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Investigation into Off-Body Links for Wrist Mounted Antennas in Bluetooth Systems

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***Abstract*—This paper presents a detailed investigation into off-body links for wrist mounted Bluetooth Low Energy (BLE) devices for an indoor environment and revolves around three low profile antennas (microstrip patch, printed monopole and external monopole). It studies the received signal strength across different usage scenarios and obstructions such as body shadow, wall and ceiling through measurement campaigns carried out in a 2-storey house. It is observed that RSSIs show little variation from the mean value at any position in a given room of the house. In the living room, the average RSSI for patch, printed and external monopole is close to -61,-73 and -61 dBm respectively. The study describes the effect of usual obstructions such as wall and ceiling to off-body links and shows that the range of RSSI for any antenna (30 dBm at P=0.5 for Patch Antenna) is bounded at one end by the CDF of wall plus body shadow and at the other end by CDF of Line of Sight (LOS). The effect of body shadowing is studied in greater detail. It is observed that the microstrip patch antenna in LOS, under a ceiling and behind a wall, drops by approximately 15dB, 5dB and 10dB at P=0.4 when it goes into body shadow. The study also suggests that the Access Point (AP) on the ceiling provides better off-body links as compared to it in the adjacent room. The study compares the overall performance of the three antennas across all possible usage scenarios, obstructions & polarizations and concludes that the external monopole and patch antenna performs better than printed monopole by approximately 10-13 dBm. Finally, the study shows the variation of Packet Error Rate (PER) with RSSI and determines threshold values of RSSI for acceptable PERs, for reliable and robust applications.**

Keywords—Indoor Propagation; Off-Body Link; Microstrip Patch; Monopole; Received Signal Strength Indicator (RSSI); Bluetooth; Body-Shadow; Packet Error Rates

I. INTRODUCTION

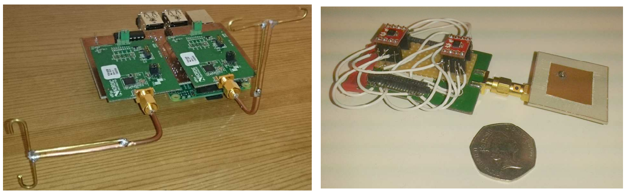
The continuous miniaturization of on-body sensors have made it possible for health sensors to be worn on wrists, attached to the user's body, carried in pockets or be a part of smart phones. It can be safely assumed that in near future, the use of wearables for medical monitoring is going to fundamentally transform the way vital health statistics are monitored without continuous in-hospital medical supervision [1-4]. An indication of this can be seen in the recently published Global Wearable Medical Device Market Outlook 2020, which predicts that the market of medical sensors will grow from USD 1.5 Billion in 2014 to USD 4.6 Billion by 2020 [5]. However, key limitations of wearable devices, which are still open research questions are signal drop due to body shadowing [6], polarization misalignments [7] due to body movements and degradation in antenna efficiency due to body proximity effects [8-10]. It is therefore imperative to understand and characterize the '*local*' environment provided by the human body moving in an indoor environment and its effect on the antenna, radio channel and therefore the wearable system's performance. It is worth mentioning that a limited number of publications have actually presented research on wrist movements. The literature came across some work [11-14] regarding off-body links for various orientations of Bluetooth wrist mounted antennas. In this context, the focus of the paper is to provide an insight into parameters such as: (1) Path loss in an indoor environment, (2) Effect of body, wall and ceiling on received signal strength (3) Comparison of potential antennas used in wearables and (4) Packet error Rate. This was achieved through a measurement campaign consisting of a number of usage scenarios, in a 2-storey terrace house in Bristol, United Kingdom (UK). The received signal strength indicator (RSSI), which is conventionally used for localization [15-18] in indoor or outdoor environments and for the determination of the channel model that relates the received signal strength with the distance [19-22], is the measured parameter in this campaign.

The remainder of the paper is organized as follows: Section II describes the measurement process, Section III details the parameters being measured and analyzed, and Section IV provides the conclusion.

II. MEASUREMENT PROCESS

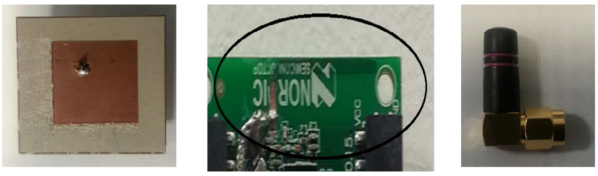
A. Hardware Description

For the RSSI measurements, the wearable device is deployed in a terrace house, in Bristol (UK) together with various access points (receivers) located in different rooms of the house. The wearable sensor (Fig. 1b) employs nRF51822 System-on-Chip (SoC) that uses Bluetooth Low Energy (BLE) for wireless communications and is programmed to operate as a BLE broadcaster transmitting periodically packets at a transmission power set to 4dBm, which is the maximum supported transmission power level [24]. A lower transmission power would results in higher PER and can be estimated by shifting the CDF graphs presented in this paper. Each receiver (Fig. 1a) is a Raspberry Pi B+ microcomputer that employs two nRF51822 radios with two orthogonally polarized dipole antennas, working in parallel as BLE Observers. Full details on the receiver antennas can be found in [23]. The prototype device is worn on the wrist of the human subject, as shown in Fig. 3c.



(a) (b)

Fig. 1: (a) Access Point (AP), (b) Wearable Device



(a) (b) (c)

Fig. 2: (a) Microstrip Patch, (b) Printed Monopole, (c) External Monopole

B. *Antenna Description*

Three antennas, shown in Fig. 2, are used with the wearables: Microstrip Patch, Printed Monopole and External Monopole Antenna. The patch antenna is 17.8 X 18.5 X 1.3 mm and constructed on RT/Duroid 6010 substrate (dielectric constant ε_r=10.2). The printed monopole antenna traced on a printed circuit board is 40 X 40 mm while the external monopole is 18 mm long with a diameter of 6mm.

C. *Floor Plan*

The off-body measurements were carried in a terrace house as shown in Fig. 3. The human subject held the wrist mounted antenna in front of the chest (Fig. 3c) and moved from position A to B (distance of 3 meters) in the living room (R1). The Access Points (A.P.) were kept at three different locations (R1, R2 & R3 as shown in Fig. 3a & Fig. 3b). The study carried out two sets of measurements to analyze different usage scenarios: (1) Without body shadowing (subject facing the access point) and (2) With body shadowing (subject facing away from the access point), resulting in 6 combinations, as shown in Table I.

TABLE I: HUMAN SUBJECT – ACCESS POINT COMBINATIONS

S. No	Human Subject	Access Point	Type of Measurement	
			Without Body Shadow	With Body Shadow
1	Living Room	R1: Living Room (AP1)	LOS	Body
2		R2: Study Room (AP2)	Wall	Wall + Body
3		R3: Bed Room (AP3)	Ceiling	Ceiling + Body

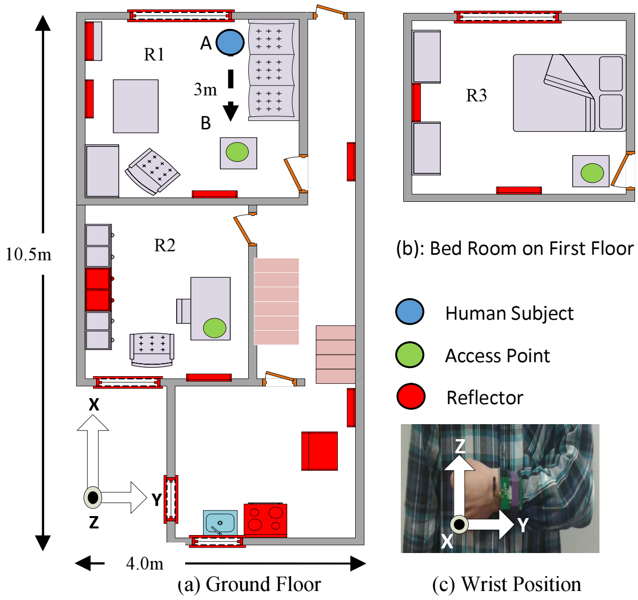


Fig. 3: Measurement Setting in SPHERE house.

III. MEASUREMENT PARAMETER AND ANALYSIS

This section compares and quantifies the parameters associated with the off-body link between a wrist mounted antenna and the AP in an indoor environment.

A. *Location Comparison*

The effect of the movement of a user on RSSI is studied as the subject moves from location A to B and data is recorded at 50cm interval, therefore 6 locations. The resulting CDFs (Fig. 4) indicate that except for the two extremities (Location 1 and 6), the CDFs of other locations overlap each other. Therefore, it can be safely assumed that for all analysis purposes, measurement at the two extreme locations are sufficient to determine the expected range (for example at P=0.4, -70 to -58 dBm) of RSSI values at the wearable device.

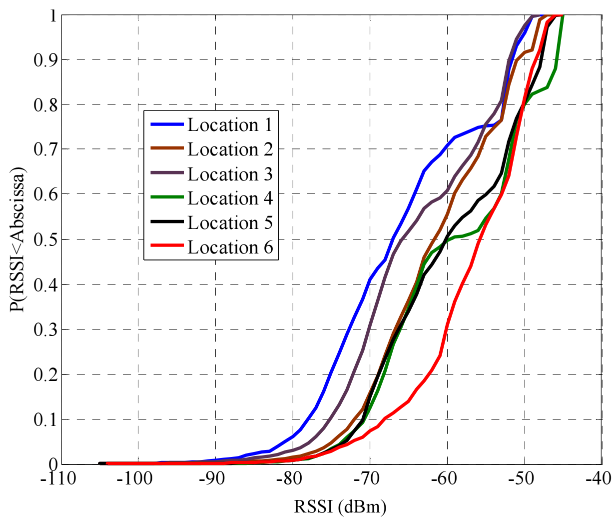


Fig 4: Location wise CDF of RSSI with AP in Living Room (R1)

The variation in RSSI values for each of the 6 locations are because of 4 factors, which are measured and included in the CDFs. The factors being: (1) The swaying of the subject on both the sides to depict natural standing posture, (2) Inclusion of Body Shadowing and LOS scenario, (3) Cross and Co-Polar links and (4) Broadcasting on all three Bluetooth Low Energy (BLE) advertising channels.

TABLE II: MEAN OF RSSI WITH AP IN LIVING ROOM (dBm)

Locations	Patch	Printed Mono	Ext Mono
Location 1	-65	-71	-67
Location 2	-61	-75	-61
Location 3	-64	-75	-60
Location 4	-58	-71	-59
Location 5	-59	-73	-60
Location 6	-56	-71	-59
Mean	-61	-73	-61

Table II shows that the mean values of the location measurements for each of the three antennas are very similar to the overall average. This implies that the position/movement of the user inside any room of the house will not have much effect on the received signal strength. It is therefore safe to assume that in a residential environment, the effect of the distance within a room has a minimal effect on RSSI in comparison to the obstructions (wall, ceiling) and body shadow.

B. Effect of Body, Wall & Ceiling on Antenna Performance

Fluctuations in RSSI due to usual obstructions (such as body, wall and ceiling) to off-body links in an indoor environment, for each of the three antennas are studied. The CDFs now include the effect of (1) Cross and Co-polar links, (2) Swaying of the subject and (3) 3 Advertising Channels (4) Movement of the subject in the living room, while the effect of body shadowing is taken out and studied separately in more detail.

As seen in Fig. 5, the range of RSSI extends from CDF of wall plus body to the CDF of LOS, providing the two boundaries to RSSI levels. It is also observed that the effect of body shadowing is more severe when the obstruction is a wall in comparison to a ceiling. For example, the microstrip patch antenna facing the AP in Line of Sight, under a ceiling and behind a wall, experiences a drop of approximately 15dB, 5dB and 10dB at P=0.4 when it goes into body shadow. Similar results for off-body links for all the three antennas are summarized in Table III.

TABLE III: SIGNAL STRNGTH (dBm) COMPARISON BETWEEN CEILING AND WALL AT P=0.5

S. No	Obstruction	Microstrip Patch	Printed Monopole	Ext Monopole
1	Ceiling	-69	-76	-65
2	Wall	-73	-86	-71

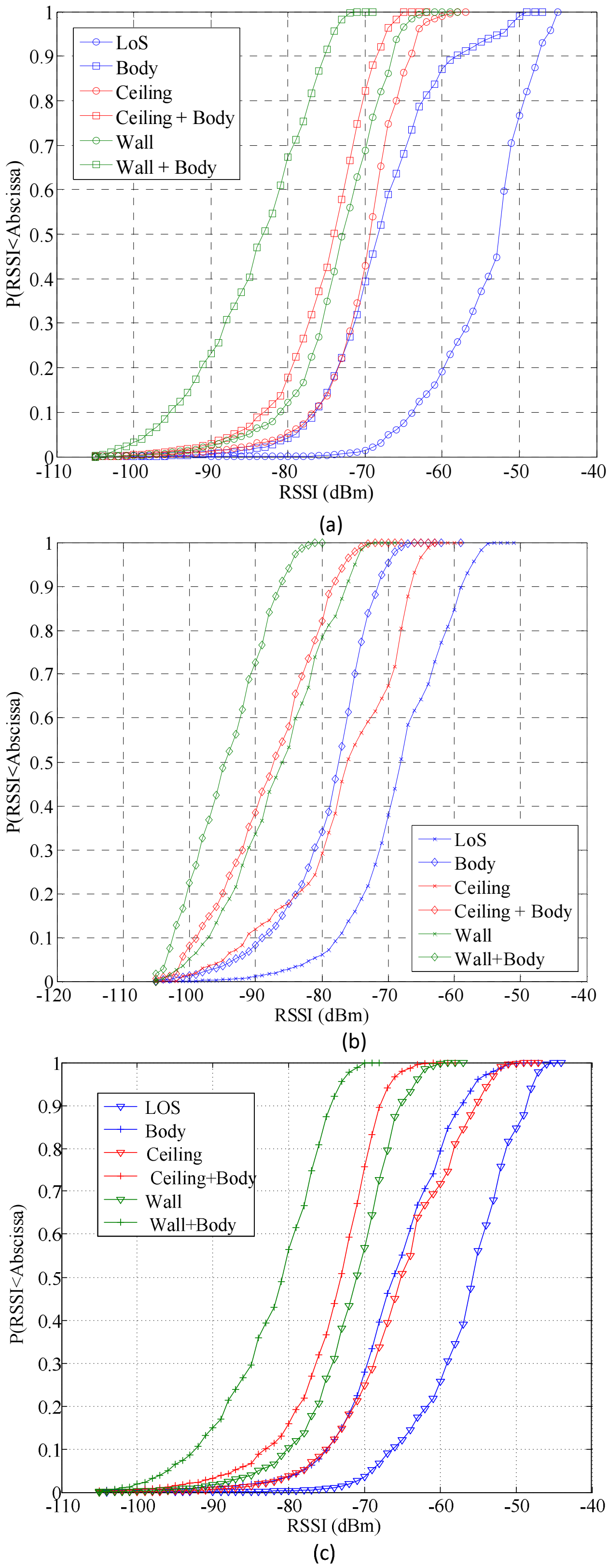


Fig. 5: Performance of antennas across different obstacles. (a) Microstrip Patch Antenna, (b) Printed Monopole Antenna, (c) External Monopole Antenna

From this analysis, it can be safely suggested that from the point of view of Bluetooth AP, installing it on the ceiling or one floor above is a better option compared to having it in the adjacent room, as it reduces the probability of body shadowing. This can be attributed to the construction material used and the angle of arrival of transmitted signals. Further, any diffraction due to body shape (head and shoulders) will not have the same effect as body shadowing.

The walls of this particular terrace house are made of concrete and therefore provide higher attenuation. However, modern houses, use plastic board and wood for making walls and ceilings, instead of concrete. Such a construction would provide lesser attenuation to transmitted signals.

C. Antenna Comparison

The CDFs for antenna comparison includes the effect of all polarizations, all AP locations, swaying, movements inside the room, obstructions and different advertising channels. This is done to compare the antenna performance over all possible usage scenarios. It is observed that the performance of external monopole and microstrip patch antenna is very similar, while the RSSI falls by almost 10-13 dBm when a Printed monopole is used.

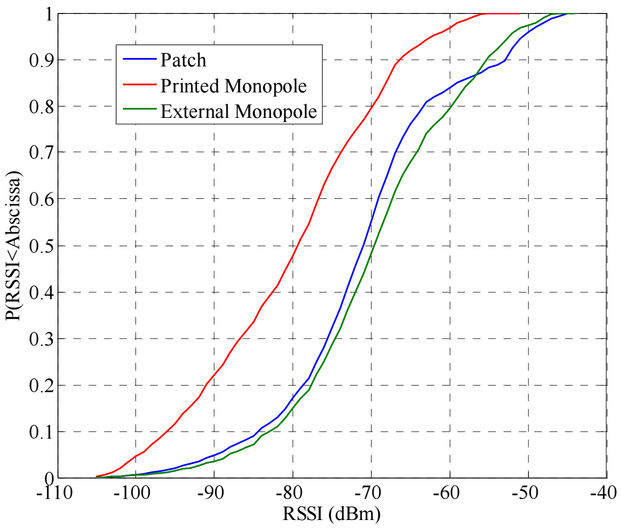


Fig. 6: Comparison between three antennas over the complete house.

The lower regions in the CDFs include RSSI value corresponding to scenarios such as the antenna in body shadow, cross-polarizations or behind obstacles such as ceiling or wall.

It is worth mentioning that although the external monopole performs better, but it is not a very aesthetic option because of its size. On the other hand, the microstrip patch antenna, not only performs better than printed monopole, but is also low profile, making it a better option for wearable devices.

D. Packet Error Rate

The packet error rate (PER) for the wearable sensor is determined by keeping the transmitted power constant and varying the distance. Fig. 7 relates PER with RSSI (dBm) and allows the reader to choose RSSI levels for acceptable PERs as per the requirement of the applications. For example, if the acceptable PER is 0.1, then the threshold level of RSSI is -97 dBm. The threshold levels can be employed to Fig. 5 and Fig. 6, to determine robustness and reliability of the system, in accordance to a usage scenario.

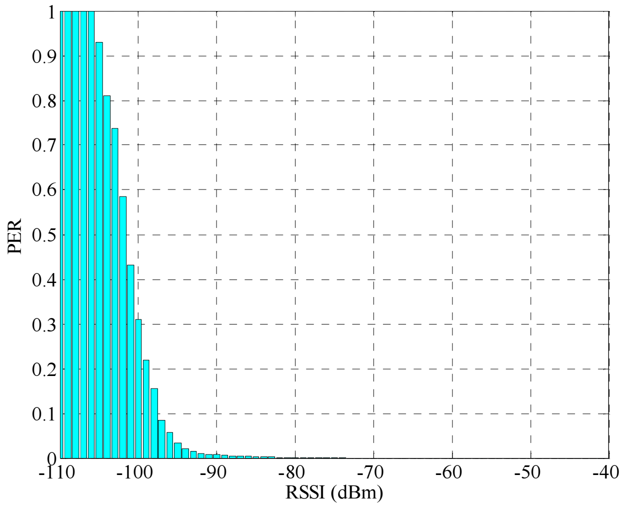


Fig. 7: PER vs RSSI

IV. Conclusion

The theme of the paper is to analyze usage based scenarios and obstructions related with off-body links between a wrist wearable Bluetooth Low Energy (BLE) device and the associated Access Points (APs).

The RSSI average of any locations in a room of the house are very close to the overall RSSI mean for the same room. RSSI average for the living room is -61, -73 and -61 dBm for Printed Patch, Printed Monopole and External Monopole respectively, which varies very little from individual location means. The study concludes that in a residential environment, the effect of the movement within a room has minimal effect on RSSI. Further, for all analysis purposes, RSSI measurements (-56 and -65 dB for the patch antenna in the living room) for two extreme locations in a room are enough.

The range of RSSI (30dBm for printed patch antenna at P=0.5) extends from CDF of wall plus body to the CDF of line of sight, providing the 'two boundaries' of RSSI levels for any usage scenario. It is observed that the effect of body shadowing is more severe when the obstruction is a wall in comparison to the ceiling. Therefore, for all possible constructions, the preferable position for AP installation is the ceiling, as it gets less affected by body shadowing. This is observed for the microstrip patch antenna facing the AP in Line of Sight, under a ceiling and behind a wall, which experiences a drop of approximately 15dB, 5dB and 10dB at P=0.4 when it goes into body shadow.

The study concludes that the external monopole and the microstrip patch antenna perform better than Printed monopole by at least 10-13 dBm over all possible usage scenarios and obstructions.

Finally, the study proposes to use RSSI thresholds based on acceptable packet error rates (PERs) for the intended Bluetooth systems. The determined thresholds can then be employed to different usage scenario for analysis and determination of robustness and reliability of the intended applications.

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