MEASUREMENT ERRORS INTRODUCED BY THE USE OF CO-AXIAL CABLING IN THE ASSESSMENT OF WEARABLE ANTENNA PERFORMANCE IN OFF-BODY CHANNELS

P. A. Catherwood[1] and W. G. Scanlon[1,2]

[1]School of Electronics, Electrical Engineering & Computer Science, The Queen's University of Belfast, Institute of Electronics, Communications and Information Technology, Queen's Road, Belfast, BT3 9DT, UK. [2]Centre for Telematics and Information Technology, University of Twente, Enschede, The Netherlands. E-mail: pcatherwood02@qub.ac.uk, w.scanlon@qub.ac.uk

Abstract: This paper presents the results of an investigation into the effect of using co-axial cables in ultra-wideband off-body radio channel characterisation and performance evaluation for wearable antennas. Experiments were carefully designed to faithfully compare the use of a co-axial feed cable for a wearable antenna versus an optic fibre feed, and thus report on any errors introduced into the measurements due to the use of such reflective cabling. Detailed results are presented for a range of body-centric antenna positions for stationary measurements and general observations for mobile tests are also introduced and discussed. Presented results show that the use of co-axial cables has a marked effect on the radio channel characterisation, affecting received power, mean delay and delay spread results, seen to greater extent in low reflection environments and for non line of sight and highly shadowed configurations. Co-axial cable-fed antenna tests yielded greater received power than with an optic-fibre feed for a user-stationary scenario in low reflection environments. As either the line of sight component or the measurement environment's reflectivity was increased, the difference between the two systems diminished. It was also found that the use of a co-axial cable altered the statistical fading channel model for mobile tests.

Introduction: Off-body communications for indoor mobile communications are subjected to shadowing effects and multipath fading due to time-varying radio channel conditions [1]. Likewise, the presence of the human body in wearable antenna applications can cause antenna-body interaction effects, which can reduce signal reliability [2]. Because it is envisaged that future technologies will implement a number of wearable communication devices [3] it is essential to understand the radio propagation channel for particular frequencies and situations by undertaking channel sounding. Such investigations lead to the generation of mathematical models for radio system developers to use in the design and implementation of target radio systems. Furthermore, these propagation studies can also serve as practical means to characterise achievable wearable antenna performance in a wide range of radio environments.

Presently, many researchers continue to characterise a wide range of radio environments using metallic co-axial cables [4–14] and it is often the case that reflective cables are routed around the human body [4], [6], [8], [11], [15]. Various equipment arrangements may include a remote Vector Network Analyser (VNA) and long cables to the test subject [4], [16–19]; portable systems with the signal generator placed in a backpack and cables routed to feed a body-mounted antenna [20],[21], or self-contained radio terminals (motes) positioned on the user's body [22–24]. All but the last arrangement have the strong potential to distort channel measurements by modifying the coupled antenna-body radiation pattern, and by secondary reflection and scattering of the launched radio signal, particularly in non line of sight (NLOS) conditions [1]. Optic fibre-fed antennas do not exhibit this effect because optic fibres are non-reflective to UHF / SHF signals and thus it is accepted that their use eliminates any electromagnetic coupling effects and secondary reflections associated with radiofrequency (RF) co-axial cables traversing the user's body.

It was hypothesised that such RF co-axial cables may distort the radio multipath descriptive parameters. Power levels and time dispersion characteristics of the power delay profiles (PDP) can vary considerably within a given environment primarily due to the mechanisms of reflection, diffraction and scattering. These phenomena distort the radio signal and generate multiple copies of the launched signal (varying in power and phase) at the receiver (Rx). However, should the metallic nature of the measurement system's cables add additional reflective effects to the time dispersive characteristics, then errors will inadvertently be introduced into the measurements.

This paper reports on a comparative study between the use of RF co-axial cable and optic fibre to feed a ultra-wideband (UWB) body-centric antenna at various common positions on the user's body. The UWB antenna was used as the transmitter for an indoor off-body time-domain mobile channel sounding system. The paper presents important findings on the measurement errors introduced by using co-axial antenna cables in channel sounding and recommends the practice of utilising optical fibre cables for propagation channel characterisation activities. While this work only considered a short cable from the waist to the antenna, it is speculated that the use of longer cables, for example in VNA-based measurements, could have a more pronounced effect. This work is timely as most researchers currently practice the use of cabling for both on-body [4–7], and off-body measurement campaigns [8–15], [25]. Furthermore, the results are relevant to related work on wearable antenna design and performance characterisation.

Experimental Arrangements: The wearable channel characterisation system consisted of an UWB source (3.1 – 6 GHz) positioned in a holster on the rear of the waist, feeding a body-mounted vertically-polarized UWB transmit antenna (launch power of –12 dBm) via either a standard 1.5 m 50Ω RG142/U solid conductor co-axial cable, or via an RF-over-fibre link (1550 nm 9/125 single mode, 0 dB gain). A frequency domain technique was employed throughout to de-convolve the measurement systems from the received signal.

Three environments were selected; a 54 m^2 anechoic chamber, a 5.8 m^2 reverberation chamber, and a 42 m^2 open-plan modern office. The anechoic and reverberation chambers offer extremities in the multipath radio channel, and the open office offers a typical and commonly used indoor environment for radio channel characterisation [26–29]. Tests were conducted for the transmit antenna placed in three body locations; to the left of the sternum of the chest; the left of centre on the front of the waist; and on the left wrist (where a wrist watch would be located). Tests were mostly stationary, with some mobile measurements also conducted, with received signal strength and signal propagation delay statistics (with respect to the first detectable signal) being recorded in each test. Antennas on the chest, waist and the wrist are considered because these are popular antenna locations for body-centric antenna research [7, 24, 30]. The antenna was held against the body in each case using adjustable synthetic elastic cuffs to minimise body-antenna separation during testing, as previously utilised by [18].

Tests were either line of sight (LOS) or NLOS depending on the orientation of the worn transmit antenna with respect to the receive antenna, which was wall mounted at a height of 2 m for each test to simulate an access point. The test user was an adult male of mass 82 kg, height 1.78 m. To minimise spurious reflections, all metallic objects such as belts, jewellery and coinage were removed from the subject. To ensure the cable and fibre measurements are faithfully comparable, the same setup and methodologies were used throughout.

Wideband power was calculated using methods previously published by [1, 31, 32], and mean excess delay (t_{mean}) and RMS delay spread (t_{RMS}) were calculated to provide a description of the temporal spread (time dispersion) of the radio channel [33, 34]. To prevent noise from affecting calculated delay statistics, a threshold was incorporated into the signal processing software to give most accurate results for t_{mean} and t_{RMS} values, as reported by [35].

Results and Discussion: The measured results showed that the use of RF co-axial cables had a marked effect on the radio channel characterisation, affecting received power, mean delay and RMS delay spread, with the effect seen to greater extent in low reflection environments and for NLOS configurations. The metallic co-axial cables act as secondary reflectors to the launched RF signal and thus distort the observation of the true radio propagation channel.

Stationary measurements All stationary measurements were taken at a nominal Tx-Rx separation of 3.2 m and all body-centric received powers were normalised with respect to an isolated antenna measurement where the antennas were at the same height and separation but the user's body was not present. For the stationary received power measurements (Table 1) it was found that NLOS received power values for the co-axial arrangement were higher than for the similar fibre-optic arrangements in the anechoic chamber and office (low/medium reflection environments). This was true for all of the antenna positions (chest, waist and wrist). The disparity between the two systems is attributable to the presence of the metallic co-axial cables reflecting or guiding some of the transmitted RF energy towards the receive antenna. Thus, the effects of body-shadowing were artificially reduced in the co-axial set-up.

Larger differences between LOS-NLOS received power values were also observed for the fibre-optic system compared with the co-axial system for all three antenna positions with-in low and medium reflective environments, as the RF cable was reflecting the signal towards the receiver in NLOS scenarios, thus artificially increasing received power. The effect was also seen to a lesser extent for LOS scenarios and barely discernable for the highly reflective environment of the reverb chamber as additional reflections from the RF cable were relatively small compared to the reverberation reflections.

For the NLOS RMS delay spread (t_{RMS}) measurements (Table 1) the anechoic and office environments displayed large differences for the two antenna feed arrangements, with the co-axial delay spreads being considerably greater than those for the optics. This was generally evident for all antenna positions and was due to the co-axial cables introducing additional signal reflections and scattering, thus increasing the delays. Also, the majority of the NLOS scenarios for the two low/medium reflection environments highlighted the t_{mean} values for the co-axial system to be larger than the equivalent optical system. No significant differences in t_{mean} or t_{RMS} values were observed for direct LOS set-ups.

TABLE 1

SUMMARY OF MEASURED STATIONARY RESULTS

Optical fibre		Power (dB)		mean (ns)		RMS (ns)	
		LOS	NLOS	LOS	NLOS	LOS	NLOS
Anechoic	chest	0.9	-12.7	3.3	3.8	4.5	3.9
	waist	0.6	-11.8	3.6	3.7	4.7	4.8
	wrist	-1.5	-7.3	3.2	15.4	4.4	4.7
Reverb	chest	-0.5	1.0	97.2	88.8	106.8	110.1
	waist	-0.6	-2.2	81.9	99.3	100.5	104.1
	wrist	-1.1	-1.9	86.2	89.5	96.4	101.3
Office	chest	3.5	-6.7	11.5	43.5	20.5	63.5
	waist	2.0	-6.7	10.7	24.1	24.1	40.6
	wrist	1.9	-10.4	8.6	19.8	15.5	43

Co-axial (RF)		Power (dB)		mean (ns)		RMS (ns)	
		LOS	NLOS	LOS	NLOS	LOS	NLOS
Anechoic	chest	3.5	-8.0	3	8.4	4.2	21.6
	waist	2.1	-8.3	2.9	4	13.5	46.5
	wrist	-2.4	-5.3	2.3	5.8	3.6	19.7
Reverb	chest	-1.2	-1.3	92.1	95.2	105.2	116.7
	waist	-2.5	-4.3	84.9	94.6	104.1	112.7
	wrist	-3.8	-2.2	77.2	82.4	100.1	106.1
Office	chest	2.3	-5.8	8	55	13.5	80.5
	waist	-0.4	-6.7	8.8	30.3	19.7	50.5
	wrist	1.0	-6.8	10	41.5	22.5	65.5

Dynamic measurements Dynamic tests were conducted to investigate natural movements of the user (swinging arms, torso movement, etc) and changing position of the transmitting user terminal with respect to the fixed receive terminal. Dynamic tests for both the anechoic chamber and open office were conducted for a linear path from 7 m to 2 m Tx-Rx LOS separation, with the transmitter moving at 0.5 ms^{-1}, and again for the return journey (NLOS) using the same walking speed and path. In the reverb chamber it was possible for both the Tx and Rx to remain stationary and to use the movement of the reflective stirrers (horizontal and vertical) on the chamber's walls in a preset manner using computer control software to continuously alter the radio path [36]. Dynamic measurements were recorded for the chest mounted antenna only for each of the three radio environments and for both LOS and NLOS.

To mathematically describe the channel parameters, for each scenario, the maximum likelihood (ML) estimates of received UWB signal amplitude and delay were calculated for a number of statistical distributions and the Akaike information criterion (AIC) [37, 38] was used to select the closest fitting distribution. For received power in the anechoic and office environments, the statistical distributions describing the propagation channel were different for the optical fed and co-axial fed antennas. In the reverb chamber both optical and co-axial fed systems were described by the same distribution (Weibull), however the parameters of these distributions were significantly different.

Delay measurements from the anechoic chamber show co-axial NLOS t_{mean} and t_{RMS} delays to be much larger than optic fibre delays due to additional reflections from the RF co-axial cabling in this low-reflection environment. Similar results, albeit to a lesser magnitude, are observed for the office. Again, the propagation channel statistical distributions were different for optical and co-axial fed antennas for both anechoic and office NLOS t_{mean} and t_{RMS} measurements, and for all reverberation measurements. NLOS scenarios in the anechoic chamber represent the largest disparity observed between the fibre-optic and co-axial system measurements.

Analysis of azimuthal radiation patterns The azimuthal radiation patterns for a chest-mounted antenna were recorded for a co-axial fed antenna and an optic-fibre fed antenna with a Tx-Rx separation of 2 m. The results (Figure 1, normalised to the maximum received power over both tests) clearly show that the co-axial cable reduces the body-shadowing effects, as the metallic cable helps to reflect some of the launched radio signal into the shadowed areas. This would have the effect of increasing received signal levels for NLOS scenarios with respect to the cable measurements, as observed in the stationary results presented earlier.

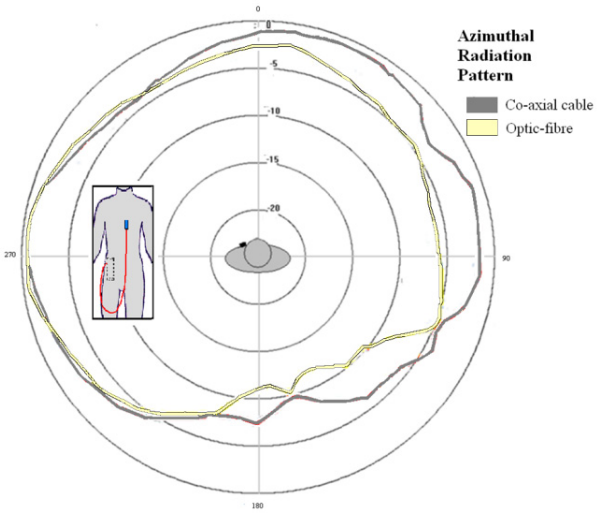

Fig. 1: Normalised azimuthal received power pattern for both types of antenna feed. Measured at 2 m separation.

Conclusions: In summary, a number of differences were observed between the fibre-optic-fed antenna system measurements and the co-axial-fed case. For most of the antenna-body mounting points in stationary tests the co-axial cable system had greater received power than the optical system for NLOS arrangements and low reflection environments; this is due to the cable providing a pseudo-direct path for the launched signal.

The same was found for the chest-mounted antennas in the dynamic tests.

For stationary delay values, the co-axial system had greater delay RMS delay spreads than the optical equivalent system for NLOS and low reflection environments which can be attributed to the reflective metallic cable introducing additional scattering and reflections to the propagation channel. This was generally true for all antenna-body mounting points for both stationary and dynamic tests. For dynamic tests, the statistical model describing the distribution of t_{mean} and t_{RMS} delay values for both system configurations were different for NLOS scenarios in the anechoic, office and reverberation environments. Overall, as the reflectivity of the measurement environment increased, the effect of the cables decreased, particularly for non-mobile scenarios. This work presents strong evidence that the use of RF co-axial cabling for off-body channel sounding in the 3.1-6.0GHz band causes inaccurate results to be recorded, introducing errors into the measurement values. It is speculated that cabling may also introduce errors for work at other frequencies and bandwidths, for other topologies, pedestrian-rich environments and for body area network measurements. It is thus essential that further investigation into these scenarios is required.

REFERENCES

[1] P.S. Hall, Y. Hao, “Antennas and Propagation for Body-Centric Wireless Communications” Publisher Artech House, 2006.

[2] W.G. Scanlon, N.E. Evans, “Numerical analysis of bodyworn UHF antenna systems,” *IEE Elect. & Comms. Eng. Jour*, vol. 13, 2, pp. 53–64, April 2001.

[3] Khan, I.; Hall, P.S., "Multiple Antenna Reception at 5.8 and 10 GHz for Body-Centric Wireless Communication Channels," *Antennas and Propagation, IEEE Trans on*, vol.57, no.1, pp.248-255, Jan. 2009.

[4] J.A. Miller, J.C. Batchelor, "Body channel characterisation using dual band button antennas," *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conf*, vol., no., pp.958-961, 23-27 March 2009

[5] A.G. Siamarou, M. Al-Nuaimi, "A Wideband Frequency-Domain Channel-Sounding System and Delay-Spread Measurements at the License-Free 57- to 64-GHz Band," *Instrumentation and Measurement, IEEE Transactions on* , vol.59, no.3, pp.519-526, March 2010

[6] A. Sani, et al. "Experimental Characterization of UWB On-Body Radio Channel in Indoor Environment Considering Different Antennas," *IEEE Trans. Antennas & Propagation*, vol.58, no.1, pp.238-241, Jan. 2010

[7] I. Khan, P.S. Hall, "Multiple Antenna Reception at 5.8 and 10 GHz for Body-Centric Wireless Communication Channels," *Antennas and Propagation, IEEE Trans on* , vol.57, no.1, pp.248-255, Jan. 2009

[8] A. Alomainy, A. Sani, A. Rahman, J.G. Santas, H. Yang, "Transient Characteristics of Wearable Antennas and Radio Propagation Channels for Ultrawideband Body-Centric Wireless Communications," *Ant and Prop, IEEE Trans*, vol.57, no.4, pp.875-884, April 2009

[9] D. Smith, L. Hanlen, Z. Jian, D. Miniutti, D. Rodda, B. Gilbert, "Characterization of the Dynamic Narrowband On-Body to Off-Body Area Channel," *Communications, 2009. ICC '09. IEEE International Conference on*, vol., no., pp.1-6, 14-18 June 2009

[10] A.A. Goulianos, T. Brown, S.Stavrou, "Power delay profile modelling of the ultra wideband off-body propagation channel," *Microwaves, Antennas & Prop, IET*, vol.4, no.1, pp.62-71, Jan. 2010

[11] P. Van Torre, et al. "Dynamic link performance analysis of a rescue worker's off-body communication system using integrated textile antennas," *Science, Measurement & Technology, IET*, vol.4, no.2, pp.41-52, March 2010

[12] Ur Rehman, M.; Gao, Y.; Wang, Z.; Zhang, J.; Alfadhl, Y.; Chen, X.; Parini, C.G.; Ying, Z.; Bolin, T.; , "Investigation of on-body Bluetooth transmission," *Microwaves, Antennas & Prop., IET* , vol.4, no.7, pp.871-880, July 2010

[13] A. Qammer, A. Akram, H. Yang, “Effect of Human Body Movements on Performance of Multiband OFDM based Ultra Wideband Wireless Communication System”, *Antennas & Prop. Conf, LAPC 2010. Loughborough*, pp.145-148, 8-9 Nov. 2010

[14] A. Michalopoulou, et al. “On-Body Channel Modelling: Measurements and Statistical Analysis”, *Antennas & Propagation Conference, LAPC 2010. Loughborough* , pp.201-204, 8-9 Nov. 2010

[15] H. Rogier, C. Hertleer, L. Vallozzi, L. Van Langenhove, "Off-body Communication for Protective Clothing," *Wearable and Implantable Body Sensor Networks, 2009. BSN 2009. Sixth International Workshop on*, vol., no., pp.301-304, 3-5 June 2009

[16] T. Cristina et al, "UWB Channel Measurements for Measures for Hand-Portable and Wearable Devices," wimob, pp.3, Third IEEE Intl. Conf. on Wireless and Mobile Computing, Networking and Communications (WiMob 2007), 2007.

[17] Y. Chen, *et al, “*Cooperative Communications in Ultra-Wideband Wireless Body Area Networks: Channel Modeling and System Diversity Analysis”, IEEE Journal on Selected areas in Comms. Vol. 27, No. 1, pgs: 5- 16, Jan 2009.

[18] A. Fort et al, “Ultra-wideband channel model for communication around the human body”, *IEEE Journal on Selected Areas in Comms.,* Vol.: 24, Issue: 4, Part: 1 , Page(s): 927 – 933. 2006

[19] A. Sani et al, “Time domain characterisation of ultra wideband wearable antennas and radio propagation for body-centric wireless networks in healthcare applications”, *5th Intl. Summer Sch. Sym. on Medical Devices and Biosensors*, Pgs: 129 - 132 2008.

[20] P.A. Catherwood & W.G. Scanlon, 'Off-body UWB channel characterisation within a hospital ward environment,' *Intl. Journal on Ultra Wideband Comms & Systems*, Special issue on Apps. of Ultra Wideband Systems in Biomedicine, Vol. 1, 4, pp. 263-272, 2010.

[21] Ziri-Castro, K.I.; Scanlon, W.G.; Feustle, R.; Evans, N.E., "Indoor channel measurements for a body-worn 5.2 GHz receiver," *Personal Mobile Comms Conf. 5th European*, pp. 191- 194, 22-25 April 2003

[22] S.L. Cotton, W.G. Scanlon, *“*Characterization and Modeling of the Indoor Radio Channel at 868 MHz for a Mobile Bodyworn Wireless Personal Area Network”, *IEEE Ant. And Prop. Letters,* Vol. 6, pg 51-55, 2007

[23] C. Oliveira, L. Pedrosa, R. Rocha; "Characterizing On-Body Wireless Sensor Networks", Proc. *NTMS'2008 workshop on Wireless Sensor Networks: theory and practice - WSN 2008*, November, 2008

[24] Khan M, Alomainy A, Hao Y, "Off-Body Radio Channel Characterisation Using Ultra Wideband Wireless Tags," *Body Sensor Networks (BSN), 2010 Intl. Conf.*, vol., no., pp.80-83, 7-9 June 2010

[25] J. Garcia, A. Arriola, G. Sasiain, D. Valderas, J.I. Sancho, X. Chen, "Characterization of phantom size and link budget for off-body communications," *Ant and Prop (EuCAP), 2010 Proceedings of the Fourth European Conf* , pp.1-5, 12-16 April 2010

[26] L. Padam et al, “Spatial Correlation and Capacity Measurements for Wideband MIMO Channels in Indoor Office Environment”. *IEEE Trans. on Wireless Comms.,* Vol. 7, No. 5, Pgs. 1560- 1571, May 2008

[27] K.I. Ziri-Castro, W.G. Scanlon, N.E. Evans, “Indoor Radio Channel Characterization and Modeling for a 5.2-GHz Bodyworn Receiver, IEEE Ant & Wireless Prop Letters, Vol. 3, pg 219-222, 2004

[28] P.L. Kafle, A. Intarapanich, A.B. Sesay, J. McRory, R.J. Davies, "Spatial correlation and capacity measurements for wideband MIMO channels in indoor office environment," *Wireless Communications, IEEE Transactions on* , vol.7, no.5, pp.1560-1571, May 2008

[29] H. Al-Tamimi, S.M. Al-Qaraawy, "UWB propagation indoor statistical channel modeling," *Computing, Communication, Control, and Management, CCCM 2009. ISECS International Colloquium on*, vol.1, pp.379-383, 8-9 Aug. 2009

[30] A.V. Vorobyov, et al, "UWB propagation channel measurements for WPAN scenarios," *Wireless Technologies, 2007 European Conf*, vol., no., pp.221-224, 8-10 Oct. 2007

[31] J. Liu, et al, "Diversity Analysis of Multi-Antenna UWB Impulse Radio Systems with Correlated Propagation Channels," *IEEE Wireless Communications and Networking Conference, 2007*, vol., no., pp.1593-1598, 11-15 March 2007

[32] Kaiser, T.; Feng Zheng; Dimitrov, E., "An Overview of Ultra-Wide-Band Systems With MIMO," *Proceedings of the IEEE* , vol.97, no.2, pp.285-312, Feb. 2009

[33] C.M.P. Ho, et aI, "Antenna Effects on Indoor Obstructed Wireless Channels and a Deterministic Image-Based Wide-Band Propagation Model for In-Building Personal Communication Systems," IntI. Journal of Wireless Info. Networks, pg 61-76, 1994.

[34] Andersen, J.B., Rappaport, T.S., Yoshida, S. ‘Propagation measurements and models for wireless communications channels’, *IEEE Comms Mag.*, Vol. 33, Issue 1, pp.42–49. Jan. 1995.

[35] Wong, S.S.M.; Lau, F.C.M.; Tse, C.K. "Propagation characteristics of UWB radio in a high-rise apartment," *Advanced Communication Technology, 2006. ICACT 2006. The 8th International Conference*, vol.2, no., pp.5 pp.-918, 20-22 Feb. 2006

[36] T.B. Welch “The Effects of the Human Body on UWB Signal Propagation in an Indoor Environment”, *IEEE Journal on Selected Areas in Communications,* Vol. 20, No. 9, December 2002.

[37] H. Akaike, “Information theory as an extension of the maximum likelihood principle,” *Proceedings of the* 2^{nd} *Intl. Symp. Information Theory*, pp. 267–281., 1973

[38] K.P. Burnham, D.R. Anderson *Model Selection and Multimodel Inference*, Springer, USA, 2002.