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Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	Channel Model for Body Area Network (BAN)
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Re:	[Body Area Network (BAN) Channel Model document]
Abstract	[This is a final document of the IEEE802.15.6 channel modeling subcommittee. It provides how channel model should be developed for body area network.
Purpose	[The purpose of this document is to provide the work of the channel modeling subcommittee and recommendations on how the channel model for BAN can be used.
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Release	The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15.

Channel Modeling Subcommittee Report

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2. Introduction

This document summarizes the activities and recommendations of the channel modeling subgroup of IEEE802.15.6 (Body Area Network). The Task Group TG6 is intended to develop Body Area Network for medical and non-medical devices that could be placed inside or on the surface of human body.

The models discussed generally characterize the path loss of BAN devices taking into account possible shadowing due to the human body or obstacles near the human body and postures of human body.

The channel model is needed to evaluate the performance of different physical layer proposals. The main goal of these channel models is a fair comparison of different proposals. They are not intended to provide information of absolute performance in different environments or body postures. The list of frequency band and number of available measurements on which the model can be based is shown in Table 1.

Description	Frequency Band
Implant	402-405
On-Body	13.5 MHz
On-Body	5-50 MHz (HBC)
On-Body	400 MHz
On-Body	600 MHz
On-Body	900 MHz
On-Body	2.4 GHz
On-Body	3.1-10.6 GHz

Table 1: List of frequency band

Since the subgroup was formed, a large number of documents has been submitted to the channel modeling subgroup or presented and discussed at IEEE802.15.6 meetings and teleconference calls. They can be found on the https://mentor.ieee.org/802.15/documents, and are cited where appropriate in this document. The channel model subgroup started its activities at the meeting in January 2007 (Taipei), and is submitting this final report in November 2008 (Dallas). Appreciation is extended to all the participants from academia and industry, whose efforts made this model possible.

Despite of significant efforts have been carried out to make models as realistic as possible, the number of available measurements on which the model can be based for wide range of frequencies (see Table 1) are insufficient.

To facilitate the use of the model, this document also includes a MATLAB program for the generation of each channel model.

The reminder of the document is organized in the following way: section 3 gives an overview as well as definition. Section 4 describes different scenarios and range of frequencies. Section 5 gives a short discussion of antenna. Section 6 gives an overview of medium. Section 7 provides channel characterization. Section 8 gives full detail on models and scenarios.

3. Definitions & Overview

An important step in the development of a wireless body area network is the characterization of the electromagnetic wave propagation from devices that are close to or inside the human body. The complexity of the human tissues structure and body shape make it difficult to drive a simple path loss model for BAN. As the antennas for BAN applications are placed on or inside the body, the BAN channel model needs to take into account the influence of the body on the radio propagation.

For the purpose of this document, we define 3 types of nodes as follows:

1) Implant node: A node that is placed inside the human body. This could be immediately below the skin to further deeper inside the body tissue
2) Body Surface node: A node that is placed on the surface of the human skin or at most 2 centimeters away
3) External node: A node that is not in contact with human skin (between a few centimeters and up to 5 meters away from the body)

For body surface communication, the distance between the transmitting and receiving nodes shall consider the distance around the body if transmitter and receiver are not placed in the same side rather than straight line through the body. This allows creeping wave diffraction to be also considered. For external node communication, the distance between transmitter and receiver shall be from the body vicinity or inside body to 2 meters away. In some cases, the maximum range for medical device shall be 5 meters.

The maximum power limitation for on-body medical device shall be decided from regional and international regulation [3].
The maximum power limitation for MICS is [1], [2]:
- ETSI (European Telecommunications Standards Institute): The output power is set to a maximum of 25 uW ERP.
- FCC & ITU-R: The output power is set to a maximum of 25 uW EIRP, which is ≈ 2.2 dB lower than the ERP level.
- The 25 uW limit applies to the signal level outside of the body (total radiating system), which allows for implant power levels to be increased to compensate for body losses.

Frequency band for implant devices (i.e. MICS) shall be 402-405 MHz as specified in [3].

The structure of the channel model for scenarios involving body surface and implant is not similar. The channel model for implant device is fundamentally different.

4. Scenarios

From [4,5], a list of scenarios can be identified in which IEEE802.15.6 devices will be operating. These scenarios along with their description and frequency band are listed in Table 2. The scenarios are determined based on the location of the communicating nodes (i.e. implant, body surface and external). The scenarios are grouped into classes that can be represented by the same Channel Models (CM).

Scenario	Description	Frequency Band	Channel Model
S1	Implant to Implant	402-405 MHz	CM1
S2	Implant to Body Surface	402-405 MHz	CM2
S3	Implant to External	402-405 MHz	CM2
S4	Body Surface to Body Surface (LOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ	CM3
S5	Body Surface to Body Surface (NLOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ	CM3
S6	Body Surface to External (LOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ	CM4
S7	Body Surface to External (NLOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ	CM4

Table 2: List of scenarios and their descriptions

The distance of external devices is considered to be a maximum of 5 meters. Possible channel models described above are graphically displayed in Fig. 1.
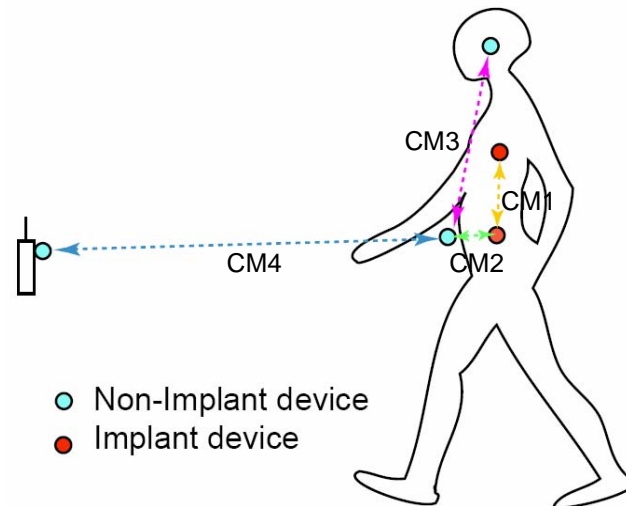
Fig. 1: Possible communication links for Body Area Networking

5. Antenna Effect

An antenna placed on the surface or inside a body will be heavily influenced by its surroundings [6]. The consequent changes in antenna pattern and other characteristics needs to be understood and accounted for during any propagation measurement campaign.

The form factor of an antenna will be highly dependent on the requirements of the application. For MICS applications, for example, a circular antenna may be suitable for a pacemaker implant, while a helix antenna may be required for a stent or urinary implant. The form factor will affect the performance of the antenna and, the antenna performance will be very important to the overall system performance. Therefore, an antenna which has been designed with respect to the body tissues (or considered the effect of human body) shall be used for the channel model measurements [7].

The BAN antennas may be classified into two main groups [8]:
  ▪ Electrical antennas, such as dipole
Electrical antenna- typically generates large components of E-field normal to the tissues interface, which overheat the fat tissue. This is because boundary conditions require the normal E-field at the interface to be discontinuous by the ratio of the permittivities, and since fat has a lower permittivity than muscle, the E-field in the fat tissue is higher.

  ▪ Magnetic antennas, such as loop
Magnetic antenna produces an E-field mostly tangential to the tissues, which seem not to couple as strongly to the body as electrical antennas. Therefore, does not overheat the fat.

There are antennas same as helical-coil, which is similar to a magnetic antenna in some respect, but its heating characteristics appear to be more like an electrical antenna. The strong E-field generated between the turns of coil is mainly responsible for tissue heating.

It should be noted that SAR in the near field of the transmitting antenna depends mainly on the *H*-field; however, SAR in the far field of the transmitting antenna depends mainly on the *E*-field.

6. Electrical Properties of Body Tissues

The human body is not an ideal medium for radio frequency wave transmission. It is partially conductive and consists of materials of different dielectric constants, thickness, and characteristic impedance. Therefore depending on the frequency of operation, the human body can lead to high losses caused by power absorption, central frequency shift, and radiation pattern destruction. The absorption effects vary in magnitude with both frequency of applied field and the characteristics of the tissue [10, 11, 12, 13].

7. Channel Characterization

7.1. Model Types
In all cases, two types of model may be generated:
- A theoretical or mathematical model
- An empirical model

A theoretical model may be traceable back to first principles and will permit precise modeling of a specific situation at radio link level. It is intended for detailed exploration of, for example, the influence of body structures on antenna patterns. It will require a detailed description of the propagation environment and is therefore probably not suitable for modeling of macro environments.

An empirical model may be traceable to an agreed set of propagation measurements and is intended to provide a convenient basis for statistical modeling of networks. Compared to the theoretical model, the empirical model will use a greatly simplified description of the environment and, although statistically accurate at network level, will not be precise at link level. Appropriate efforts will be made to ensure that the two sets of models are consistent with each other.

7.2. Path Loss

Unlike traditional wireless communications, the path loss for body area network system (on body applications), is both distance and frequency dependent. The frequency dependence of body tissues shall be considered.

The path loss model in dB between the transmitting and the receiving antenna as a function of the distance d based on the Friis formula in free space is described by [14, 15]:

$$PL(d) = PL_0 + 10n \log_{10}\left(\frac{d}{d_0}\right) \qquad (1)$$

where PL_0 is the path loss at a reference distance d_0, and n is the path-loss exponent.

The reference path loss near the antenna depends on the separation between the antenna and the body due to antenna mismatch. This mismatch indicates that a body-aware antenna design could improve system performance.

7.3. Shadowing

Due to the variation in the surrounding of human body or even movement of body parts, the received power will be different from the mean value for a given distance as shown in equation (1). This phenomenon is called shadowing, reflects the path loss variation around the mean. The shadowing should be considered for stationary position of human as well as for the body movements.

When considering shadowing, the total path loss PL can be expressed by:

$$PL = PL(d) + S \qquad (3)$$

where PL(d) is expressed by the equation (1) and S represents the shadowing component.

7.4. Power Delay Profile

Because of multipath reflections, the channel response of a wireless body area network channel looks likes a series of pulses. In practice the number of pulses that can be distinguished is very large, and depends on the time resolution of the measurement system. The power delay profile of channel is an average power of the channel as a function of an excess delay with respect to the first arrival path.

7.5. Fading

In the body area network communications, propagation paths can experience fading due to different reasons, such as energy absorption, reflection, diffraction, and shadowing by body, and

as well as body posture. The other possible reason for fading is due to multipath, because of office environment and environment around the body. Fading can be categorized to two groups; small scale fading and large scale fading.

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                         ┌─────────────────────┐
                         │   Channel Fading    │
                         └─────────────────────┘
                            /              \
        ┌──────────────────────┐      ┌──────────────────────┐
        │  Large Scale Fading  │      │  Small Scale Fading  │
        └──────────────────────┘      └──────────────────────┘
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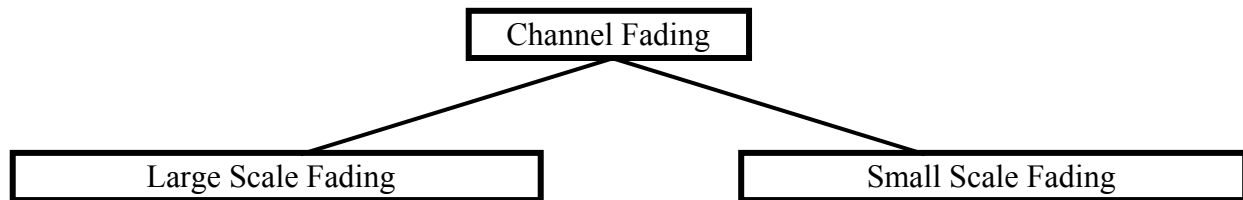
7.5.1. Small Scale Fading

Small scale fading refers to the rapid changes of the amplitude and phase of the received signals within a small local area due to small changes in location of the on body device or body positions, in a given short period of time. The small scale fading based on multipath time delay spread can be divided to the flat fading and frequency selective fading.

7.5.2 Large Scale Fading

Large scale fading refers to the fading due to motion over large areas; this is referring to the distance between antenna position on the body and at location in the room (home, office, or hospital).

Averaging the attenuation between each antenna position on the body and each antenna location in the room will removes the effect of small scale fading due to small changes in the user position around the room.

8. Models and Scenarios

8.1. In-Body

Since physical measurement and experimental study inside human body is not feasible [17], a 3D simulation & visualization scheme was used to study the propagation characteristics of MICS. The human body model used in this study includes (frequency dependent) dielectric properties of 300+ parts in a male human body with a maximum resolution of 2mm. The implant antenna used in this study is a multi-thread loop antenna with the following characteristics [18]:

- Size: 8.2 x 8.1 x 1 mm
- Metallic Layer: Copper, t=0.036 mm
- Substrate: D51 (NTK), ε_r=30, $\tan\theta = 0.000038$, and t=1mm
- The metallic layer is covered by RH-5, ε_r=1.0006, $\tan\theta = 0$, t =1mm

Parameters of a statistical path loss model have been extracted that fits the following equation.

$$PL(d) = PL(d_0) + 10n \log_{10}(d/d_0) + S \quad \text{where} \quad S \sim N(0, \sigma_s) \text{ and } d_0 = 50mm$$

The parameters corresponding to CM1 and CM2 are expressed in the tables in section 8.1.1 and 8.1.2. Details of the model derivation can be found in [19,20].

8.1.1. Implant to Implant CM1 (Scenario S1) for 402-405 MHz

Implant to Implant	$PL(d_0)(dB)$	n	$\sigma_s(dB)$
Deep Tissue	35.04	6.26	8.18
Near Surface	40.94	4.99	9.05

8.1.2. Implant to body surface CM2 (Scenario S2) for 402-405 MHz

Implant to Body Surface	$PL(d_0)(dB)$	n	$\sigma_s(dB)$
Deep Tissue	47.14	4.26	7.85
Near Surface	49.81	4.22	6.81

Remark: A distance of up to 20mm directly from the body surface has been considered in the derivation of the above parameters. One should keep in mind that layers of clothing could cause additional loss to the signal.

8.1.3. Implant to external CM2 (Scenario S3) for 402-405 MHz

The scenario S3 for CM2 can be approximated by considering a combination of scenarios S2 and S6 (or S7). In the simple case of an environment where there are no objects or obstacles, a free space path loss can be added to CM2 to account for the additional loss that the implant signal will go through once it leaves the body. This usually occurs after around 10 cm away from the body surface.

On the other hand, if there are objects within the 5 meter distance of the human body, a channel model for scenarios S6 or S7 (at 400 MHz) can account for the impact of these objects; and

therefore, such model can be added to CM2 to emulate scenario S3. (Remark: the path loss model for S6 (or S7) in this case should not include the on-body TX antenna gain pattern.)

8.2. On-body

8.2.1. Body surface to body surface CM3 (Scenarios S4 & S5) for 13.5 MHz

Measurement for frequency range of 13.550-13.571 MHz has been performed in [21]. The important observation at these frequencies is that the body channel exhibits path loss that is nearly similar to free space. However, the available bandwidth is quite small (21 KHz). The following table summarizes the measurement results. Further detail on set-up, derivation and data analysis can also be found in [21].

Description	Signal amplitude reduction						dB loss in relation to air			
Through the hand	3.3%						-0.15			
Through the wrist	2.8%						-0.12			
Torso, front to back	3.4%						-0.15			
Through the thigh	1.9%						-0.08			
Through the ankle	2.8%						-0.12			
Left ear to right ear	2.0%						-0.09			
Left ear to right ear, wearing metal glasses	1.5%						-0.07			
Distance through body (cm)	7.6	10.2	12.7	15.2	17.8	20.3	22.9	25.4	27.9	30.5
Received signal P-P (mV)	6.93	4.74	2.93	1.86	1.25	0.837	0.633	0.471	0.384	0.305

8.2.2. Body surface to body surface CM3 (Scenario S4 & S5) for 5-50 MHz

Human body can also be used as a communication media over the range of frequencies 5-50MHz. No modulation is needed in this form of communication which is referred to as Human Body Communication (HBC). The channel model for HBC is composed of the frequency response and the noise characteristics. Measurement process to obtain this channel model has been outlined in [22].

The following table and transfer function summarizes the result of frequency response that corresponds to fingertips of one hand to the other. Since, this scenario causes the most amplitude attenuation, these results have been chosen for the HBC channel model.

Parameters	Conditions
Locations of transmitter and receiver	Fingertips of each hand
Transmission distance (cm)	150
Contact location of signal electrode	Fingertip of thumb
Size of signal electrode (cm^2)	2x2
Load impedance of receiver	10 MΩ
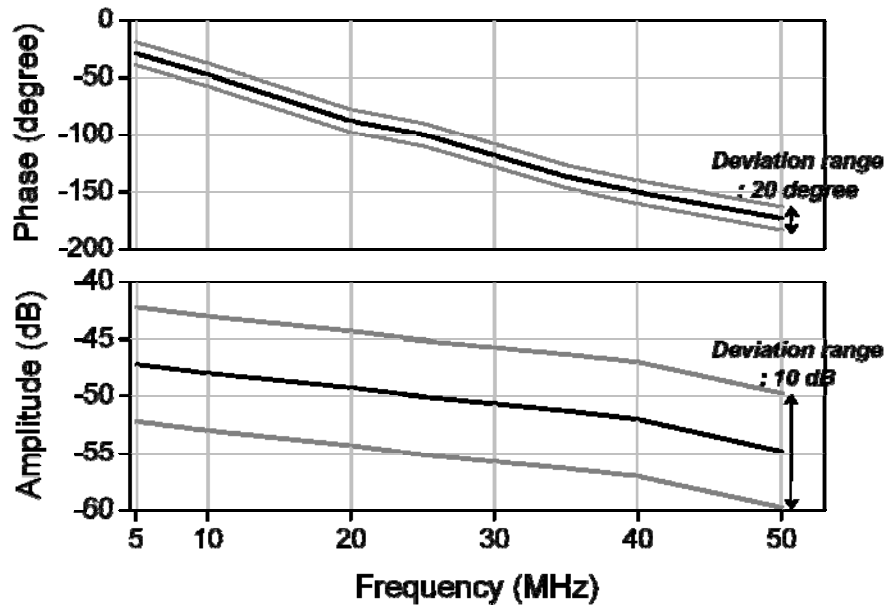
The noise has a Gaussian distribution as follows. The mean and variance values are zero and 2.55×10^{-5} respectively.
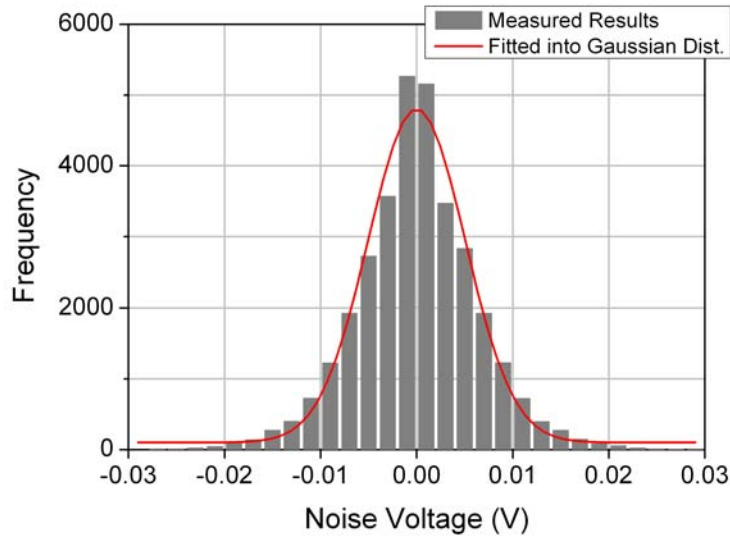
8.2.3. Body surface to body surface CM3 (Scenario S4 & S5) for 400 MHz

The following path loss model is based on measurements that cover frequencies of 400-450 MHz. Further measurement set up, derivation and data analysis can be found in [23]. The table below summarizes the model and corresponding parameters.

	Hospital Room	Anechoic Chamber
Path loss model	$PL(d)[\text{dB}] = a \cdot \log_{10}(d) + b + N$	
a	3	22.6
b	34.6	-7.85
σ_N	4.63	5.60

- *a* and *b* : Coefficients of linear fitting
- *d* : Tx-Rx distance in mm.
- *N* : Normally distributed variable with standard deviation σ_N

8.2.4. Body surface to body surface CM3 (Scenario S4 & S5) for 600 MHz

The following path loss model is based on measurements that cover frequencies of 608-614 MHz. Further measurement set up, derivation and data analysis can be found in [23]. The table below summarizes the model and corresponding parameters.

	Hospital Room	Anechoic Chamber
Path loss model	$PL(d)[\text{dB}] = a \cdot \log_{10}(d) + b + N$	
a	16.7	17.2
b	-0.45	1.61
σ_N	5.99	6.96

- *a* and *b* : Coefficients of linear fitting
- *d* : Tx-Rx distance in mm.
- *N* : Normally distributed variable with standard deviation σ_N

8.2.5. Body surface to body surface CM3 (Scenario S4 & S5) for 900 MHz

8.2.5. A

The following path loss model is based on measurements that cover frequencies of 950-956 MHz. Further measurement set up, derivation and data analysis can also be found in [23]. The table below summarizes the model and corresponding parameters.

	Hospital Room	Anechoic Chamber
Path loss model	$PL(d)[\text{dB}] = a \cdot \log_{10}(d) + b + N$	
a	15.5	28.8
b	5.38	-23.5
σ_N	5.35	11.7

- *a* and *b* : Coefficients of linear fitting
- *d* : Tx-Rx distance in mm.
- *N* : Normally distributed variable with standard deviation σ_N

8.2.5. B

The following model is based on measurements at frequency of 915 MHz. Details of the measurement set up, derivation and data analysis can be found in [24]. The path loss follows an exponential decay around the perimeter of the body. It flattens out for large distance due to the contribution of multipath components from indoor environment. The table below summarizes the model and corresponding parameters.

Path loss model	$PL(d)[dB] = -10\log_{10}\left(P_0\, e^{-m_0 d} + P_1\right) + \sigma_P n_P$
$P_0\,[\text{dB}]$	-1.9
$M_0\,[\text{dB/cm}]$	2.1
$P_1\,[\text{dB}]$	-59.4
$\sigma_p\,[\text{dB}]$	3.2

- P_0 : The average loss close to the antenna
- M_0 : The average decay rate in dB/cm for the surface wave traveling around the perimeter of the body
- P_1 : The average attenuation of components in an indoor environment radiated away from the body and reflected back towards the receiving antenna
- σ_p : The log-normal variance in dB around the mean, representing the variations measured at different body and room locations. This parameter will depend on variations

in the body curvature, tissue properties and antenna radiation properties at different body locations.
- n_p: Zero mean and unit variance Gaussian random variable

The small scale fading is represented by a Ricean distribution with K factor that decreases as the path loss increases. The delay spread is normally distributed. The table below summarizes the model and corresponding parameters.

Small-scale fading	$K_{dB} = K_0 - m_K P_{dB} + \sigma_K n_K$	
K_0 [dB]	40.1	
m_k [dB]	0.61	
σ_k [dB]	2.4	
Parameters of the mean value of the delay spread		
Distance [cm]	t_{rms} [ns]	
15	3	
45	9	
Parameters of the 90% cumulative value of the delay spread		
Distance [cm]	t_{rms} [ns]	
15	5	
45	15	

- K_0 : The fit with measurement data for the K-factor for low path loss
- m_k : The slope of the linear correlation between path loss and K-factor
- P_{dB} : Path loss in dB
- σ_k : The log-normal variance of the measured data between path loss and K-factor
- n_k : Zero mean and unit variance Gaussian random variable

8.2.5. C

The following path loss measurements is at frequency of 820 MHz. Details of the measurement set up, derivation and data analysis can be found in [25]. The table below summarizes the results. As observed, the dominant factor affecting fading in the channel appears to be the movement of the test subject. This is to be expected as movement causes the separation and orientation of the antennas to change.

Path loss	$PL[dB] = P_{tx} - P_{rx} + G_{amplifiers} - L_{cable}$								
		Receiver at right hip					Receiver at chest		
Action	Chest	Right Wrist	Left Wrist	Right Ankle	Left Ankle	Back	Back	Right Wrist	Right Ankle
Standing	57.4	50.2	59.8	54.3	68.7	61.8	66.3	54.5	54.3
Walking	52.9	38.4	63.6	48.1	55.5	57.1	63.8	51.3	56.9
Running	44.1	37.2	60.2	48.9	54.2	62.3	66.3	49.4	54.1

- P_{tx}: Transmitted power
- P_{rx}: The RMS received power
- $G_{amplifiers}$: Amplifier gain
- L_{cable}: Cable loss

The characterization of Small-scale fading at 820 MHz for a dynamic BAN channel where devices are placed on body surface can be found in [26]. The fading Rate (number of fades per second), Duration (time below mean), and Magnitude (attenuation below mean) are measured for four different speeds (walking: 3 kph and 6 kph, Running: 9 kph and 12 kph) of object test. The location of transmitters and receivers on human body are shown in blow table.

Receiver Location	Transmitter Location					
	Chest	Right Wrist	Left Wrist	Right Ankle	Left Ankle	Back
Right Hip	✓	✓	✓	✓	✓	✓
Chest		✓		✓		✓

The following figures summarize the result of this measurement. The Gamma distribution is the best fit to average fade duration. The best fit to fade magnitude is the Gamma distribution fitted to a dB scale (i.e. the given Gamma distribution is directly fitted to the values in decibels of the empirical data for Fade magnitude), called a Gamma-dB fit.

Fading rate

Fading duration

Fading magnitude
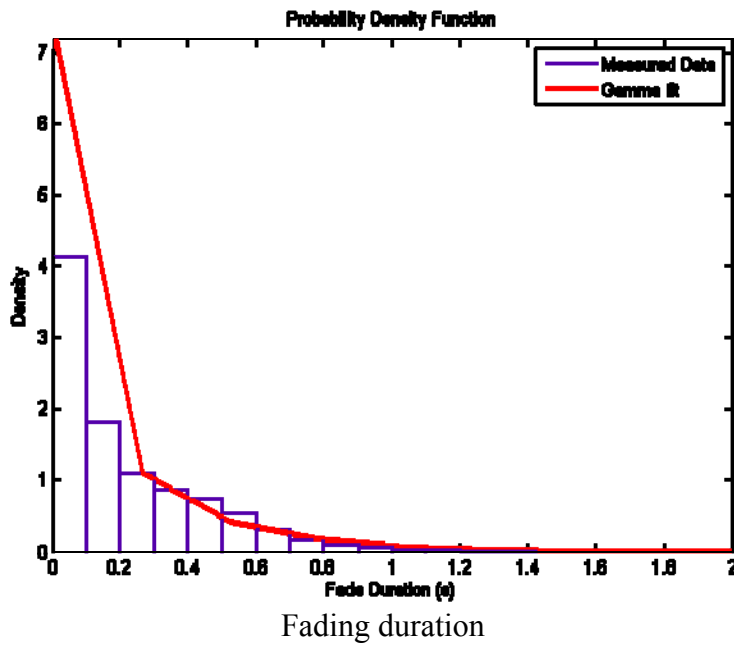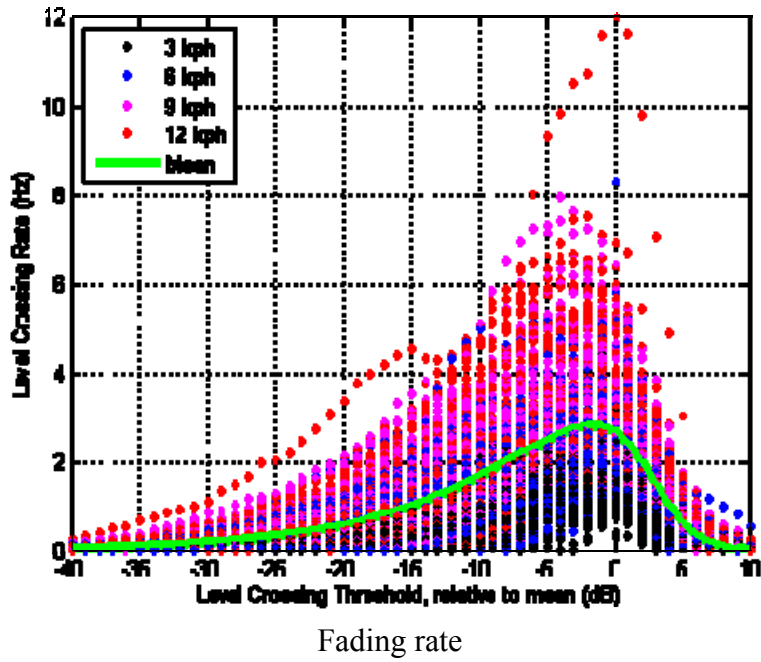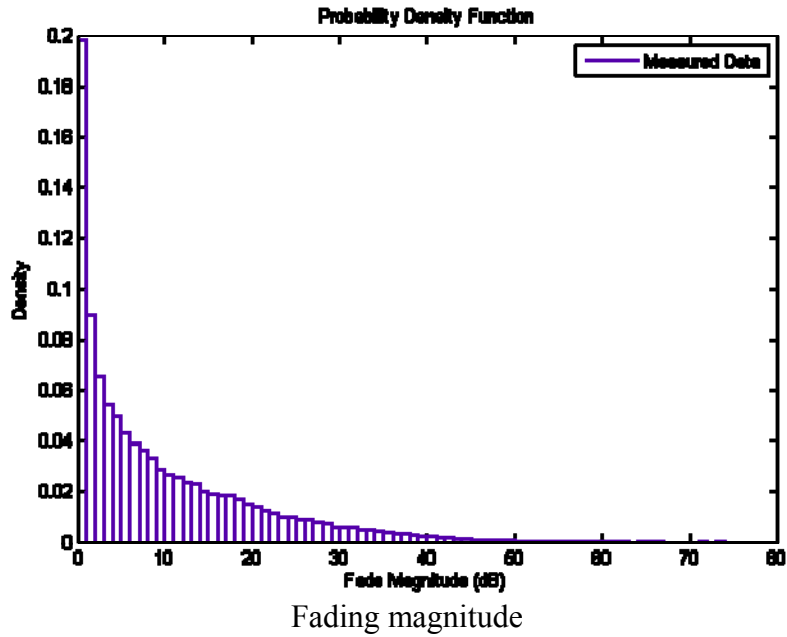
The outage probability represents the probability of a minimum requirement on the satisfactory reception over the intended coverage area..

Outage probability
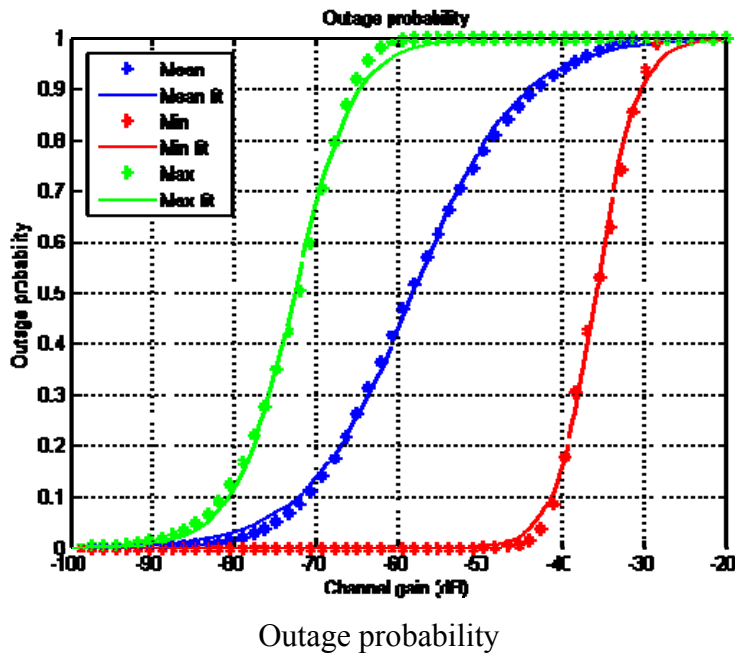
8.2.6. Body surface to body surface CM3 (Scenario S4 & S5) for 2.4 GHz

8.2.6. A

The following path loss model is based on measurements that cover frequencies of 2.4-2.5GHz. Details of the measurement set up, derivation and data analysis can be found in [23]. The table below summarizes the model and corresponding parameters.

	Hospital Room	Anechoic Chamber
Path loss model	$PL(d)[\text{dB}] = a \cdot \log_{10}(d) + b + N$	
a	6.6	29.3
b	36.1	-16.8
σ_N	3.80	6.89

- *a* and *b* : Coefficients of linear fitting
- *d* : Tx-Rx distance in mm.
- *N* : Normally distributed variable with standard deviation σ_N

8.2.6. B

The following model is based on measurements at frequency of 2.45 GHz. Details of the measurement set up, derivation and data analysis can be found in [24]. The path loss follows an exponential decay around the perimeter of the body. It flattens out for large distance due to the contribution of multipath components from indoor environment. The table below summarizes the model and corresponding parameters.

Path loss model	$PL(d)[dB] = -10\log_{10}\left(P_0 \, e^{-m_0 d} + P_1\right) + \sigma_P n_P$
P_0 [dB]	-25.8
m_0 [dB/cm]	2.0
P_1 [dB]	-71.3
σ_p [dB]	3.6

- P_0 : The average loss close to the antenna
- M_0 : The average decay rate in dB/cm for the surface wave traveling around the perimeter of the body

- P_1 : The average attenuation of components in an indoor environment radiated away from the body and reflected back towards the receiving antenna
- σ_p : The log-normal variance in dB around the mean, representing the variations measured at different body and room locations. This parameter will depend on variations in the body curvature, tissue properties and antenna radiation properties at different body locations.
- n_p : Zero mean and unit variance Gaussian random variable

The small scale fading is represented by a Ricean distribution with K factor that decreases as the path loss increases. The delay spread is normally distributed. The table below summarizes the model and corresponding parameters.

Small-scale fading	$K_{dB} = K_0 - m_K P_{dB} + \sigma_K n_K$
K_0 [dB]	30.6
m_k [dB]	0.43
σ_k [dB]	3.4
Parameters of the mean value of the delay spread	
Distance [cm]	t_{rms} [ns]
15	6
45	16
Parameters of the 90% cumulative value of the delay spread	
Distance [cm]	t_{rms} [ns]
15	11
45	22

- K_0 : The fit with measurement data for the K-factor for low path loss
- m_k : The slope of the linear correlation between path loss and K-factor
- P_{dB} : Path loss in dB
- σ_k : The log-normal variance of the measured data between path loss and K-factor
- n_k : Zero mean and unit variance Gaussian random variable

8.2.6. C

The following path loss measurements is at frequency of 2.36 GHz. Details of the measurement set up, derivation and data analysis can be found in [25]. The table below summarizes the results. As observed, the dominant factor affecting fading in the channel appears to be the movement of the test subject. This is to be expected as movement causes the separation and orientation of the antennas to change.

Path loss	$PL[dB] = P_{tx} - P_{rx} + G_{amplifiers} - L_{cable}$								
		Receiver at right hip					Receiver at chest		
Action	Chest	Right Wrist	Left Wrist	Right Ankle	Left Ankle	Back	Back	Right Wrist	Right Ankle
Standing	65.3	44.5	74.7	60.9	70.7	75.3	73	70.5	66.3
Walking	59.1	47.3	59.8	53.9	58.5	67.4	72	64.9	62.4
Running	55.9	36.3	52.5	55	59	68.5	71.7	57.4	63.3

- P_{tx}: Transmitted power
- P_{rx}: The RMS received power
- $G_{amplifiers}$: Amplifier gain
- L_{cable}: Cable loss

8.2.7. Body surface to body surface CM3 (Scenario S4 & S5) for 3.1-10.6 GHz

8.2.7. A

The following path loss model is based on measurements that cover frequencies of 3.1-10.6 GHz. Measurement set up, derivation and data analysis can be found in [23]. The table below summarizes the model and corresponding parameters.

	Hospital Room	Anechoic Chamber
Path loss model	$PL(d)[dB] = a \cdot \log_{10}(d) + b + N$	
a	19.2	34.1
b	3.38	-31.4
σ_N	4.40	4.85

- a and b : Coefficients of linear fitting
- d : Tx-Rx distance in mm
- N : Normally distributed variable with zero mean and standard deviation σ_N

A power delay profile (PDP) model for 3.1 – 10.6 GHz is also given in [23]. The table below summarizes this model and corresponding parameters.

PDP Model	$$h(t) = \sum_{l=0}^{L-1} a_l \exp(j\phi_l)\delta(t - t_l)$$ $$10\log_{10}|a_l|^2 = \begin{cases} 0 & l = 0 \\ \gamma_0 + 10\log_{10}\left(\exp\left(-\dfrac{t_l}{\Gamma}\right)\right) + S & l \neq 0 \end{cases}$$ $$p(t_l \mid t_{l-1}) = \lambda \exp(-\lambda(t_l - t_{l-1}))$$ $$p(L) = \frac{\overline{L}^L \exp(\overline{L})}{L!}$$ ϕ_l is modeled by a uniform distribution over $[0, 2\pi)$

	γ_0	-4.60 dB
a_l	Γ	59.7
	σ_S	5.02 dB
t_l	λ	1.85 ns
L	$\overline{L}$	38.1

- a_l : path amplitude for the l-th path
- t_l : path arrival time for the l-th path
- ϕ_l : phase for the l-th path
- L : the number of the arrival paths
- $\delta(t)$: the Dirac function
- Γ : an exponential decay with a Rician factor γ_0
- S : a normal distribution with zero-mean and standard deviation of σ_S.
- λ: path arrival rate
- $\overline{L}$: the average number of the L

8.2.7. B

The following path loss model is based on measurements that cover frequencies of 3.1-10.6 GHz. Measurement set up, derivation and data analysis can be found in [24]. The table below summarizes the corresponding parameters.

Path loss model	$PL(d)[\text{dB}] = P_0[dB] + 10\,n\log_{10}\left(\dfrac{d}{d_0}\right)$		
Around torso			
Antenna separation from body surface	0 mm	5 mm	10 mm
P_0 [dB]	56.1	48.4	45.8
d_0 [m]	0.1	0.1	0.1
n	5.8	5.9	6.0
Along torso			
Antenna separation from body surface	0 mm		5 mm
P_0 [dB]	56.5		44.6
d_0 [m]	0.1		0.1
n	3.1		3.1

- n: Path loss exponent
- P_0: Path loss at the reference distance
- d_0: Reference distance

8.2.7. C

Measurement for the UWB frequency band ranges of 3.1-5.1 GHz and 7.25-8.5 GHz has been performed in [27]. The following table summarizes the measurement results. Further detail on set-up, derivation and data analysis can also be found in [27].

8.2.7.C.A

Transmitter antenna is placed in left waist and receiver antennas are located in several different positions to observe the effect of body posture.

a. 3.1-5.1 GHz

	Action	left ear(dB)	right ear(dB)	left wrist(dB)	right wrist(dB)	right waist(dB)	left ankle(dB)	right ankle(dB)
Anechoic Chamber	Standing	62.2	61.6	64.9	67.5	64.2	72.8	69.1
	Sitting	71.9	65.7	55.6	69.9	65.9	76.3	73.9
Office Room	Standing	73.8	70.4	61.4	70.9	74.3	76.4	68.3
	Sitting	62.3	72.1	65.6	76.3	74.7	79.8	75.7

b. 7.25-8.5 GHZ

	Action	left ear(dB)	right ear(dB)	left wrist(dB)	right wrist(dB)	right waist(dB)	left ankle(dB)	right ankle(dB)
Anechoic Chamber	Standing	81.7	83.9	69.3	63.9	76.1	76.8	77.1
	Sitting	84.4	85.2	73.6	75.5	82.38	79.8	95.2
Office Room	Standing	75.5	75.6	80.6	66.4	71.9	74.4	75.8
	Sitting	67.1	84.5	67.0	67.1	67.5	70.6	83.4

8.2.7.C.B

To study the effect of body movement on channel model, the transmitter antenna is placed in left waist and receiver antennas are located in several different positions, while arm and leg are moved in forward or side directions.

a. 3.1-5.1 GHz

		Anechoic Chamber		Office Room	
		mean	stdev	mean	stdev
Left wrist	Forward direction	65.7	4.3	71.7	5.8
	Side direction	70.9	6.0	76.6	7.7
Right wrist	Forward direction	72.9	4.4	73.6	2.3
	Side direction	71.8	5.9	75.1	3.1
Left ankle	Forward direction	74.6	2.5	76.4	0.1
	Side direction	67.9	6.8	70.4	8.4
Right ankle	Forward direction	70.8	2.5	69.9	2.3
	Side direction	72.8	5.3	69.6	1.9

b. 7.25-8.5 GHz

		Anechoic Chamber		Office Room	
		mean	stdev	mean	stdev
Left wrist	Forward direction	76.9	6.6	74.1	3.4
	Side direction	77.4	10.1	78.1	4.7
Right wrist	Forward direction	79.7	7.1	73.0	7.1
	Side direction	79.5	8.1	75.9	6.0
Left ankle	Forward direction	82.4	7.9	75.9	2.2
	Side direction	77.4	0.8	75.7	1.9
Right ankle	Forward direction	85.4	11.7	77.5	2.5
	Side direction	82.0	6.9	78.1	3.3

8.2.8. Body surface to external CM4 (Scenario S6 & S7) for 900 MHz

The following path loss measurements is at frequency of 820 MHz. Details of the measurement set up, derivation and data analysis can be found in [28]. The table below summarizes the results. The transmitter is placed on the chest and the receiver is away from the body with various distances as outlined.

Distance (m)	LOS				NLOS			
	1	2	3	4	1	2	3	4
Standing	43.51	52.73	54.60	49.78	60.13	56.34	64.67	58.67
Walking	42.05	48.80	51.56	52.07	45.93	61.44	62.07	63.62

8.2.9. Body surface to external CM4 (Scenario S6 & S7) for 2.4 GHz

The following path loss measurements is at frequency of 2.36 GHz. Details of the measurement set up, derivation and data analysis can be found in [28]. The table below summarizes the results. The transmitter is placed on the chest and the receiver is away from the body with various distances as outlined.

Distance (m)	LOS				NLOS			
	1	2	3	4	1	2	3	4
Standing	53.81	53.12	56.04	64.72	61.81	68.64	60.12	63.10
Walking	44.46	51.59	52.14	60.81	59.48	70.30	63.98	62.56

8.2.10. Body surface to external CM4 (Scenario S6 & S7) for 3.1-10.6 GHz

8.2.10.A

Measurement for the UWB frequency band of 3.1-10.6 GHz has been performed in [29]. On-body antenna characteristics were measured in anechoic chamber, while channel measurements were done in office environment. For this measurement, the Tx antenna is fixed near to wall, while the Rx antenna (placed 0n body) positions were changed in office area. The effect of ground is considered in measurements. All data were averaged for statically analysis, therefore, the detail data of each measurement is not provided. The Further detail on set-up, derivation and data analysis can be found in [29]. The following figures summarize the delay profile of front, side, and backside of body while the Tx antenna is in the front of body.

| Front of body | side of body | Backside of body |
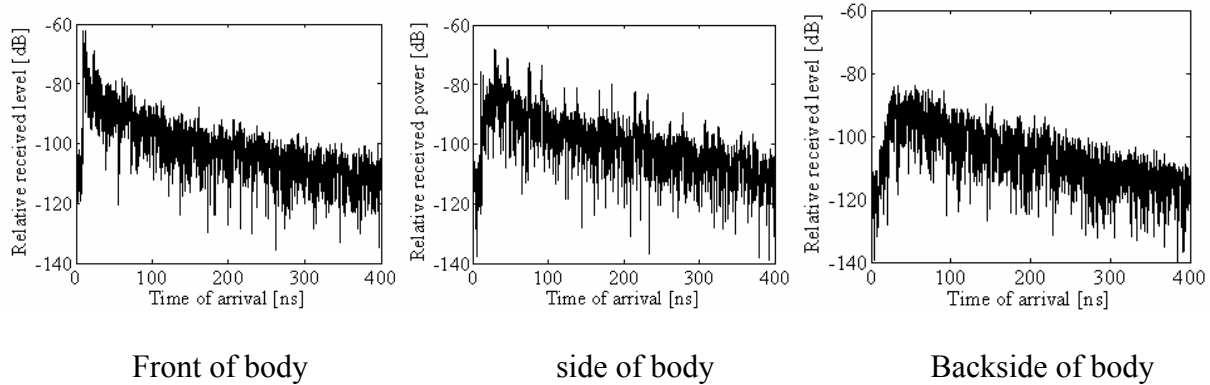
Model	$$h(t) = \sum_{m=0}^{\infty} \alpha_m \delta(t - \tau_m)$$ $$\overline{\left| \alpha_m \right|^2} = \Omega_0 e^{-\tau_m / \Gamma - k[1 - \delta(m)]}$$ $$k = \Delta k (\ln 10 / 10)$$ $$\tau_0 = d / c$$		
Direction of Body	Γ[ns]	K (Δk[dB])	σ[dB]
0	0.224	1.47 (6.4)	7.30
90	0.184	0.691 (3.0)	7.08
180	0.187	0 (0)	7.03
270	0.191	0.345 (1.5)	7.19

- $h(t)$: Complex impulse response
- m : Number of ray
- a_m : Amplitude of each ray
- τ_m: Sampling rate of system
- k: Effect of K-factor (NLOS)
- Ω_0: Path loss (depends on the environment and LOS situation)
- D: Tx-Rx distance
- C: Velocity of light

8.2.10.B

Measurement for the UWB frequency band ranges of 3.1-5.1 GHz and 7.25-8.5 GHz has been performed in [27]. Further detail on set-up, derivation and data analysis can also be found in [27].

8.2.10. B. A. Effect of receiver antenna height

The transmitter antenna is placed on wooden stand at fixed height of 1 m from ground and receiver antenna is placed on wooden stand and located at different height, from 0.25 to 1.5 m with step of 0.25 m. The distance between transmitter and receiver are 1 m and 3 m. The tables below summarize the results.

a. 3.1-5.1 GHz

Rx Antenna Height	0.25m	0.5m	0.75m	1.0m	1.25m	1.5m
Tx-Rx Distance 1m	45.5	45.4	44.2	43.8	44.5	44.2
Tx-Rx Distance 3m	54.5	53.7	53.0	52.9	53.7	53.7

b. 7.25-8.5 GHz

Rx Antenna Height	0.25m	0.5m	0.75m	1.0m	1.25m	1.5m
Tx-Rx Distance 1m	53	52	53.4	52.2	52.2	52.6
Tx-Rx Distance 3m	54.7	54.9	61.7	62.2	61.7	55.3

8.2.10. B.B. Effect of body posture

The transmitter antenna is placed on wooden stand at fixed height of 1 m from ground and receiver antenna is located on body with 3 m away from transmitter. The measurements have been performed for standing and sitting positions. The tables below summarize the results.

a. 3.1-5.1 GHz

Action	Anechoic Chamber (dB)				Office Room (dB)			
	Right ear	Right wrist	Right waist	Right ankle	Right ear	Right wrist	Right waist	Right ankle
Standing	66.9	63.3	56.1	59.4	62.8	61.9	55.1	60.7
Sitting	60.4	61.1	60.6	55.7	60.4	61.6	54.5	57.1

b. 7.25-8.5 GHz

Action	Anechoic Chamber (dB)				Office Room (dB)			
	Right ear	Right wrist	Right waist	Right ankle	Right ear	Right wrist	Right waist	Right ankle
Standing	69.3	63.7	70.4	69.5	72.4	72.1	75.7	68.1
Sitting	71.5	64.2	71.9	63.8	74.4	73.9	76.3	73.7

8.2.10. B. C Effect of body movement

The transmitter antenna is placed on wooden stand at fixed height of 1 m from ground and receiver antenna is located on body with 3 m away from transmitter. The measurements have

been performed while arm and leg are moved in forward or side directions. The tables below summarize the results.

a. 3.1-5.1 GHz

		Anechoic Chamber		Office Room	
		Mean (dB)	Stdev (dB)	Mean (dB)	Stdev (dB)
Wrist	Forward direction	58.2	4.2	60.7	3.9
	Side direction	63.6	3.5	64.5	2.2
Ankle	Forward direction	64.0	6.5	61.4	1.1
	Side direction	57.2	3.1	61.0	0.5

b. 7.25-8.5 GHz

		Anechoic Chamber		Office Room	
		Mean (dB)	Stdev (dB)	Mean (dB)	Stdev (dB)
Wrist	Forward direction	64.6	2.3	73.1	2.0
	Side direction	64.0	1.8	73.9	2.5
Ankle	Forward direction	66.1	4.8	65.4	3.8
	Side direction	66.0	4.8	69.1	1.4

8.3. Real time channel for body surface to body surface CM3 (Scenario S4 & S5) at 4.5 GHz

A real time channel measurements by use of channel sounder has been performed in [30]. The channel measurements were carried out in an anechoic chamber with center frequency of 4.5 GHz and bandwidth of 120 MHz. Details of the measurement set up, derivation and data analysis can be found in [30]. The measurements are focusing on the fading effect due to movements of the human body, therefore conducted in an anechoic chamber, where the mutipath from the surrounding objects are negligible.

The transmitter antenna was fixed on around navel. The table below summarize the position of receiving antennas and distance between Tx and Rx antennas.

Position	Distance [mm]
Right wrist	440 ~ 525
Right upper arm	360
Left ear	710
Head	650
Shoulder	310
Chest	230
Right rib	183
Left waist	140
Thigh	340
Ankle	815 ~ 940

To provide a statistical model, the probability distribution functions such as normal, log-normal and Weibull distributions have been tried to fill the measurement results. The tables below summarize the normal, log-normal and Weibull distributions.

Position	(Normal) $\quad f(x \mid \mu,\sigma) = \dfrac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$		
	Still μ/σ [dB] (-log L)	Walking μ/σ [dB] (-log L)	Up-down μ/σ [dB] (-log L)
Right wrist	1.0000 / 0.1279 (-6303)	3.0875 / 4.4063 (28972)	8.9461 / 5.1576 (30220)
Right upper arm	1.0000 / 0.1500 (-4735)	3.2443 / 1.7012 (19332)	7.3374 / 6.1415 (32061)
Head	1.0000 / 0.0666 (-12706)	0.4477 / 0.2445 (4535)	0.9058 / 1.2629 (16207)
Right ear	1.0000 / 0.1349 (-5826)	0.7303 / 0.3014 (101)	0.8205 / 0.8232 (12148)
Shoulder	1.0000 / 0.0335 (-19782)	2.6849 / 1.4627 (2153)	1.5437 / 1.3265 (17519)
Chest	1.0000 / 0.3481 (3600)	3.6360 / 2.4688 (17849)	7.1082 / 9.2594 (36609)
Right rib	1.0000 / 0.1654 (-3812)	0.8572 / 0.2744 (1256)	4.7043 / 2.9597 (24784)
Left waist	1.0000 / 0.0399 (-17978)	0.7264 / 0.1609 (-4018)	0.5458 / 0.3105 (2456)
Right thigh	1.0000 / 0.0964 (-9254)	0.6500 / 0.4388 (5831)	1.1357 / 0.6949 (10272)
Right ankle	1.0000 / 0.0787 (-11025)	1.6070 / 0.9968 (14248)	1.2489 / 1.2220 (16122)

- μ : Mean value
- σ : Variable value
- *-LogL*: Negative log liklihood

Position	(Log-Normal) $f(x\,\|\,\mu,\sigma)=\dfrac{10/\ln 10}{x\sigma\sqrt{2\pi}}e^{-\frac{(10\log_{10}x-\mu)^2}{2\sigma^2}}$		
	Still μ/σ [dB] (-log L)	Walking μ/σ [dB] (-log L)	Up-down μ/σ [dB] (-log L)
Right wrist	-0.0652 / 0.9531 (-1114.1)	-3.9908 / 11.7727 (14948)	8.4456 / 3.4836 (31047)
Right upper arm	-0.0491 / 0.6544 (-4800.9)	4.4491 / 2.4972 (18735)	6.3009 / 5.6692 (31093)
Head	-0.0100 / 0.2969 (-12476)	-3.5392 / 3.2052 (2983.8)	-3.6932 / 5.3385 (7601)
Right ear	-0.0400 / 0.5921 (-5815.6)	-4.1465 / 2.4654 (-1005.5)	-3.3130 / 5.2458 (8384.1)
Shoulder	-0.0024 / 0.1453 (-19806)	-1.8011 / 2.0549 (2507.8)	0.2165 / 4.1023 (14537)
Chest	-0.2359 / 1.4019 (2315)	3.6360 / 2.4688 (16779)	5.0788 / 6.4077 (29907)
Right rib	-0.0470 / 0.6043 (-5657.3)	-0.8883 / 1.3994 (818.79)	5.7033 / 3.2101 (24051)
Left waist	-0.0035 / 0.1742 (-17942)	-1.4965 / 0.9770 (-4109.5)	-3.5588 / 3.3466 (3337.8)
Right thigh	-0.0191/ 0.4017 (-9717)	-2.6924 / 2.6453 (2970.7)	-0.5995 / 3.7712 (11098)
Right ankle	-0.0131/ 0.3352 (-11251)	0.9424 / 3.7030 (14861)	-1.1303 / 4.7167 (12357)

- μ : Mean value
- σ : Variable value
- *-LogL*: Negative log liklihood

Position	(Weibull) $f(x\mid a,b)=\dfrac{b}{a}\left(\dfrac{x}{a}\right)^{b-1}e^{-\left(\frac{x}{a}\right)^{b}}$		
	Still a/b (-LogL)	Walking a/b (-LogL)	Updn a/b (-LogL)
Right wrist	1.0478 / 7.7411 (-5770.3)	1.4690 / 0.4510 (14629)	10.0006 / 1.7319 (29786)
Right upper arm	1.0655 / 7.3618 (-4529.3)	3.6759 / 2.0325 (18625)	7.5368 / 1.0787 (29631)
Head	1.0297 / 17.9473 (-13029)	0.6360 / 1.5519 (3061.7)	0.8015 / 0.8228 (8458.3)
Right ear	1.0594 / 7.7870 (-5394.6)	0.5071 / 1.9516 (-840.12)	0.8224 / 1.0055 (7959.7)
Shoulder	1.0165 / 29.8877 (-18940)	0.8237 / 2.6536 (1913.3)	1.6534 / 1.2203 (14452)
Chest	1.1203 / 2.9913 (3487.2)	3.0419 / 1.9575 (16909)	6.3808 / 0.8247 (29393)
Right rib	1.0742 / 4.9107 (-1979.2)	0.9539 / 3.2009 (1357.2)	5.2709 / 1.6440 (23654)
Left waist	1.0190 / 28.9055 (-17946)	0.7915 / 4.9572 (-3903.2)	0.6117 / 1.7907 (1823.7)
Right thigh	1.0464 / 9.6410 (-7951.2)	0.7325 / 1.6297 (3867.9)	1.2626 / 1.6251 (9539.3)
Right ankle	1.0379 / 11.8572 (-9813.1)	1.7880 / 1.6227 (13323)	1.2867 / 1.0759 (12124)

- *a* : Scale factor
- *b* : Shape factor
- *-LogL*: Negative log liklihood

The below table summarize the best fitting distributions for dynamic channel at 4.5 GHz.

Position	Still	Walking	Up-down
Right wrist	Normal	Weibull	Weibull
Right upper arm	Log-normal	Weibull	Weibull
Head	weibull	Log-normal	Log-normal
Right ear	Normal	Log-normal	Weibull
Shoulder	Log-normal	Weibull	Weibull
Chest	Log-normal	Log-normal	Weibull
Right rib	Log-normal	Log-normal	Weibull
Left waist	Normal	Log-normal	Weibull
Right thigh	Log-normal	Log-normal	Weibull
Right ankle	Log-normal	Weibull	Weibull

- ✓ Normal distribution seems to fit the still posture best, but it can be seen that fittings with any distributions have large from the PDFs.
- ✓ Log-normal distribution shows good match in cases of still postures and small movements such as walking posture in case of head , right ear, chest, right rib, left waist, right thigh, and stand up/down posture in case of head.
- ✓ Weibull distribution can represent much better large movement behaviors such as walking posture in case of right wrist, right upper arm, shoulder, right ankle, and all stand up/down postures except for head.

9. MATLAB code program

9.1. In-body

9.2. On-body

A. The following MATLAB code can be used to generate frequency response of human body communication (HBC), which based on ETRI's measurement results [22].

```
function channel_output_data = channel(channel_description, vin, input_data)
% ================================================================
% Parameter setting
% ================================================================
% - channel_description
% 1 -> Average value: Frequency response has mean value.
% 2 -> Uniformly distributed value: Frequency response has
%     uniform distribution in the deviation range.
% - vin: Voltage of transmitting signal
% - input_data: Unipolar NRG Signaling Data (ex/[1 0 1 0 0 1....0 ])

   if(channel_description==1)
      channel_mag = 0;
      channel_pha = 0;
   elseif(channel_description==2)
      channel_mag= sign(rand(1)-0.5).*rand(1)*5;
      channel_pha= sign(rand(1)-0.5).*rand(1)*10;
   end
   input_data = input_data*vin;


% ================================================================
% Intrinsic Channel Model
% ================================================================
%   Channel (FIR filter) Sampling frequency: 100 Mhz
   mesh = 0.5 ;
   Fchip = 50*1e6;
   Fchip = Fchip / 1e6 ;
   % Values at 0 Mhz & 55 Mhz are interpolated
   f=[0  5 10 15 20 25 30 35 40 45 50 55];
   AmpdB=[-45 -47.2 -48 -48.65 -49.3 -50 -50.7 -51.35 -52 -53.4 -54.8 -57.5];
   PhaseDegree=[-15 -29.2 -47.4 -67.55 -87.7 -102.65 -117.6 -133.8 -150 -161.35 -172.7 -
177.5] ;
   % For compensation of simulation channel response
```

```
compensation = 6.5;
Amp = 10.^((AmpdB+channel_mag+compensation)/20);
Phaseradian = (pi/180)*(PhaseDegree+channel_pha);
Amptmp = zeros(0,0);
Phasetmp = zeros(0,0);
for i=2:length(f)
   step = ((f(i)-f(i-1))/mesh);
   Ampstep = (Amp(i)-Amp(i-1))/step;
   Phasestep = (Phaseradian(i)-Phaseradian(i-1))/step;
   tmp0 = [Amp(i-1): Ampstep : Amp(i)];
   if i==length(f)
      Amptmp = [Amptmp tmp0(1:length(tmp0))];
   else
      Amptmp = [Amptmp tmp0(1:length(tmp0)-1)];
   end
   tmp1 = [Phaseradian(i-1): Phasestep : Phaseradian(i)];
   if i==length(f)
      Phasetmp = [Phasetmp tmp1(1:length(tmp1)) ];
   else
      Phasetmp = [Phasetmp tmp1(1:length(tmp1)-1) ];
   end
end
Amptmp_ext = [Amptmp(1:(Fchip/mesh+1)) fliplr(Amptmp(2:(Fchip/mesh+1)))];
Phasetmp_ext = [Phasetmp(1:(Fchip/mesh+1)) (-fliplr(Phasetmp(2:(Fchip/mesh+1))))];
Freq_response = Amptmp_ext.*exp(j*Phasetmp_ext);
Time_res = ifft(Freq_response, length(Freq_response));
Fsample = (length(Time_res)-1) * (mesh*10^(6));
Max_index = find(Time_res==max(Time_res));
h = [Time_res(Max_index : 1 : Max_index+32)];
h= real(h);
ch_delay = (length(h)-1)/2;
% ====================================================================
% Channel and Noise
% ====================================================================
   tmp = conv(input_data, h);
   data_channel = tmp(1: length(tmp)-ch_delay*2 ) ;
   %Noise variance
   Var_NB =  2.545e-005;
   Noise = randn(length(data_channel),1)* sqrt(Var_NB);
   data_channel_noise = data_channel + Noise';
   % Human Body Channel Response Output
   channel_output_data = data_channel_noise;
```

B. The following MATLAB code can be used to generate path loss model for 400, 600, 900 MHz and 2.4, 3.1-10.6 GHz. The power delay profile for UWB band is also provided. The MATLAB code is based on NICT's measurement results [23].

1. CM3
   1.1 Path loss

```
function path_loss_in_db = pathloss(frequency, N_ch, distance)

% ===  Path loss model based on measurement results in a hospital room ===
% frequency:  frequency bands ( 1: 400MHz, 2: 600MHz, 3: 900MHz, 4: 2450MHz, 5: UWB)
% N_ch:  # of path loss realizations
% distance:  distance between Tx and Rx in mm
% =========================================================

% ==================== Channel parameter ===============
% a and b: parameters in linear fitting
% sigma_s: standard deviation of a Normal distribution
if frequency == 1
   a   = 5.13;
   b   = 29.6;
   sigma_s = 5.49;
elseif frequency == 2
   a   = 15.5;
   b   = 3.08;
   sigma_s = 6.56;
elseif frequency == 3
   a   = 16.2;
   b   = 4.27;
   sigma_s = 5.55;
elseif frequency == 4
   a   = 7.84;
   b   = 34.1;
   sigma_s = 3.98;
elseif frequency == 5
   a   = 19.8;
   b   = 5.97;
   sigma_s = 4.17;
end
% =========================================================

% =============== Path loss realizations ===============
% -- Path loss in dB
```

```
path_loss_in_db = a*log10(distance)+b+sigma_s*randn(1,N_ch);
% ============================================================
1.2 Power delay profile

function [h_norm, t] = cir_uwb_cm3(N_ch)

% ===  Channel impulse responses based on measurement results in a hospital room ===
% h_norm: normalized channel impulse responses
% t: time information for each path
N_ch = 100;   %# of on channel impulse responses (CIRs)
% ============================================================
% ================== Parameters ==================

%L_av = 20.2; % Average number of the arrival paths
%sigma_s = 5.94; % Standard deviation on the amplitude level
%Gamma = 61.3; % Exponential decay factor
%gamma_0 = -3.3; % Rice factor
%lambda = 6.18; % Time difference between neighboring arrival paths

% ================== Parameters ==================
L_av      = 38.1;        % Average number of the arrival paths
sigma_s   = 5.02;         % Standard deviation on the amplitude level
Gamma     = 59.7;          % Exponential decay factor
gamma_0   = -4.60;          % Rice factor
lambda    = 1.85;        % Time difference between neighboring arrival paths
ts        = 5.0125*10^-10; % Sampling time
% ============= Calculate CIR realizations =============
for n_ch = 1 :N_ch
  T_p    = 0;
  N_path = max(1,poissrnd(L_av));
  for n_p = 1 :N_path
    if T_p == 0
      amp_path = 1;
    else
      amp_path = 10^((10*log10(exp(-T_p/Gamma))+gamma_0+sigma_s*randn)/20);
    end
    t(n_ch,n_p) = T_p;
    h(n_ch,n_p) =  amp_path*exp(sqrt(-1)*rand(1)*2*pi);
    h2(n_ch,n_p) = amp_path;
    T_p = T_p + poissrnd(lambda)*ts;
  end
 % Normalization
  h_norm(n_ch,1:N_path) = h(n_ch,1:N_path)/sqrt(sum(abs(h(n_ch,:).^2)));
  h2_norm(n_ch,1:N_path) = h2(n_ch,1:N_path)/sqrt(sum(abs(h2(n_ch,:).^2)));
```

```
    end
  stem(h2(1,:));
  end
```

2. CM4
    function [h_norm, t] = cir_uwb_cm4(N_ch)

```
% === Channel impulse responses based on measurement results in a hospital room ===
% h_norm: normalized channel impulse responses
% t: time information for each path
N_ch = 100;    % # of channel impulse responses (CIRs)
% ========================================================
% ================== Parameters ==================
L        = 200;         % # of arrival paths
body_direction = 1;        % 1: 0 deg, 2: 90 deg, 3: 180 deg, 4: 270 deg
ts        = 5.0125*10^-10; % Sampling time
% ---
if body_direction == 1
   Gamma      = 0.224;        % [ns]
   delta_k    = 6.4;         % [dB]
   sigma      = 7.30;         % [dB]
elseif body_direction == 2
   Gamma      = 0.184;        % [ns]
   delta_k    = 3.0;         % [dB]
   sigma      = 7.08;         % [dB]
elseif body_direction == 3
   Gamma      = 0.187;        % [ns]
   delta_k    = 0;         % [dB]
   sigma      = 7.03;         % [dB]
elseif body_direction == 4
   Gamma      = 0.191;        % [ns]
   delta_k    = 1.5;         % [dB]
   sigma      = 7.19;         % [dB]
end
% ================================================
% ================ Realizations ==================
 for n_ch = 1 :N_ch

     T_p = 0;
     for n_p = 1 :L
       if T_p == 0
         amp_path = 1;
       else
         amp_path = exp(-T_p*10^9/Gamma-delta_k*log(10)/10);
```

```
            end
            t(n_ch,n_p) = T_p;
            h(n_ch,n_p) = amp_path*exp(sqrt(-1)*rand(1)*2*pi);
%           h2(n_ch,n_p) = amp_path;
            T_p = T_p + ts;
         end
       h_norm(n_ch,1:L) = h(n_ch,1:L)/sqrt(sum(abs(h(n_ch,1:L)).^2));
%      h2_norm(n_ch,1:L) = h2(n_ch,1:L)/sqrt(sum(abs(h2(n_ch,1:L)).^2));
     end
      % ==================================================
    end
```

C. The following MATLAB code can be used to generate a signal power profile in terms of received power with respect to transmit power, which is based on NICTA's measurement results at 820 MHz. [31]

```
function [signal,time_samp] = generate_power_profile_wmban()
% Generate a signal (in terms of received power with respect to transmit
% power) for a mobile wireless body area network based on extensive
% measurement campaign carried out at NICTA.
% Return values:
%   signal    - Received power profile relative to transmit power (dB)
%   time_samp - Timing epoch of each sample in 'signal' vector (s)
%
% The following definitions apply to generated signal -
%     Fade:               Contiguous portion of signal that crosses
%                         below the mean signal power.
%     Fade duration:      Time below mean signal power for faded
%                         portion of signal.
%     Fade depth/magnitude: Maximum attenuation of individual fade
%                         portion relative to mean (within each
%                         individual fade).
%     Level crossing rate:  The inverse of the time where power profile
%                         drops below mean to when it next crosses
%                         below mean.
%
% In line with the aim of this function -
%     In particular, this function attempts to generate a signal whereby
%     the statistical distribution of its: 1) fade durations; 2)
%     fade magnitudes; and 3) level crossing rate match the respective
%     distributions found in NICTA's channel measurements. The statistical
%     distribution of the generated signal around the mean also matches
%     that of NICTA's channel measurements.
```

```
%
% The following is a summary of the method used: -
%    1. Generate an initial signal that matches the desired fading
%       statistics using order statistics.
%       Notes:
%         - An appropriate set of Weibull distributed [Weibull1951]
%           random numbers are generated according to best fit to signal
%           statistical distribution around mean from NICTA's
%           measurements.
%         - Jake's model is used to generate a Rayleigh fading power
%           profile with an appropriate rate of fading.
%         - A Weibull fading signal power profile is generated by ordering
%           Weibull distributed random numbers according to the ordering
%           of the Rayleigh power profile.
%         - This signal will have appropriate fade durations and level
%           crossing rates
%
%    2. The initial signal is then manipulated such that in such a way
%       to make its fade depth statistics match those found in NICTA's
%       measurements. This occurs in the following manner:
%       2a. The signal is treated in portions, each portion being a fade
%           followed by a non-fade (a contiguous portion of the signal
%           above the mean power).
%       2b. Iterate through all the signal portions and compare each
%           fade to the desired fade depth statistics. The current
%           signal portion is manipulated depending on this comparison
%           in one of three ways.
%            - Good match to desired statistics: Keep the current
%              signal portion and insert it into the output signal.
%            - Too much attenuation: Remove the parts of the fade that
%              have too much attenuation. The remaining signal portion
%              is then inserted into the output signal.
%            - Bad match to desired statistics: Discard the current
%              signal portion.
%       2c. Due to the unnatural ordering that results from the fade
%           depth manipulation described above, the non-discarded
%           portions of the signal are reordered (though not reordering
%           within portions).
%       Note: This manipulation does not significantly affect match of
%       level crossing rates and fade duration of signal to statistics
%       from NICTA's measurements.
%
%    3. Adjust the final signal so its mean is equal to the mean
%       specified by the user.
```

%
% Note: This function calls a number of sub-functions to perform the above
% steps. These sub-functions contain more detailed explanation of the
% method described here.
%
% Note: A number of simulation parameters may be set in the following
% section of the code.
% First initialize rand, Matlab's function to produce uniform randomly
% distributed numbers on [0,1] to different state to previous use. This will
% be used in generation of various random numbers.
rand('state',sum(100*clock));
%---
% Simulation parameters
%---
% The simulation parameters below may be changed to appropriate values of
% your choosing.
% Time (s)
time = 20;
% Time in seconds over which signal is generated
% Carrier frequency (MHz)
car_frequency = 820;
% Carrier frequency of transmitted signal.
% * Allowed range: 400 -- 2500 MHz
% * 820 MHz corresponds to NICTA's measurements.
% Sample rate (kHz)
sample_rate = 1;
% Sample rate of received power profile.
% * Allowed range: 0.75 -- 15 kHz.
% * 1 kHz corresponds to NICTA's measurements.
% Relative body movement velocity (km/h)
vel = 1.5 + 4 * rand;
% This is a rough approximation of Rx movement velocity with respect to
% scatterers and/or transmitter Tx. It is used to generate a signal with

% an appropriate rate of fading in the signal generating sub-function to this
% function.
% * Allowed range: 1.5 -- 20 km/h
% * Values of 1.5 -- 5.5 to correspond best to NICTA's measurements.
% Mean path loss (dB)
a = 60.2; % Scale parameter
b = 6.6; % Shape parameter
mean_path_loss = a*(-log(rand))^(1/b);
% This statistic gives a Weibull distributed random number representing
% mean path loss. With the values of a=60.2 and b=6.6, the statistic

% approximately reflects Weibull distribution of mean path loss from
% NICTA's measurement campaign, but this mean path loss can be set
% arbitrarily to any value of your choosing.
% * Note also this statistic follows directly from the Weibull cumulative
%   distribution function.
% * Recommended range: 35 -- 70 dB
%   Note: Appropriate generation of a set of Weibull distributed faded signals
%   with a varied set of typical mean path losses according to the above
%   statistic results in a distribution characteristic approximately matching that
%   of a specific Lognormal distribution. This specified Lognormal
%   distribution with log mean of -13.3 and log standard deviation 2.49
%   was reported on NICTA's measurement campaign, as a best fit to the
%   12.7 million measurements (where mean path loss is not removed) [Miniutti08].
%---
% Generate signal according to above parameters
%---
signal = gen_sig_wmban(vel, car_frequency, sample_rate, time, mean_path_loss);
% Note that the mean_path_loss in dB specified above is equal to -10*log10(mean(signal))
% Plot signal in dB, against time;
fs = sample_rate * 10^3; % Sampling rate (Hz)
time_samp = (1:length(signal)) / fs;
plot(time_samp, 10*log10(signal));
xlabel('Time (s)')
ylabel('Channel gain (dB)')
title('Channel gain from Tx to Rx for mobile wireless body area network')
%---
% References:
% [Miniutti08] D. Miniutti, L. Hanlen, D. Smith, A. Zhang, D. Lewis, D.
%   Rodda and B. Gilbert, "Characterisation of large-scale
%   fading in BAN channels", October 2008.
% [Weibull1951] Weibull, W. A., "A statistical distribution function of
%   wide applicability", Journal of Applied Mechanics, vol. 18,
%   pp. 292-297, 1951.
%---
% Subfunctions (this is where the real work is done)
%---
%%%
%%
function signal = gen_sig_wmban(vel, car_frequency, sample_rate, time, mean_path_loss)
% This function creates a received power profile vector for a received
% signal for an on-body mobile wireless BAN.
%
% Return value:
%   signal - A power profile (or power envelope) of absolute magnitude

```
%   (not dB) describing receive power as a fraction of transmit power. The
%   mean of the signal is determined by the input parameter mean_path_loss.
%
% Parameters:
%   vel          - Speed of movement of body for Rx with respect to
%                   scatterers and/or Tx (km/h)
%   car_frequency  - Carrier frequency (MHz)
%   sample_rate    - Rate at which signal envelope is sampled (kHz)
%   time           - Time over which signal is generated (s)
%   mean_path_loss - Expected mean path loss for the channel (dB)
% Check that parameters lie within suitable ranges
if car_frequency < 400 || car_frequency > 2500
   disp('Carrier frequency should be in range 400 -- 2500 MHz')
   signal = [];
   return
end
if sample_rate < 0.75 || sample_rate > 15
   disp('Sample rate should be in range 0.75 -- 15 kHz')
   signal = [];
   return
end
if vel < 1.5 || vel > 20
   disp('Velocity should be in range 1.5 -- 20 km/h')
   signal = [];
   return
end
%--------------------------------------------------------------------------
% Set parameters used to generate signal.
%--------------------------------------------------------------------------
% Maximal Doppler frequency (Hz)
fd = vel / 3.6 * car_frequency * 10^6 / (3 * 10^8);
% Note that this is an approximate target value as fades in the generated
% signal are manipulated later in the code.
% Sample rate (Hz)
fs = sample_rate * 10^3;
% Doppler fading parameter (normalized Doppler spread)
p = fd / fs;
% Total number of samples over which final signal sig is generated
% This may be increased below, depending on two conditions.
nsamp = round(time*fs);
%--------------------------------------------------------------------------
% Increase number of samples if required
%--------------------------------------------------------------------------
```

% Given that samples of the signal's power envelope are discarded when we
% later manipulate the fade depths, we may need to increase the number of
% samples here so we don't "run out" of samples later. If, at the end of
% manipulating the fade depths there are still samples left over, then the
% signal is truncated to the correct length.
% The two conditions that are used to determine whether we need to increase
% the number of samples were found by extensive empirical testing. These
% conditions are:
%   1. carrier frequency is less than 800 MHz and time specified is less
%   than 30s; or
%   2. time specified is less than 20s.
time_change = 0; % Keep track of whether time parameter has been changed
if car_frequency < 800 && time < 35
    time = 35;
    nsamp1 = nsamp;
    nsamp = round(time*fs);
    time_change = 1;
end
if time < 20
    time = 20;
    nsamp1 = nsamp;
    nsamp = round(time*fs);
    time_change = 1;
end
%---
% Signal generation loop
%---
% In some very isolated cases (in particular given certain values of
% velocity, carrier frequency, time and sample rate) we may "run out" of
% samples in the signal generation routine (although this is still very
% unlikely). Thus, to avoid an error, we run a while loop until there are
% enough samples (in the great majority of cases there will be only one
% iteration of this loop).
enough_samples_indicator = 0;
while enough_samples_indicator == 0,
    %---
    % Below we generate an initial Weibull fading power profile with
    % approximate specified Doppler fading parameter (normalized Doppler
    % spread).
    %
    % Order statistics of a Rayleigh power profile with the specified
    % Doppler fading parameter are used to order randomly generated Weibull
    % distributed numbers to obtain a Weibull faded signal.
    %

% The order of the same length Rayleigh faded signal (corresponding to
% Rayleigh distribution of specified Doppler parameter) determines the
% order of the Weibull distributed random numbers to produce a relevant
% Weibull faded signal profile with approximate Doppler parameter.
%--
% First generate a vector of Weibull distributed random numbers around
% the mean, Al.
% Note that it is necessary to generate more random samples than are
% asked for as we will later discard some samples when manipulating the
% fade depths.The code below uses a multiplier of 1.6 to specify how
% many samples should be generated. This number was chosen by empirical
% testing and is generally large enough to allow discarding of samples
% in the final signal after fade manipulation and as small as possible
% to produce a final signal that most accurately reflects the desired
% statistics.
randnum = rand(1, round(1.6*nsamp)); % Uniformly distributed random numbers on (0,1)
% The following Weibull parameters are derived from the best overall
% data fit (with mean path loss removed - i.e. power profile normalized
% to mean) from NICTA's measurement campaign.
a = 0.9926; % Weibull shape parameter
b = 0.9832; % Weibull scale parameter
   Al = a*(-log(randnum)).^(1/b); % Weibull distributed random numbers
AdB = 10*log10(Al); % Convert to dB
   % Exclude those values above and below the mean that didn't occur in
% all 12.7 million measurements as they are unrealistic in the context
% of what received signal powers can be reasonably expected. Note that
% these discards will be very rate and should not affect the Weibull
% distribution in any significant way.
AdB = AdB(AdB>-73 & AdB<21);
% Generate a Rayleigh fading signal power profile using Jakes' model,
% whereby the ordering of Rayleigh fading generated statistics is used
% to create an appropriately ordered Weibull fading signal (based on
% the Rayleigh signal ordering with the same Doppler parameter over the
% length of the Weibull distributed samples).This method for producing
% appropriately ordered Weibull fading follows from the methods to
% produce Nakagami-m fading in [Filho07] and Lognormal fading in
% [Cotton07].
% NB: This is only an initial signal generation; following this we
% will manipulate this signal so that fade depths correspond to those
% from NICTA's measurement campaign.
% Rayleigh_power: a Rayleigh power profile generated using Jakes' model
% with appropriate Doppler fading parameter
Rayleigh_power = abs(jakesm_siso(length(AdB),p)).^2;
% I is the indexing of the sorted Rayleigh_power (in ascending order)

% with respect to the original generated Rayleigh power profile
[Habs_s, I] = sort(Rayleigh_power);
% Including the mean path loss (in dB) we generate a set of received
% signal powers (unordered), P (in dB), based on Weibull random numbers
% generated.
P = AdB - mean_path_loss;
A_f = 10.^(P/10); % Absolute values of generated received signal powers
% Sort the initial signal according to Rayleigh ordering
initial_signal = sort(A_f);
initial_signal(I) = initial_signal;
% This initial signal is a Weibull faded signal power profile with
% approximate Doppler parameter (or normalized Doppler spread) p, and
% Weibull shape and scale parameters (a and b), as specified.
%--
% Manipulate fade depths
%--
% The initial_signal generated above will, in general, not have the
% desired distribution of fade depths, so the signal must be
% manipulated to achieve the desired distribution. We now call a
% function that will manipulate the initial signal. This function will
% produce a signal with a distribution of fade depths (in dB) that
% approximate those from NICTA's measurement campaign.
signal_dB = manipulate_fade_depths(initial_signal, mean_path_loss);
% Note that the Doppler fading parameter of the signal returned from
% the function below will not exactly match the input initial_signal to
% this function. However, it will still remain a rough approximation of
% the desired doppler fading parameter.
% If we have generated enough samples in the final signal then we can
% end the while loop. Otherwise, we perform another iteration of the
% loop.
if length(signal_dB)>=nsamp
    enough_samples_indicator = 1;
end
end %(while)
% Final generated signal is truncated to total number of desired samples.
% Note that the final generated signal power profile is an absolute
% magnitude (not dB).
signal = 10.^(signal_dB(1:nsamp)/10); % Truncate and convert from dB to absolute magnitude
% If we changed the effective time to help signal generation, further
% truncate signal to time desired in function call.
if time_change == 1,
    signal = signal(1:nsamp1);
end
% Finally, we readjust the signal so its mean matches the specified mean

% path loss (mean will have changed slightly due to fade manipulation).
signal_mean_dB_non_fixed = 10*log10(mean(signal));
signal_dB_fin = 10*log10(signal) - (mean_path_loss + signal_mean_dB_non_fixed);
signal = 10.^(signal_dB_fin/10);
%---
% References:
% [Filho07] Filho, J.C.S.S, Yacoub, M. D. and Fraidenraich, G., "A Simple
%   Accurate Method for Generating Autocorrelated Nakagami-m
%   Envelope Sequences", IEEE Communication Letters, vol. 11, no.
%   3, pp. 231-233, Mar 2007.
% [Cotton07] Cotton, S. L. and Scanlon, W. G., "Higher Order Statistics for
%   Lognormal Small-Scale Fading in Mobile Radio Channels", IEEE
%   Antennas and Wireless Propagation Letters, vol. 6, pp. 540-543,
%   2007.
%%%
function Hs = jakesm_siso(N1, p)
% This function generates Rayleigh fading for a single-input single-output
% system according to Jakes' model [Jakes74].
% Return value:
%   Hs - Complex fade amplitudes
% Parameters:
%   N1 - Desired number of samples for the channel response
%   p - Doppler fading parameter (or normalized Doppler spread by sample rate)
Ns = 50; % Number of scatterers (chosen to get appropriately 'rich' scattering in Rayleigh fading)
c = 1 / sqrt(Ns); % Normalization factor
ts = repmat(2*pi*rand(1,Ns), N1, 1);
ft = 2*pi*p*repmat((1:N1)', 1, Ns) .* repmat(cos(2*pi*rand(1,Ns)), N1, 1);
Hs = sum(c*exp(-j*(ft+ts)), 2);
%---
% Reference:
% [Jakes74] Jakes, W. C., "Microwave Mobile Communications", Ed. John
%   Wiley, New York, 1974.
%%%
function signal_dB = manipulate_fade_depths(initial_signal, mean_path_loss)
% This function manipulates the initial_signal power profile parameter in
% such a way as to produce a signal power profile (in dB) with the desired
% distribution of fade depths.
% This is achieved in the following manner:
%   * The signal is treated in portions, each portion being a fade followed
%   by a non-fade (a contiguous portion of the signal above the mean
%   power).
%   * Iterate through all the signal portions and compare each fade to the
%   desired fade depth statistics. The current signal portion is
%   manipulated depending on this comparison in one of three ways.

```
%    - Good match to desired statistics: Keep the current signal portion
%      and insert it into the output signal.
%    - Too much attenuation: Remove the parts of the fade that have too
%      much attenuation. The remaining signal portion is then inserted into
%      the output signal.
%    - Bad match to desired statistics: Discard the current signal
%      portion (including the non-fade part of the portion).
%   * Due to the unnatural ordering that results from the fade depth
%   manipulation described above, the non-discarded portions of the signal
%   are reordered (though not reordering within portions).
% We note that no manipulation of the non-faded portion is necessary.
% This method has been found to be statistically accurate from empirical
% testing. Furthermore, the resultant final signal power profile properties
% (and appearance) are a good match to NICTA's measured power profiles.
% Return value:
%   signal_dB - A signal  power profile in dB with appropriate fade depth
%   distribution
% Parameters:
%   initial_signal - Signal to be manipulated
%   mean_path_loss - Desired mean path loss for output signal
% Notes:
% - The mean of signal_dB is generally within 1dB of the specified mean
% path loss, due to the manipulation of the fades. That is, it doesn't
% match mean_path_loss exactly, but the function that calls this one will
% make an appropriate adjustment to the mean.
% - signal_dB will have a Doppler fading parameter that is a rough
% approximation to that specified in function that calls this function.
% - The length of the vector signal_dB will be shorter than that of the
% initial_signal.
%---------------------------------------------------------------------------
% Find: 1) the number of fades in the initial signal; and 2) where these
% fades occur.
%---------------------------------------------------------------------------
% Find the number of fades in the initial signal, by first quantising the
% signal around the mean
quantised = initial_signal / mean(initial_signal) < 1;
crossings_up  = find(diff(quantised) == -1); % Index of when signal crosses above threshold of
the mean, suggesting the end of a fade
crossings_down  = find(diff(quantised) == 1); % Index of when signal crosses below threshold
of the mean, suggesting the beginning of a fade
% Remove stray crossings at start & end of data
if(length(crossings_up) > 1 && length(crossings_down) > 1)
   if(crossings_up(1) < crossings_down(1))
      crossings_up(1) = [];
```

```
      end
   if(crossings_down(end) > crossings_up(end))
      crossings_down(end) = [];
   end
end
% Hence the number of fades in the initial signal is...
nfades = length(crossings_up);
%--------------------------------------------------------------------------
% Generate reasonable expected fade depths for each fade from a
% distribution that is based upon NICTA's measurement campaign.
%--------------------------------------------------------------------------
% We generate a vector of appropriately distributed fade magnitudes (in dB)
% over the number of fades found in the signal. The distribution is a
% Weibull distribution that approximates the fade magnitude distribution
% (in dB) found in NICTA's measurement campaign.
% Note that the best fit for the fade magnitudes is actually a Gamma
% distribution (gamma parameters: shape = 0.669, scale = 14.46), but the
% Weibull is a very good approximation.
randnum = rand(1,nfades); % Uniformly distributed random numbers on (0,1)
a = 8.4; % Weibull shape parameter
b = 0.77; % ; Weibull scale parameter
wp = a*(-log(randnum)).^(1/b); % Weibull distributed random numbers
fade_mags = -mean_path_loss - wp; % Place Weibull random numbers around mean path loss
% Exclude those fades that didn't occur in all 12.7 million of NICTA's
% measurements as they are unrealistic in the context of what fade depths
% can be reasonably expected. Note that such values will be very rare in
% the generation of fade_mags and their exclusion should not affect the
% Weibull distribution significantly.
fade_mags = fade_mags(fade_mags > -mean_path_loss-73); % Desired fade magnitudes
% Sort these fades in descending order (for convenience)
fade_mags = sort(fade_mags, 2, 'descend');
% For ease of manipulation we convert our signal into dB
initial_signal_dB = 10*log10(initial_signal);
% Find the index of the start of the first fade
index_start_fade = crossings_down(1);
%  - index_start_fade is the index of the start of fade in the signal
% If the initial signal starts in a fade, then we create an empty output
% signal to begin with. Otherwise, we insert the first portion of the
% initial signal (the portion before any fades have occurred) into the
% output signal.
if index_start_fade-1 > 0,
   signal_dB = initial_signal_dB(1:(index_start_fade-1));
else
   signal_dB = [];
```

```
end
% Find how many crossings above the threshold of the mean there are.
% This will be used in final signal generation.
total_crossings = length(crossings_up);
% Initialise a counter to keep track of how may signal portions we have
% used so far.
kt = 0;
%------------------------------------------------------------------------
% Fade manipulation:
% Apply the previously described method of keeping/clipping/removing faded
% sections of the initial signal.
%------------------------------------------------------------------------
% Iterate over each fade & non-fade portion of the initial signal
for j = 1:total_crossings
    % Find the index of the crossing (above the mean) in the initial
    % signal. This index marks the end of the fade.
    index_end_fade = crossings_up(j) - 1;
    % Find the portion of signal that corresponds to this fade
    current_fade = initial_signal_dB(index_start_fade:index_end_fade);
    % Find the magnitude/depth of the current fade
    current_fade_magnitude = min(current_fade);
    % Compare the current fade magnitude to the sorted vector of desired
    % fade magnitudes. We find the index of the closest desired fade depth
    % whose fade is of greater magnitude than the current fade magnitude.
    ks = max(find(fade_mags>current_fade_magnitude));
    % If such an index exists we manipulate the initial faded signal
    % portion appropriately
    if isempty(ks)
        % No matching fade depth was found, do not use this portion of the
        % signal.
        ts = 0; % Flag that the current signal portion was not used
    else
        fm = fade_mags(ks); % Find the value of given fade depth
        % Remove this fade magnitude from the vector of possible magnitudes
        % (we only use each fade magnitude once).
        fade_mags = fade_mags(fade_mags~=fm);
        % Remove the parts of the current signal portion which have too
        % much attenuation.
        current_fade = current_fade(current_fade>fm);
        % Use the current signal portion?
        if ~isempty(current_fade)
            kt = kt + 1; % Increase counter of signal portions used
            ts = 1; % Flag that the current signal portion was used
        else
```

```
        % The current signal portion is empty, can't use it.
        ts = 0; % Flag that the current signal portion was not used
    end
  end
  %-----------------------------------------------------------------------
  % Collect all the fades together
  %-----------------------------------------------------------------------
  % If we have not iterated through all of the fades then insert the
  % current signal portion (fade + non-fade) into a cell array of signal
  % portions, as appropriate. This cell array will be used to generate
  % the final output signal.
  if j+1 <= total_crossings
    % Set index for start of next fade
    index_start_fade = crossings_down(j+1);
    % If current signal portion was used...
    if ts == 1
      % Take the current fade as well as the next contiguous non-fade
      % portion of the signal and insert it into the cell array.
      signal_portion{kt} = [current_fade,
initial_signal_dB((index_end_fade+1):(index_start_fade-1))];
    end
  else
    % There is no non-fade portion following the current fade, so we
    % just add the fade to the cell array.
    if ts == 1,
      signal_portion{kt} = current_fade;
    end
  end
  % If all the generated fade depths have been used, exit the 'for' loop
  if isempty(fade_mags),
    break;
  end
end %(for)
%---------------------------------------------------------------------------
% Jumble the signal
%---------------------------------------------------------------------------
% We finally jumble up each signal portion that we stored in the cell array
% (note: not jumbling within portions). This is necessary due to the
% unnatural ordering of fades that occurs from our method of matching fade
% depths.
Rp = randperm(kt);
for kl = 1:kt,
  signal_dB = [signal_dB,signal_portion{Rp(kl)}];
end
```

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