A Survey of On-Body Antenna Arrays

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Abstract: This manuscript presents a survey of the existing literature on on-body antenna arrays. These can be used to enable wireless communication to and from different on-body nodes in a wireless body area network and are also used in medical applications. The design process and the required characteristics of on-body antenna arrays are discussed. On-body antenna arrays should be small, lightweight, and low-profile to ensure user comfort. The different types of on-body antenna arrays are discussed as well. On-body antenna arrays differ in the type of antenna element and in the geometric configuration of the array. The gain of the antenna arrays normalized to its area is compared and it is found that in the current state of the art this quantity reduces with increasing frequency from 36 dBi to 0.7 dBi. From our literature review, we draw important lessons that can be used to develop future on-body antenna arrays.

Index Terms: On-body antenna array, Body-centric wireless communication, Wireless body area network (WBAN)

1. Introduction

On-body antenna arrays are collections of interconnected on-body antennas. Together, these antennas collectively transmit or receive radio-frequency electromagnetic fields (RF-EMF) with the aim to communicate data wirelessly, perform microwave imaging, or achieve targeted dielectric heating. On-body antennas have different characteristics, depending on their application and a wide variety of such antennas exist. They consist of different materials, operate at different frequencies, etc. Several reviews have been made about on-body antennas [1]–[3], which focus on different types of on-body antennas. The review in [1] focuses on wearable antennas at $60\,\mathrm{GHz}$, the review in [2] focuses on ultra-wideband (UWB) wearable antennas, and the review in [3] focuses on electromagnetic band-gap integrated wearable antennas. None of these prior reviews focuses on on-body antenna arrays, so there is currently no single source in literature that can be used by antenna designers to obtain the specifications and properties of such arrays. This is the first time a review of on-body antenna arrays is presented, according to the authors' knowledge.

A typical application of on-body antenna arrays is in so-called wireless body area networks (WBANs). WBANs have received much attention due to their applications in healthcare, military and sports [4], [5]. These networks connect wireless on-body nodes and can be used e.g., for continuously monitoring a patient's health remotely. Motion sensors can also be used to track movement in military and sports applications, e.g., for observing and improving the training of an athlete. A key part of these WBANs are on-body antennas that enable wireless communication between different on-body nodes.

Therefore, in this paper, a systematic review of on-body antenna arrays is presented. The goal of this review is to provide an overview of the existing on-body antenna arrays for WBANs in literature and discuss future improvements, new designs and lessons learned. Additionally, some medical applications of on-body antenna arrays will be discussed. The novelty of this review lies in the fact that it focuses solely on on-body antenna arrays in comparison to pre-existing reviews which only focus on some specific on-body antenna types. The outline is as follows. Section 2 describes general design requirements for on-body antenna arrays. Section 3 presents the results of our review of on-body antenna arrays intended for RF communication. Section 4 considers the RF-EMF exposure of the user by on-body antenna arrays. Section S.3 (supplementary material) discusses the design aspects of antenna arrays for medical applications like microwave imaging and hyperthermia treatment. Section 5 provides an outlook on future research on this topic and Section 6 contains the conclusion.

2. Design Requirements

This section will outline the main considerations that have to be made, when designing an on-body antenna and how these translate into requirements for wearable antenna array design. This section focuses on the design requirements of arrays intended for wireless communication. On-body antenna array design requires optimizing or finding a trade-off between a set of antenna (array) parameters. The most commonly used parameters are illustrated in Fig. 1a and discussed in Section S.1 in the supplementary materials. In general, body-worn antennas should be small, lightweight and low-profile [1]–[3]. However, the dimensions of an antenna are not freely chosen, since they are related to the operating frequency. A higher operating frequency means smaller dimensions and therefore most on-body antennas operate at micro- and millimeter waves, i.e., between $0.9\,\mathrm{GHz}$ and $77\,\mathrm{GHz}$ [6], [7]. A lightweight antenna will ensure the user's comfort. The human body will absorb part of the radiated electromagnetic energy by the on-body antenna. Ideally, an on-body antenna radiates while minimizing this exposure. Using an on-body antenna with a ground plane can reduce the backward radiation and consequently reduce the exposure [8].

When an antenna is placed close to or on a human body, antenna parameters will change due to the coupling between the human body and the antenna [9]–[11]. The relative high permittivity and conductivity of the human body [12] can lead to a shift in resonance frequency and result in an impedance mismatch. Therefore, it is necessary to retune the antenna after designing it in free space. For this reason, antennas with wide bandwidths or very high isolations to surrounding dielectric materials are preferred. This isolation can be obtained by introducing a ground plane.

A body-worn antenna will be used to communicate with other antennas inside, on the body, or off the body through various wireless channels [13]. Due to the lossy nature of the human body, high propagation losses can occur in these channels [14]. To mitigate these losses, antennas with a high gain in these on-body channels can be used. An option to increase channel gain is to use antenna arrays. An increasing number of antenna elements will lead to a higher antenna gain (see Section 3.8), but also to a larger array due to the physical area occupied by the individual antenna elements and the minimum separation distance between the elements, required to achieve decoupling between the elements. The minimum separation distance is related to the operating frequency. A higher frequency will result in a smaller separation distance. This increase in area decreases the wearability of the array. Therefore, a trade-off needs to be made between the size and the gain of the antenna array. The separation distance of the antenna elements will affect the exposure of the user. Choosing an interelement spacing of $> 0.5\lambda$ will result in grating lobes and will consequently increase the exposure [8].

Single on-body antennas are faced with two disadvantages that can be mitigated by using an array: (1) A single antenna has a fixed radiation pattern and (2) single on-body antennas have limited gain. Antenna arrays provide a straightforward solution to both issues: (1) by steering multiple antenna elements, an array can have a dynamic radiation pattern and (2) by combining multiple antenna elements, a higher gain can be obtained. The direction and amplitude of the radiation pattern of an on-body antenna depend on the amplitudes and the relative phases between the elements, and feeding of these elements requires specific design of a feeding network, e.g., using (microstrip) transmission lines, phase shifters, splitters and combiners, amplifiers, etc. The design process of such an array consists thus of not only designing the antenna element and the feeding network, but also of designing the array system, i.e., inter-element spacing and orientation, such that radiation patterns can be formed in the desired direction(s).

The choice of fabrication technique and used materials will influence the design of the on-body

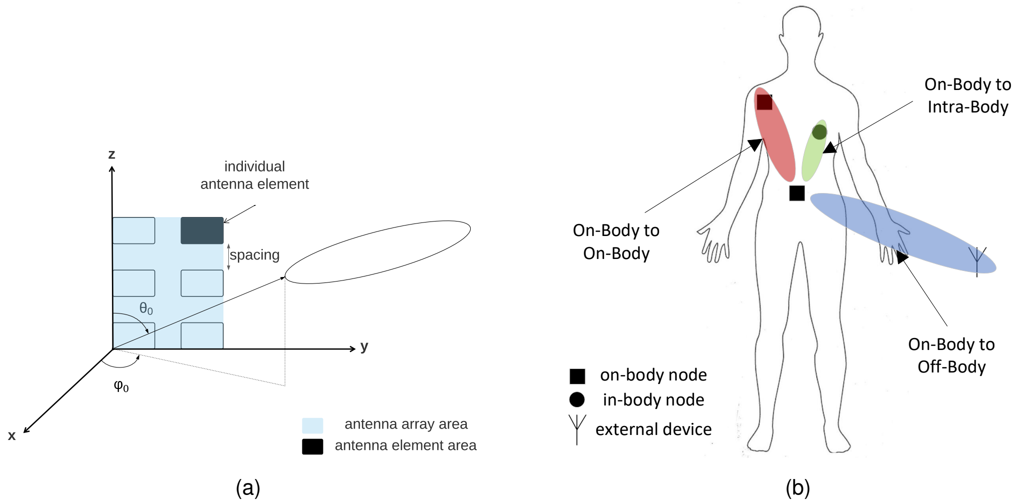


Fig. 1. (a) Illustration of an antenna array in the yz-plane with the beam direction along θ_0 and ϕ_0. The rectangles represent individual antenna elements. (b) Different communication links in a WBAN.

antenna array. Conformal and flexible antennas on the one hand and rigid antennas on the other hand, require different materials and fabrication techniques. Using textile materials, it is possible to make the antenna flexible and easy to integrate into clothes. This type of on-body antenna array is further discussed in Section 3.2. On-body arrays can also be realized by inkjet-printing [15], [16] and screen printing [7], [17] the radiating elements on a thin, flexible substrate. This results in very thin and flexible antenna arrays. A screen-printed layer will have a thickness between $10\text{-}20\,\mu\mathrm{m}$ and an inkjet-printed layer will have a thickness of $0.5\,\mu\mathrm{m}$ [15]. These can be printed on plastic or paper substrates of $100\text{-}200\,\mu\mathrm{m}$ thickness to achieve a flexible stack. These thinner layers will result in fewer cracks in the metal layer when the antennas are bent.

The required radiation characteristics, i.e., direction of maximum radiation, channel excitation and polarization, depend on the application for which the antenna array is used.

2.1. WBAN Links

The three possible communication links in a WBAN are: (1) on-body to on-body, (2) on-body to intra-body, (3) on-body to off-body. Each of these links uses a different channel (Fig. 1b). Therefore, they each have different requirements for the antenna. The antenna arrays used for the on-body to intra-body link are out of scope in this review, since we focus here on on-body antenna arrays for on- and off-body communication and the requirements for these antennas differ a lot from the requirements of the antennas used in the other two links [18]. Note that the on-body to intra-body link here refers to the wireless communication link and does not refer to the links used for medical applications in Section S.3.

2.2. On-Body Communication

For on-body communication, different on-body devices will communicate with each other (Fig. 1b, in red). The body surface is used as a communication channel, which can result in a higher attenuation than free space. The propagation during on-body communication is a combination of surface waves and space waves [19]. Surface waves propagate along the interface between air and the body and space waves propagate in the air surrounding the body. The propagation loss or attenuation of free space waves does not depend on the polarization of the waves. However, surface waves do have a polarization dependency [19]. As an example of this polarization dependency, the lowest attenuation of surface waves for the $2.45\,\mathrm{GHz}$ ISM band is found for a perpendicular polarization to the body surface [10], [20]. In practice, a perpendicular polarization will mean antennas with a high profile [10], [11], [20], [21] which is not comfortable for the user.

Additionally, the maximum radiation needs to be along the body surface and the radiation away and towards the body needs to be minimized.

2.3. Off-Body Communication

For off-body communication, the on-body antennas communicate with off-body devices, e.g., data sent to an external device. In this case, the antenna array will need to have its maximum radiation away from the user as opposed to along the body surface, which was the case in on-body communication. However, it should be noted that in the case of a collocated antenna array on one side of the body, the external antenna can be shielded by the body. In this case, the radiation still needs to go around the body surface.

3. On-Body Antenna Arrays

The high gains required for body-centric communication can be obtained by an antenna array consisting of multiple antenna elements [22]. Usually, the antenna elements are identical. The total field emitted by an array depends on the interelement spacing, the excitation amplitude and phase of the individual elements and the geometrical configuration of the array. Fig. 2 shows common types of antenna arrays: a uniform linear array (ULA), uniform rectangular array (URA), uniform circular array (UCA), and a distributed antenna array where the elements are distributed at convenient on-body locations. On-body antenna arrays can also be classified according to their on-body deployment, rather than their geometrical configuration. A (circular) array can be placed in different ways on a human body. The array can be placed in a plane parallel to the body on a specific part of the body (collocated), it can be wrapped around the body, e.g., around the waist or a limb (wrapped), or it can be spread over the entire body or torso (distributed). A linear array can be used to control the beam of the antenna in one dimension, e.g., elevation angle θ_0 when the array is placed along the z-axis. A planar, wrapped, or distributed array can be used to control the beam in two dimensions, i.e., (θ_0, ϕ_0) [22].

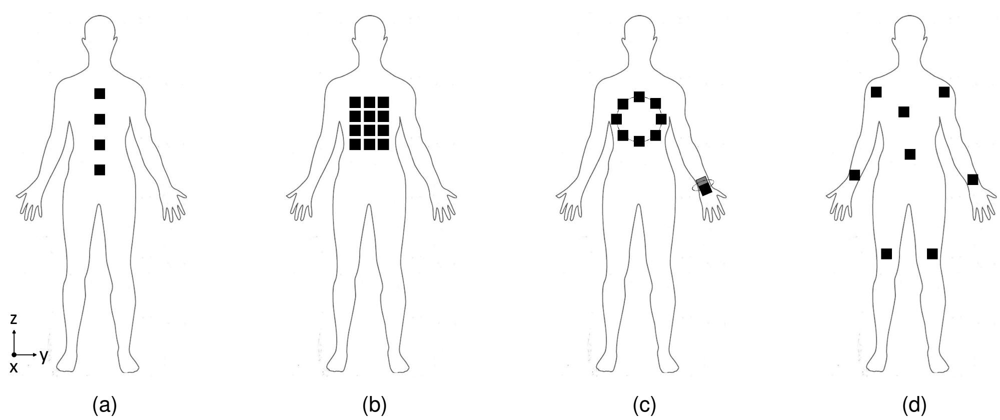


Fig. 2. On-body antenna arrays: (a) Linear array. (b) Rectangular array. (c) Circular arrays. (d) Distributed array.

Besides their geometrical configuration and its on-body deployment, on-body arrays are also characterized by the type of antenna elements used in the array, the materials used to create the array, or the antenna parameter for which the array was optimized. Therefore, we have subdivided the literature on on-body antenna arrays into the following categories that are discussed in Section 3: patch antenna arrays, textile antenna arrays, antenna arrays with improved isolation, parasitic arrays, circular arrays, on-body antenna arrays used for beam steering, distributed antenna arrays. Section S.2 (supplementary material) discusses other interesting on-body antenna arrays that are not covered in the other categories. Table S.1 (supplementary material) lists these on-body antenna arrays, subdivided based on the targeted communication channels. The array configuration is given together with two important antenna parameters, i.e., array dimensions and gain. Note that on-body gain does not imply gain in the direction of the body, but indicates the gain when the antenna is placed on the body. The direction of maximal gain varies from one reference to the next.

3.1. Patch Antenna Arrays

The patch antenna is the most common type of on-body antenna, since this type of antenna has a low profile, which makes it suitable for wearable applications. It consists of a radiating patch placed above a ground plane with a dielectric substrate in between [22]. The ground plane shields the user from the radiation and consequently minimizes the RF-EMF exposure [8]. Additionally, it will make the antenna performance less sensitive to the presence of the human body [23], [24]. Fig. 3a shows an example of a textile 2x1 patch antenna array designed in [25] operating at $2.45\,\mathrm{GHz}$. The maximum radiation of the patch antenna is away from the body if the ground plane is worn touching the body's surface. This makes it ideal for off-body communication, but less ideal for on-body communication. However, patch antennas were also used for on-body communication in [26], [27].

The most popular patch shape is rectangular [8], [16], [23], [25], [27]–[51], since there exist approximate formulas [22] for the dimensions of a rectangular patch antenna which makes their design relatively easy. In [26], a dual polarization 2x2 array of circular patch antennas is designed for both on- and off-body communication in WBAN at $28\,\mathrm{GHz}$.

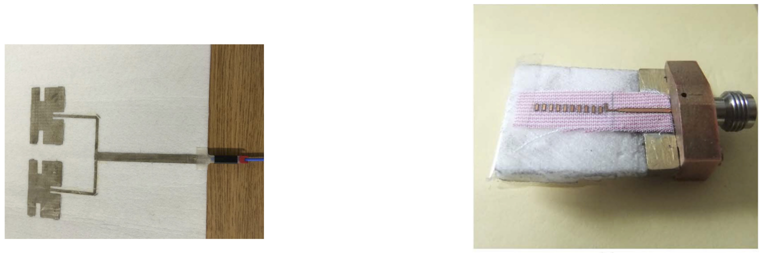
Besides rectangular and circular patches, there exist more complex patch shapes that are used for on-body antennas. Ring-shaped [52], T-shaped [15] and octagonal [53] patches are chosen to make the antenna element and consequently the array smaller. To make the antenna even more compact, slots can be introduced in the radiating elements, which is done in [15], [16], [25].

In [24], a 4x1 antenna array operating at $2.45\,\mathrm{GHz}$ consisting of tip-truncated equilateral triangular patch antennas is designed to minimize the coupling between the different antenna elements. The antenna array system is fully integrated into a rescue-worker's vest. In [54], a circular conformal array consisting of E-shaped patches resonating at $3.4\,\mathrm{GHz}$ is designed. The choice of patch shape results in a wider bandwidth in comparison to a rectangular patch. In [55], an 8x8 cross-shaped patch antenna array operating at $13.5\,\mathrm{GHz}$ is designed for WBAN. The antenna elements can realise two orthogonal linear polarizations and a circular polarization by exciting different ports. In [56], a hexagonal patch with a slotted ring antenna array is presented to obtain dual band operation, i.e., $2.45\,\mathrm{GHz}$ and $3.5\,\mathrm{GHz}$.

3.2. Textile Antenna Arrays

Textile antennas are often considered as on-body antennas due to their straightforward integration in clothes. At radiofrequencies ($0.9\,\mathrm{GHz}$-$5.8\,\mathrm{GHz}$), conductive textiles are used for the radiating elements and ground planes in combination with a textile substrate [6], [24], [25], [27], [31], [34], [39], [44], [46], [47], [54], [56]–[60]. This makes the antenna flexible, which makes it more comfortable for the user to wear. At millimeter waves, the radiating elements of the antenna are much smaller and higher accuracy is needed to fabricate these. Therefore, a thin and flexible metallic foil was used instead in combination with a textile substrate to make a 2x2 patch antenna array [23] for short-range off-body communications and a Yagi-Uda antenna [61] for on-body high-data-rate communications at $60\,\mathrm{GHz}$. The use of a textile substrate still makes the antenna flexible. Textile substrates often have a low real and imaginary part of the dielectric constant, which reduces the losses and improves the impedance bandwidth [52].

When designing a textile antenna, flexibility needs to be considered. The textile can be twisted, folded, and bent. This deformation can affect the antenna performance. In [23], a 2x2 patch antenna array is studied under bending and crumpling conditions. It was shown that the antenna array remained matched in the 57-$64\,\mathrm{GHz}$ band under bending in the H-plane. When the antenna array is bent in the H-plane, the radiating edges of the patches remain unbent. Therefore, the resonance frequency remains unchanged. The free space gain decreased from $9.0\,\mathrm{dBi}$ to $7.9\,\mathrm{dBi}$ when the bending radius decreased from $15\,\mathrm{mm}$ to $5\,\mathrm{mm}$. The array also remained matched under crumpling conditions, but the radiation pattern was strongly affected. The effect of the



(a) (b)

Fig. 3. Textile antenna arrays: (a) 2x1 patch antenna array operating at $2.45\,\mathrm{GHz}$ (image taken from [25]). (b) Yagi-Uda antenna operating at $60\,\mathrm{GHz}$ (image taken from [61]).

TABLE I
On-Body Antenna Arrays with Improved Isolation

Paper	Spacing[a]	Isolation (dB)	
		Free Space	On-Body
[36]	0.10λ	-15	-
[52]	0.052λ	-26	-
[62]	0.008λ	-27	-
[63]	0.06λ	-32	-38
[56]	0.10λ	-30	-

[a] edge to edge

deformation on the antenna performance was also studied in [7], [24], [31], [47]. From these studies, it can be concluded that the antenna performance under various bending conditions can remain unaffected when choosing appropriate materials. Therefore, in most cases, the antenna array can be designed in its planar form.

In [59], the flexibility of the textile is used for beam steering. A planar log-periodic dipole array (LPDA) consisting of 12 dipoles is designed for body-worn applications to operate between $0.9\,\mathrm{GHz}$ and $3\,\mathrm{GHz}$. Frequency-dependent beam steering is obtained by bending the dipole array at specific lengths.

3.3. Antenna Arrays with Improved Isolation

For on-body antenna arrays, the dimensions of the array should be as small as possible. A small array area implies small spacing between the array elements and consequently a potentially increased coupling. Therefore, the papers listed in Table I have focused on improving the isolation such that a smaller spacing than $\lambda/2$ between the elements of the on-body antenna array can be taken. The isolation is improved by introducing c-shaped slots [36], an '8'-shaped stub [52], a parasitic structure [62], a shorted strip and two slits [63], and a line patch and rotating one patch by $90°$ [56]. In [48], a combination of a defected ground structure and split ring resonators is used as an isolator to improve the isolation under bending of the array (Fig. 4). The mutual coupling varies between $-27.1\,\mathrm{dB}$ and $-31.3\,\mathrm{dB}$ under different bending conditions with an isolator and between $-17.9\,\mathrm{dB}$ and $-23.2\,\mathrm{dB}$ without an isolator.

The obtained isolations and the used spacings for the above papers are summarized in Table I. In general, several prior investigations have demonstrated that high antenna isolation can be achieved with a spacing less than 0.5λ in wearable antenna arrays and [63] suggests that these techniques could also be used on the human body. These results are promising for the development of future, compact on-body antenna arrays.

3.4. Parasitic Arrays

A parasitic array consists of one or more driven antenna elements and several parasitic antenna elements [22]. The currents in these parasitic elements are induced by mutual coupling with the

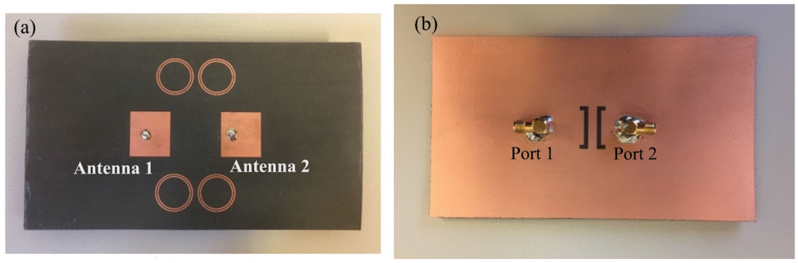


Fig. 4. On-body antenna array with split ring resonators and a defected ground plane to improve the isolation. (a) Front view. (b) Back view. (Images taken from [48])

driven element not connected directly to the source or load. In most antenna arrays, this coupling is avoided, since this will degrade the performance of the array. However, in parasitic arrays, mutual coupling is used to improve the directivity and gain of the antenna. These parasitic elements can also be used to direct the beam in a wanted direction. A parasitic array is sometimes not considered an antenna array, since it consists of only one driven element. However, we did include a brief discussion of these arrays in our review because they can be important building blocks in certain WBAN applications.

Beam Steering Parasitic Array: A parasitic array can act as a reflector or as a director. A reflector radiates more power away from the antenna and a director directs the power in its direction. When the parasitic elements are shorted to a ground plane, they act as a reflector and when they are not shorted, they act as a director. This is used to beam switch in a (sector) top-loaded monopole antenna array [21] and a parasitic array of patch antennas [7]. Here, the reflectors and directors are fixed.

The reflectors and the directors can also be controlled. This is done for parasitic arrays consisting of dipoles using variable capacitors [6], [64] or PIN diodes [57], [65] and with patch antennas using PIN diodes [66]. In [6], the beam can be steered in 3 directions, i.e., $0°$, $45°$, and $315°$. This is illustrated in Fig. 5.

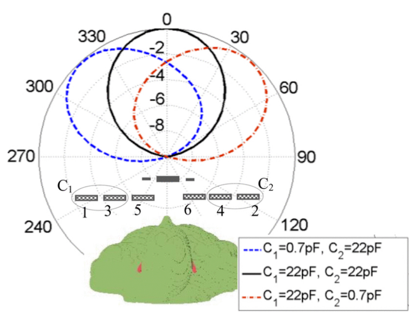


Fig. 5. Simulated radiation pattern of the beam steering parasitic antenna array designed in [6]. (Image taken from [6])

Yagi-Uda Antenna: In [61], a Yagi-Uda antenna is designed to operate at $60\,\mathrm{GHz}$ for on-body high-data-rate communications (Fig. 3b). A Yagi-Uda antenna has a maximum radiation parallel to the body surface when it is placed parallel to the body. This makes it suitable for directive on-body communication.

In [67] and [68], an antenna array of four printed parallel Yagi-Uda antennas and a substrate integrated waveguide (SIW) Yagi-Uda antenna are designed for $60\,\mathrm{GHz}$ on-body communication, respectively.

Surface Wave Parasitic Array: In [20], a parasitic array is designed for on-body communication at $2.45\,\mathrm{GHz}$ for body-worn devices. The array consists of a printed monopole with parasitic elements placed parallel to the driven monopole. The parasitic elements are added to enhance the launching of the surface waves. The antenna has a low profile, which is often not the case with vertically polarized antennas while being capable to launch a sufficient strong surface wave.

In general, the current literature on on-body parasitic arrays demonstrates that parasitic elements can be used to enable (on-body) beam steering and enhance the on-body channel gain. This approach can be beneficial in comparison to using multi-element active arrays in terms of system complexity and energy consumption.

3.5. Circular Arrays

The human body will influence the radiation pattern of an antenna. A single antenna placed on the front of the body will have poor backwards radiation due to the shielding of the human body. This can be mitigated by placing another antenna on the back of the body. This is investigated in [58]. A circular array can thus be used to achieve an omnidirectional radiation pattern, which is desirable for both on-body and off-body communication [27], [37], [44], [58], [69], [70].

In [37], a circular array consisting of patch antennas is designed to operate at $5\,\mathrm{GHz}$ for long-time health monitoring. The performance of the circular array is investigated with single, four, eight and sixteen patch antennas distributed uniformly across a cylinder that represents the human trunk. Again it is seen that the human body hinders the propagation of the EMFs. In [70], a cylindrical array of dipole antennas is designed to operate at $5\,\mathrm{GHz}$. The beam pattern is investigated as a function of circular arrays present in the cylindrical array.

In [27], a circular array consisting of patch antennas resonating at $5.8\,\mathrm{GHz}$ is designed (Fig. 6). it is investigated how to achieve omnidirectionality and avoid radiation nulls with a circular array. This is also investigated in [44].

Fig. 6. Circular antenna array operating at $5.8\,\mathrm{GHz}$. (Image taken from [27])

Only a few on-body circular antenna arrays are mentioned in literature (6 circular arrays versus 54 linear/rectangular arrays), despite their potential. We believe that circular arrays have a large potential, since they can be used to achieve an omnidirectional radiation pattern and they can be integrated into a belt or a wristband which simplifies rooting between the antennas.

3.6. On-Body Antenna Arrays Used for Beam Steering

An antenna array can be used to steer the beam in the desired direction [22]. This is useful in both on-body and off-body communication. To obtain a beam in the desired direction, the fields of the separate elements need to interfere constructively in that direction and destructively in the other directions. Since a user is mobile, the direction in which on-body or external nodes will be found, constantly changes. Therefore, it is useful that the direction of the beam can be adapted. This is commonly referred to as adaptive beamforming.

The direction of the beam depends on the phase difference between the different antenna elements in the array. This phase difference can be fixed, e.g., by the length of the feed lines, or can be changed by using one port per antenna element. This is not ideal for an on-body antenna, since it will increase the size of the array. As mentioned earlier, parasitic elements can also be used to steer the beam depending on if they act as a reflector or a director. This has the advantage of needing only one port instead of multiple ones. The reflectors and directors can be fixed [7], [20], [21], [61], [67], [68] or controlled by using e.g., varactor diodes [6], [57], [64]–[66], [71].

3.7. Distributed Antenna Arrays

Distributed on-body antenna arrays are arrays, where the antennas are distributed over the body in convenient places not in a particular geometric configuration (Fig. 2d). These antenna arrays are often not explicitly designed for improving the gain. Therefore, these on-body arrays are not considered in the analysis of Section 3.8. The positioning of these antenna elements depends on the application of the antenna array, e.g., a personal distributed exposimeter [72]–[74] and for investigating (dynamic) channel models [75]–[78].

3.8. Comparison of On-Body Antenna Arrays Parameters

Fig. 7a shows an overview of the obtained maximum antenna gain in free space as a function of the area of the antenna array for the different on-body antenna arrays. The distributed antenna arrays were not considered, since the area for these would correspond to the human body area and the array is usually not used to increase the gain. If only the dimensions of a single antenna element were given, a spacing between the antenna elements of 0.5λ was assumed and approximate dimensions of the array are used based on the values given in the papers. It was also assumed that the gain values were given in dBi. The smallest fabricated array (blue triangles) is the SIW Yagi-Uda antenna designed in [68] operating at $60\,\mathrm{GHz}$ with an area of $1.0672\,\mathrm{cm}^2$ and the largest is the 4x1 patch antenna array designed in [24] operating at $2.45\,\mathrm{GHz}$ with an area of $864\,\mathrm{cm}^2$. From Fig. 7a, we can conclude that the measured gains are situated between $0.42\,\mathrm{dBi}$ (2x1 patch antenna array [45]) and $15.7\,\mathrm{dBi}$ (4x1 printed Yagi-Uda antennas [67]) for the fabricated antenna arrays. Fig. 7a also shows higher gains, i.e., $16.04\,\mathrm{dBi}$ (4x4 patch antenna array [35]) and $22.8\,\mathrm{dBi}$ (8x8 patch antenna array [55]), but these are only achieved with simulations and not verified with measurements.

When designing an on-body antenna array, there will be a trade-off between the size of the array and the obtained gain. More elements will increase the gain, but will also increase the size of the array. This can be seen in Fig. 7b. A good on-body antenna array will therefore be small in size with an acceptable gain. The antenna array consisting of 64 patches [55] shows the highest gain, i.e., $22.8\,\mathrm{dBi}$. The lowest gain, i.e., $0.42\,\mathrm{dBi}$ is found for the 2x1 patch antenna array presented in [45]. For 2, 4, 8, and 12 elements, the minimum obtained gain is $0.42\,\mathrm{dBi}$ (2x1 patches [45]), $2.1\,\mathrm{dBi}$ (2x2 patches [26]), $0.5\,\mathrm{dBi}$ (circular array of dipoles [79]), and $4\,\mathrm{dBi}$ (planar LPDA [59]), respectively. For 2, 4, 8, and 12 elements, the maximum obtained gain is $11.45\,\mathrm{dBi}$ (2x1 patches [25]), $14.8\,\mathrm{dBi}$ (4x1 patches [24]), $14.8\,\mathrm{dBi}$ (4x2 patches [33]), and $12.2\,\mathrm{dBi}$ (parasitic array of dipoles [65]), respectively.

As mentioned before, a good on-body antenna array has a high gain, but is small in size. Therefore, a higher value of $Gain/A$ will lead to a better on-body antenna array. However, it is difficult to compare the areas of arrays operating at different frequencies, since a higher frequency will result in smaller antenna elements and consequently more elements can be placed in the same area or a smaller antenna array is obtained using the same number of elements. A solution to this is to use the normalized area, i.e., $A_{norm} = A/\lambda^2$. A good on-body antenna array should be small relative to its wavelength and have a high gain. Fig. 7c shows the normalized gain as a function of frequency, with $Gain_{norm} = Gain/A_{norm}$. Almost all measured normalized gains are less than $10\,\mathrm{dBi}$. There are only two arrays with a measured normalized gain above $10\,\mathrm{dBi}$. The first array is the patch antenna array designed in [52]. An '8'-shaped stub was placed between the antenna elements to improve the isolation. As a result, the elements could be placed closer together which leads to a smaller area and a higher normalized gain. The second array is the parasitic array consisting of sector top-loaded monopoles presented in [21]. The sector top-loading of the monopoles reduces the ground plane size which results in a smaller area. However, this also increases the height of the array which is not practical. The other normalized gains above $10\,\mathrm{dBi}$ are simulation results and therefore represent ideal cases. From Fig. 7c, we can conclude that the normalized gain reduces with increasing frequency from $36\,\mathrm{dBi}$ to $0.7\,\mathrm{dBi}$. This trend is

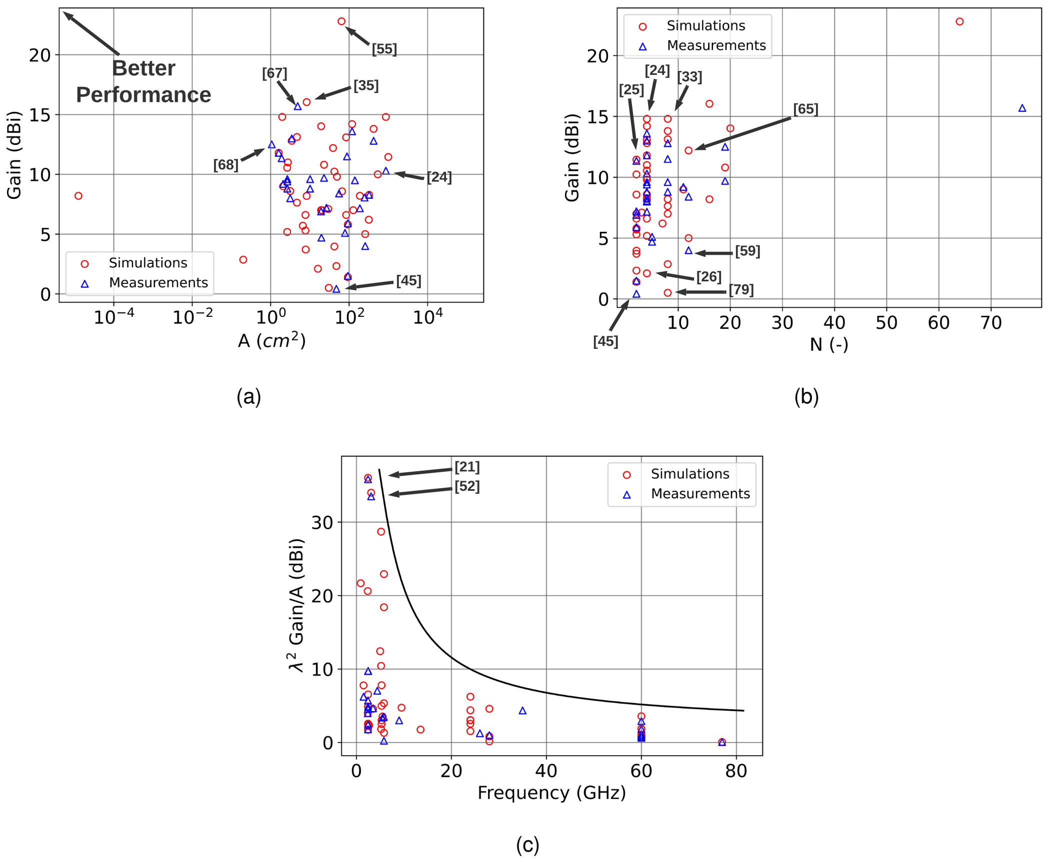


Fig. 7. (a) Free space gain as a function of area. (b) Free space gain as a function of number of elements. (c) Normalized free space gain as a function of frequency.

shown by the black curve. There is a research opportunity at mm-waves to develop on-body arrays with comparable normalized gain as can currently be found at lower RF frequencies.

4. RF-EMF Exposure

The human body will absorb part of the radiated electromagnetic energy by the on-body antenna array. The absorption depends on the antenna design and the frequency of the electromagnetic waves, e.g., a higher frequency generally results in a more localized absorption due to the smaller penetration depth. The exposure can be quantified in terms of the specific absorption rate (SAR). Table II lists the peak SAR averaged over 1 and $10\,\mathrm{g}$ for the on-body antenna arrays studied in this review, which have listed such values. These SAR values scale linearly with the input power into an antenna array and therefore put a limit to the maximal power that can be emitted by the arrays. The local SAR limit (averaged over $10\,\mathrm{g}$) for the general public is $2\,\mathrm{W/kg}$ for frequencies below $6\,\mathrm{GHz}$ [80]. The on-body antenna arrays designed in [8], [30], [33] operate at $60\,\mathrm{GHz}$ and will result in a more localized absorption. Therefore, the quantity used to describe the exposure in these papers is the peak power density averaged over 1 and $20\,\mathrm{cm}^2$. The exposure limits for the general public for these quantities are $200\,\mathrm{W/m}^2$ and $10\,\mathrm{W/m}^2$ for the power density averaged over $1\,\mathrm{cm}^2$ and $20\,\mathrm{cm}^2$, respectively. Note that for frequencies above $6\,\mathrm{GHz}$, exposure should be described in terms of the absorbed power density (S_{ab}) averaged over $4\,\mathrm{cm}^2$ and additionally for frequencies above $30\,\mathrm{GHz}$ averaged over $1\,\mathrm{cm}^2$ according to current exposure guidelines defined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [80].

TABLE II
Peak SAR averaged over 1 and $10\,\mathrm{g}$ and peak power density averaged over 1 and $20\,\mathrm{cm}^2$ of the on-body antenna arrays.

Paper	Frequency (GHz)	Input Power (W)	SAR (W/kg)		power density (W/m^2)	
			1 g	10 g	1 cm^2	20 cm^2
[6]	0.9	1	3.5	2.0	-	-
[81]	4.5-6.5	-	0.59	-	-	-
[24]	2.45	2	-	0.0124	-	-
[27]	5.8	0.1	0.29/0.105[a]	-	-	-
[29]	5.8	-	-	0.313	-	-
[39]	2.38	0.1	-	0.02	-	-
[64]	2.45	0.25	1.35	0.85	-	-
[65]	5.2	2	3.33	1.34	-	-
[60]	5.2	0.5	-	0.0942	-	-
[63]	2.4	0.1	1.52	-	-	-
[8]	60	0.5	-	-	13.1/685.9/11.2[b]	4.6/39.7/1.8[a]
[30]	60	0.322	-	-	38	-
[33]	60	1.4	-	-	-	9.48

[a] dual polarization [b] 3 different feeding techniques

5. Lessons Learned and Future Research

There exists a variety of on-body antenna arrays in literature. These on-body antenna arrays can differ in the type of antenna element, e.g., patch antennas, slot antennas, etc. They can also differ in the geometric configuration of the array, e.g., linear array, rectangular array, etc. These on-body antenna arrays have different characteristics, but there are general considerations that apply to all on-body antenna arrays. The antenna arrays need to be compact, since they are body-worn. The characteristics depend on the communication link in the WBAN, i.e., on-body communication or off-body communication. The on-body antenna arrays designed for off-body communication had their maximum radiation away from the body to communicate with an external device. This differs from the on-body antenna arrays designed for on-body communication. On-body communication makes use of surface waves. Since it is known that a monopole effectively launches these surface waves in the $2.45\,\mathrm{GHz}$ ISM band, several papers have tried to obtain a monopole-like radiation with their antenna arrays, since a monopole is not practical due to its high profile. One way to do this is to still use monopoles, but top-loading these with a disc to reduce the height [21]. Another way to do this is to use dipoles in a collocated circular array [79], [82]. The most common on-body antenna array is a patch antenna array. Most of the patch antenna arrays are designed for off-body communication as the antennas have their maximum radiation away from the body.

A higher frequency resulted in a lower normalized gain for the antenna arrays found in literature. Future research can include designing arrays at mm-waves with comparable normalized gains that are found at lower frequencies.

An interesting on-body antenna array is a circular array wrapped around a limb or waist. These are useful since the human body can shield different antenna elements from each other. The circular arrays can thus be used to achieve an omnidirectional radiation pattern. They are also practical, since they can be integrated into a belt or a wristband. Only a few of these circular arrays are mentioned in literature (6 circular arrays versus 54 linear/rectangular arrays), despite their potential. This type of array could potentially be used to achieve uniform on-body coverage for situations where the on-body nodes in a WBAN are spread over the entire body. This requires further research.

6. Conclusion

An overview of the existing on-body antenna arrays, their performance and potential in literature is presented. This was never done up to now. These antenna arrays operate at frequencies between $0.9\,\mathrm{GHz}$ and $77\,\mathrm{GHz}$. The design process of the on-body antenna arrays is discussed, as well as the required characteristics.

The performance of the on-body antenna arrays is discussed and compared. The antenna arrays have an area between $1.07\,\mathrm{cm}^2$ and $864\,\mathrm{cm}^2$ for frequencies between $0.9\,\mathrm{GHz}$ and $77\,\mathrm{GHz}$. The measured gains are situated between $1.5\,\mathrm{dBi}$ and $15.7\,\mathrm{dBi}$. The highest obtained gain with simulations is $22.8\,\mathrm{dBi}$, but this is not verified with measurements. More antenna elements will lead to a higher gain, but also to an increase in area of the array. An antenna array consisting of 64 patch antennas has the highest gain, i.e., $22.8\,\mathrm{dBi}$. The lowest gain, i.e., $0.42\,\mathrm{dBi}$ is found for a 2x1 patch antenna array. The normalized gain was also discussed, since it is difficult to compare antenna array areas for different operating frequencies. It was found that the normalized gain reduces with increasing frequency. Additionally, it was found that almost all measured normalized gains are less than $10\,\mathrm{dBi}$.

Two medical applications, i.e., microwave imaging and hyperthermia treatment, of on-body antenna arrays are discussed. The general design requirements, i.e., compact and low-profile, also apply, since they are wearable. Additionally, a trade-off needs to be made between the penetration depth of the EMFs and the resolution of the image (MWI) or the size of the focus spot (hyperthermia treatment).

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