

Human-Centric Connectivity Enabled by Body-Coupled Communications

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ABSTRACT

With the growing number of mobile devices surrounding a person's body, there is an increasing need to connect this electronic equipment efficiently into a wireless body-area network. In this article we review the body-coupled communications technology, which we show to be a viable basis for future BANs. In BCC, the human body is used as a signal propagation medium, which provides a key benefit — the communication is centered around the user and limited to his or her close proximity, that is, this technology provides human-centric connectivity. This enables unique applications that are illustrated in this work. Moreover, we outline the fundamental properties of the BCC technology and provide different trade-offs and challenges for modulation and protocol design. This article also discusses the outlook for BCC and suggests a number of important research topics.

INTRODUCTION

Driven by the desire to interconnect portable electronic and network devices surrounding a person's body, the concept of a body-area network (BAN) was introduced recently. In a BAN, the different nodes placed on and near the human body can wirelessly exchange information with each other. For these networks that also are referred to as personal-area networks [1], different radio frequency (RF) wireless solutions have been, and are being, developed. Possible applications of these BANs are in the area of consumer-electronic (CE) connectivity, for example, where a headset can be connected without wires to both a media player and a mobile phone. Another application area is a body-sensor network for healthcare, for example, where vital signs can be monitored with multiple networked sensors on the body. In this work, we focus on the first class of applications.

When compared to other network topologies, there are distinct challenges for BANs that are driven by two main constraints. On the one hand, one wants to enable reliable wireless communication between portable devices in close proximity to the entire human body and, therefore, one must take into account the body's influence on the propagation of the communication signals. On the other hand, a key considera-

tion is the interference between BANs belonging to different persons: in a scenario in which every person carries his own body network, interference and security management become critical issues, especially in crowded spaces such as a conference center, a cinema, or a restaurant.

Both problem domains, more or less, can be addressed by different parts of the RF-based communication system. However, since the 1990s, the idea of using the human body itself as a propagation medium [2–5] seems a promising approach to find a direct solution to these issues. The human body is no longer an obstacle to cope with, but it becomes the very center of the network that is spatially limited to the body itself or to its very proximity. This last feature makes this technology, which we refer to as body-coupled communications (BCC), a very scalable networking approach, because interference is possible only between people in very close proximity, or even in direct contact, with each other.

The special characteristics of BCC make this technology a *human-centric connectivity* technology. First, BANs are limited in range to the minimal personal proximity of their users, making the networks individual and private, with high-communication reliability and low-power requirements for long battery lifetime. Furthermore, due to its inherent body-centric communication properties, BCC is well suited as a basis for applications based on intuitive interaction (e.g., touching something) and as an enabler for safe and convenient transactions.

The remainder of this article provides an overview of the characteristic features of BCC. We review BCC with respect to the physical properties, applications, and communication protocols. We conclude the article with an outlook on future developments and key research topics for BCC.

COMMUNICATION PRINCIPLE

The very principle of BCC is that a small electric field is intentionally induced onto the human body to propagate a signal between devices that are in its proximity or in direct contact with it. Since this idea was presented for the first time, several studies in this area have appeared, proposing different possible transceiver solutions and architectures. Nevertheless, only two conceptually different ways to induce the electric

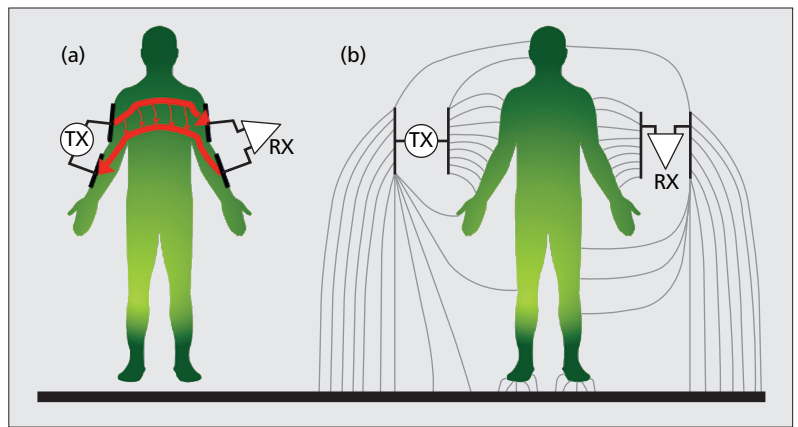
signal onto the body can be identified, and these are illustrated schematically in Fig. 1.

The first option, referred to here as the *transmission-line approach*, is to apply an electrical signal between two electrodes directly attached to the human body [3]. Based on the same concept, two electrodes are attached to the body at the receiver side, which are used to sense the differential signal there. Practically speaking, in this approach, the human body is treated as a special kind of transmission line.

The second approach, here referred to as the *capacitive approach*, uses the environment as a reference to force or detect a variation of the electric potential of the human body [2]. For this purpose, a differential pair of electrodes is used both for transmitting and receiving. At the transmitter side, a signal is applied between the electrodes: this generates a variable electric field in close proximity of the human body [6]. If the operation frequency is sufficiently low, for example, a few tens of megahertz, the human body acts as a floating conductor in a variable electrical field so that its electric potential changes with the transmitted signal. The receiver side uses two electrodes to differentially detect the varying electric potential of the person with respect to the environment. It is worth noting that the geometry and orientation of the electrodes plays an important role in maximizing the signal transfer from transmitter to body and from body to receiver. In an optimal configuration, one electrode must have a much higher capacitive coupling to the person than the other, so that a differential electric potential can be effectively transferred from the person to the device or vice versa. Practically speaking, here the human body is seen as a conductor that forms a bridge between transceivers that are capacitively coupled to it.

These two solutions present specific advantages and drawbacks from the technical and application point of view. The first important difference between the two solutions is that the communications behavior in the capacitive approach is strongly influenced by the environment around the body (e.g., the presence of objects made of conducting material influences the signal return path to ground), whereas in the transmission-line approach, the behavior is influenced more by the body's physical parameters. Both approaches are sensitive to the location on the body where the transceivers are placed: the transmission-line approach due to the dependence on the distance and the orientation along the body; the capacitive approach because the devices can be somewhat capacitively coupled directly between each other, but also because changes in the relative capacitive coupling between electrodes of the same device and body can lead to different signal-transfer characteristics.

From the application perspective, a significant difference between the two approaches is that the capacitive one does not necessarily require a direct contact to the human body, whereas for the transmission-line approach, this is preferred, if not necessary. In other words, the transmission-line approach requires the transceiver devices to be fixed to the person with the electrodes possibly in direct contact to the



■ **Figure 1.** Coupling mechanisms for BCC: a) the transmission line approach; b) the capacitive approach.

skin, whereas the capacitive devices need only be in the proximity and more loosely coupled. For that reason, we consider the capacitive approach to be the most relevant and hence, focus on this approach.

FREQUENCY RANGE AND BANDWIDTH

The frequency range of interest to BCC is much lower than typically considered for RF BANs. Whereas for the latter frequency, currently, bands of 2.4 GHz and 5 GHz and above are considered; frequencies below 100 MHz are of interest for BCC. At frequencies above approximately 100 MHz, the carrier wavelength approaches the length of (parts of) the human body, namely, smaller than 3 m. Consequently, the human body acts as an antenna, and the communication is no longer limited to the human body. This is undesirable because only devices placed on or near the same body are supposed to communicate.

Because very low frequencies are very susceptible to all kinds of electromagnetic interference, 100 kHz is considered as a reasonable lower frequency of the communications band. This yields a frequency band between 100 kHz and 100 MHz that is considered relevant for BCC operation in the BAN context. Note that in contrast to RF solutions, the size of the BCC device is not determined by the carrier frequency because it does not require an antenna adapted to it.

CHANNEL CHARACTERIZATION

To design a suitable connectivity solution based on capacitive BCC, a good understanding of the on-body channel is essential. Two relevant parameters for system design are the mean and variation in attenuation induced by the signal propagation. The former determines the required transmit power and receiver sensitivity, whereas the latter determines the required dynamic range of the receiver.

Characterization of the galvanic-coupled, on-body channel is presented in [3]. The on-body channel for the more attractive capacitive coupling has been characterized in other contributions [7, 8]. In these papers, however, at least

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one of the transmitters and receivers of the measurement set up is connected to ground earth through a main connection, making the characterized channels different from the channel experienced during BAN operation. Also, some use low-input impedances for the receiver, for example, 50 Ω , which limits the effective system bandwidth.

Therefore, we developed a channel characterization system, where both transmitter and receiver were isolated from any device connected or heavily coupled to earth ground. This better resembles the actual situation of a wireless BAN. Both transmitter and receiver were battery-fed and connected only by an optical cable for synchronization. The transmitter essentially consists of a direct-digital synthesizer that is operated by sweeping the frequency band of interest, namely, from 100 kHz to 60 MHz. The output power was 12 dBm. The receiver, with an input impedance of 100 k Ω , basically consists of a power detector with a dynamic range of 95 dB, which measures the received power for the different frequencies. The measurement system connected to a person is shown in Fig. 2a. Here the couplers consist of two parallel electrodes that are isolated from each other and from the skin. More details about the measurement system can be found in [9].

Among others, different measurements were made to characterize the influence of the location of the BCC nodes on the body, different coupler geometries, and body motion. The main results are discussed here to illustrate the impact of these parameters on signal attenuation.

Figure 2b illustrates the five coupler positions used, namely, three on the right arm, one on the chest, and one on the back of the right leg. The influence of the coupler location on channel attenuation is shown in Fig. 2c. As expected, the propagation loss increases with increased distance between the transmitter and receiver on the body. For propagation on the arm, the loss varies between 55 and 45 dB from the lower to the higher frequencies. For the chest-leg and leg-arm channel, 10 to 15 dB more loss occurs, but the frequency behavior is similar. The latter results show that even for large distances on the body, and for communications between the front and back of the body, reasonable signal attenuation is achieved, where the latter aspect is generally difficult in RF-based BANs. The maximum signal attenuation was typically found to be below 80 dB.

The results from measurements with different separations between the differential electrodes forming a coupler, an example of which is presented in Fig. 2d, show that a higher separation between the electrodes reduces the propagation loss. Too high of a separation between the electrodes is, however, impracticable for BAN nodes due to size constraints. Therefore, an electrode separation of 1 cm is considered a suitable trade-off between size and signal attenuation. Note that in a practical system, the space between the electrodes would be used to place the electronics of the BCC node.

The experimental results, moreover, confirmed that the body channel is essentially frequency flat and that no frequency selective

fading occurs. Also, other measurements validated that the communication range of BCC is indeed limited to the close proximity of the human body.

Also the influence of body movement was studied to understand the variation in signal attenuation that occurs when a person is moving. From results presented in [9], we can conclude that the standard deviation of movement was below 2.5 dB. From this we conclude that the signal-level variability during body movements is very limited. This is in contrast to what was found for RF-based BAN solutions. For these systems, the body shadowing does create large channel variability due to body movements, namely, in the range of 30 to 40 dB [10]. This poses quite a challenge for the design of RF transceivers, which is not an issue for BCC receivers.

SIGNAL MODULATION

The insights about the channel and the basic properties of BCC are important for designing a suitable modulation scheme. Unlike RF solutions, the whole signal bandwidth of almost 100 MHz can be used by a single BAN because the communication range is limited to the human body, and the frequency band can be reused for every BAN. This allows the use of wideband modulation techniques such as direct-sequence spread spectrum or frequency hopping. One can trade off noise and interference robustness against achieved data rate, depending on the application.

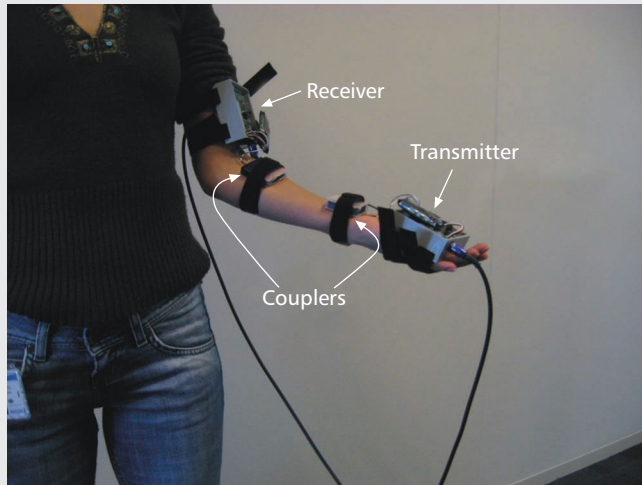
For low data-rate applications, however, it might be beneficial to design a narrowband solution, for example, based on frequency shift keying (FSK), which can potentially reduce power consumption and interference susceptibility.

As the frequency dispersion of the channel is limited, it is not very beneficial to apply multi-carrier techniques such as orthogonal frequency-division multiplexing (OFDM). Also, the signal detection can be relatively simple because the low dispersion allows for a simple equalizer.

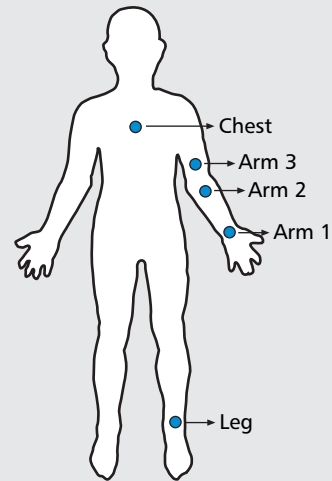
Because the frequencies of interest for BCC are low, that is, below 100 MHz, the signals can typically be generated by a low-frequency digital and analog subsystem that would be comparable to the baseband processing of a standard RF transmitter; no high-frequency front end is required. The same holds true for the receiver. Because the high-frequency stages of the analog front end determine mostly the power budget of an RF solution, a BCC solution omitting these can achieve much lower power consumption. Typically the power consumption is comparable to that of the baseband section of an RF solution. Recent implementations of BCC transceivers show that power levels of 1 nJoule/bit are achievable [4, 5], with data rates of 8–10 Mb/s at bit-error rates of below 10^{-3} .

APPLICATIONS

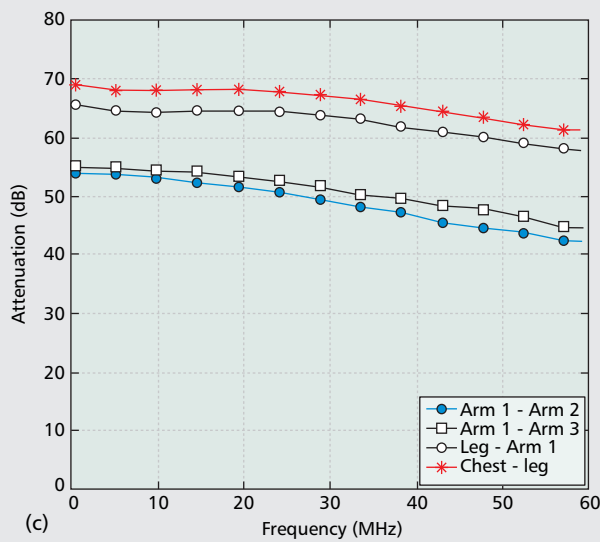
The BCC-based applications can be classified corresponding to two major technology concepts. The first class is called identification,



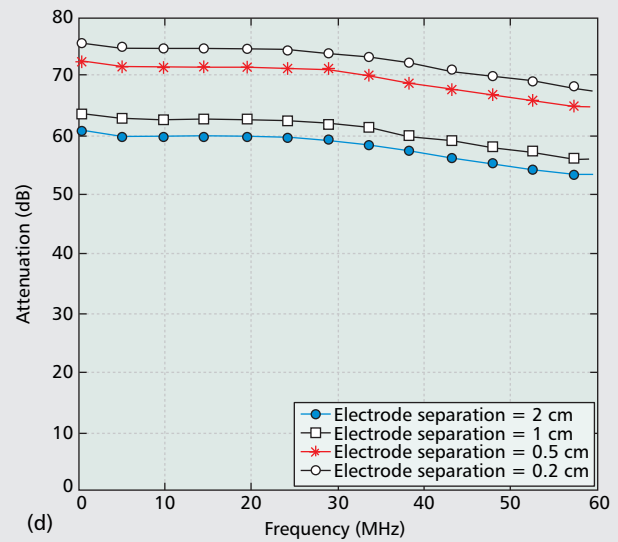
(a)



(b)



(c)



(d)

Figure 2. BCC channel characterization system and results: a) channel characterization system attached to the arm at positions “arm 1” and “arm 2”; b) measurement positions on the human body; c) influence of transceiver location on the signal attenuation as function of frequency; d) influence of electrode separation on the signal attenuation as function of frequency.

security, and control (ISC); it is characterized by the fact that the information transmission is not in itself the goal of the application. This means that the communication is an enabler for simplifying, accelerating, or securing an application that could be realized by another technology.

On-body interaction characterizes the second class of applications, which are called body-based data exchange (BBDE). Here the data transmission in itself is the goal of the application. A good example is music streaming over the body between a player and a headset. In the following, we detail these two application classes.

ISC

RF-enabled portable consumer devices, for example, mobile phones, headsets, and MP3 players, have attracted increasing interest over the last years. These devices must interact with each other or with other devices. Often it is nec-

essary to set up an RF communication link between two or more devices, for example, using Bluetooth, ZigBee, or WLAN. This requires that the devices discover each other and exchange the information required for the link set up. This can be a lengthy or troublesome procedure when performed in the conventional way because it typically requires manual intervention by the user.

BCC enables an intuitive user interaction to solve this problem. When BCC is added to RF devices, it enables the establishment of a communication link between two — or a network with several — RF devices, using BCC as a control channel. When a user touches two wireless devices, for example, a mobile phone and a display device (e.g., TV, monitor), these devices automatically can start interacting and exchange the required configuration parameters through BCC. In a similar way, additional wireless devices can be added to an existing wireless network by touching the new device



Figure 3. A user identification application using BCC: a) identification setup for user authentication on a laptop using a BCC identification tag on the user's wrist and a USB connected BCC transceiver; b) inside of the BCC transceivers with 3 cm × 5 cm electrodes. The upper transceiver, as worn at the wrist in a), is battery fed. The lower device additionally implements a USB connection, which is also used as power supply.

and one of the devices of the already established network.

A prime example of ISC is for user identification, which in Fig. 3a is illustrated for user authentication on a laptop. Here, the user is identified using a BCC transceiver tag on the body acting as a personal identifier. In this example, the BCC tag is placed on the user's wrist. By touching a BCC transceiver attached through a universal serial bus (USB) to the laptop, the authentication procedure is initiated and performed through BCC. The BCC transceiver we developed for the ISC application class, which enables among others, this identification application, is shown in Fig. 3b. Because the required throughput is small, it is based on a narrowband 125-kHz FSK solution, achieving a data rate of 4 kb/s.

BBDE

The second application class, BBDE, is the use of BCC for communication between several devices on or close to a person's body. Instead of using RF as in the previous case, the devices use BCC directly to exchange data.

Here BCC introduces significant advantages for end users handling their mobile devices. First, the minimal power consumption enables a long run time for applications, such as an MP3 player streaming music to headphones. Second, data can be exchanged between mobile devices of people touching each other — allowing, for example, easy music or video sharing. Furthermore, with multiple mobile devices that users carry with them, such as an MP3 player, mobile phone, watch, or a personal digital assistant (PDA), a joint BCC headset avoids the troublesome handling of individual output devices for each system. In the same system, data can be exchanged or shared between the user's devices, for example, between a portable multimedia player and a mobile phone.

COMPETITIVE TECHNOLOGIES

In addition to the BCC technology, there are several RF-based technologies that can be used to realize some of the ISC or BBDE applications introduced above. We compare the relevant parameters of several of them in Table 1.

Bluetooth is a long-range, high data-rate solution. It enables point-to-point connections between devices and is widely used in CE products. IEEE 802.15.4 is a low data-rate communication solution aimed at monitoring and control applications and used as the basis for ZigBee. The relatively large RF range of both technologies does not enable ISC and has the disadvantage of overlapping coverage areas between different BANs, reducing their suitability for the BBDE application. Near field communications and radio-frequency identification (RFID) are short-range radio solutions used for logistic, payment, and identification purposes. These could be used to realize some ISC applications but are less practical than BCC because they do not allow for intuitive interaction. Also, these do not enable the BBDE applications.

COMMUNICATION PROTOCOLS

The two application classes differ regarding several factors that highly influence the design of the communication protocols for a BCC system. Therefore, it is important to understand the fundamental characteristics of the application layer to derive the challenges these impose on the design of the medium access control (MAC) and network layers. This understanding also enables us to compare BCC with standard radio technologies with respect to the illustrated applications classes.

NETWORK LAYER

As shown above, BCC communication covers the entire body, and the physical (PHY) layer enables any node to communicate in a single

	Bluetooth v. 2.0	IEEE 802.15.4	RFID UHF	NFC	BCC
Frequency	2.4 GHz	2.4 GHz	860–960 MHz	13.56 MHz	100 kHz–100 MHz
Range	100m	20 m	5 m	0.1 m	On and near the body
Max. data rate	3 Mb/s	250 kb/s	160 kb/s	424 kb/s	10 Mb/s [4]
Enables ISC?	--	-	+	+	++
Enables BBDE?	+	+	-	--	++

■ **Table 1.** Comparison of BCC with relevant RF technologies.

hop with the rest of the network. Hence, there is no requirement for a routing protocol.

MAC LAYER

A direct implication of a single-hop network is that request to send/clear to send (RTS/CTS)-like mechanisms are not required. These are commonly used in wireless networks to deal with the hidden terminal problem, which is less present in BCC networks, where the PHY layer is designed so that all nodes are reachable in a single hop.

The MAC layer design is highly influenced by the supported application classes. The most obvious differences between ISC and BBDE are the required throughput and the resulting communication patterns. Whereas an ISC application requires — rarely and irregularly — the transmission of few bits, for example, for an identifier, a BBDE application requires a large data rate (up to 10 Mb/s), regularly over long periods of time. The number of nodes realizing the application plays another important role in the required throughput. When we consider the ISC class as an example, it is clear that a simple identification application might only involve two nodes, whereas a node association application concerns a network consisting of numerous nodes. So in general, both the information flow between two nodes and the global network traffic are strongly application dependent.

Moreover, the two application classes require a different trade-off between reliability and latency. High reliability is required for ISC because the nodes exchange important information, such as network addresses to enable wireless communication or security keys for authentication of nodes. In both cases, the relevance of the information is such that erroneous communication simply prevents the application. On the other hand, latency is less of an issue; the application can tolerate a delay for initial information exchange. When we consider BBDE, the requirements for reliability of the communication, for example, of streaming multimedia content are less stringent. The latency, however, must be low because a delay would strongly decrease the perceived application quality.

The above motivates the requirement for an adaptive MAC layer because BCC networks preferably should support both application classes. Consequently, the system should enable low-power, low data-rate communications, as well as

higher rate transfers. It should provide high reliability at the cost of latency, but also enable streaming applications with low latency at the cost of reliability.

Currently no communication standard provides such adaptability features. The IEEE 802.15.4 standard provides a data rate that is sufficient for ISC, but does not enable BBDE. Bluetooth fulfills the data rate requirement of BBDE, but only enables peer-to-peer communication, which precludes large networks. Moreover, neither provides adaptability.

NETWORK TOPOLOGY

The BCC network architecture also is largely influenced by the applications. Whereas an application of the BBDE class may benefit from a star topology, for example, where a central device could poll nodes to collect data; an application of the ISC class is enabled only by a mesh structure. In the latter scenario, the number of nodes attached to the body can be highly variable, and consequently, it is difficult to distribute roles among the nodes in the network. Taking the example of node association, a single node cannot continuously detect new nodes and check the presence of already known nodes. Namely, if this particular node is removed from the BAN, the whole application would be disabled. Hence, we consider the mesh architecture to be the most appropriate for BCC networks to avoid a single point of failure.

CONCLUSIONS AND OUTLOOK

BCC has been introduced in terms of basic principles, communications channel, and protocol properties, as well as new types of applications being enabled. BCC appears to be a promising solution for efficient BANs because it shows good performance in terms of power and bandwidth, and because using the human body as a communication medium creates new opportunities for overcoming known problems of RF systems, such as shadowing by the human body and interference between different networks. First implementations of integrated energy-efficient solutions have been presented in the literature [4, 5].

To advance BCC further, several challenges must still be addressed from the technical point of view. Work was performed to achieve a modeling of the signal transfer along the human

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The realization of an optimized protocol stack, in particular concerning the MAC layer, is an important research area due to the specific BCC channel and application properties.

body, but this work is not exhaustive because it has not been performed on a statistically relevant population. Moreover, the influence of the external environment, for instance, due to interference, generates an additional source of variability that has not been completely addressed yet. This knowledge can be used to yield a definitive conclusion on an optimal approach for an energy efficient physical layer. The realization of an optimized protocol stack, in particular concerning the MAC layer, is an important research area due to the specific BCC channel and application properties.

Finally, from the user perspective, human-centered connectivity is well achieved by BCC. On the one hand, it enables a paradigm shift toward intuitive applications on user-device interaction and content sharing, as well as on device sharing. On the other hand, it provides, along with its communication and security protocols, a reliable, safe, and private communication environment.

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BIOGRAPHIES

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