CHAPTER 5

Diversity Antennas for BAN Applications

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Introduction

Wireless body area network (WBAN) defines a network of wearable devices showing wireless communication capabilities. First, WBANs were initially used in the healthcare domain for continuous monitoring and logging vital parameters of patients suffering from chronic diseases (such as diabetes). Sports, military, or security were other applications [1].

Body-worn antennas have two requirements: they must be efficient in the presence of biological tissues and their polarization/pattern features should match the incoming direction and the polarization of the incident waves. In a radio link between two body-worn antennas, several types of waves contribute to the channel, i.e. creeping and surface waves guided around the body surface, direct waves, waves reflected/scattered by the environment (ground, walls, etc.), and waves reflected by other parts of the body (legs or arms). As a result, deep fadings are commonly observed and antenna diversity makes sense to fight the fadings in the BAN context [2–6].

In [2], it was demonstrated that on-body antenna diversity is less effective for line-of-sight (LOS) links like the waist–chest link. In [3], the spatial diversity was investigated for monopoles at 2.4, 5.8, and 10 GHz and it was shown that the best diversity gain is obtained at any frequency for the waist–head and waist–ankle links, i.e. for non-line-of-sight (NLOS) links. In [4], space and pattern diversities were tested with monopoles (space diversity) and annular slot-monopole antennas (pattern diversity), the conclusion being that space diversity is the best choice at 2.45 GHz for spacings as small as 3 cm (~λ/4). In [5] and [6], planar inverted-F antennas (PIFAs) and printed IFAs were used to evaluate the influence of the antenna orientation. All these studies conclude that a good diversity gain is only reached for NLOS channels and dynamic channels with large movements.
In [7], Serra proposed diversity antennas favouring either waves reflected by the environment or creeping modes, which can alternatively be the dominant incident waves depending on the scenario, i.e. the antenna locations, the body gesture, and the environment.

This chapter also concerns antennas showing pattern diversity, but emphasis is put on the miniaturization of the antenna structure. Two miniaturized diversity antenna structures dedicated to wireless body area networks are described for 2.45 GHz applications. The first one combines a PIFA and a top-loaded monopole [8]. The structure is based on a \((\lambda_0^*\lambda_0)\) total surface antenna design with two concentric slots [7]. The prototype described below combining a top-loaded monopole and a PIFA located on the same ground plane is reduced to \((\lambda_0/2^*\lambda_0/4)\). The second structure associates a slot loop and a concentric dielectric resonator antenna (DRA) [9].

Both structures yield distinct patterns, roughly broadside and end-fire, which fit the different natures of the received waves. The signals received by the two types of waves will be uncorrelated at the receiver input only if a strong isolation is observed between the broadside and end-fire ports.

The antenna performances are first described in terms of measured return loss, port isolation, and computed radiation patterns in the presence of a numerical body phantom. Then, the added value of diversity is experimentally determined for a transmitter on the chest and receivers on the hip, the belly and the back of a human person, and for three scenarios: still subject in an anechoic chamber, moving subject in an anechoic chamber, and moving subject in an indoor environment.

2 Antenna Diversity Based on Co-Located Planar Inverted-F Antenna (PIFA) and a Top-Loaded Monopole

2.1 Generalities on antenna diversity applied to BAN

Pattern diversity makes use of uncorrelated radiation patterns to recombine uncorrelated signals with various well-known techniques (switched combining, selection combining, equal-gain combining, or maximal-ratio combining). In the BAN context, monopole-like patterns omni-directional in the plane tangent to the body surface are suitable for collecting the creeping waves travelling around the body. In outdoor environments, most of the received power will come from the creeping waves, and scattered waves will be negligible except in the vicinity of the floor, for instance for antennas in the shoes or around the ankle. On the other hand, PIFA patterns do not have significant dips in directions normal to the body surface and are sensitive to both \(E_\theta\) and \(E_\phi\) polarizations. Therefore, PIFAs are appropriate miniaturized antenna to collect the fields scattered by all obstacles in an indoor environment. The field strength of both types of modes will vary according to the body movements and antenna locations. As a result, antenna diversity appears as a credible solution to handle various BAN scenarios and improve the link budget.
2.2 Design of the co-located top-loaded monopole and PIFA

The diversity antenna associates a PIFA etched on the upper surface of the substrate with a small ground plane (35 × 30 mm²) and a top-loaded monopole realized on a separate ground plane (20 × 30 mm²) and etched on the lower surface of the substrate (Fig. 1). The whole structure is built on a 1.6-mm-thick FR4 dielectric substrate. The total surface of the diversity antenna is 55 × 30 mm². The monopole height is 9.6 mm. The diameter of the top-loading disc is 15 mm. The monopole is matched to 50 Ω with a printed microstrip L matching network combining a large
line acting as a parallel capacitor and a narrow line modelled by a series inductance. The PIFA height is 3.2 mm.

Distinct miniaturized antennas are used but dimensions are kept small, thanks to isolation levels greater than 20 dB provided by decoupling slots etched in the PIFA ground plane. This good port isolation limits the influence of one antenna on the radiation pattern of the other antenna despite their close vicinity.

2.3 Measurement of the co-located top-loaded monopole and PIFA

The coupling between co-localized antennas is reduced by etching parallel $\lambda/4$ slots in the ground plane. These slots act as a stop-band filter limiting the current flow for proper dimensions, spacings, and locations of the slots (see Fig. 1). The slots are driven in phase opposition that results in a reduced parasitic radiation as observed in Fig. 2, where the E-field produced by the PIFA around the monopole vanishes when the ground plane is slotted.

Figure 3 shows the measured S-parameters for an antenna structure located 3 mm above the torso. $S_{21}$ is reduced from -10 to -20 dB and below when slots are introduced. The 9-mm spacing optimization between the two slots allows a maximum rejection at 2.45 GHz with 19.5-mm-long and 1-mm-wide slots. The PIFA matching is not affected by the presence of the body compared with the free-space case. The monopole antenna is more sensitive. Its resonance is shifted downwards (~50 MHz) when the antenna is placed on the body surface. The achieved common matching bandwidth is 2.6% around 2.45 GHz for $S_{11} < -10$ dB with decoupling slots.

The computed efficiencies for the PIFA and the top-loaded monopole are, respectively, 73% and 93% in free space. These values drop to 49% and 40%, respectively, in the presence of the phantom with 3-mm foam spacers between the ground plane and the body.

2.4 Radiation patterns in the presence of a body phantom

Radiation patterns are simulated using HFSS software by including a homogeneous dielectric cylinder (perimeter: 92 cm; length: 40 cm) modelling the torso.

Figure 2: Near E-field at 2.45 GHz without (left plot) and with slots (right plot) etched in the ground plane when the PIFA is excited.
The electrical parameters of the tissues are \( \varepsilon_r = 50, \sigma = 1.5 \text{ S/m} \). In the vertical plane normal to the body surface (\( yOz \)), the radiation patterns are plotted for the PIFA and the top-loaded monopole on-body and in free space (Fig. 4). The radiation patterns are affected by the body. For both antennas, the \( E_{\phi} \) component parallel to the lossy body surface is strongly attenuated. The monopole has a dip at broadside and a negligible \( E_{\phi} \) component while the PIFA pattern is characterized by a combination of \( E_{\theta} \) and \( E_{\phi} \) components and a non-zero pattern around broadside. These features make the PIFA more sensitive than the monopole to the signals scattered by the environment or at least differently sensitive.

In the azimuthal \( xOy \) plane tangent to the body surface, the simulated azimuthal gain in any direction is approximately -5 dBi for the monopole. Conversely, the maximum azimuthal gain for the PIFA is -5 dBi, i.e. the monopole pattern is more omnidirectional than the PIFA one. We conclude that the monopole pattern is more suitable to receive creeping waves from unknown azimuthal angles and that the proposed structure has strong diversity capabilities, with distinct patterns in the elevation plane and a dominant monopole pattern in azimuth.

The cylindrical phantom is obviously a rough estimation of the human body but it is expected that the main trends and conclusions remain valid to analyse the diversity performance in the next sections.

### 2.5 Experimental set-up to evaluate the diversity performance

The transmitting monopole antenna and the receiving diversity antenna under test are worn by a male subject as shown in the schematic of the experimental setup (Fig. 5). An Agilent network analyser E8361C PNA is used as a two-port
narrowband receiver (one port connected to the top loaded monopole and the other to the PIFA) with an IF bandwidth set to 10 kHz. The PNA is synchronized to the RF source (0 dBm at 2.4 GHz) which feeds the transmitting monopole antenna mounted on a small ground plane (30 × 30 mm²). The antenna heights above the body are fixed by foam spacers of 3 mm mounted on each antenna backside. The transmitting monopole is fastened to a large elastic strip around the belt so that it can slide along it. The receiving diversity antenna is fixed on another strip in the middle of the chest. The body movements are facilitated by the use of flexible cables RG-316 (1.5 dB/m loss at 2.4 GHz) while repeatability is assured by holding in place the cables with adhesive tapes. By placing the TX and RX cables orthogonally and far from each other, one reduces the cross coupling between the antennas.

It is well known that a small antenna with unbalanced feedings and a limited ground plane sees currents flowing along the outer part of its coaxial cable. These currents radiate and distort the radiation pattern. The insertion of a cylindrical

Figure 4: (Left) Top-loaded monopole and (right) PIFA. Simulated radiation patterns in the y0z plane normal to the body: θ component (plain line) and φ component (dotted line). (a) On body and (b) in free space.
ferrite rod on the cables and close to the SMA connectors can greatly reduce the parasitic currents.

Three scenarios are defined in this chapter. In scenario 1 located in an anechoic chamber, the subject is in static position to evaluate only the contribution of the surface and creeping waves. In scenario 2, the subject is to make large movements in the anechoic chamber to add the effect of the waves scattered by the body. In scenario 3, the subject simulates a slow walk with large arm movements in a rich scattering environment with desks, shelves, chairs, etc. Unlike scenarios 1 and 2, the received signals in scenario 3 are affected by off-body scattered waves.

Three links are considered for each scenario: chest-to-belly (0°), chest-to-hip (90°), and chest-to-back (180°). The angle corresponds to the rotation of the transmitter with respect to the belly position. For each link, a measurement campaign was composed of three consecutive runs repeated at three different times. For each run, a set of 20,001 samples is recorded during 60 s (one sample each 3 ms).

2.6 Diversity measurements

Table 1 summarizes the main results of the measurement campaign for each link. $P_{\text{stat}}$ is the average measured power received by the monopole or the PIFA in the diversity antenna for scenario 1. Comparing scenario 2 with 1 and scenario 3 with 1, the absolute power gains of average power are $G_{\text{anecdyn}}$ and $G_{\text{indyn}}$, respectively. $P_{\text{SCanec}}$ is the mean power obtained once the selection combining scheme has been applied to scenario 2. Let us call $G_{\text{SCin}}$ the increase of average power observed in scenario 3 after the signal combination has been applied.
The diversity gain (DG) is defined as \( DG = \frac{S_{sc}}{N_{sc}} \), where:

- \( S_{sc} = \frac{S}{N} \) is the largest of the monopole and PIFA signal-to-noise ratio.
- \( S_{sc} = \frac{S}{N} \) represents the signal-to-noise ratio after selection combining.

The DG is defined for a 1% outage. As the noise is assumed identical before and after combination \( N_{max} = N_{sc} \), we finally have \( DG = S_{sc} - S_{max} \).

The diversity gains for scenarios 2 and 3 are called \( DG_{anec} \) and \( DG_{in} \), in Table 1, respectively.

In the chest-to-belly link (0°), the signal is larger on the monopole antenna for all three scenarios which results in a clear power imbalance. This indicates that the surface/creeping waves are the dominant propagation mechanisms as the monopole is more efficient than the PIFA in receiving waves propagating along the body. As the power imbalance is large, DG is null. For this link, the diversity antenna could be switched on the monopole permanently. Using the method-of-moments estimator, it has been checked that the cumulative distribution function (cdf) curves respect a Rice model. This confirms that the excitation of the surface/creeping modes results in a LOS path.

For the chest-to-hip link (90°) and in the anechoic chamber, the power gains of average power between the still and moving person are \( G_{anecdyn} = 4.5 \) dB for the PIFA and \( G_{anecdyn} = 0.3 \) dB for the monopole. It proves that the contribution of the power brought by the waves scattered by the moving parts is more important for the PIFA than for the monopole. This can also be deduced from the relative difference between the average received power \( P_{stat} \) for both antennas, which is smaller in scenario 2 (Δ\( P_{stat} = 3.4 \) dB = 44.6–41.2 dBm) than in scenario 1 (Δ\( P_{stat} = 6.3 \) dB = 37–30.7 dBm).

In the indoor scenario 3 and the chest-to-hip link, the power gain improvement compared with scenario 2 is 1.8–0.3=1.5 dB for the monopole and 5.6–4.5= 1.1 dB for the PIFA, which shows the capacity of both antennas to take advantage of the waves scattered by the lab environment. Finally, it appears that the effectiveness of diversity gain flows from the waves scattered by the environment and not from creeping waves, as indicated by the measured values \( DG_{anec} = 0 \) dB and \( DG_{in} = 2 \) dB, respectively. Nevertheless, the diversity performance indoors is quite limited because the monopole reception is dominated by the LOS path.

Table 1: Measured diversity performances and power gains.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( P_{stat} ) (dBm)</th>
<th>( G_{anecdyn} ) (dB)</th>
<th>( G_{indodyn} ) (dB)</th>
<th>( P_{sc_{anec}} ) (dBm)</th>
<th>( DG_{body} ) (dB)</th>
<th>( G_{SC_{indoor}} ) (dB)</th>
<th>( DG_{indoor} ) (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° Mono</td>
<td>−30.7</td>
<td>+0.8</td>
<td>+1.7</td>
<td>−29.9</td>
<td>0</td>
<td>+0.9</td>
<td>0</td>
</tr>
<tr>
<td>0° PIFA</td>
<td>−37.0</td>
<td>+0.2</td>
<td>+0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90° Mono</td>
<td>−41.2</td>
<td>+0.3</td>
<td>+1.8</td>
<td>−40.1</td>
<td>0</td>
<td>+1.4</td>
<td>2</td>
</tr>
<tr>
<td>90° PIFA</td>
<td>−44.6</td>
<td>+4.5</td>
<td>+5.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180° Mono</td>
<td>−68.0</td>
<td>+4.0</td>
<td>+11</td>
<td>−63.9</td>
<td>3.2</td>
<td>+6.9</td>
<td>7</td>
</tr>
<tr>
<td>180° PIFA</td>
<td>−76.4</td>
<td>+4.2</td>
<td>+14.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The diversity gain (DG) is defined as \( DG = \frac{S}{N} \), where:

- \( S_{max} = \frac{S}{N} \) is the largest of the monopole and PIFA signal-to-noise ratio.
- \( S_{sc} = \frac{S}{N} \) represents the signal-to-noise ratio after selection combining.
For the chest-to-back link (180°), the monopole ($G_{\text{anecdyn}} = 4$ dB and $G_{\text{indyn}} = 11$ dB) and the PIFA ($G_{\text{anecdyn}} = 11$ dB and $G_{\text{indyn}} = 14.6$ dB) equally take benefit from the multipaths. Hence, surface waves are no longer predominant as the direct path around the body is strongly attenuated. Now, the diversity scheme in scenario 2 is more effective ($DG_{\text{anec}} = 3.2$ dB) and even more in scenario 3 ($DG_{\text{in}} = 7$ dB).

Figure 6 shows the CDF curves for the chest-to-back link with both antennas. The chest-to-back link has Rayleigh features in scenarios 2 and 3 for the PIFA and in scenario 3 for the monopole as verified again by using the method-of-moments estimator. A Rice model fits both the monopole and the PIFA CDFs only for scenario 1 only where a pure LOS propagation is expected. For the top-loaded monopole, the smallest levels of signal are identical for all scenarios. This proves the presence of an important direct path (creeping wave). Adding scattered waves only increases the mean signal value. For the PIFA and in scenarios 2 and 3, the contribution of scattered waves makes the CDFs slide up to higher signal levels. It indicates a stronger sensitivity of the PIFA to the environment with higher mean power values.

3 Diversity Antenna Based on Concentric Slot Loop and Dielectric Resonator Antenna (DRA)

3.1 Antenna geometry

This part proposes a two-port body wearable antenna providing dual patterns and showing larger DG values than the structures described in [10]. Its performance in terms of DG is evaluated for different positions of the receiving and transmitting antennas on the body surface.

The antenna is depicted in Fig. 7a and b. The ground plane dimensions are 36 mm × 36 mm. The substrate is characterized by its dielectric constant 2.2 and its height is 0.508 mm. Two 50 W microstrip feed-lines are etched on the opposite
side of the ground plane. Port 1 feed-line excites the slot loop etched on the ground plane. Port 2 feed-line excites a DRA [11] placed within the circumscribed limit of the slot loop region. The circumference of the loop is \( l_g = 98 \) mm. The loop should provide a broadside radiation pattern while the DRA excited in its TM01 mode should yield an end-fire type radiation pattern.

The slot loop is interrupted by a gap of width \( s = 11 \) mm. The gap position is located at a null of the E-field in the slot at 2.4 GHz so that the influence of the port 2 feed-line below is minimized. Consequently, this feeding strategy also improves the isolation between the ports. The DRA is vertically fed by a 1-mm-diameter probe of height \( h = 5 \) mm connected to the under-laid microstrip line. A metallic disc (diameter 3 mm) is removed from the ground plane to avoid the probe shortening. The antenna dimensions are detailed in Table 2.

### 3.2 Antenna modelling

To numerically estimate the body influence on the antenna performance with HFSS, a dielectric cylindrical phantom \((\varepsilon_r = 53\) and loss tangent \(= 0.002\)) with a radius of 20 cm and a height of 40 cm is planted below the antennas. The numerical body surface is located 10 mm below the antenna ground plane. The slot loop’s pattern is presented in Fig. 8b. The E-plane and H-plane are symmetric in the
Table 2: Dimensions of the slot loop and DRA.

<table>
<thead>
<tr>
<th>Antenna type</th>
<th>Design values</th>
<th>Feed line size</th>
<th>Stub length, $L_s$</th>
<th>Resonance frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 1 (slot loop)</td>
<td>Loop radius = 15.5 mm</td>
<td>Length ($L$) = 7.5 mm</td>
<td>4.5 mm</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Port 2 (DRA)</td>
<td>DRA diameter = 30 mm</td>
<td>Length ($L$) = 18 mm</td>
<td>0</td>
<td>2.4 GHz</td>
</tr>
</tbody>
</table>

Figure 8: Radiation patterns: Port 1: slot loop excitation: (a) measured in free space and (b) simulated on phantom. ----, $x0z$ plane (phi = 0°): $E_q$; --, $x0z$ plane (phi = 0°): $E_f$. (c) measured in free space and (d) simulated on phantom. ----, $x0z$ plane (phi = 0°): $E_q$; ----, $x0z$ plane (phi = 0°): $E_f$. Port 2 DRA excitation: (c) measured in free space and (d): simulated on phantom. ----, $x0z$ plane (phi = 0°): $E_q$; ----, $x0z$ plane (phi = 0°): $E_f$. 
broadside direction. The DRA’s end-fire radiation pattern is presented in Fig. 8d with a symmetric E-plane in elevation. It is checked that no significant changes of the patterns and resonant frequencies are observed with the phantom size. The DRA efficiency drops from 98% to 78% without and with body while the slot-loop efficiency drops from 94% to 77%.

3.3 Measured radiation patterns and S-parameters

The measured return loss and isolation curves are given in Fig. 9. The return loss bandwidths (≤-10dB) for port 1 (slot loop) and port 2 (DRA) are in the ranges 2.387–2.425 and 2.35–2.45 GHz, respectively. This yields a common 1.5% bandwidth. The -12 dB isolation at 2.4 GHz is sufficient for an effective diversity recombination of the signals. The free-space radiation patterns of the slot-loop show broadside features with low cross-polarization levels (Fig. 8a). An asymmetry is observed in the x0z (E) and y0z (H) planes. The large back radiation results from the small ground plane and the lack of backing plate. The DRA’s radiation pattern shows end-fire characteristics (Fig. 8c) and a symmetric shape in the elevation plane x0z. We conclude that the DRA’s radiation pattern is less affected by the ground plane size than the slot loop.

3.4 Experimental evaluation of the diversity performances

The experimental setup described below is fully detailed in [12] and identical to the one described in Section 2.5. The transmitting monopole antenna mounted on a small ground plane (30 × 30 mm) is placed 10 mm above the body and fixed on a large elastic strip around the belt that can slide along it. The receiving diversity antenna is fixed on another strip at the centre of the chest. Foam spacers of 10 mm mounted on each antenna backside ensure a fixed antenna height above the body and strongly limit the antenna detuning due to the body. As in Section 2.5, three links are studied: Link 1: chest-to-belly (0°); Link 2: chest-to-hip (90°); and Link 3: chest-to-back (180°).

The person under test simulates a slow walk characterized by large movements of arms in a lab room that is a rich scattering environment. For the three links, the envelope correlation factor (ECF) factor between the signals received at both ports remains below 0.4. The CDF curves are plotted once the selection combining method is applied to combine the power samples. A 1% outage probability is used in the DG calculations. For Link 1 (chest-to-belly), no DG is observed as the LOS link between transmitting and receiving antennas implies a clear power imbalance that in turn nullifies the diversity performance. For Link 2 (chest-to-hip), a non-zero DG is measured (DG = 4 dB) as the link is partially LOS and partially non-LOS (NLOS) with a lower power imbalance. For Link 3, (chest-to-back), both antennas are in NLOS conditions, which eliminates the power imbalance and yields DG = 9.5 dB.
Two dual radiation pattern diversity antennas for on-body communications have been successfully tested on the body and then analysed in different scenarios. First, a miniaturized radiating structure using two antennas has been characterized in terms of $S$-parameters, simulated radiation patterns, and CDFs. The measured data are obtained for indoor and anechoic chamber environments, with on-body links showing different distributions of scattered and direct waves. In this way, the contribution from the body and the environment is clearly isolated. When the surface/creeping waves are dominant, the top-loaded monopole provides the highest signal, and diversity does not bring any added value. However, for scenarios where the surface waves are dominated by or equivalent to the waves reflected by the environment, the monopole and PIFA signals are sufficiently uncorrelated with similar received powers. Consequently, good performances are obtained when a selection diversity scheme is applied. For instance, $DG = 7$ dB is obtained for the chest-to-back link.

In the second structure combining a loop antenna and a DRA, a maximum 9.5 dB $DG$ is achieved when diversity performance tests are carried out in rich fading environments. This value is close to the one (10 dB) theoretically reached in pure Rayleigh environments. It is obtained with balanced efficiencies of 77% and 78%.
for the slot loop and the DRA, respectively. For both antennas, size reduction should be improved for a potential integration into clothes. However, the total height (<1 cm) is reasonable for professional applications (firemen, policemen, soldiers, etc.) where very low profiles are not the key issue unlike the communication reliability, which must be maintained for harsh environments and for various gestures, positions, and movement scenarios.

References


