2013-07-08

Footwear-Centric Body Area Network with Directional UWB Antenna

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Recommended Citation

D. Gaetano, V., Sipal, P., Mcevoy, M.J., Ammann, C., Brannigan, L., Keating, F. & Horgan, F. (2013) Footwear-centric body area network with directional UWB antenna, *Electronics Letters* , vol.49, no.14, pp., July 4. doi:10.1049/el.2013.1596

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DOI: 10.1049/el.2013.1596

Footwear-centric body area network with directional UWB antenna

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A footwear-centric body area network employing a directional antenna is compared with waist-centric systems using omnidirectional and directional antennas. The impact of body movements on path gain is analysed for two bands at 3.99 GHz and 7.99 GHz. The path gain and data rate results demonstrate that footwear-centric configurations are equivalent or better than waist-centric body area networks.

Introduction: In wireless body area networks (WBAN), the hub is typically located at the waist to coordinate data from other sensors [1]. Omnidirectional antennas are employed to cover upper and lower body areas but lower gain patterns can impair link reliability.

As an alternative, a directional Vivaldi antenna for a footwear-centric configuration is reported and assessed in terms of path gain and the guaranteed minimum data rates defined in the IEEE 802.15.6-2012 standard for WBANs [2, 3]. UWB channels were selected for low power consumption, resilience to multipath fading and an adequacy for the short propagation range within a body area [2, 3]. Footwear can comfortably incorporate kinetic-energy harvesting and electronic sensors for medical or sporting applications without a significant adverse impact on a user's gait or stride [4, 5].

The footwear Vivaldi antenna is on a substrate 37.1 × 37.1 × 0.2 mm^3 with a curve which is described as follows:

$$x=0.191\times e^{0.173y} \text{ for } 0 < y < 21 \text{ mm} \qquad (1)$$

It provides a directional radiation pattern towards the upper body which minimizes interference to off-body networks. Waist-centric measurements were taken with an omnidirectional monopole 20 × 32.8 × 0.2 mm^3 positioned in the upper body areas. Cumulative distribution functions of body area path gain are presented.

Methodology: Both antennas are matched in the bandwidth of interest when in close proximity to the various body areas shown in Fig. 1. The left shoe, the left waist, the left and right upper arms, the sternum and the 4^{th} vertebrae are representative of candidate sensor positions. Three link configurations are reported:

- Waist-centric hub monopole and node monopole antennas (*M/M*)
- Footwear-centric hub Vivaldi and node Vivaldi antennas (*V/V*)
- Waist-centric hub monopole and node Vivaldi antennas (*M/V*)

The measurements were performed on two people of 1.75 m height with weights of 70 kg and 80 kg in an 8 × 8 m^2 laboratory area with metallic furniture and a reinforced concrete floor and ceiling. S_{21} values were recorded at the low and high band frequencies of 3.9936 GHz and 7.9872 GHz with a bandwidth of 499.2 MHz. These bands were selected as they are the mandatory regional bands for IEEE 802.15.6 UWB impulse radio (IR). 261 link measurements per person for the hub-node combinations were recorded under the following conditions: (a) 4 second duration for a standing position in a static channel; (b) 12 second duration while walking in a static channel, and; (c) 10 second duration while standing in a dynamic channel where people made random movements in the laboratory near the subject.

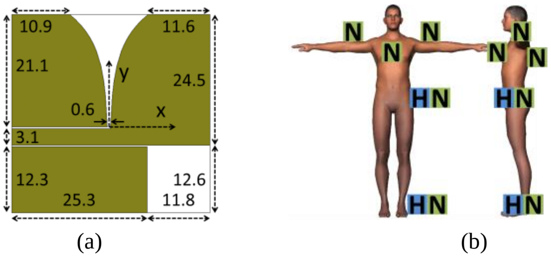

Fig. 1 (a) *Vivaldi geometry (mm) with (b) hub (H) and node (N) body positions.*

Results and Performance Discussion: The Vivaldi antenna is 50% and 56% efficient at 4 GHz and 8 GHz respectively. These simulated results correspond to applied conditions for the antenna positioned on the lateral side of the left shoe, 10 mm from the foot. It is matched over the band with gains of 5.1 dBi at 4 GHz and 6.4 dBi at 8 GHz.

Similarly, the monopole antenna is 25% and 48.5% efficient at 4 GHz and at 8 GHz respectively. The simulated results are for the antenna being displaced 6 mm from the left waist.

Inspection of the data indicates that the right upper arm incurs the least path gain from the left foot and left waist due to direct path shadowing. Low band path gain results for the three hub-node configurations for right upper arm with the foot and waist on the 70 kg person are shown in Fig. 2. Despite the increased distances, it is evident that the footwear-centric setup outperforms the waist-centric approach.

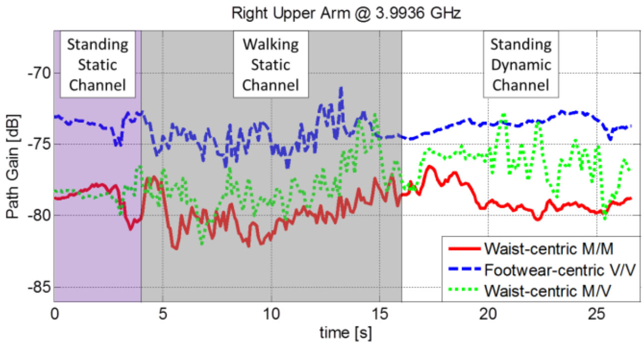

Fig. 2 *Comparison of the measured path gain for the right upper arm.*

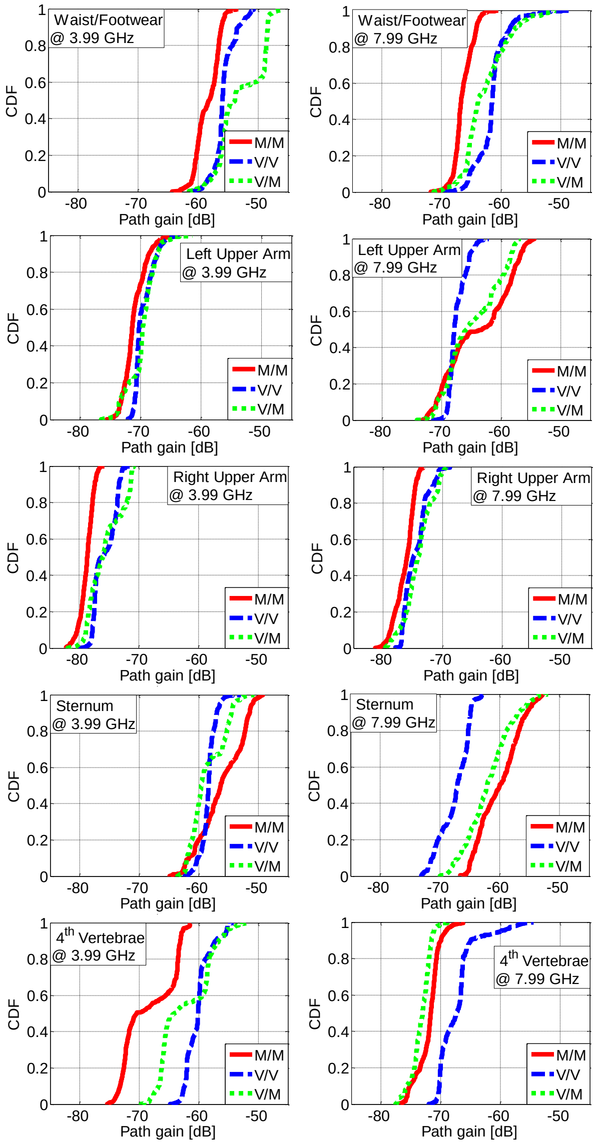

Fig. 3 *Path gain for different node positions.*

Cumulative distribution functions (CDFs) of the measured path gain for each of the hub-node configurations are shown in Fig. 3. The increased horizontal spread of values denotes shadowing, antenna pattern misalignment and fading variations, etc., that are due to body movement. The high band performs better than the low band for the left and right upper arm. In other cases, the low band is better since there is less path loss at lower frequencies. In most of the analysed cases, the footwear-centric configuration performs better than the waist-centric configuration. An exception is the sternum area, where the distance between the hub and sensor node in the waist-centric system is significantly shorter.

The CDFs results are summarized in Table 1 which shows the achieved maximum data rates for an IEEE 802.15.6 compliant IR-UWB system. The measured data-rates are based on the received signal strength calculated using the path gain and the maximum transmitter power. For example, the minimum and maximum data rates of 0.3948 Mbps and 12.636 Mbps correspond to the received signal strength of -91 dBm and -76 dBm, respectively. Where the minimum 0.3948 Mbps data rate was not guaranteed due to path gains being less than -76.7 dB, the outcomes are reported as the percentage of successful 0.3948 Mbps data rate measurements.

Table 1 Achieved maximum data rates for 522 path gain measurements across two people for the *M/M*, *M/V* and *V/V* WBAN configurations.

Frequency	3.99 GHz			7.99 GHz		
Hub and Antennas Postions	Waist-centric [Mbps]		Footwear-centric [Mbps]	Waist-centric [Mbps]		Footwear-centric [Mbps]
	M/M	*M/V*	*V/V*	*M/M*	*M/V*	*V/V*
Footwear/ Waist	6.3	12.6	12.6	0.8	0.8	1.6
Left Upper Arm	0.4	0.4	0.8	0.8	0.4	0.8
Right Upper Arm	*0.2%*	*57%*	*87%*	*61%*	*57%*	*86%*
Sternum	3.2	6.3	6.3	3.2	1.6	0.8
4th Vertebrae	0.4	1.6	3.2	*99%*	*96%*	0.8

Inspection of the data rates in Table 1 indicates that the footwear-centric system performs equivalently or better than a waist-centric system, except for links to the sternum area. In fact, the footwear-centric system is significantly better for nodes on the vertebrae since the hub location mitigates the shadowing impact. The right upper arm area is the farthest distance and it is not possible to guarantee a minimum data rate for all the measurements. However, the footwear-centric hub provides better link availability for the lowest data rate.

Conclusion: Antenna designs for footwear-centric wireless body area networks show that they are competitive with waist-centric configurations in terms of propagation path-gain and compliance with the IEEE 802.15.6-2012 standard for WBANs. A foot-based directional antenna provides good wireless coverage for typical sensor node positions for standing and walking conditions. It is envisaged that such radio link advantages will encourage the development of kinetic energy harvesting and other footwear-based electronic sensors for medical and sporting applications.

Acknowledgments: This work was supported by the Science Foundation Ireland grant 09/IN.1/I2652 and with the Government of Ireland Fellowship for Engineering, Science and Technology funded by the Irish Research Council.

04 July 2013
doi: 10.1049/el.2013.1596
One or more of the Figures in this Letter are available in colour online.

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