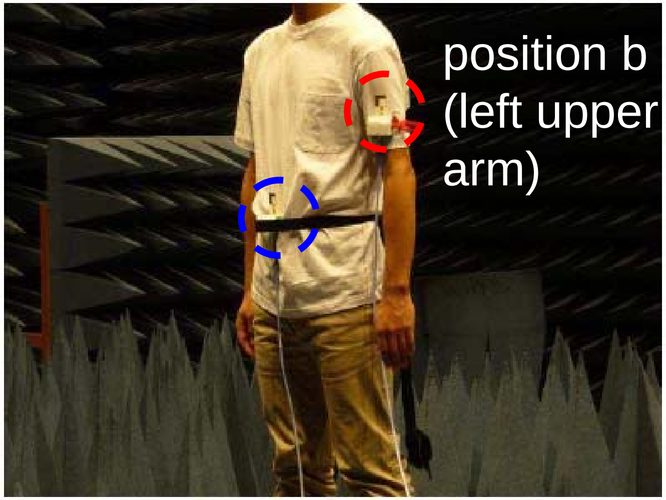
Measurement setup

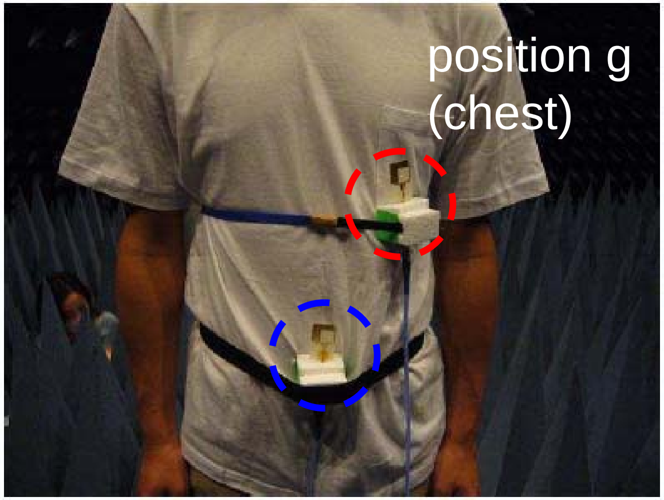
- Measurement positions



a	left wrist
b	left upper arm
c	left ear
d	head
e	right ear

f	shoulder
g	chest
h	right rib
i	left waist





Measurement setup

- Measurement environments
  1. Hospital room (Size: 7.0 m x 9.0 m x 2.5 m)

  2. Anechoic chamber
     - without reflections from the floor

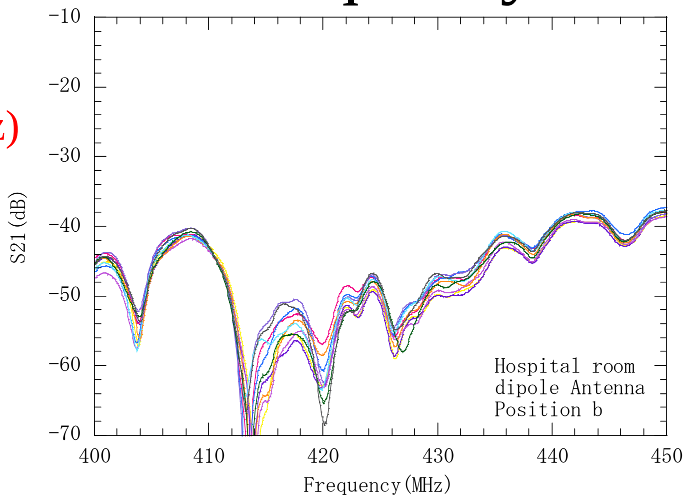
Measurement results

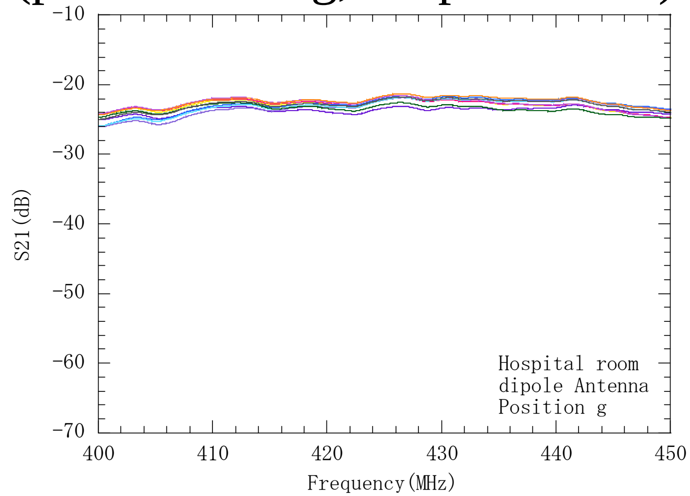
- S21 for each frequency band (position b & g, hospital room)

400 MHz

(400-450MHz)

(10 samples)

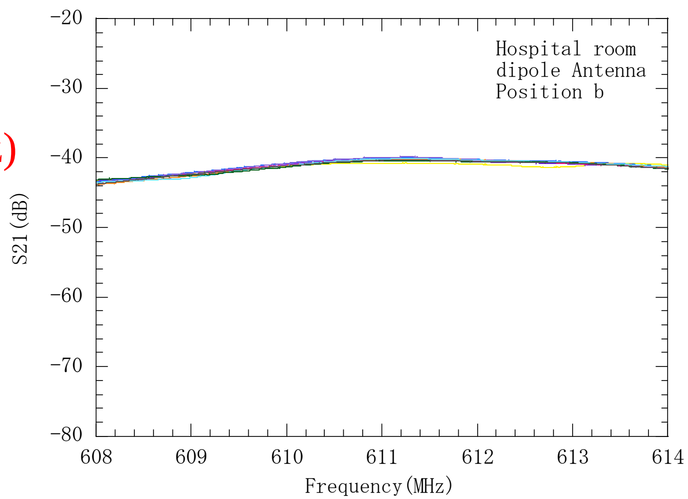


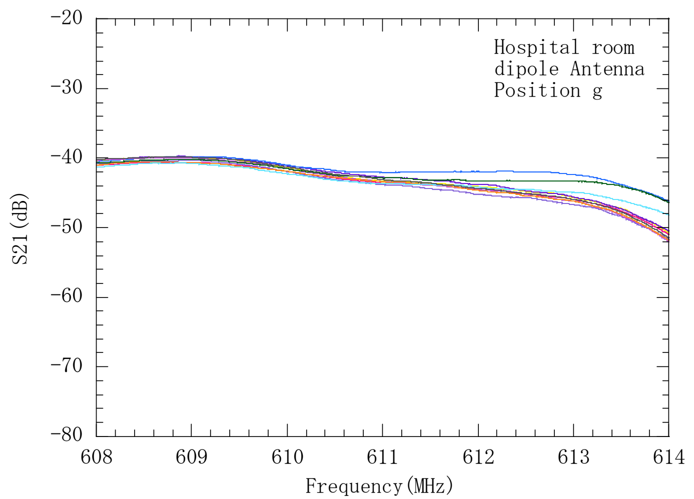


600 MHz

(608-614MHz)

(10 samples)



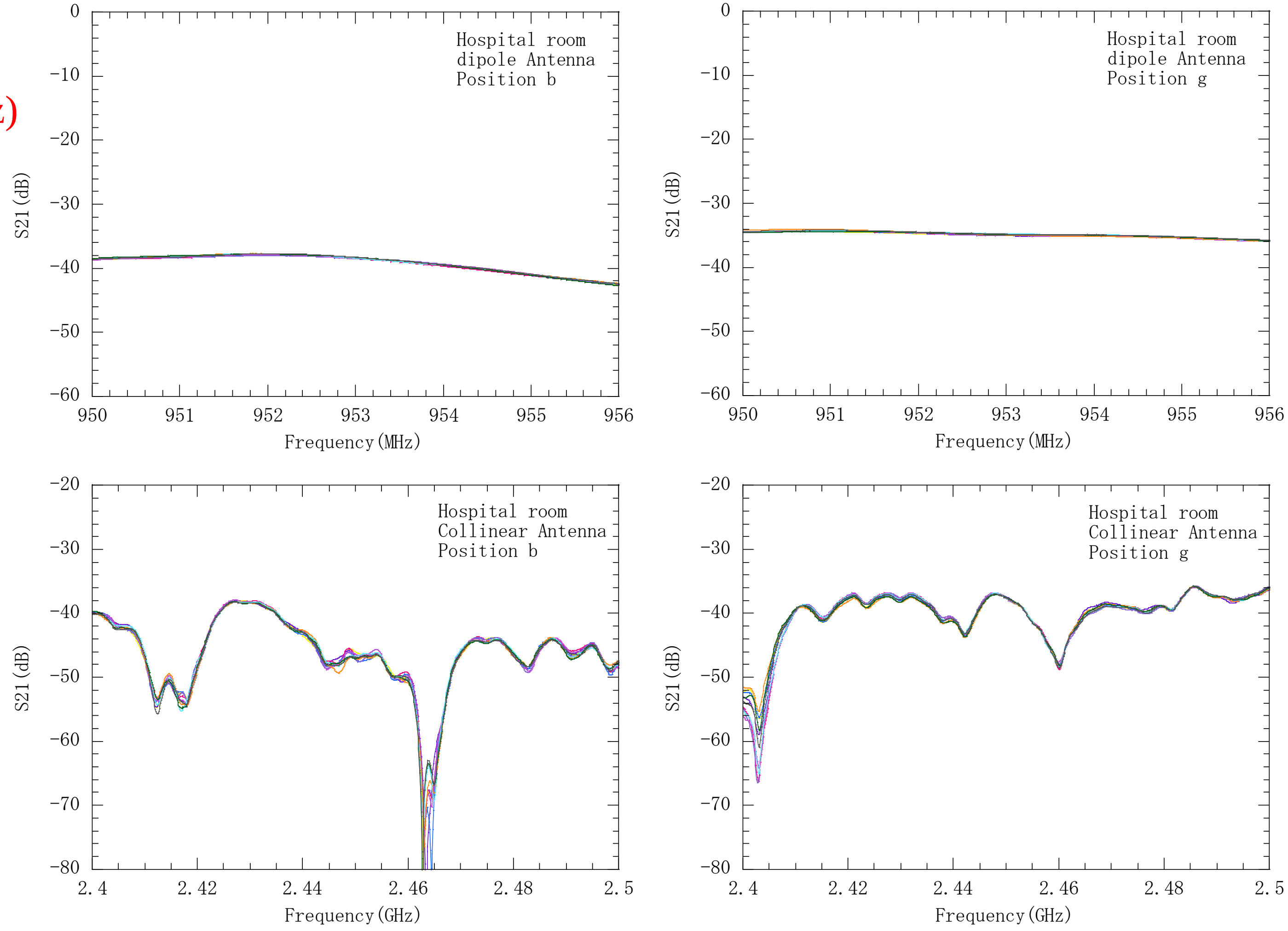


Measurement results

- S21 for each frequency band (position b & g, hospital room)

900 MHz
(950-956MHz)
(10 samples)

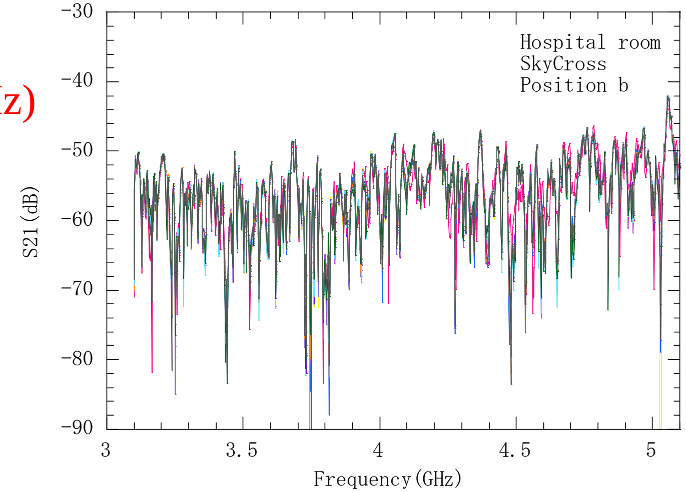
2.4 GHz
(2.4-2.5GHz)
(10 samples)

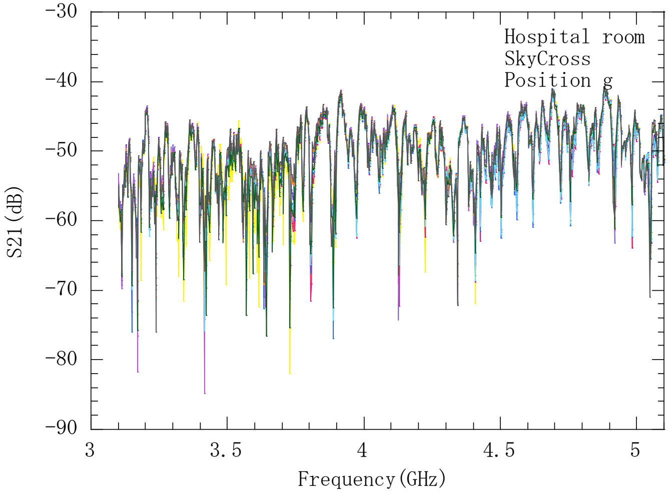


Measurement results

- S21 for each frequency band (position b & g, hospital room)

UWB
(3.1-5.1GHz)
(10 samples)

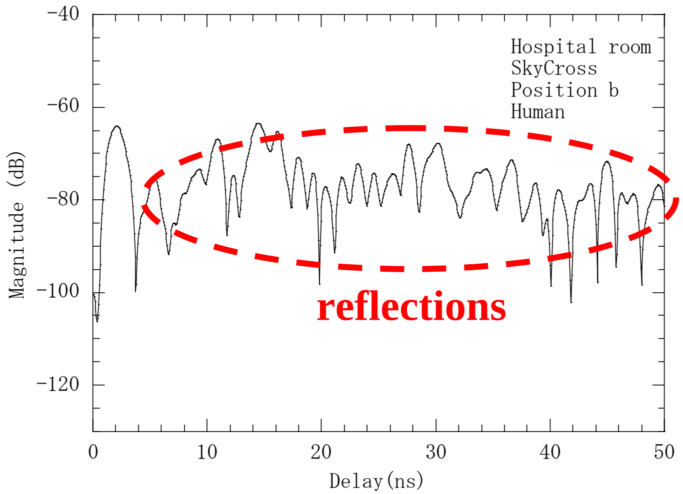


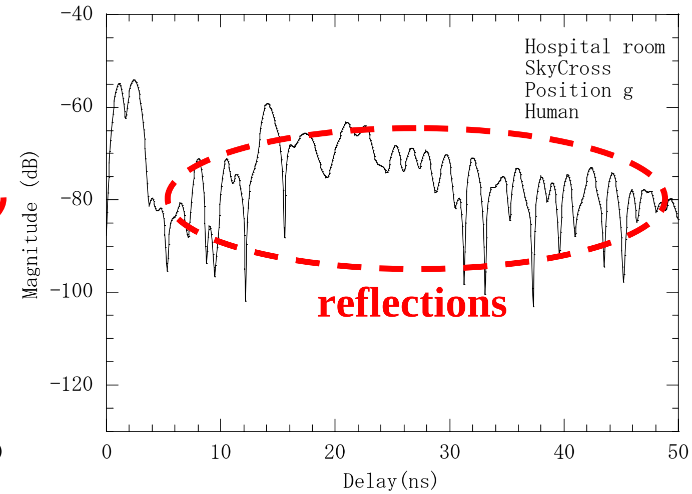


Measurement results

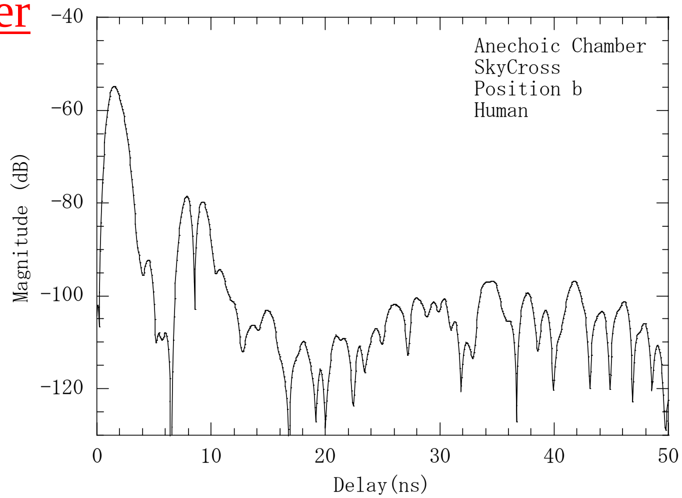
- Time domain waveforms (UWB band)

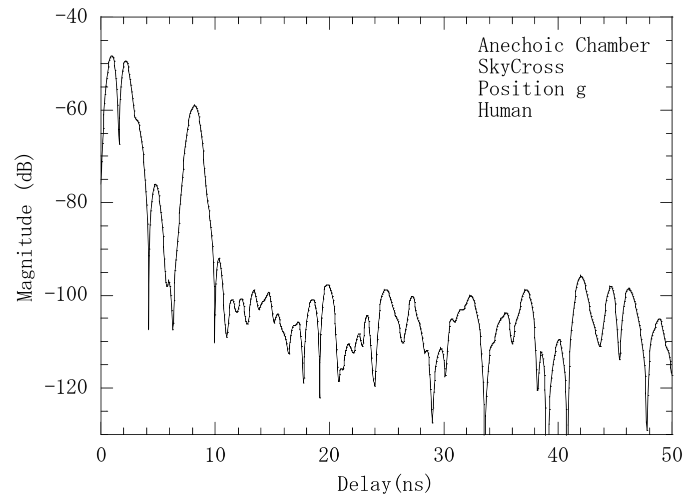
Hospital room





Anechoic chamber





Channel models for wearable WBAN

1. Power profile model
   - only for UWB band

2. Path loss model
   - for both narrow band (NB) and UWB band

- Note: these models are not position-specific models.

WBAN channel model - power profile model -

Power profile model

$$h(t)=\sum_{l=0}^{L-1} a_l \exp(j\phi_l)\delta(t-t_l)$$

- $\delta(t)$: Dirac function
- ϕ_l : Phase component uniformly distributed over [0, 2π)
- L : The number of arrivals
- a_l : Tap weight of the l th path
- t_l : Delay of the l th path [ns]

Tap weight (path amplitude) : a_l

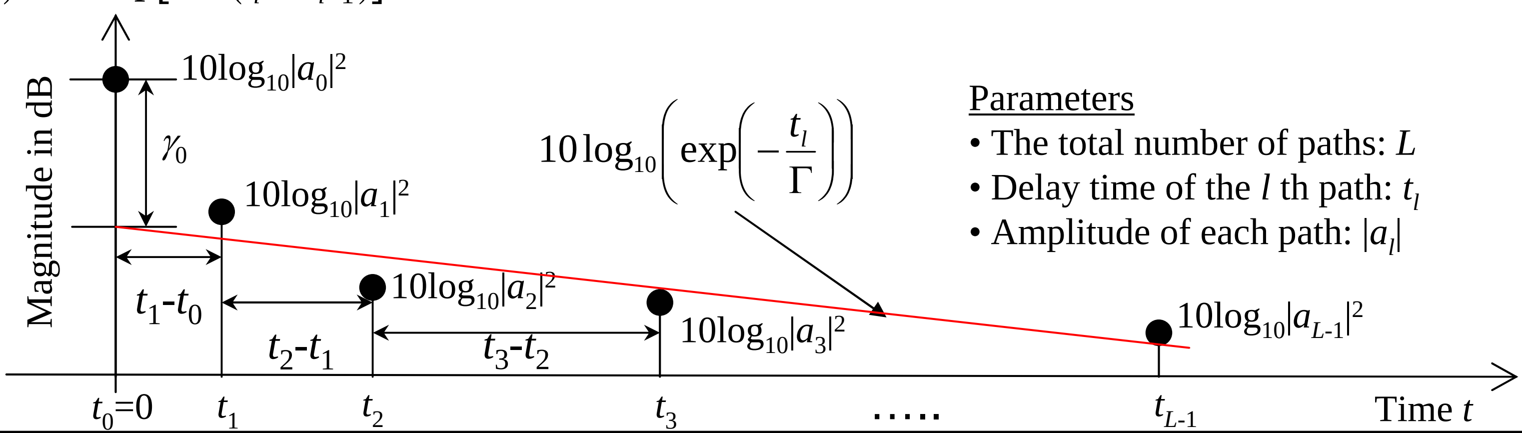
$$10\log_{10}|a_l|^2 = \begin{cases} 0 & l=0 \\ \gamma_0 + 10\log_{10}\left(\exp\left(-\frac{t_l}{\Gamma}\right)\right)+S & l\neq 0 \end{cases}$$

- γ_0 : Rice factor [dB]
- Γ : Decay time [ns]
- S : Normally distributed variable with standard deviation σ_S

Delay (path arrival time) : t_l

$$p(t_l \mid t_{l-1}) = \lambda \exp[-\lambda(t_l - t_{l-1})]$$

- λ : Path arrival rate



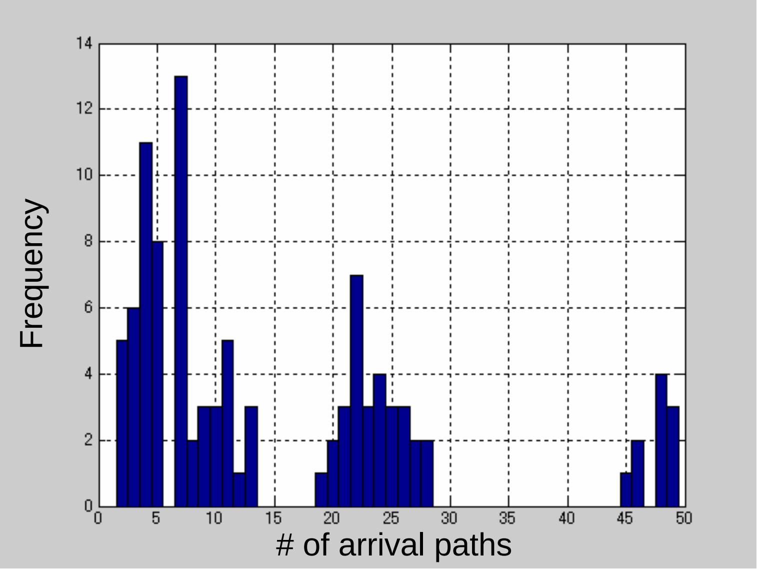
Parameters
- The total number of paths: L
- Delay time of the l th path: t_l
- Amplitude of each path: $|a_l|$

WBAN channel model - power profile model -

- The number of taps (# of arrival paths): L
  - Poisson distribution $$pdf_L(L) = \frac{(\bar{L})^L \exp[\bar{L}]}{L!}$$

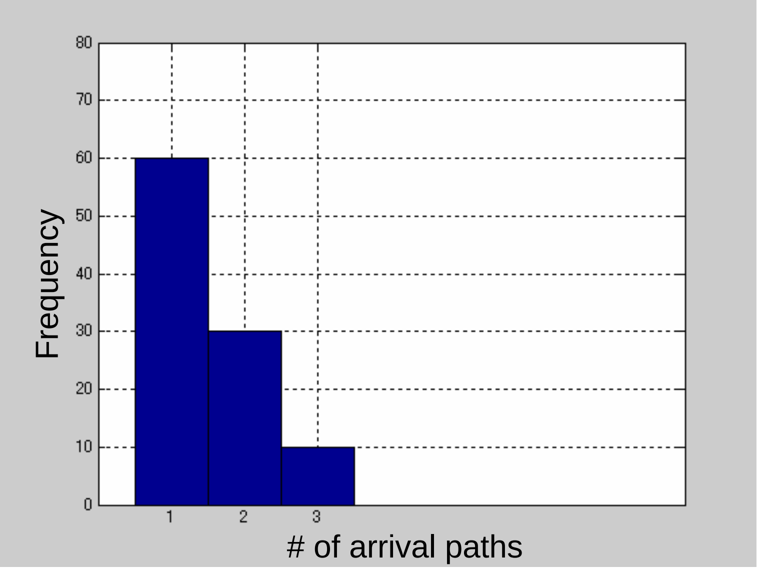
Hospital room

parameters	value
$\bar{L}$	15.6



Anechoic chamber

parameters	value
$\bar{L}$	1.5



WBAN channel model - power profile model -

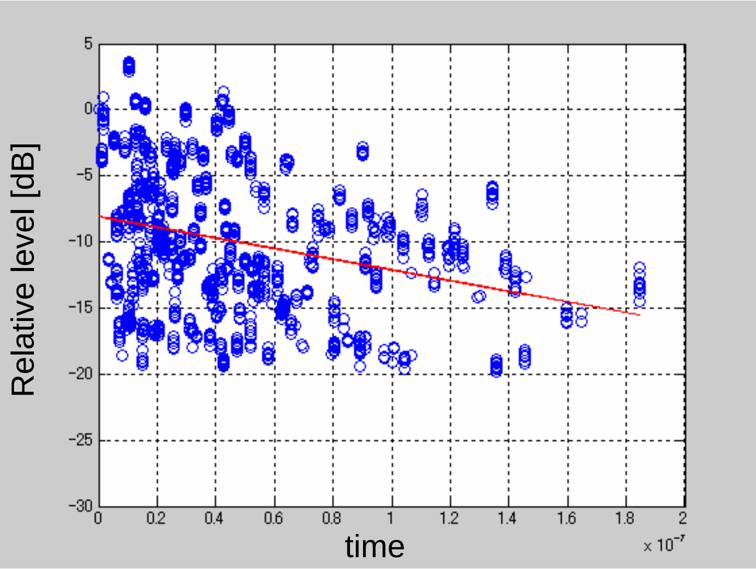
- Tap weight (path amplitude): a_l
  - Exponential decay factor Γ and ambiguity component S

$$10\log_{10}|a_l|^2 = \begin{cases} 0 & l=0 \\ \gamma_0 + 10\log_{10}\left(\exp\left(-\frac{t_l}{\Gamma}\right)\right) + S & l \neq 0 \end{cases}$$

S : Normally distributed variable with standard deviation σ_S

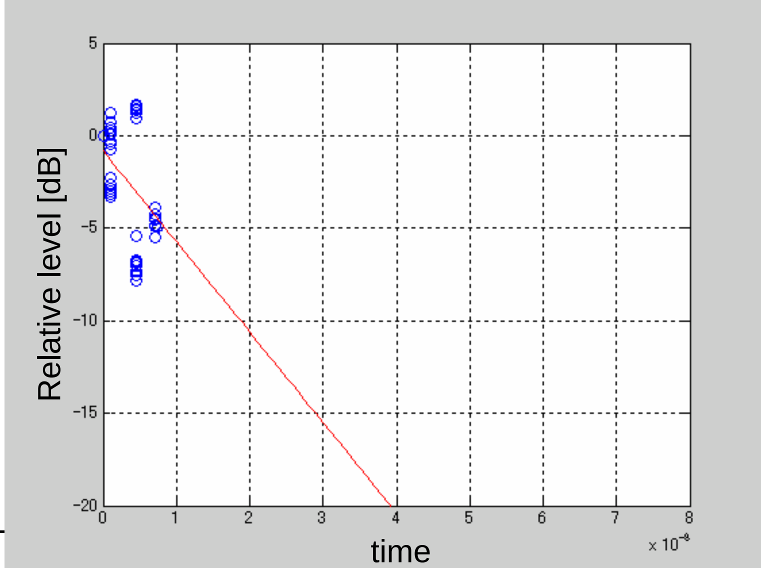
Hospital room

parameters	value
γ_0	-8.08 dB
Γ	155.7 ns
σ_S	4.94 dB



Anechoic chamber

parameters	value
γ_0	-0.48 dB
Γ	8.88 ns
σ_S	2.87 dB



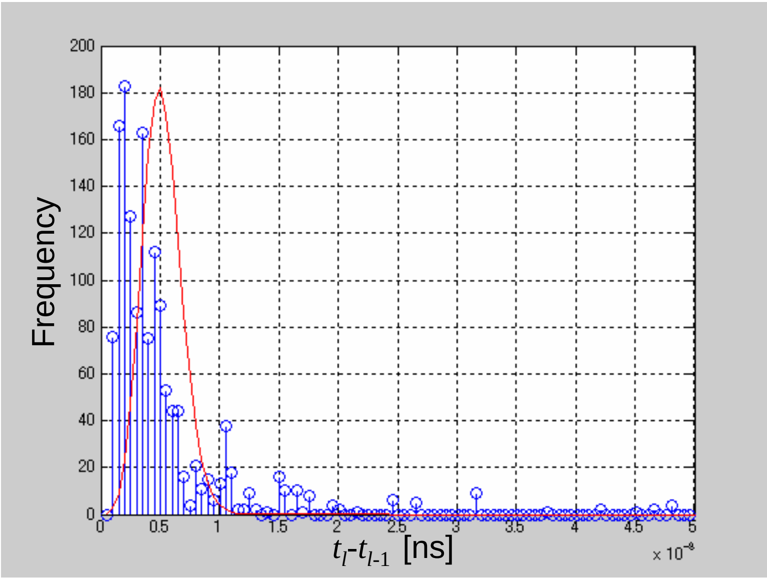
WBAN channel model - power profile model -

- Delay (path arrival time): t_l
  - Poisson distribution

$$p(t_l \mid t_{l-1}) = \lambda \exp[-\lambda(t_l - t_{l-1})]$$

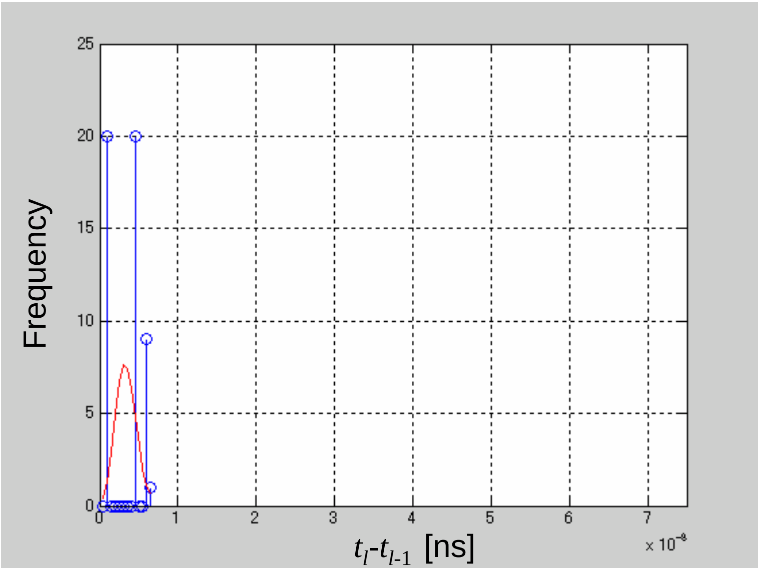
Hospital room

parameters	value
λ	5.17 ns



Anechoic chamber

parameters	value
λ	6.82 ns

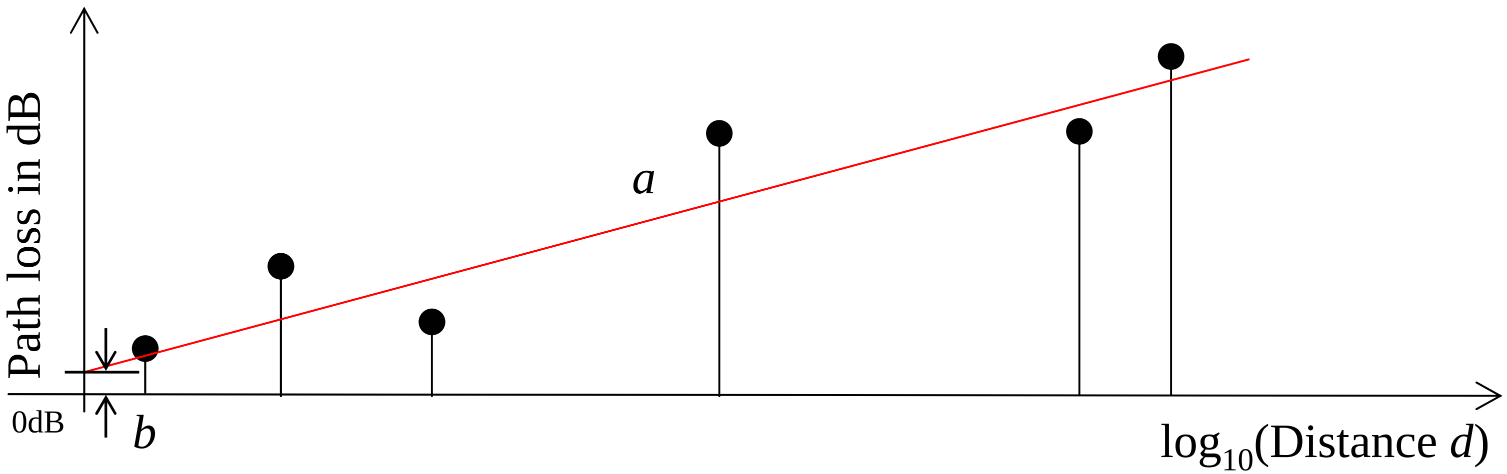


WBAN channel model - path loss model -

Path loss model

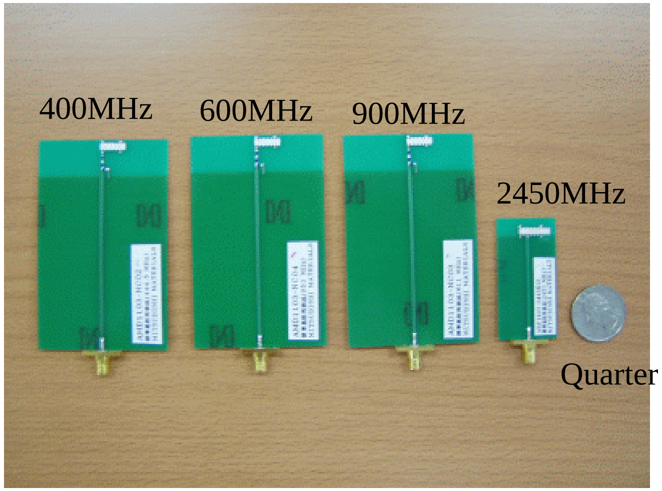
$$PL(d) \text{ in dB} = a\log_{10}(d) + b + N$$

- PL: path loss
- a and b : coefficients of linear fitting
- d : Tx-Rx distance in mm.
- N : Normally distributed variable with standard deviation σ_N



WBAN channel model - path gain model -

- On the WBAN antenna
  - In the measurements for frequency bands towards narrow band systems, large size antennas (include a standard dipole antenna) were used.
  - However, the use of such big antennas is not realistic in most of BAN applications.
  - So, we have also measured channel responses using a chip antenna (shown below) in the chest position (position index is “g”).
  - The difference between the averaged signal levels of the antenna used in the whole measurement and that of the chip antenna is calculated in the channel models as parameter “c”.



Chip antennas for frequency band of 400, 600, 900, and 2450MHz.

Path loss model **400 MHz**

$$PL(d)[\mathrm{dB}] = a \cdot \log_{10}(d) + b + c + N$$

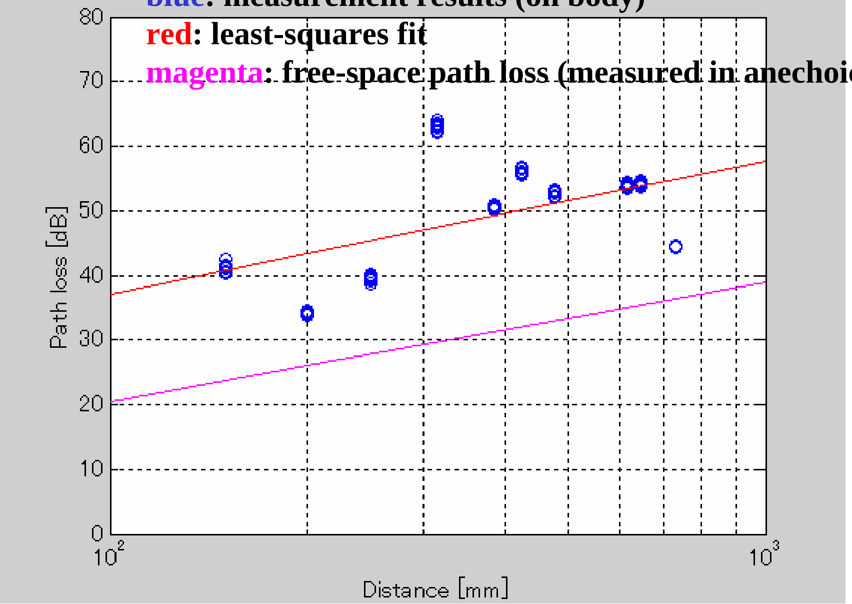
Hospital room

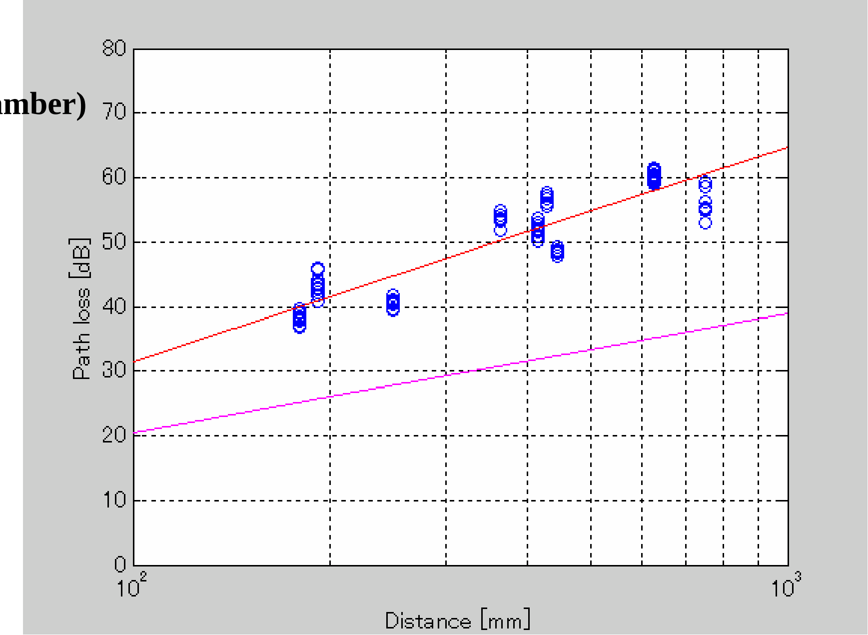
Parameters	value
a	20.6
b	12.4
c	-16.5
σ_N	7.2

Anechoic chamber

Parameters	value
a	46.4
b	-40.4
c	-16.5
σ_N	2.7

blue: measurement results (on body)
red: least-squares fit
magenta: free-space path loss (measured in anechoic chamber)





Path loss model 600 MHz

$$PL(d)[\mathrm{dB}] = a \cdot \log_{10}(d) + b + c + N$$

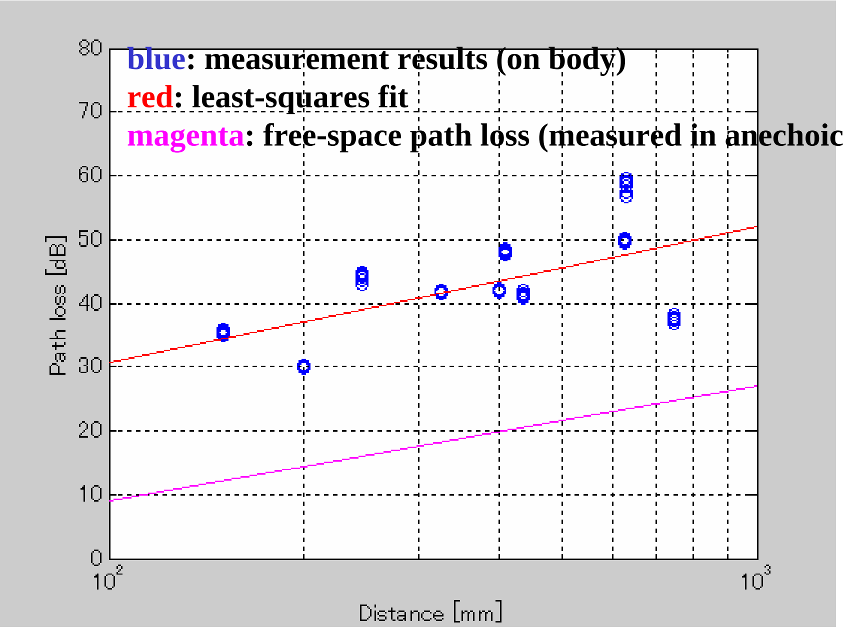
Hospital room

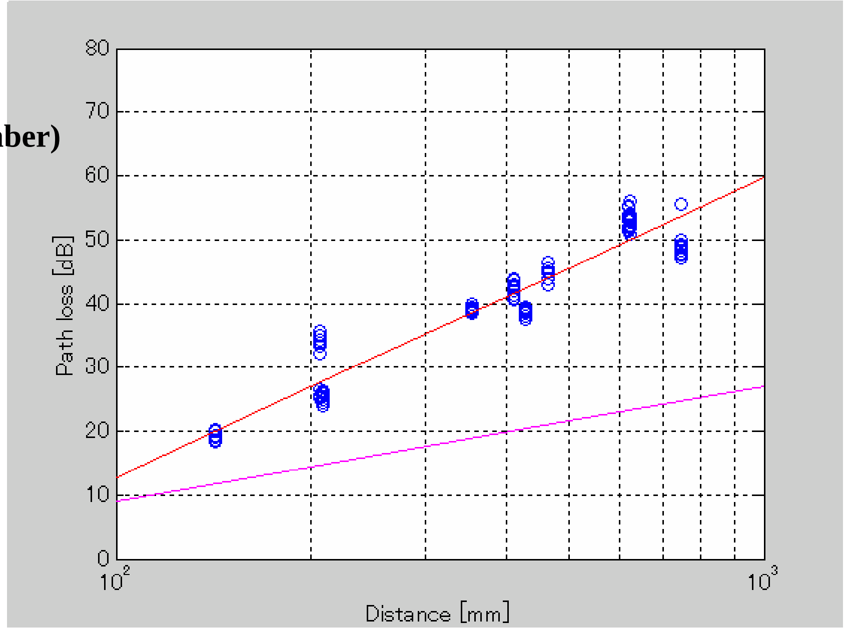
Parameters	value
a	21.1
b	-10.5
c	-0.9
σ_N	6.0

Anechoic chamber

Parameters	value
a	46.9
b	-80.0
c	-0.9
σ_N	3.3

blue: measurement results (on body)
red: least-squares fit
magenta: free-space path loss (measured in anechoic chamber)



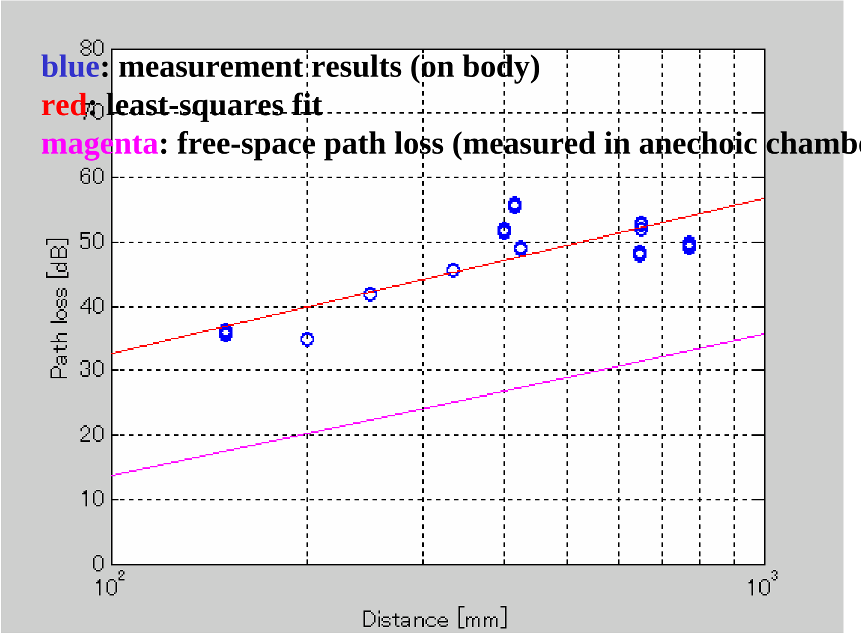


Path loss model 900 MHz

$$PL(d)[\mathrm{dB}] = a \cdot \log_{10}(d) + b + c + N$$

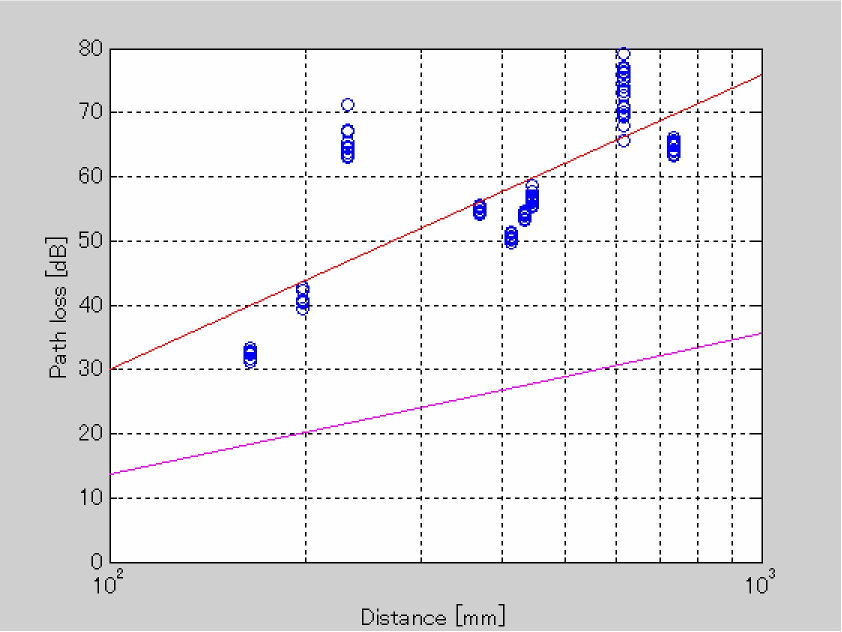
Hospital room

Parameters	value
a	24.2
b	-8.9
c	-7.0
σ_N	3.9



Anechoic chamber

Parameters	value
a	45.8
b	-54.5
c	-7.0
σ_N	8.3

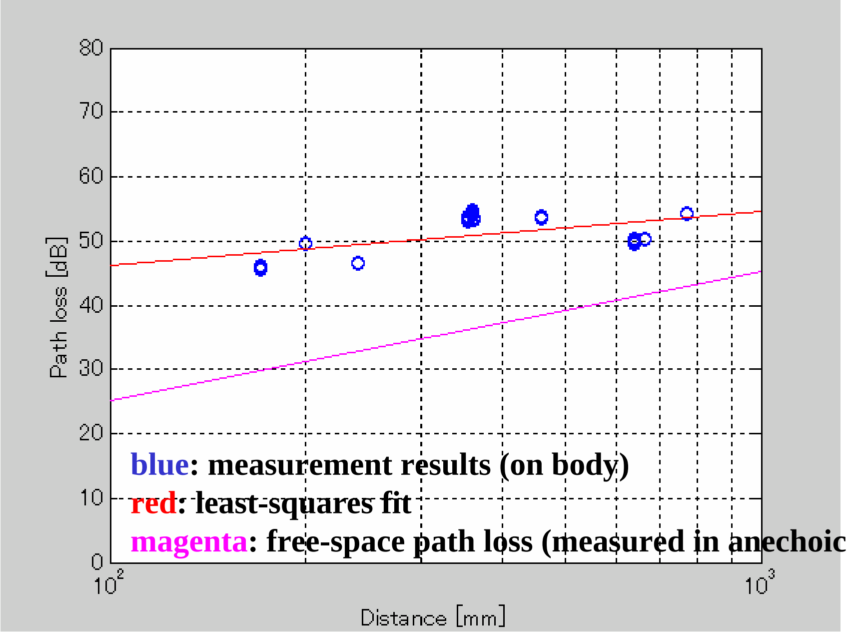


Path loss model 2.4 GHz

$$PL(d)[\mathrm{dB}] = a \cdot \log_{10}(d) + b + c + N$$

Hospital room

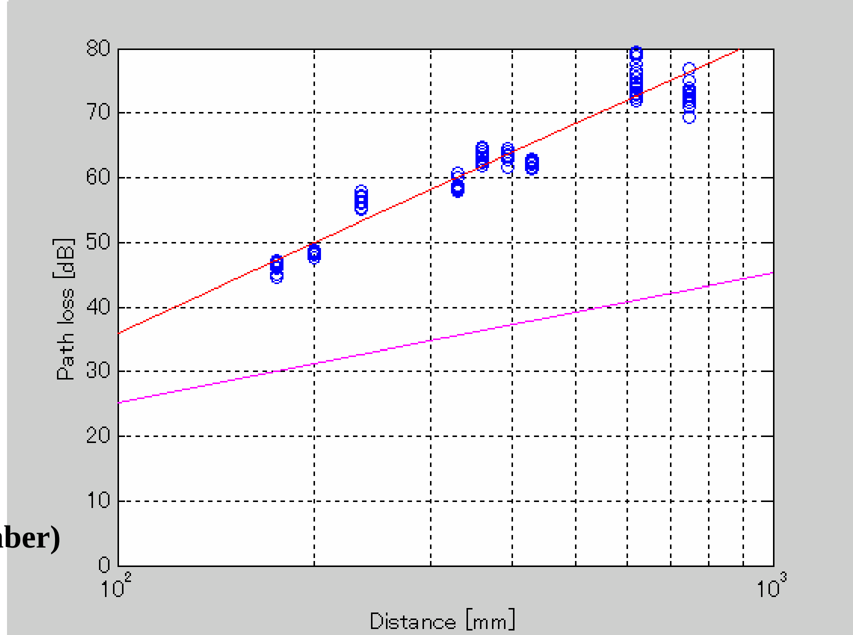
Parameters	value
a	8.32
b	37.2
c	-7.5
σ_N	2.5



blue: measurement results (on body)
red: least-squares fit
magenta: free-space path loss (measured in anechoic chamber)

Anechoic chamber

Parameters	value
a	46.4
b	-49.4
c	-7.5
σ_N	2.7

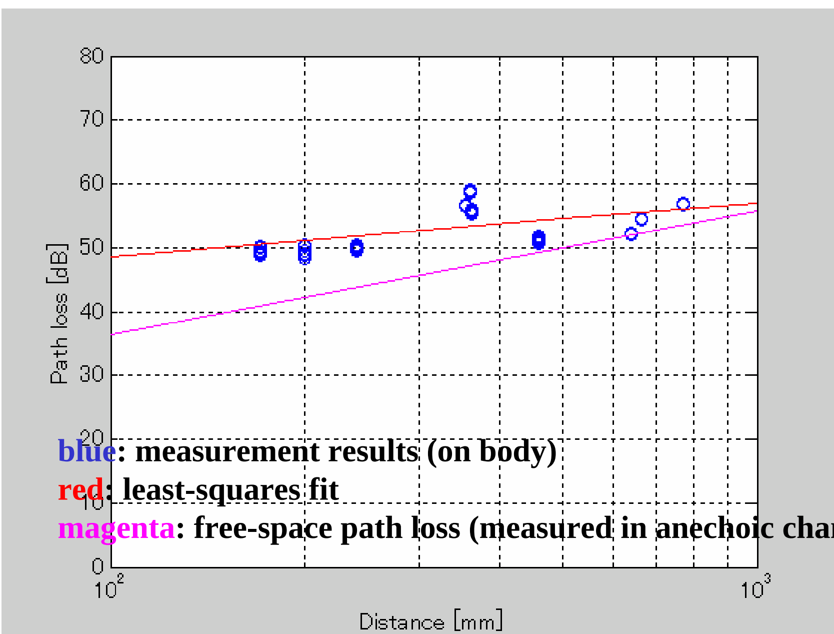


Path loss model UWB

$$PL(d)[\mathrm{dB}] = a \cdot \log_{10}(d) + b + N$$

Hospital room

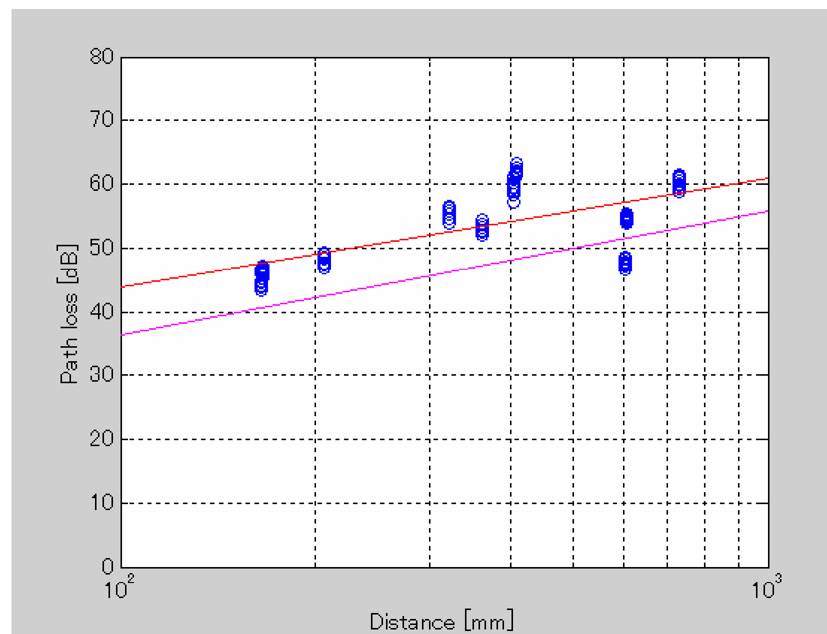
Parameters	value
a	8.43
b	31.8
σ_N	2.8



blue: measurement results (on body)
red: least-squares fit
magenta: free-space path loss (measured in anechoic chamber)

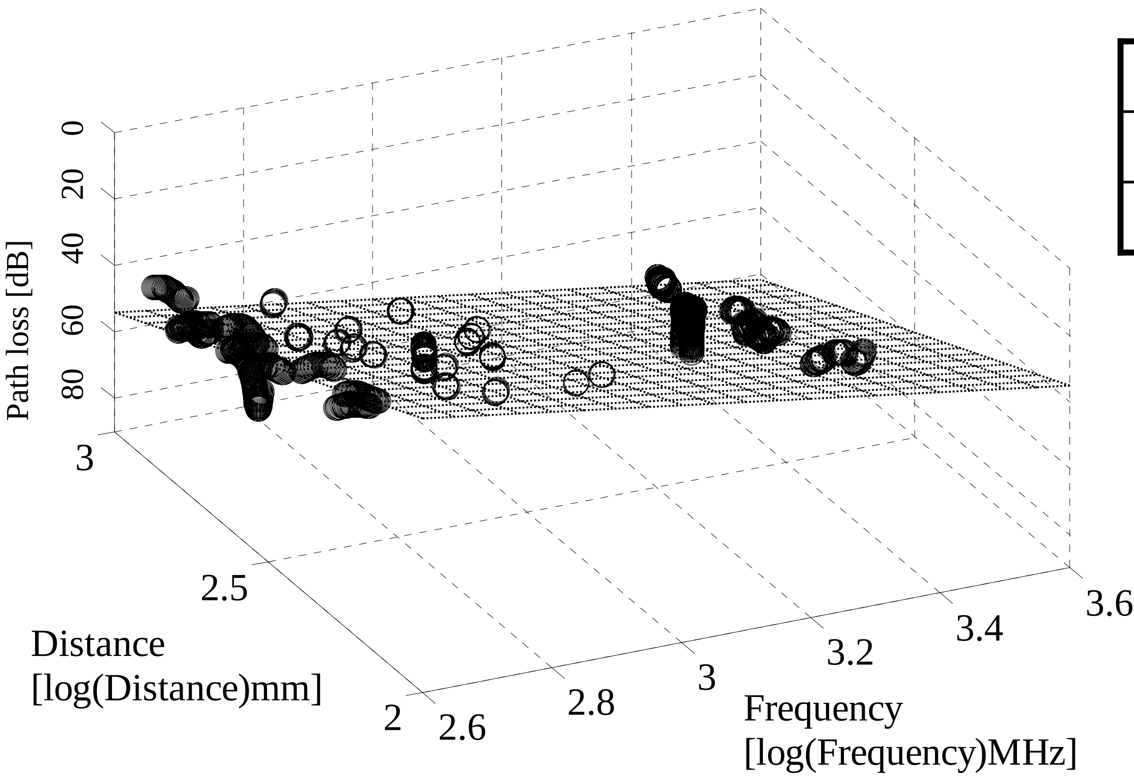
Anechoic chamber

Parameters	value
a	17.0
b	9.8
σ_N	4.66



Path loss model

$$PL(d, f)[\mathrm{dB}] = a \cdot \log_{10}(d) + b \cdot \log_{10}(f) + N_{d,f}$$



a	-27.6
b	-46.5
$N_{d,f}$	157

Channel models for implantable WBAN

Outline

1. Simulation setup
   - Frequency
     - 403.5 MHz
2. Simulation results
   - Air content
   - Muscle content

Simulation setup

- Simulation was conducted in the frequency-domain.
  - S21 of the channel were calculated.
  - Simulation software (SEMCAD) has used.
    - FDTD with UPML is used.
    - 100MHz width pulse has inputted.
    - S21 of 403.5MHz has extracted.
    - Transmitting antenna is half wave length dipole.
    - Receiver is 5mm line element.

Measurement setup

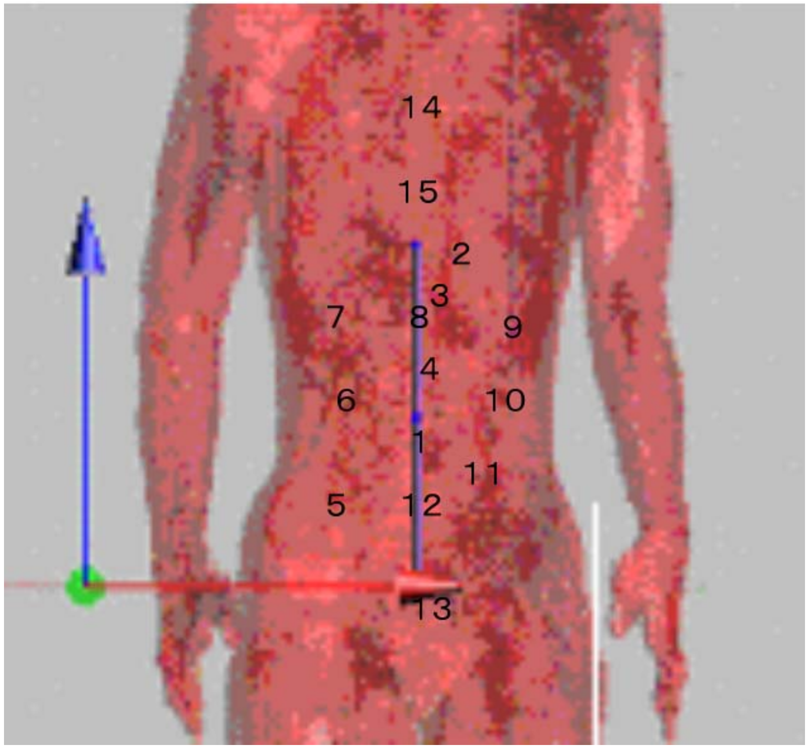
- Frequency and antenna

Band	Center freq.	Antenna
400 MHz	403.5 MHz	Transmit: ½ λ dipole Receive: 5mm line element (x, y, z direction)

- Human body
  A male numerical phantom is used.
- Content of the stomach, small and large intestines
  - Air or Muscle

Simulation setup

- Receiving positions are set in body.



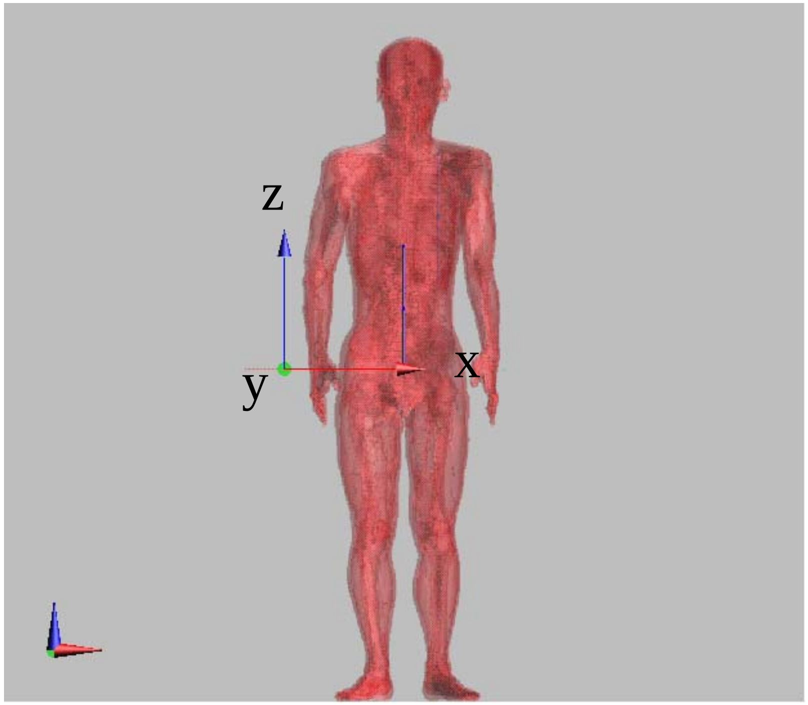
1	Transmitting antenna (on body)
2	Stomach
3	Duodenum
4	Small intestine
5	Large intestine 1
6	Large intestine 2
7	Large intestine 3
8	Large intestine 4
9	Large intestine 5
10	Large intestine 6
11	Large intestine 7
12	Large intestine 8
13	Large intestine 9
14	Esophagus 1
15	Esophagus 2

Simulation setup

- Simulation environments
  - UPML (Uniaxial Perfect Matching Layer) is applied for the boundary.
  - A 100MHz width pulse is inputted.
  - Voltage of the receiving element is calculated for 403.5 MHz.
  - Cell size of basic numerical human model is 2mm.
  - Spacial resolution is 450x600x590 (85 Mcells)

Simulation results

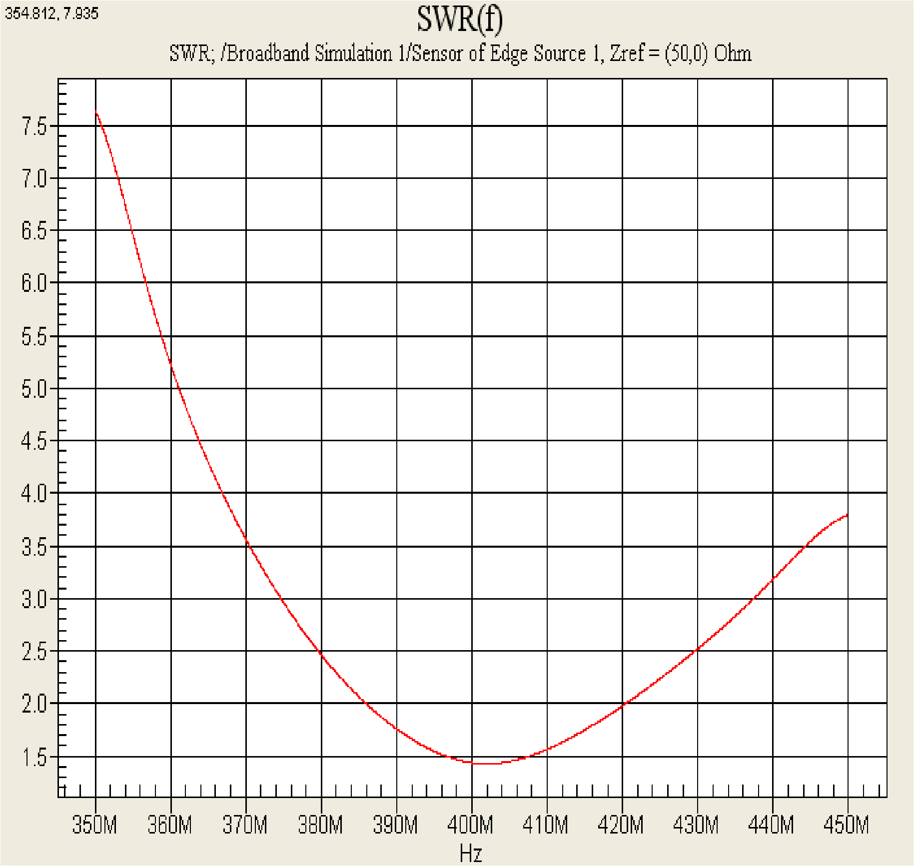
- Simulation model (NICT male numerical human model*). The central blue lines show the dipole antenna for transmission.



*Tomoaki Nagaoka, Soichi Watanabe, Kiyoko Sakurai, Etsuo Kunieda, Satoshi Watanabe, Masao Taki and Yukio Yamanaka, "Development of Realistic High-Resolution Whole-Body Voxel Models of Japanese Adult Male and Female of Average Height and Weight, and Application of Models to Radio-Frequency Electromagnetic-Field Dosimetry " Physics in Medicine and Biology, Vol.49, pp.1-15, 2004.

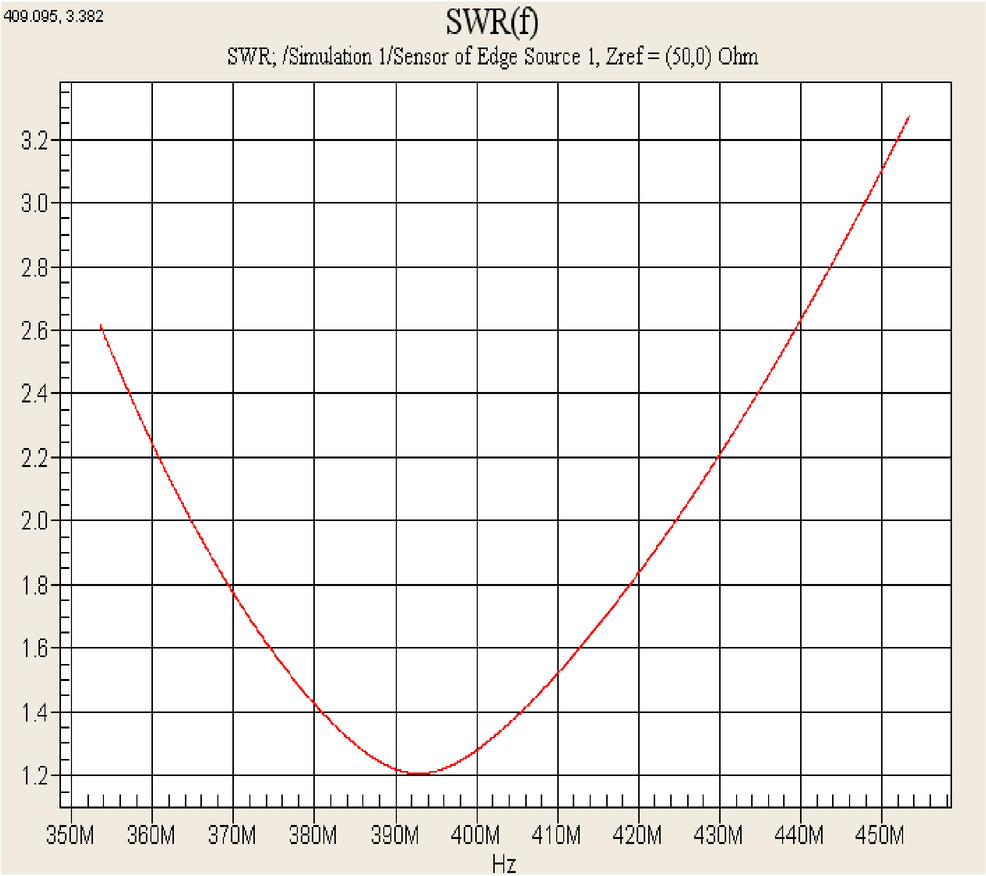
Simulation results

- VSWR for the Transmitting dipole antenna (in Free space).



Simulation results

- VSWR for the Transmitting dipole antenna (on Body).

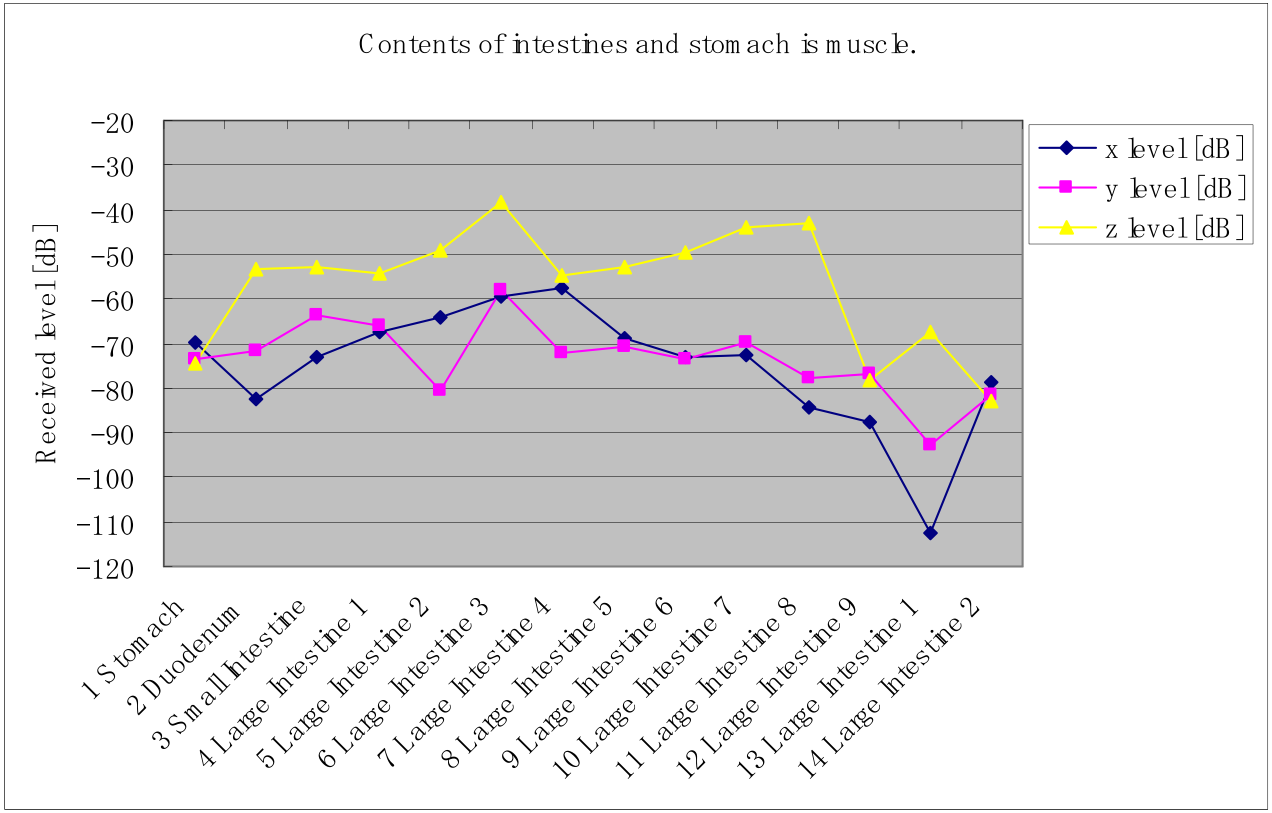


Simulation results: Transmitting antenna characteristics

- In free space, the VSWR of the dipole antenna is lower than 1.5 at 403.5MHz.
- On the body, the center frequency is shifted to the lower frequency (393MHz), and the minimum VSWR is decreased to 1.2.

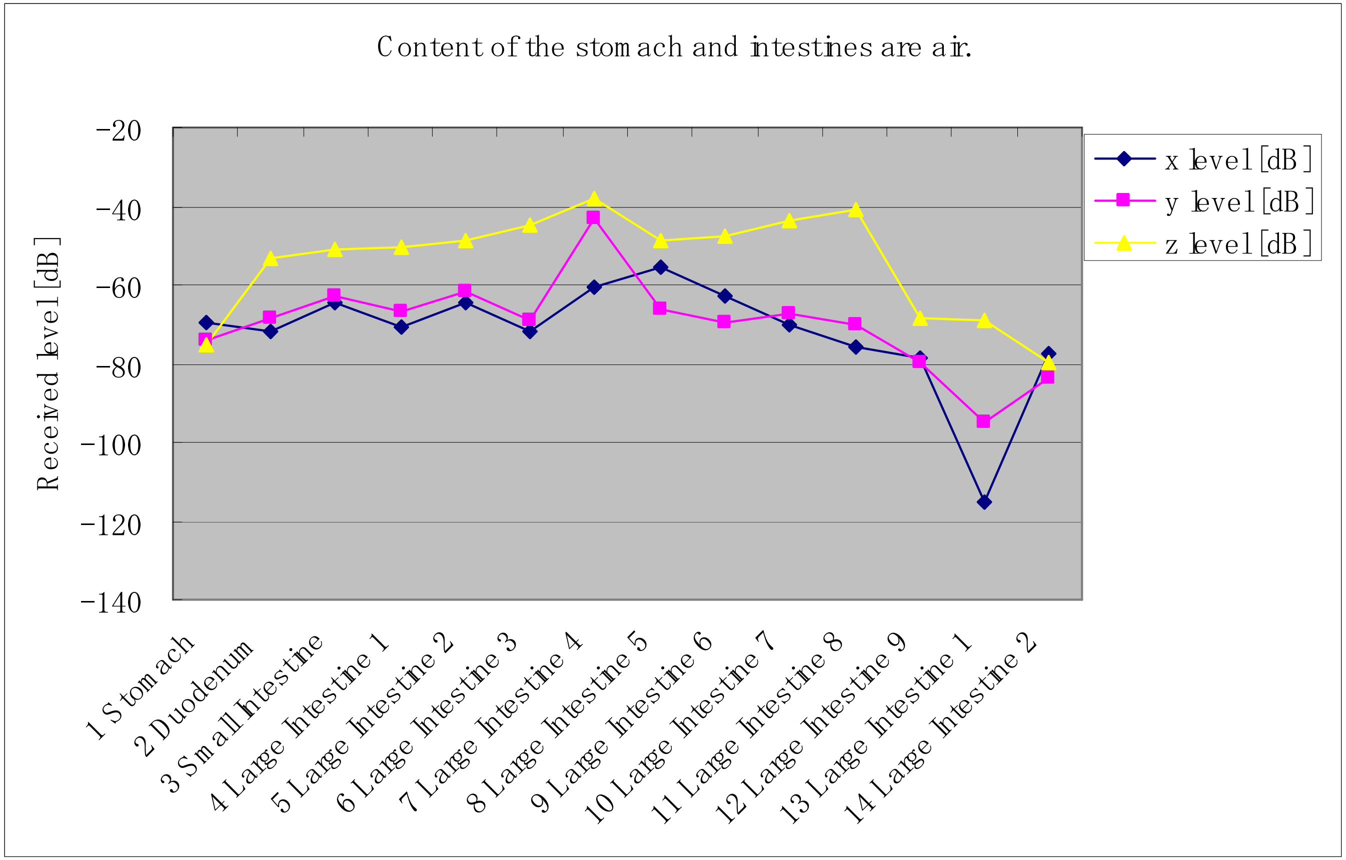
Simulation results

- Received amplitudes for receiving points
  Case 1: contents of stomach and intestines are muscle.



Simulation results

- Received amplitudes for receiving points.
  Case 2: contents of stomach and intestines are air.



Simulation results

- Statical results for the measurement.

	x level [dB]	y level [dB]	z level [dB]
Mean	-72.10	-69.82	-54.18
Stddev.	14.08	11.75	13.24
Maximum	-55.54	-43.23	-38.18
Minimum	-115.41	-95.04	-79.66
Fluct.	59.86	51.82	41.48

Muscle content case.

	x (air) level [dB]	y (air) level [dB]	z (air) level [dB]
Mean	-75.09	-73.50	-56.77
Stddev.	13.92	8.50	13.68
Maximum	-57.56	-57.92	-38.18
Minimum	-112.47	-92.96	-82.69
Fluct.	54.91	35.04	44.51

Air content case.

Simulation results: conclusion:

- The received level of the main polarization is about -54 dB.
- Received level of the case one (contents are muscle) is about 3 dB greater than the case two.
- Difference between the main polarization and the cross polarization is around 17 dB.

Simulation results: discussion:

- Transmitting antenna will be replaced to practical antennas (e.g. loop antenna or chip antenna).
- Receiving antenna will also be replaced as a loop coil antenna.
- To compromise received levels of the calculation, a level difference between experiment and the simulation will be added to the received level of the simulation.
- The simple pass loss model shall be obtained by introducing distance factor.