On the WBAN Radio Channel Modelling for Medical Applications

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***Abstract*— Radio channel modelling for wireless body area network (WBAN) has attained a lot of activities in the last years. The reason is the huge activity increase at WBAN applications in healthcare and monitoring. Also standardization procedure has required proper channel models. This paper summary the radio channel measurement and modelling activities for WBAN applications carried out in hospital environment by the Centre for Wireless Communications, University of Oulu, Finland. To fulfil the environmental requirements, the actual measurements were carried out at the Oulu University Hospital premises, in the typical final use places. Different scenarios and link topologies were covered at the measurements. The results show that WBAN channel differs from, e.g., typical office channel models and there is an evident need for aimed channel models for close body communication.**

I. Introduction

The use of wireless body area networks (WBAN) is a modern way to monitor human's physiological parameters or behavioural changes, and convey the information measured from the body, or even inside a body, seamlessly and imperceptible to remote recipient or electronic database for ubiquitous access. WBAN health monitoring system consists of detectors (sensors) and data communication parts. Depending on the application, a set of sensors used can vary between different patients and their specific health requirements. This causes need to support different kind of traffic and traffic loads inside a WBAN network. On the other hand, dissimilar applications and radio interfaces can allocate different parts of the frequency spectrum at hand. Due to the frequency dependency, and the impact of environment on the propagating signal, accurate and dedicated radio channel models are needed also for WBAN system design. For example, general office channel models do not fit to WBAN propagation environment.

Human body is a complex environment due to the close body communications property. A body structure is complex, and human tissues have different electrical properties, both which are impacting on the propagating electromagnetic signal. Moreover, the movement of a body causes extra changes in the specific radio links; for example, in wrist to chest link is varying from line-of-sight link to non-line-of-sight link depending on the phase of the walking cycle and the speed of the person.

The WBAN channel realizations and models have an influence from the environment where the wireless body area network operates. There are several existing WBAN channel models available, e.g., [1]-[6]. Also IEEE802.15.6 has defined channel models during its WBAN standardization work [7]. However, there was a lack of WBAN channel models which are based on the measurements carried out at the real hospital environment. Our experimental work has been carried out to fill this gap by providing hospital specific WBAN radio channel models.

II. Channel Measurements

The WBAN channel measurements carried out by CWC covered all together several environments and rooms; anechoic chamber, class room and different hospital rooms. To get realistic environmental features included in the measurement results, three hospital cases were involved in our experiment, namely: operation theatre (surgery room), typical ward room and corridor. The main goal of this experimental work was especially to generate realistic WBAN channel models to be used in designing WBAN applications for hospital usage and to be compared with other created channel models.

The measurements were carried out using a Agilent 8720ES vector network analyzer (VNA) [8] having an internal time domain option which made it possible to show a measured response of a radio channel either in a frequency domain (frequency response) or in a time domain (impulse response). The antennas used in the experiments were SkyCross SMT-3TO10M-A antennas [9]. The frequency spectrum covered an ultra wideband (UWB) band between 3.1 GHz and 10 GHz. In the measurements, 100 consecutive frequency responses were measured. The results are based on the statistical analysis of the individual channel responses and their average behaviours. The parameters used during the measurements are shown in Table I.

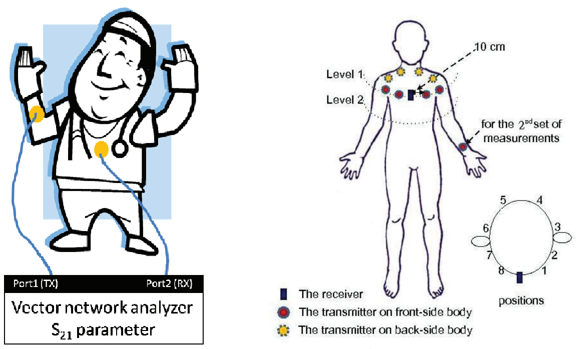
TABLE I
MEASUREMENT PARAMETERS

PARAMETER	VALUE
Frequency band	3.1 to 10.6 GHz
Bandwidth	6.9 GHz
IF bandwidth of the VNA	3.0 kHz
Number of points over the band	1601
Maximum detectable delay	231 ns
Sweep time	800 ms
Average noise floor	-120 dBm
Transmit power	0 dBm
Tx and Rx cables loss	7.96 dB

The anechoic chamber was used to produce reference results while the other places took into account also the environmental specific propagation features. Due to the diverse condition of a patient when being hospitalized, there are several possible links that WBAN connections need to be covered; some patients are staying in bed all the time, but some of them are free to move around. Part of the links are based on connections between on-body nodes, i.e., nodes attached to the skin, and part of the links can connect body network or node to a node locating somewhere in a room, thus being an access point to backbone network. Both of these cases were covered in our experiments.

The generic measurement setups are shown in Fig. 1. In the first case, the antennas were attached to a chest and a wrist of a person (Fig. 1a). To increase the generality of the results of the on-on-body measurements, the transmitter antenna positions were changed to cover different realistic WBAN links, as showed in Fig. 1b. In this case, the receiver antenna was kept in the middle of the chest. In addition, measurements for on-off-body link were carried out. In these measurements, the antennas are placed in wrist and in a pole locating 2 m away from the body at 2 m height.

Nevertheless, to get full understanding on signal propagation in a WBAN environment, also models for in-on-body and in-in-body links need to be defined. The latter links cover typically cases where implants' condition is monitored or communication with capsule endoscopy type devices. However, these links are currently excluded from our empirical studies and thus omitted in this paper.



a) b)

Fig. 1. The measurement setup. a) Antennas attached to chest and wrist, b) The antenna positions during on-body measurements.

The measurements included in scenarios where a patient was either standing; walking (pseudo walking); lying in bed; or lying and eating in a bed. The scenarios having movement (walking and eating cases) were measured using a pseudo movement procedure where the position of a person was changed following the movement cycle but during the recordings the movement was frozen. The reason for using pseudo movement cycle was the fact that during the recordings, the movement is not allowed due to the rather long sweeping time VNA needs to generate one frequency response of the channel. Thus, the channel (link) was kept unchanged during the savings. The measurement environments and different scenarios are summarized in Table II. Due to the versatility of the possible links that WBAN application need to cover in hospital environment, it is not possible to entirely measure all of those. However, our experiment gives a many-sided approach to the problem.

TABLE II
WBAN MEASUREMENT ENVIRONMENTS AND SCENARIOS.
A1 IS ON-ON LINK AND A2 IS ON-OFF LINK.[1]

Environments	**Scenarios**				
Anechoic chamber	Standing around the body	standing for A1, A2	lying for A1, A2	walking* for A1, A2	lying with moving arm* A1, A2
Class room	standing for A1, A2	sitting for A1, A2	lying for A1, A2		
Hospital: regular room	standing for A1, A2	lying for A1, A2	walking* for A1, A2	lying with moving arm* A1, A2	
Hospital: corridor	standing for A1, A2	walking* for A1, A2	walking with a drippole* for A1, A2		
Hospital: surgery room (operation theatre)	lying for A1, A2 with medical devices on	lying for A1, A2 with medical devices off	lying for A1, A2 with medical devices off with people randomly walking	lying for A1, A2 with medical devices off with people randomly walking and using mobile phone	

III. CHANNEL MODELLING

The original results of CWC's WBAN channel modelling work are shown in [6],[10]-[15]. In addition to WBAN channels, CWC have carried out earlier measurements towards general radio channel models for hospital environment, as reported in [16] for intensive care unit, X-ray and operation theatre cases.

In the next sub-chapters, the summaries of the WBAN channel studies are given for different environments.

A. Anechoic chamber

The anechoic chamber was used as the first environment to study signal propagation in WBAN. The original idea was to validate the measurement system performance, its proper functionality and provide reference results for real hospital measurements.

However, the results pointed out an interesting feature of the near body signal propagation. One of the persons attended to experiments happened to have a titanium alloy aortic valve implant. The measurements indicate a difference in the measured channel impulse responses if compared to cases where person has an implant or did not have. Thus being underneath the skin, the metallic part of the implant impacted on the electromagnetic propagation features when antenna is close to the implant. Fig. 2. shows examples of the measured impulse responses for link between level 1 – position 2 and a chest (see Fig. 1b). As can be seen, the channel impulse response has a lower peak when an implant was involved in.

[1] "*" denotes pseudo-movement

This observation was evident and it was later confirmed also with the 3D immersive visualization environment [17].

The other observation was that the UWB signal is not propagating through the body in back-to-front links' case but rather circulates the body in the close vicinity.

Instead of attaching antenna straight to skin but using a dielectric material between the antenna element and skin, the radiation efficiency was improved [10]. This is due to the fact that the antenna was designed to free space.

The propagation statistics is also affected by the age, sex, clothing, etc. of the person wearing the WBAN. This is due to the different electrical properties the body under study have. In addition, the movement has an impact on statistics of distinguished path amplitudes. It can be seen the Weibull distribution is the most appropriate distribution for most cases in the pseudo-dynamic situations [10].

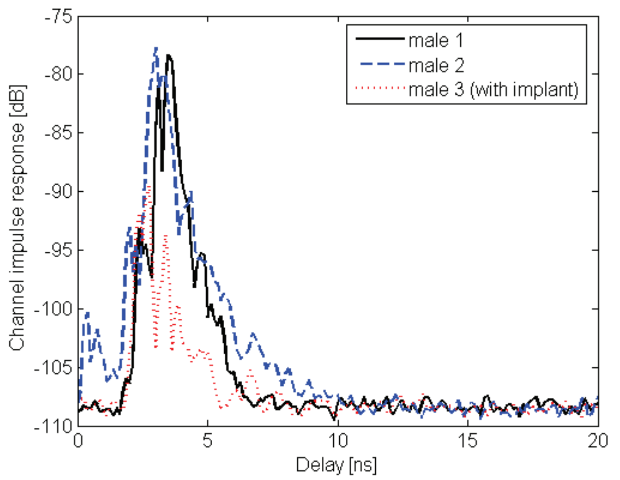


Fig. 2. Measured impulse responses. One person had an aortic implant. Link: chest to level 1-position 2.

B. *Hospital cases*

1) *Amplitude responses:* The amplitude responses were studied for both on-on-links (A1) and on-off-links (A2). In A1 cases, the antenna positions were changes to cover more links. The measurements covered standing, laying and pseudo movement situations. As presented in Table II, the measurements carried out in a hospital included in different types of links and environments.

From the impulse responses, the effects of a human body and an environment can be clearly separated since they fall in two different regions in the delay profiles, as shown in Fig. 3. These results differ significantly from the results carried out in an empty room where the lengths of the measured impulse responses were more than ten times longer, as presented in [16]. As a result, it can be concluded that there is an evident need for dedicated WBAN channel models.

In a pseudo dynamic environment, the energy capture in selective rake receiver differs with the number of rake fingers used. However, this is typical feature in rake receivers. The average energy captures of the strongest path only, the two strongest paths and the three strongest paths for the link between a chest and a left wrist in the walking case are 52%, 74%, and 82%, respectively [14]. Based on this observation, a rake receiver with three fingers is a reasonable choice for complexity point-of-view to capture enough energy for detection.

2) *Root mean square (RMS) delay spread:* The measured impulse responses in different environments have been statistically analysed. On the average, RMS delay spread τ_{RMS} depicts the time frame the signal can be seen in the channel after the first path has been detected. Fig. 4 a-b show the mean and standard deviation for τ_{RMS} values for anechoic chamber, ward, corridor and operation theatre for links A1 (chest-wrist) and A2 (wrist-pole) with standing and laying subject [6][11]. τ_{RMS} the mean excess delay, τ_m, are defined as

$$\tau_{RMS} = \sqrt{\frac{\sum_{i=0}^{L-1}(\tau_i-\tau_m)^2\cdot|h(\tau_i)|^2}{\sum_{i=0}^{L-1}|h(\tau_i)|^2}} \quad (1)$$

and

$$\tau_m = \frac{\sum_{i=0}^{L-1}\tau_i\cdot|h(\tau_i)|^2}{\sum_{i=0}^{L-1}|h(\tau)|^2}, \quad (2)$$

where $h(\tau)$ is channel impulse response, L is number of paths and τ is delay.

As can be seen, the τ_{RMS} is larger is A2 link than A1 link. In average, the mean τ_{RMS} is around 9 ns ignoring results from anechoic chamber. Before calculating the mean and standard deviation values, the impulse responses were truncated above the noise level, which is four times the standard deviation of noise, which is around -108 dBm [11]. Survived paths have then been included.

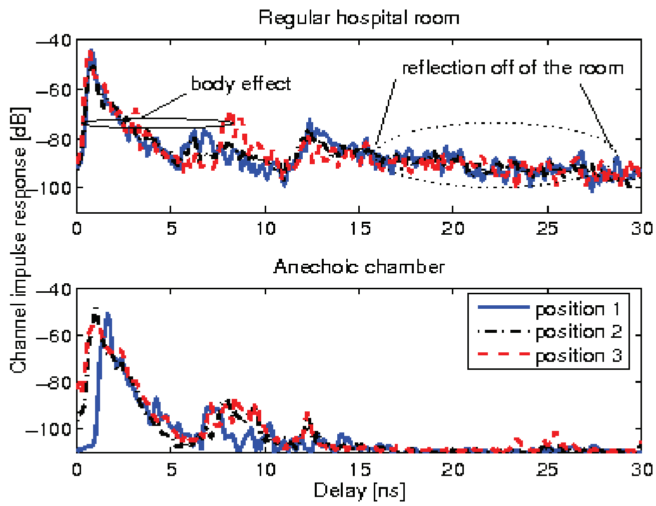


Fig. 3. Measured channel impulse responses. The subject is lying down and having a meal in a regular hospital room. The measured link is between a chest and a wrist.

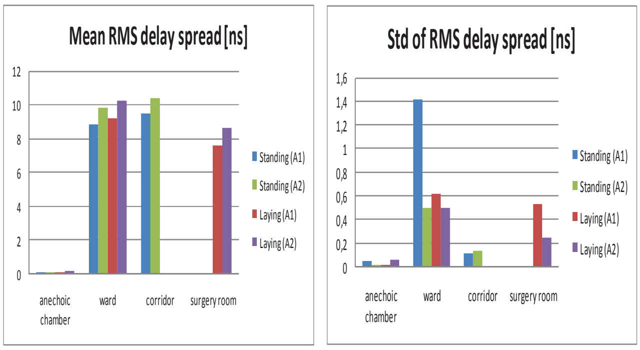


Fig. 4. RMS delay spreads: a) mean and b) standard deviation.

IV. Channel Models

Due to the very high discrimination of the consecutive propagation paths the UWB signal have, a typical tapped delay line presentation is not appropriate for the UWB channel models.

The channel models generated for the studied WBAN applications are based on the two exponential decaying functions according to the two distinguishable clusters which can be observed from the impulse responses. The parameters to fit mathematical solution to measured ones are Ricean factor γ_0 and exponential decaying factor Γ as [11]

$$10\log_{10}|a_l| = \begin{cases} 0, l = 0 \\ \gamma_{01} + 10\log_{10}\left(\exp\left(\frac{-t_l}{\Gamma_1}\right)\right), 1 \le l \le l_1 \\ \sum_{m=1}^{M}\left(\gamma_{02m} + 10\log_{10}\left(\exp\left(\frac{-t_1}{\Gamma_{2m}}\right)\right)\right), l_2 \le l \le L-1 \end{cases} \quad (3)$$

where γ_{01}, γ_{02m}, $\Gamma 2$ and $\Gamma 2$ are corresponding factors for those two clusters. The parameters are shown in Table III for ward and corridor environments for links A1 and A2 [11]. Both standing and laying conditions are also covered. In A1 case, the second cluster consists of six distinguishable paths in standing scenario.

Amplitude variations can be modelled with log-normal distribution with zero-mean and standard deviation σ. Values fitting first and second regions are also shown in Table III [11].

The path arrival times, thus, the time difference between the consecutive arriving paths are exponentially distributed by

$$p(t_l|t_{l-1}) = \begin{cases} \lambda_1\exp\left(-\lambda_1(t_l - t_{l-1})\right), 1 \le l \le l_1 \\ \lambda_2\exp\left(-\lambda_2(t_l - t_{l-1})\right), l_2 \le l \le L\text{-}1 \end{cases} \quad (4)$$

where t is an arrival time and λ is path arrival rate in a cluster. The path arrival time follows Poisson distribution [11]. The last parameter describing the WBAN radio signal propagation is the number of arrival paths L, which also follows Poisson distribution

$$p(L) = \frac{\mu_L^L \exp(\mu_L)}{L!}, \quad (5)$$

where μ_L is the average of L. Average number of arrival paths is collected to Table III [11]. All the parameter fittings have been made following the least square method.

TABLE III
Channel Parameters

	Regular ward				Corridor	
	Standing		Laying down		Standing	
	A1	A2	A1	A2	A1	A2
γ01 [dB]	-61	-74	-64	-65	-47	-27
γ02 [dB]	-91, -82, 19, -87, -6, -99	-83	-85	-84	-82	-82
Γ1	1.11	6.67	3.12	4.14	0.77	1.47
Γ2	30.30, 31.25, 2.44, 29.41, 4.55, 108.7	31.25	32.26	29.41	24.39	24.39
$\sigma\chi$1 [dB]	2.45	4.41	6.31	4.86	3.75	1.96
$\sigma\chi$2 [dB]	2.07, 2.21, 1.62, 1.44, 1.2, 0.91	2.8	3.5	2.79	4.04	2.46
1/λ1 [ns]	3.717	8	4.764	6.024	6.024	6.024
1/λ2 [ns]	6.125	5.43	6.369	8	1.667	1.667
μL	324	323	324	323	324	324

V. Utilization of the Models

The channel model used in the system simulation has an impact, e.g., on the bit error rate (BER). The CWC's WBAN channel model is developed for hospital environment and thus includes typical out-of body reflections caused by the environment. The impact and difference of CWC's channel model and IEEE802.15.6 model on BER is studied in [18]. Both on-body approaches independently ended up to log-normal amplitude distribution. However, the IEEE model is based on a single cluster model, whereas double cluster model is applied in the CWC's model.

The performance of different UWB receivers in the CWC's WBAN channel defined for hospital applications have reported in [19]-[21]. The studied ultra wideband receivers were a coherent rake receiver, a binary orthogonal non-coherent receiver and an energy detector (ED). ED seems to be the most sensitive for multipath propagation. On the other hand, with fairly high signal-to-noise ratio, ED has quite good performance. Thus, being simple and cheap implementation, ED loses in the performance to more complex receivers also in WBAN environment [21].

VI. Conclusions

This paper discusses on radio channel measurements and modelling for wireless body area networks that are targeted to hospital environment.

In UWB frequency band, the radio channel in a close proximity of a body has its own impact to the propagating signal. Due to the impact of human body on electromagnetic signal propagation, the energy of channel impulse responses less than 5–6 ns are decaying rapidly. On the other hand, the reflections from the environment will generate a large number of multipath components that are arriving later.

The multipath propagated signal components coming from the environment can be separated from their WBAN counterparts due to their longer delays. The received signal power depends, for example, on sex, age, posture of the person and also if the person has implants.

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REFERENCES

[1] J. Ryckaert, P. De Doncker, R. Meys, A. De Le Hoye, S. Donnay, "Channel Model for Wireless Communication around Human Body," Electronics letters, vol. 40, no. 9, April 29, 2004.

[2] A. Fort, C. Desset, J. Ryckaert, J.P. De Doncker, L. Van Biesen, S. Donnay, "Ultra Wide-Band Body Area Channel Model," in Proc. IEEE International Conference on Ultra Wideband, Zurich, Switzerland, 2005.

[3] K. Tai, H. Harada, R. Kohno, "Channel Modeling and Signaling of Medical Implanted Communication Systems and a Step to Medical ICT," in Proc. Mobile and Wireless Communications Summit, Budapest, Hungary, 2007.

[4] A. Alomainy, Y. Hao, Y. Yuan, and Y. Liu, "Modelling and Characterisation of Radio Propagation from Wireless Implants at Different Frequencies," in Proc. European Conference on Wireless Technology, Manchester, UK, 2006.

[5] H. Sawada, T. Aoyagi, J. Takada, K. Y. Yazdandoost, R. Kohno, "Channel Model for Wireless Body Area Network," in Proc. the 2nd International Symposium on Medical Information and Communication Technology, Oulu, Finland, 2007.

[6] A. Taparugssanagorn, A. Rabbachin, M. Hämäläinen, J. Saloranta, J. Iinatti, "A Review of Channel Modelling for Wireless Body Area Network in Wireless Medical Communications," in Proc. Wireless Personal Multimedia Communication Symposium, Saariselkä, Finland, 2008.

[7] K. Y. Yazdandoost and K. Sayrafian-Pour, "Channel Model for Body Area Network (BAN)," doc: IEEE P802.15-08-0780-09-006, April, 2009.

[8] http://cp.literature.agilent.com/litweb/pdf/5968-5163E.pdf

[9] http://skycross.com/Products/PDFs/SMT-3TO10M-A.pdf

[10] A. Taparugssanagorn, C. Pomalaza-Ráez, R. Tesi, M. Hämäläinen, J. Iinatti, "Effect of Body Motion and the Type of Antenna on the Measured UWB Channel Characteristics in Medical Applications of Wireless Body Area Networks," in Proc. 2009 IEEE International Conference on Ultra Wideband, Vancouver, Canada, 2009.

[11] A. Taparugssanagorn, C. Pomalaza-Ráez, A. Isola, R. Tesi, M. Hämäläinen, J. Iinatti, "UWB Channel Modelling for Wireless Body Area Networks in a Hospital," International Journal of Ultra Wideband Communications and Systems, Vol. 1, No. 4, 2010, pp. 226 – 236.

[12] A. Taparugssanagorn, C. Pomalaza-Ráez, A. Isola, R. Tesi, M. Hämäläinen, J. Iinatti, "Preliminary UWB Channel Study for Wireless Body Area Networks in Medical Applications," accepted to International Journal of Ultra Wideband Communications and Systems.

[13] A. Taparugssanagorn, B. Zhen, R. Tesi, M. Hämäläinen, J. Iinatti, R. Kohno, "A UWB WBAN Channel Model based on A Pseudo-Dynamic Measurement," Springer Link, DOI: 10.1007/s12243-010-0228-5.

[14] A. Taparugssanagorn, B. Zhen, R. Tesi, M. Hämäläinen, J. Iinatti, R. Kohno, "A Dynamic Channel Model of UWB-WBAN for Some Medical Applications," in Proc. the 4th International Symposium on Medical Information and Communication Technology, Taipei, Taiwan, 2010.

[15] A. Taparugssanagorn, C. Pomalaza-Ráez, R. Tesi, M. Hämäläinen, J. Iinatti, R. Kohno, "UWB Channel Characteristics in the Proximity of a Dynamic Human Body for WBAN Medical Applications," in Proc. the 4th International Symposium on Medical Information and Communication Technology, Taipei, Taiwan, 2010.

[16] L. Hentilä, A. Taparugssanagorn, H. Viittala, M. Hämäläinen, "Measurement and Modelling of an UWB Channel at Hospital," in Proc. the 2005 IEEE International Conference on Ultra Wideband, Zürich, Switzerland, 2005.

[17] W.-B. Yang, K. Sayrafian-Pour, J. Hagedorn, J. Terrill, K.Y. Yazdandoost, A. Taparugssanagorn, M. Hämäläinen, J. Iinatti, "Impact of an Aortic Valve Implant on Body Surface UWB Propagation: A Preliminary Study," in Proc. the 5th International Symposium on Medical Information and Communication Technology, Montreux, Switzerland, 2011.

[18] H. Viittala, M. Hämäläinen, J. Iinatti, A. Taparugssanagorn, "Different experimental WBAN channel models and IEEE802.15.6 models: comparison and effects," in Proc. the 2nd International Symposium on Applied Sciences in Biomedical and Communication Technologies, Bratislava, Slovakia, 2009.

[19] V. Niemelä, A. Rabbachin, A. Taparugssanagorn, M. Hämäläinen, J. Iinatti, "Performance of IEEE 802.15.4a UWB WBAN Receivers in a Real Hospital Environment," in Proc. the 4th International Symposium on Medical Information and Communication Technology, Taipei, Taiwan, 2010.

[20] V. Niemelä, J. Iinatti, M. Hämäläinen, A. Taparugssanagorn, "On the Energy Detector, P- and S-Rake Receivers in a Measured UWB Channel Inside a Hospital," in Proc. the 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies, Rome, Italy, 2010.

[21] V. Niemelä, A. Rabbachin, A. Taparugssanagorn, M. Hämäläinen, J. Iinatti, "A Comparison of UWB WBAN Receivers in Different Measured Hospital Environments," in Proc. the 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies, Rome, Italy, 2010.