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Received Signal Characteristics of Outdoor Body-to-Body Communications Channels at 2.45 GHz

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Abstract— **In this paper we conduct a number of experiments to assess the impact of typical human body movements on the signal characteristics of outdoor body-to-body communications channels using flexible patch antennas. A modified log-distance path loss model which accounts for body shadowing and signal fading due to small movements is used to model the measured data. For line of sight channels, in which both ends of the body-to-body link are stationary, the path loss exponent is close to that for free space, although the received signal is noticeably affected by involuntary or physiological-related movements of both persons. When one person moves to obstruct the direct signal path between nodes, attenuation by the person's body can be as great as 40 dB, with even greater variation observed due to fading. The effects of movements such as rotation, tilt, walking in line of sight and non-line of sight on body-to-body communications channels are also investigated in this study.**

I. INTRODUCTION

The desire to share real-time information between co-located body area networks will require the creation of a new type of mobile ad hoc network known as a body-to-body network (BBN) [1]. In a BBN, nodes either carried or worn, by a person will intentionally transmit information to wireless nodes located on other persons in the nearby area. Body-to-body communications and BBNs will find applications in a range of areas such as teams sports, medical, first responder and the military as well as opening exciting opportunities for new social networking experiences.

To engineer robust hardware such as antennas and transceiver circuitry, and optimise protocols to be used in BBNs, it is necessary to develop a key understanding of the wireless communications channel for this niche application. Hardware designed to operate in BBNs will require the same careful attention to antenna-body interaction effects [2] and time-variant body movement effects as found in on-body [3-6] and off-body [7] communications. To complicate these issues, body-to-body communications will suffer from dual node mobility as both ends of the link will be either bodyworn or carried by the user. This may include dual-body shadowing events, when the users are orientated such that their bodies obstruct the main line of sight (LOS) path. Not only will node hardware have to contend with significant variations in received signal levels, but protocols will have to be resilient to extended periods of outage and have the ability to readily reroute communications through other nearby BBN users.

II. MEASUREMENT SYSTEM AND EXPERIMENTS

The bodyworn nodes used in this study consisted of the body sensor node (BSN) platform developed by Imperial College London [8]. The transceiver section of the node utilised a Texas Instruments CC2420, which has a linear dynamic operating range of approximately 100 dB, maximum transmit power of 0 dBm and a receive sensitivity of −95 dBm. A transmitter node was configured to transmit a continuous wave signal with a power level of 0 dBm at 2.45 GHz and a receiver node which was programmed to record the 8-bit received signal strength indicator (RSSI) obtained from the CC2420 every 16 ms. The BSN nodes were modified to replace the on-board chip antenna with a novel, flexible patch antenna (Fig. 1) [9] that was designed to be resonant on the body with a peak gain in the off-body direction of +9.5 dBi.

The experiments conducted in this study were performed in an outdoor playing field at the Victoria Park recreational facilities in Belfast, United Kingdom. The measurement environment consisted of a level grass play area which was bounded on three sides by trees and shrubbery and situated beside a soccer pitch adjoining on the remaining side. The area over which the measurements were performed was at least 50 m from each of these boundaries. The transmit and receive nodes were attached without the use of a dielectric spacer to the central chest region of two adult males of height 1.95 m and mass 105 kg (person A) and 1.82 m and mass 95 kg (person B) respectively using a small strip of Velcro®. The units were mounted directly on the test subject's clothing so that the ground plane of the antenna was parallel to the body surface.

Fig. 1 Body sensor node with flexible antenna used in trials.

A range of different body-to-body communications scenarios were considered. These included: 1) *stationary LOS* - where person A stood stationary at a position 15 m from person B so that both antennas were in direct LOS. Measurements were conducted for approximately 10 s at each position and repeated from 15 metres separation to 1 m in 1 m steps; 2) *stationary NLOS* - where person A stood stationary at a distance of 1 m from person B with their body rotated through 180° such that the antenna on person A's chest was now in NLOS. Similar to scenario 1, measurements were conducted in 1 m steps to a maximum separation distance of 15 m; 3) *rotation* - where persons A and B stood facing one another with a separation distance of 1 m. Person A then performed a full 360° rotation, moving from direct LOS through to complete NLOS (180°) before returning to an LOS orientation. Rotational measurements were repeated at separation distances of 5 m, 10 m and 15 m; 4) *tilt* – which was identical to scenario 3, except in this instance, persons A and B remained in direct LOS, while person A tilted their body forward from an upright position, through a 45° angle before returning to the upright position. These measurements were also conducted at separation distances of 5, 10 and 15 metres; 5) *walking LOS* – where person A stood in LOS at a distance of 15 m from person B, and then walked at a normal pace (~0.88 ms^{-1}) towards person B until he reached the point 1 m from person B; 6) *walking NLOS* – this scenario was identical to scenario 5, except in this instance person A started with their back towards person B at a separation distance of 1 m and walked to the 15 m point.

III. RESULTS

A. Stationary LOS and NLOS (Scenarios 1 and 2)

1) *Stationary LOS:* Fig. 2 shows the log-distance path loss obtained for scenario 1 when both persons were in direct LOS. Unlike off-body communications channels [9], the deviation of the measured signal from that predicted by the log-distance path loss model was significant as shown. The increased variability in body-to-body communications presumably arises due to the physiological and slight body movements of both persons during the experiments whereas in the off-body channel measurements made in [9], one end of the link was static. Because of this we use the modified log-distance path loss equation from [9] and given in (1) which consists of two extra parameters which can account for both significant movements (X_{BS}) and small movements (X_{SM}) of the body. As discussed in [9], the body shadowing term (X_{BS}) relates to slower physiological processes such as respiration and biomechanical actions such as movements of the limbs. The small movement term (X_{SM}) will then account for rapid fluctuations in the signal due to much smaller changes in body posture akin to small scale fading. In (1), $P_{0(\mathrm{dB})}$ is the path loss measured at a reference distance (in these experiments, 1 m), n is the path loss exponent, d is the distance between the transmit and receive antennas and d_0 is the reference distance.

$$P_{(dB)} = P_{0(dB)} + 10n\log\left(d/d_0\right) + X_{BS(dB)} - X_{SM(dB)} \quad (1)$$

Using linear regression, the n and $P_{0(\mathrm{dB})}$ parameters were estimated as $n = 2.1$ and $\mathrm{P}_{0dB} = 39.8$ dB. The path loss exponent for LOS matches well with that for free space propagation. At each individual distance sample point, the X_{BS} component was extracted from the measurement data by first removing the estimated path loss and then applying a moving average filter of 20 samples or equivalently 320 ms. Using maximum likelihood estimation (MLE), the μ and σ parameters of the lognormal probability density function (PDF) most likely to have generated the X_{BS} component of the signal were obtained. It was quickly observed that MLE parameter estimates for the majority of cases were comparable. Consequently, the mean of the parameter estimates were then found and are presented alongside all other parameter estimates in Table 1. The X_{SM} component of the received signal was then obtained by removing the path loss and X_{BS} component from the raw data and fitted with the Ricean PDF using the technique discussed above. The general parameter estimates for the model are provided in Table 1.

2) *Stationary NLOS:* One issue that became evident from this study which will have implications for the future design of hardware to be used in BBNs is the dynamic range required for operation. Even though the receiver section of the CC2420 has a linear dynamic operating range of approximately 100 dB, for scenarios where one body shadows the direct LOS path and when the straight line distance between the two persons exceeded 6 m, the received power regularly entered the region beyond the noise threshold of the receiver. Because of this, only 6 sample sets from 1 to 6 m were available for the fitting of the modified log-distance path loss model to the NLOS data. While it could be argued that a more omnidirectional antenna may help to sustain the link in this scenario, the subsequent reduction in antenna gain may reduce the distance over which the hardware could effectively operate or equivalently, if an extra gain stage is introduced to the transmit and receive chains, significantly reduce battery life or increase the size of the device if a greater capacity battery is used.

The parameter estimates for this scenario are given in Table 1. For body-to-body signal propagation in which one person's body completely shadows the direct LOS, the path loss exponent was $n = 1.9$ which is comparable to that for free space. However the path loss at the 1 m reference distance was significantly increased, with an extra 40 dB signal attenuation compared to the LOS case. This undesirable consequence of body shadowing is further exacerbated by an increase in the spread of the X_{BS} component of the received signal (Table 1).

TABLE I
ESTIMATED PARAMETERS FOR BODY-TO-BODY PATH LOSS MODELS

Scenario	n	$P_{0(\mathrm{dB})}$	X_{BS}	X_{SM}
1	2.1	39.8	$\mu = 0.00, \sigma = 0.05$	$A = 1.00, s = 0.04$
2	1.9	77.9	$\mu = 0.00, \sigma = 0.11$	$A = 1.00, s = 0.04$
3	–	–	–	$A = 0.96, s = 0.14$
4	–	–	–	$A = 1.00, s = 0.04$
5	2.9	29.6	$\mu = 0.00, \sigma = 0.20$	$A = 1.00, s = 0.05$
6	1.5	79.6	$\mu = 0.02, \sigma = 0.28$	$A = 0.98, s = 0.16$

B. Rotation and Tilt (Scenarios 3 and 4)

3) *Rotation*: Fig. 3 shows the local mean signal power level as person A performed a complete rotation from direct LOS through 360°. Note that the estimated path loss has not been included in the calculation of the local mean and thus in this respect is distinct from X_{BS}. Even at the relatively short separation distance of 1 m, the local mean received power can vary by as much as 50 dB. Although the general pattern of the received signal was similar at the 5 m, 10 m and 15 m separation distances, it became impossible to distinguish the true depth of the shadowing events due to the received signal being subject to occasional excursions below the noise threshold of the receiver. Fig. 4 shows the empirical PDF of the small scale fading throughout the rotation at 1 m. As can be seen from Fig. 3, signal variation about the local mean is typically within a few decibels during the stages where the two antennas are in direct or partial LOS. However, when person A's body begins to obstruct the LOS path, the magnitude of the X_{SM} component can be seen to increase presumably due to the more changeable propagation paths supporting the wireless link. Also shown in Fig. 4 is a Ricean PDF which is shown to provide a good fit to the data (Table 1). The Ricean-k parameter [9], which is an estimate of the ratio of the dominant component and the scattered contribution was found to be $k = 23.2$, which suggests the existence of a strong dominant signal component over the duration of this measurement scenario.

4) Tilt: The effect of a tilting action by one end of a body-to-body communications link is shown in Fig. 5. In these examples, the complete tilt movement occurs over a duration of 7 s. It is quite clear that the variation in the received signal level is reduced as the distance between the users increases. This was most likely due to the shape of the radiation pattern of the antenna [9] which was less susceptible to larger variations in gain at the 5 m, 10 m and 15 m separation distances. At the 1 m separation distance the variation in received signal was greatest. Here the signal level can vary by as much as 10 dB as person A tilted through a 45° angle.

C. Walking LOS and NLOS (Scenarios 5 and 6)

5) *Walking LOS*: To calculate the estimated received signal power at a particular distance in person A's journey towards person B, time was translated to distance using the estimate of person A's walking speed. Using equation (1) and converting the measured received signal power to path loss, the exponent n and path loss at the reference distance were calculated and are given in Table 1. The path loss exponent when person A was mobile (Fig. 6) was greater than that for the stationary scenario. This was possibly due to the fact that when person A is mobile, the measured signal power is more likely to experience greater variation of the body shadowing component. This is confirmed by the parameter estimates of the lognormal PDF fitted to the X_{BS} component of the measured signal power (Table 1). The Ricean-k factor for this scenario was again extremely large ($k \sim 200$) showing that under direct LOS conditions, there is very little fading due to small body movements.

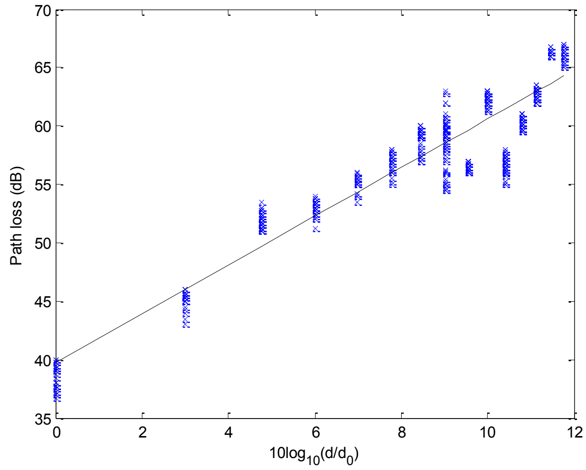

Fig. 2 Path loss model (black line) fitted to measured data (blue shapes) for scenario 1.

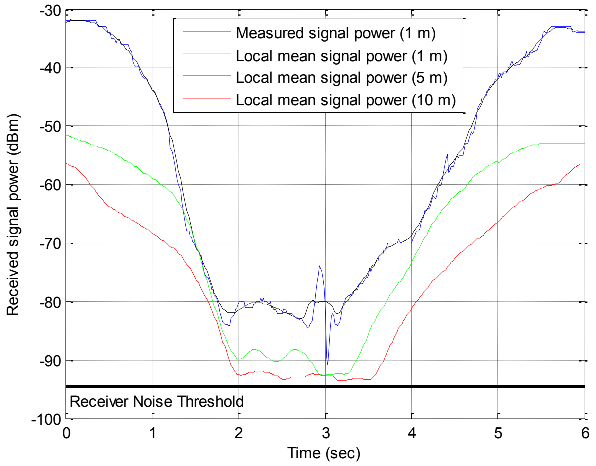

Fig. 3 Received signal power as person A performed a complete rotation at a separation distance of 1 m from person B. Also shown for comparison local mean signal power at 1, 5, and 10 m.

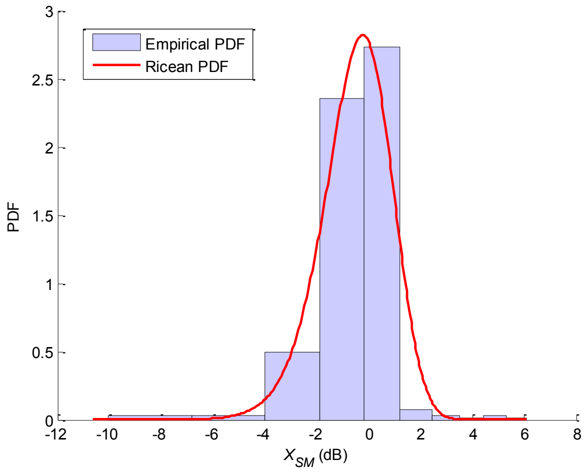

Fig. 4 Empirical PDF of X_{SM} component for scenario 3.

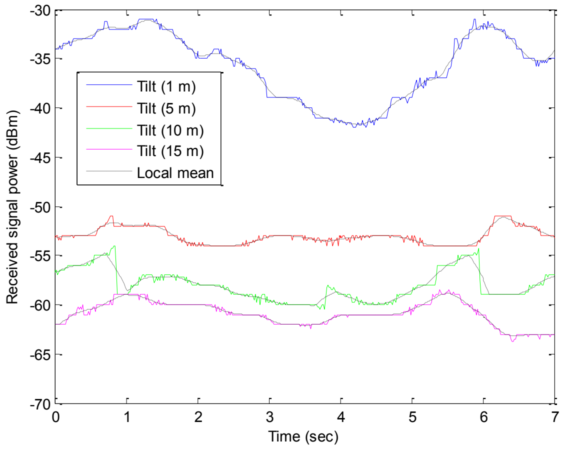

Fig. 5 Signal power and local mean power level as person A performed a tilting actions at a separation distance of 1, 5, 10 and 15 m from person B.

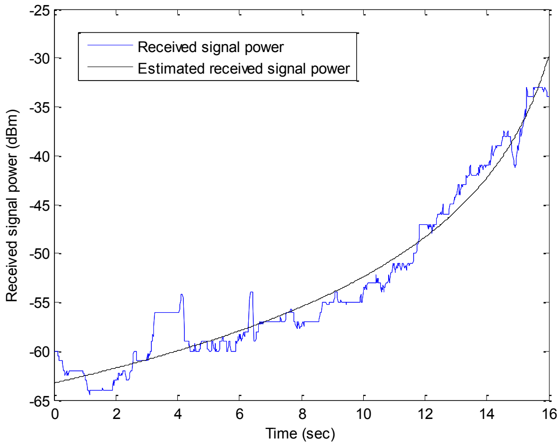

Fig. 6 Received signal power and estimated signal power as person A walked in LOS towards person B from 15 m to 1 m points.

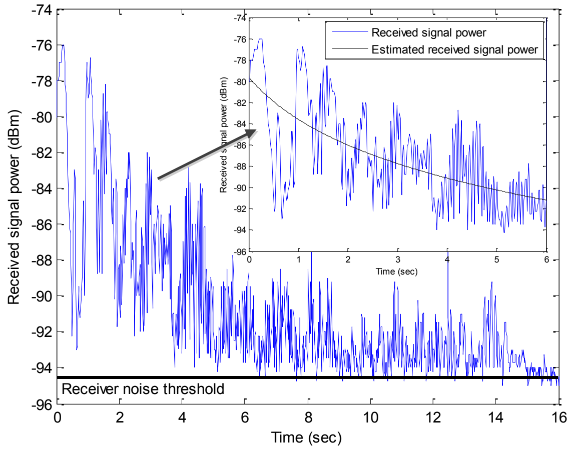

Fig. 7 Received signal power and estimated signal power as person A walked in NLOS away from person B from 1 m to 15 m points.

6) Walking NLOS: Again, due to the received signal power regularly extending below the receive sensitivity of the body sensor node, only the first 6 s of person A walking in NLOS from person B were used in this analysis. Fig. 7 shows the measured signal power for the complete duration of scenario 6 with the 6 s of samples used for the analysis inset. Using the same procedure as scenario 5 for treating the data, the estimated parameters for equation (1) are given in Table 1. While the path loss exponent for walking in NLOS is lower than the equivalent stationary measurements, the variability of the received signal is greatly increased, presumably due to the constantly changing signal paths used to sustain the link as person A moves away from person B. This effect can be seen quite clearly from the MLE parameter estimates of the lognormal and Ricean models of the X_{BS} and X_{SM} components respectively (Table 1). Here, the spread of the σ parameter and the magnitude of the s parameter are increased compared to all of the other scenarios considered in this study.

IV. CONCLUSIONS

For stationary outdoor LOS body-to-body communications, involuntary movements of both ends of the link can lead to noticeable deviations in the received signal than that predicted by the log-distance path loss model. When one person orientates themselves so that their body shadows the direct signal path, as anticipated, the received signal is significantly attenuated and subject to even greater variation. During rotational movements by one person in the body-to-body link, the local mean signal can drop by as much as 50 dB, with even greater change when the person moves through the maximum shadowing region where the person's body begins to obstruct the direct LOS. For tilting movements, variation in the received signal is most noticeable when the two persons are closest together. Finally, when one person in the body-to-body link becomes mobile, the path loss exponent and body shadowing components are found to increase for both LOS and NLOS movement.

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