Effect of transformer symmetry on intrabody communication channel measurements using grounded instruments[1]

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ABSTRACT

Transformers with one winding terminal symmetrical with respect to ground (capacitances between their terminals and ground are the same) are referred to as balun transformers, and are often used for decoupling in the measurements of the intrabody communication (IBC) system transmission characteristics. We measured IBC system amplitude and phase transmission characteristics using three types of galvanic decouplers: non-symmetric RF transformers, balun transformers with center tap grounded and balun transformers with center tap floating. Four possible electrode configurations (AA, AB, BA, and BB) and four electrode arrangements (GSGS, GSSG, SGGS, and SGSG), result in a total of 16 measurement scenarios for each of three measurement setups. We showed that the change in the measured amplitude for different signal and ground electrode arrangements while measuring with non-symmetric transformers is influenced by the transformer symmetry to the ground, and not the capacitive intrabody communication transmission characteristics. The change of the amplitude in case symmetric balun transformers are used is negligible for practical purposes.

Keywords: Capacitive coupling, Electrode configuration and arrangement, Intrabody communication (IBC), Transformer symmetry

SAŽETAK

Utjecaj simetrije transformatora na mjerenja prijenosne karakteristike sustava za prijenos signala ljudskim tijelom prilikom korištenja uzemljenih uređaja.

Transformatori kojima su priključci jednog namota simetrični u odnosu na masu (kapaciteti između priključaka i mase su jednaki) se nazivaju balun transformatori i često se koriste za galvansko odvajanje prilikom mjerenja prijenosne karakteristike sustava za prijenos signala ljudskim tijelom (IBC). Mi smo mjerili amplitudnu i faznu prijenosnu karakteristiku IBC sustava korištenjem tri načina galvanskog odvajanja transformatorima: nesimetričnim RF transformatorima, balun transformatorima s uzemljenim srednjim izvodom i balun transformatorima s plivajućim srednjim izvodom. Četiri konfiguracije elektroda (AA, AB, BA i BB) i četiri načina spajanja signalne i referentne elektrode na tijelo (GSGS, GSSG, SGGS i SGSG), rezultiraju s ukupno 16 scenarija za svaki od tri mjerna postava. Pokazali smo da na promjenu amplitude prijenosne karakteristike uslijed zamjene položaja signalne i referentne elektrode prilikom mjerenja s nesimetričnim RF transformatorima utječe simetrija izvoda transformatora

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prema masi, a ne karakteristika kapacitivnog IBC sustava. Promjena amplitude prilikom mjerenja balun transformatorima je bila zanemariva za praktične namjene.

Ključne riječi: Kapacitivna sprega, konfiguracija i položaj elektroda, prijenos signala ljudskim tijelom, simetrija transformatora

1 Introduction

Intrabody communication (IBC), also known as human body communication (HBC), is a wireless communication technique in which the human body becomes an integral part of the communication channel, [1, 2]. Transmitter and receiver IBC units are placed directly on the skin or in its close proximity, and their maximal distance is the subject's height. In the capacitive coupling approach, the signal transmission path is closed through the human body, and the signal return path is closed capacitively through the environment. Finding a proper procedure and measurement setup for measuring capacitive IBC channel characteristics while keeping the IBC signal path intact is a very challenging task, since introducing any kind of measuring equipment into the IBC channel modifies the return signal path and, usually, influences the measurement results. Whenever the power-line-powered measuring equipment is used for measuring IBC channel transmission characteristic, part of the signal is coupled through the power-line and the measured transmission gain is somewhat higher than in a realistic IBC scenario, [3-7].

Using independent battery-powered transmitter and receiver isolated mutually and from the earth ground (environment) is theoretically the correct way of measuring the IBC channel transmission characteristic. However, this configuration has many practical shortcomings, because it is very difficult to precisely sweep the signal frequency over a wide frequency range, and to detect the received signal strength by using small low-powered battery devices. For this reason, in practical implementations a galvanic decoupling between the human body together with the electrodes, which represent an interface to the test subject, and the measuring instruments (usually a network analyzer, signal generator or oscilloscope) is made. Consequently, the general capacitive IBC measurement setup consists of a device under test (human body), human body interface (electrodes connected in different manners), decoupling hardware, and measuring instrumentation. Galvanic decoupling is usually realized using an optical link [8] or, much more often, connecting transformers between the transmitter/receiver electrodes and the rest of the measuring equipment [4-7, 9-14]. However, the influence of the transformers on the measured results has been commented in a few papers only recently [7, 11-14].

Sakai *et al.* analyzed influence of the RF transformers on the measured capacitive IBC channel characteristics in [11, 12] and found that the value of the capacitance between primary and secondary windings of the transformer (interwinding capacitance, IWC) can influence the results drastically. Interwinding capacitance of four tested baluns varied from 1.1 pF to 32.0 pF, which resulted in a 40 dB difference between the minimal and maximal amplitude of the measured capacitive IBC channel transmission characteristics. The lowest amplitude was measured using a transformer with the lowest interwinding capacitance. Pereira *et al.* in [7] developed a model of the extended IBC channel which includes a capacitive IBC channel and the test fixture (RF transformers and the transition between the coaxial cables and the other parts of the system) used in the measurements. They tested two RF transformers and measured interwinding capacitances of 27.2 pF and 8.6 pF (which were 32.0 pF and 10.9 pF in [11], respectively). The model simulation results agreed well with the measured amplitude channel characteristics in the frequency range from 1 MHz to 70 MHz, and showed that the effect of the test fixture on the channel measurement results is present even after the calibration of the measurement setup. Adding test fixture to the capacitive IBC channel model increased the amplitude of the measured capacitive IBC channel transmission characteristics by 43–50 dB. Callejón *et al.* studied the influence of different measurement equipment and conditions on the IBC channel [14]. They focused on the galvanic coupling IBC mainly in the frequency range between 10 kHz and 1 MHz and analyzed differences when using transformers or battery powered devices, the effect of the load resistance, the use of different measurement equipment (signal generator, oscilloscope, network and spectrum analyzer), and the effects caused by different cables and connections. Three grounding strategies in a setup with a vector network analyzer (VNA) and the same balun as in [7, 11] with IWC approximately 10 pF were 1) without transformers, 2) transformer at the transmitter VNA port, and 3) transformer at the transmitter and receiver VNA ports. The results obtained using grounding strategies 2 and 3 were equivalent. Measured IBC channel amplitude transmission characteristics in [7, 11, 12, 14] all increase 20 dB/decade, the amplitude value at the single frequency increases with interwinding capacitance of the transformers, and it is comparable for the same RF transformers.

In the measurements of the capacitive IBC channel transmission characteristics using grounded equipment and transformers, transformer winding terminals connected to the human body should be balanced, i.e. symmetrical with respect to the ground, [13, 15]. This means that switching the signal and ground electrodes of the same transmitter/receiver electrode pair should have no influence on the measured transmission amplitude characteristics. However, some of the commercial RF transformers used in the measurements of the IBC system transmission characteristics [4-7, 9-14] do not have symmetrical capacitances between their 'balanced' terminals and ground. This issue was not previously discussed in the available literature and might result in drastically different measurement results and their misinterpretation.

In this paper we expand the results published in [13] and show that the arrangement in which the signal and ground electrodes are connected to the body has a significant influence on the transmission characteristics measurement results when non-symmetric RF transformers are used for galvanic decoupling. The change in the measured amplitude for different electrode arrangements is influenced by the transformer symmetry to the ground, and not the capacitive intrabody communication transmission characteristics. We will also show that there is negligible change in the measured amplitude in case symmetric balun transformers are used.

The paper is organized as follows: in Section II the theory behind galvanic decoupling using RF transformers, electrode configurations, signal and ground electrode arrangements, and the measurement setup are described. In Section III the measurement results and discussion are given, and in Section IV the conclusion and measurement recommendations are presented.

2 Measurement setup

2.1 General IBC system

Electrodes of an IBC battery-powered transmitter, as well as the electrodes of an IBC battery-powered receiver, placed on the body, can be considered as being balanced to the ground. Transmitter represents the source, and receiver represents the load of a balanced circuit. In a general balanced case, which mimics battery powered IBC transmitter and receiver devices as in Fig. 1, the sources U_{S1} and U_{S2} together produce the signal current I_S, while common-mode interference voltages U_{N1} and U_{N2} produce opposite interference currents I_{N1} and I_{N2}, [15]. The total voltage U_L developed across the load is:

$$U_L = I_S\left(Z_{L1} + Z_{L2}\right) + I_{N1}Z_{L1} - I_{N2}Z_{L2}\,. \qquad (1)$$

For a balanced condition $Z_{S1} = Z_{S2}$, $U_{S1} = U_{S2}$, $U_{N1} = U_{N2}$, $I_{N1} = I_{N2}$, and $Z_{L1} = Z_{L2}$ so (1) reduces to:

$$U_L = I_S\left(Z_{L1} + Z_{L2}\right),$$

which is the voltage only due to the signal current originating in the source.

When there is a capacitive coupling between the load terminals 1 and 2 and the environment (i.e. between the human body and the environment), capacitive interference voltage U_3 couples to the system through parasitic capacitances C_{31} and C_{32}, as in Fig. 1. Induced voltage U_{C1} at the load terminal 1 is:

$$U_{C1} = \frac{Z_{L1}}{Z_{L1} + Z_{31}} U_3\,,$$

and voltage U_{C2} at the load terminal 2 is:

$$U_{C2} = \frac{Z_{L2}}{Z_{L2} + Z_{32}} U_3\,.$$

In the measurements of IBC channel transmission characteristics, load terminals 1 and 2 are receiver signal and ground electrodes. They are placed on or very near the body, so the impedance Z_{31} approximately equals Z_{32}. As already mentioned, $Z_{L1} = Z_{L2}$, so the voltages U_{C1} and U_{C2} are equal and cancel themselves at the load.

A difference between the source and load ground potentials, U_G in Fig. 1, results in equal voltages at load terminals 1 and 2, which also cancel themselves in the load. Therefore, for accurate measurement results, balanced windings center tap source (transmitter) and load (receiver) terminals do not necessarily need to be grounded or at the same potential.

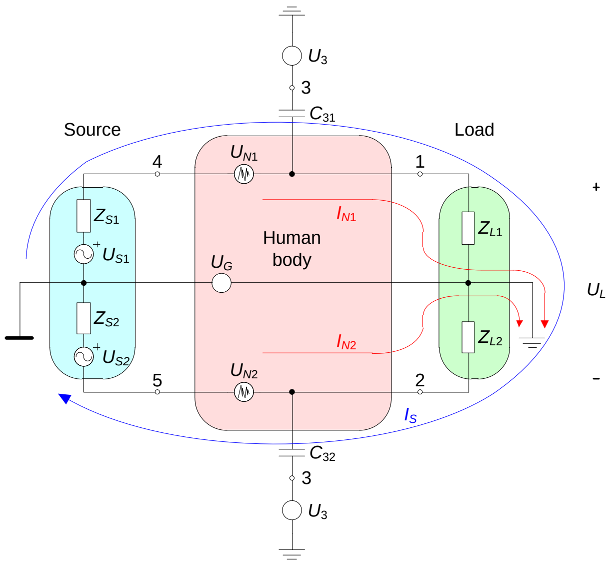

Figure 1.A general case of a balanced IBC system

2.2 Decoupling transformers

A balun transformer is a two-winding transformer designed to convert a single-ended signal to one balanced with respect to ground (differential signal), [15-17]. The balanced winding may or may not be center-tapped. A center-tap would ideally be at a virtual ground and may be either grounded, connected to a DC potential or left floating. In the balanced system common mode signals will induce equal currents in each terminal of the balanced circuit and equal voltages from each side to ground. As a result, no common mode signal appears at the load terminals.

In the measurements of the IBC channel transmission characteristics, when either the same device is used for signal generation and measurement or when grounded instruments are used, two decoupling transformers are needed: one as a source between the transmitter electrodes (signal electrode S TX and ground electrode G TX) and the instrument, and the other as a load between the receiver electrodes (signal electrode S RX and ground electrode G RX) and the instrument, with the balanced windings of both transformers connected to the human body, and the unbalanced windings connected to the measuring instrument, as in Fig. 2. In this setup balanced transformer terminals 4 and 5 mimic the source and balanced terminals 1 and 2 mimic the load from Fig. 1 and C_b is the capacitance between the human body and the environment. However, in practice due to the parasitic coupling between the balanced terminals and the environment, as well as between the balanced and unbalanced terminals, balanced conditions are not always fulfilled.

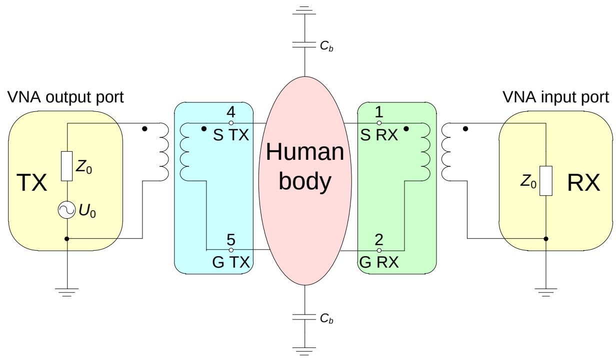

Figure 2.Measurement setup with galvanic decoupling using transformers

In this paper two types of transformers are used: Mini-Circuits® FTB-1-6*A15+ [18], also used in [4, 5, 7, 11-13] (similar model FTB-1-1 in [6, 7, 10-12, 14]), and North Hills™ 0300BA [19] transformers. Mini-Circuits® FTB-1-6 is a coaxial RF transformer designed to operate between 10 kHz and 125 MHz frequency and has two female BNC connectors. Shield of the BNC connector at the primary side is connected to the transformer casing, and the secondary side is isolated from the casing and the primary side. North Hills™ 0300BA is a general purpose balun transformer designed for operations from 100 kHz to 125 MHz. Primary and secondary side are isolated from each other and from the casing. Unlike the Mini-Circuits® FTB-1-6 transformer, North Hills™ 0300BA has a secondary center tap available. Both transformers are 1:1 50 Ω models and have very low insertion loss.

The longitudinal balance of the transformer is a measure of its symmetry with respect to the ground, [16]. Let C_{bal1} be the capacitance between the balanced winding high terminal and the unbalanced side ground, and C_{bal2} the capacitance between the balanced winding low terminal and the unbalanced side ground, as in Fig. 3.

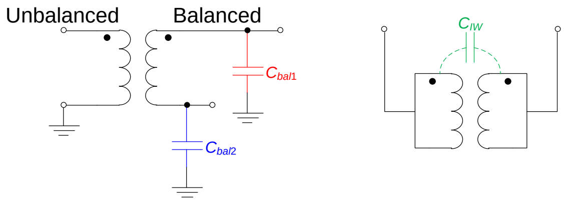

Figure 3.Balanced winding terminals capacitances to ground (left) and interwinding capacitance (right)

For a perfectly symmetrical balun transformer, these capacitances should be equal in the whole frequency range. They were measured for both transformers using precision impedance analyzer Agilent 4294A and a 16048A test lead, which operates up to 30 MHz. The results are presented in Fig. 4 for Mini-Circuits® FTB-1-6 (dashed line) and North Hills™ 0300BA (full line) transformers, respectively.

In the case of a Mini-Circuits® FTB-1-6 transformer, capacitances C_{bal1} and C_{bal2} were not the same in the whole frequency range. The value of C_{bal1} was 28 pF at 100 kHz and 7 pF above 2 MHz and C_{bal2} value was a constant 27 pF. Therefore, since the Mini-Circuits® FTB-1-6 transformer isolated winding is not symmetrical with respect to ground, it should not be referred to as a balun transformer. However, North Hills™ 0300BA truly is a balun transformer, since the capacitances between the balanced side and the ground, although frequency-dependent, differ less than 1.5 pF.

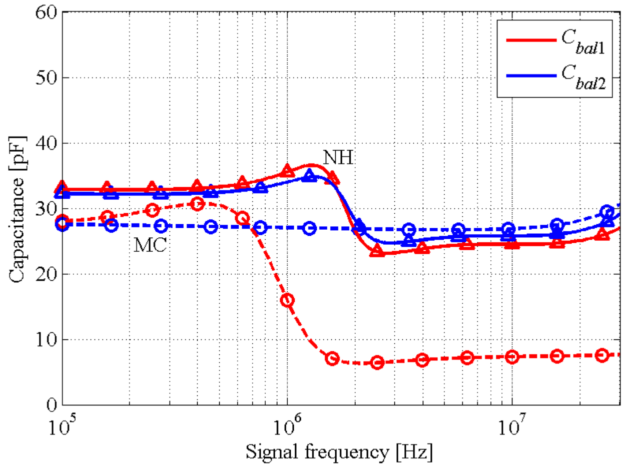

Figure 4.Capacitances between transformer secondary winding terminals and a measuring instrument ground

Another important parameter of a transformer is the parasitic capacitance between the primary and secondary winding, i.e. interwinding capacitance C_{IW} in Fig. 3. It allows flow of the common mode signal through the transformer, thus affecting the measurement results. In [11, 12] the authors have compared several different types of RF transformers that have different interwinding capacitances. They proved that transformers separate transmitter and receiver grounds from each other and from the instrument ground, but the amplitude of the measured transmission characteristics highly depends on the value of interwinding capacitance: for higher interwinding capacitances measured transmission amplitude is higher. The C_{IW} value was measured connecting high and low clamp of each winding together and measuring the capacitance between the primary and secondary side, as in Fig. 3 right, using precision impedance analyzer Agilent 4294A. The obtained results are 26 pF for Mini-Circuits® FTB-1-6 (values reported in the literature: 27.2 pF in [7] and 32.0 pF in [11]), and 23 pF for North Hills™ 0300BA transformer.

2.2.1 Decoupling transformers implementation

Decoupling transformers are placed between the measuring instrument and the electrodes, which are then placed on or near the body. Since the Mini-Circuits® FTB-1-6 transformer output is not symmetric to the ground, a coaxial cable, which is inherently asymmetric, was used for connecting the transformer to the electrodes. Electrode clamps were soldered to a 21 cm long coaxial cable: signal electrode to the inner conductor, and the ground to the cable shield.

In order to keep the symmetry of the measurement setup, the balun transformers North Hills™ 0300BA should be connected to the electrodes with a symmetrical cable. If coaxial cable is used in a balanced system, two short cables with grounded shields should be used, [15]. Provided a cable is no longer than 1/20 of a wavelength a single ground connection is enough; otherwise on longer cables multiple grounds may be necessary, [15]. The highest frequency used in the measurement was 100 MHz which has a wavelength of 3 m, so the distance between the successive ground points had to be shorter than 15 cm. For a good electric field shielding it is also necessary to minimize the length of the center conductor that extends beyond the shield, [15]. Connecting shielded cable close to the measurement electrodes mitigates the effects of stray capacitance [20]. Therefore, for connecting North Hills™ 0300BA balun transformers balanced winding terminals to the electrodes two parallel coaxial cables 21 cm long were used, with 11 cm-long shield. The length of unshielded center conductor was 1.5 cm between the balun and the shield, and 8.5 cm between the shield and the electrodes. One end of the cable shield was soldered to the ground plane of the balun transformer at the secondary center tap. Shields were soldered together in 5 points every 3 cm, except between the last two points which were 2 cm apart. A photo of both transformers with cables and electrode clamps can be seen in Fig. 5.

Figure 5.A photo of Mini-Circuits® FTB-1-6 (down) and North Hills™ 0300BA (up) transformers with cables and electrode clamps

2.3 Electrodes

Both a transmitter (TX) and a receiver (RX) of an intrabody communication system have a signal (S) and a ground (G) electrode, which can be connected to the human body in two ways, namely:

configuration A - both signal and ground electrodes of the same transmitter/receiver electrodes pair are placed on the body, the impedance between the electrodes is predominantly resistive;

configuration B - one electrode of the transmitter/ receiver pair is placed on the body, and the other one is 2 cm above it, in the air; the impedance between the electrodes is predominantly capacitive.

In the configuration A we used two standard Ambu® Blue Sensor Ag/AgCl electrodes with the conductive paste, placed directly on the test subject's skin, 2 cm apart. In the configuration B, the electrode on the skin was Ag/AgCl electrode, and the electrode pointing towards environment was 2 cm x 2 cm bare copper electrode, placed 2 cm above the Ag/AgCl electrode.

In general, there are four possible ways of connecting transmitter and receiver as a part of a capacitive IBC channel: A transmitter - A receiver (AA), A transmitter - B receiver (AB), B transmitter - A receiver (BA), B transmitter - B receiver (BB). The first letter in the electrode configuration acronym corresponds to the transmitter and the second letter to the receiver electrodes configuration, Fig. 6. Two signal (S) and two ground (G) electrodes in the capacitive IBC system can be connected to the body in four different arrangements, namely GSGS, GSSG, SGGS, and SGSG. Electrodes arrangement (positions of signal and ground electrodes) acronyms consisting of four letters in Fig. 6 are always marked looking from the wrist to the elbow, in counterclockwise direction. First two letters of the acronym correspond to the transmitter, and the last two letters to the receiver electrodes. Middle letters always refer to the electrodes on the skin, and the outer letters refer to the electrode on the skin for the electrode configuration A, and the electrode in the air for the configuration B.

There are sixteen possible combinations of different electrodes configurations and arrangements. Four of the sixteen combinations for different signal and ground electrode arrangements are presented in Fig. 6. The remaining combinations can be determined analogously.

In the literature the most common electrode configurations are AA, referred to as galvanic, and BB as a capacitive. In [21] configurations AA, AB, BA, and BB are referred to as cases 2-2, 2-1, 1-2, and 1-1 respectively. Usually, only electrode arrangement GSSG is tested.

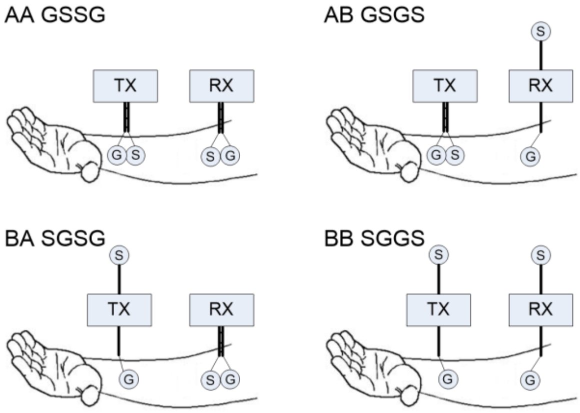

Figure 6.Electrodes configurations and arrangements

2.4 Measurement setups

Measurements of the transmission characteristics were performed using Rohde&Schwarz® ZVL13 vector network analyzer as a transmitter and a receiver. The analyzer is power-line-powered, with 50 Ω characteristic impedance, and is capable of measuring full 2-port *S*-parameters from 9 kHz to 13.6 GHz without additional equipment. Measured noise level was -110 dB (> 1 MHz) with 1 kHz intermediate frequency filter. A full two-port TOSM (through-open-short-match) calibration was performed prior to the measurements. In all the measurements of the IBC channel transmission characteristic the excitation signal frequency was swept from 100 kHz to 100 MHz. The signal output power was kept at 0 dBm, which is well below the recommended safety limits (0.08 W/kg for the whole body average SAR, and 20 mA for the maximum allowed contact current), [22]. Decoupling transformers were placed between the instrument and the transmitter electrodes, and between the receiver electrodes and the instrument, as in Fig. 2, with unbalanced winding connected to the instrument and the other side of both transformers was connected directly to the test subject's body. Total of three measurement setups (comprising capacitances C_{bal1} and C_{bal2}) were tested:

1) galvanic decoupling using unbalanced RF transformers (Fig. 7 left);

2) galvanic decoupling using balanced RF transformers with center tap connected to the ground potential (Fig. 7 right, position 1);

3) galvanic decoupling using balanced RF transformers with center tap floating (Fig. 7 right, position 2).

Measurements were performed on a single test subject in the same environment. Transmitter and receiver electrodes were placed on the subject's left forearm, and the distance between the nearest Ag/AgCl transmitter and receiver electrodes was set to 16 cm. Four possible electrode configurations (AA, AB, BA, and BB) and four electrode arrangements (GSGS, GSSG, SGGS, and SGSG), result in a total of 16 measurement scenarios for each of three measurement setups.

3 Measurement results and discussion

The results presented in this section are the amplitude and phase of the measured S_{21}-parameter, i.e. amplitude and phase transmission characteristic, for a given setup. All four S-parameters were measured simultaneously, and S_{21} and S_{12}-parameters were identical, which proves that the capacitive intrabody communication channel is reciprocal.

3.1 Decoupling using unbalanced RF transformers

In the case of a Mini-Circuits® FTB-1-6 transformer its 'balanced' winding terminals were not symmetrical with respect to ground, as shown in Fig. 4. Capacitances C_{bal1} and C_{bal2} were not the same in the whole frequency range, which is emphasized using different colors in Fig. 7 left. In Fig. 8 the S_{21} amplitudes (first column) and phases (second column) measured for the same transmitter electrode configurations (TX A first row, TX B second row) and all arrangements are illustrated in the same graph.

The two upper graphs in Fig. 8 show the amplitude and phase of the transmission characteristics obtained for the electrode configurations AA (blue lines) and AB (green lines). For the configuration AA switching the signal and ground electrodes does not change the overall symmetry of the measurement setup, so the change of the measured amplitude was below 2 dB. This is in accordance with the fact that in a galvanic coupling [23, 24], when all four electrodes are in the contact with the skin, switching ground and signal electrode should not introduce significantly different measured signal amplitude, since the impedance between the electrodes remains the same and is predominantly resistive. Also, the phase is the same for all four electrode arrangements (+90° up to 10 MHz, afterwards it decreases to -180° at 100 MHz). A resonance at 4 MHz is visible in all measurement results.

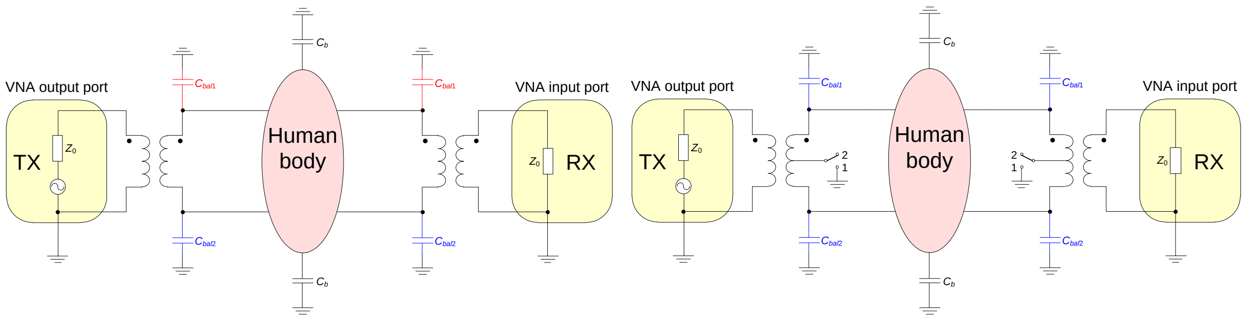

Figure 7.Measurement setup using Mini-Circuits® FTB-1-6 RF transformers for decoupling (left) and (right) North Hills™ 0300BA balun transformers with center tap connected to the ground potential (position 1) and floating (position 2)

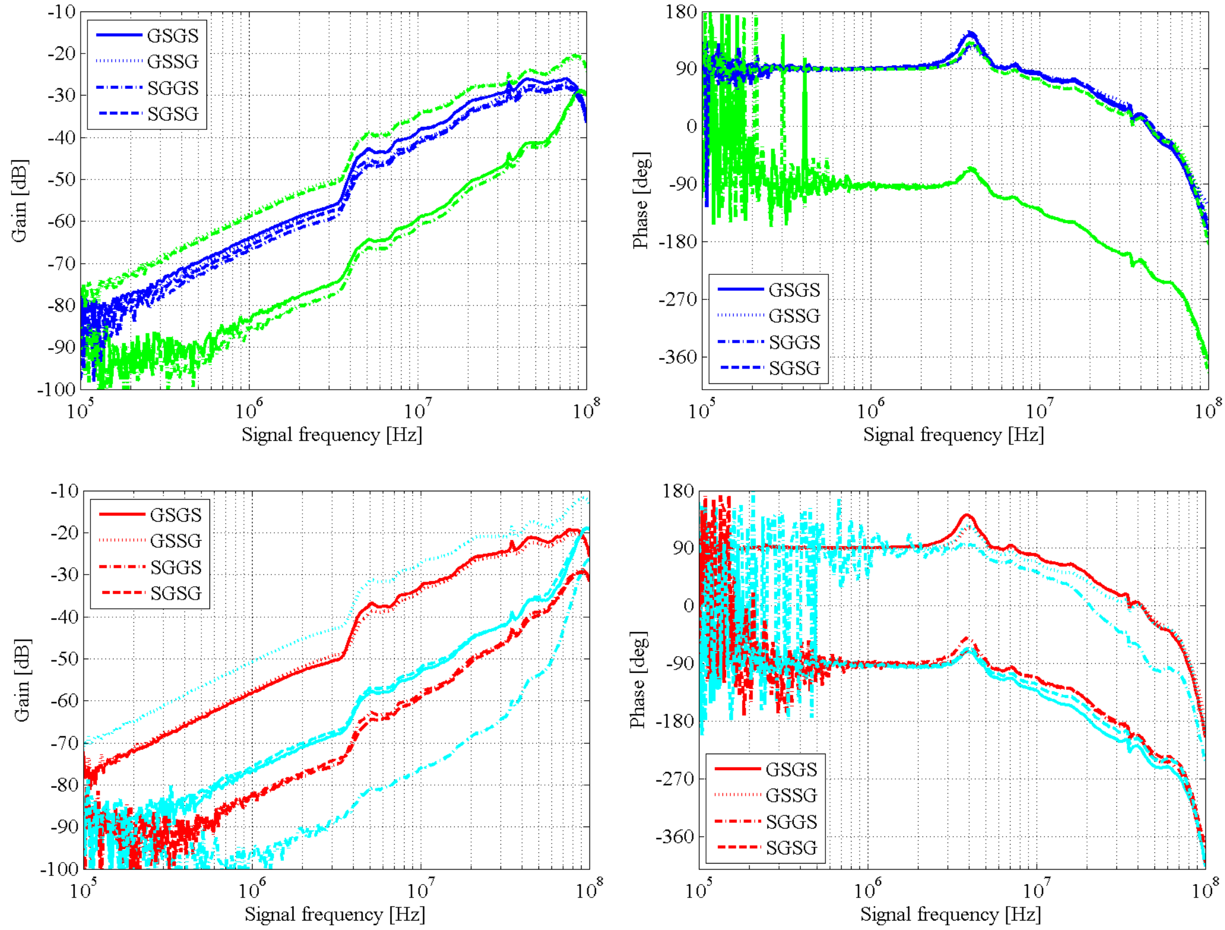

Figure 8.Amplitudes and phases measured using unbalanced RF transformers for different electrode configurations (AA – blue line, AB – green line, BA – red line, and BB – cyan line) and arrangements

In AB configuration case, the highest amplitude was achieved when the receiver signal electrode was on the skin and the ground electrode was in the air, regardless of the order of the transmitter signal and ground electrodes on the skin (GSSG and SGSG arrangements). The opposite arrangement of the receiver electrodes (signal electrode in the air, and the ground electrode on the skin, i.e. GSGS and SGGS arrangements) reduced the measured gain amplitude for 25 dB up to 20 MHz. Switching the transmitter A electrodes arrangement and keeping the receiver B electrodes arrangement the same, resulted in the minimal change of the measured gain: difference between GSSG and SGSG arrangements amplitude (dotted and dashed lines, respectively) was below 0.6 dB, and between GSGS and SGSG arrangements amplitude (full and dash-dot lines) was below 2 dB. The phase was +90° up to 10 MHz for the measurements which resulted in the highest amplitude (GSSG and SGSG arrangements), and -90° for the measurements with the lower amplitude (GSSG and SGSG arrangements). Switching transmitter (configuration A) signal and ground electrodes positions had no influence on the measured phase. Switching receiver (configuration B) signal and ground electrodes positions changed the phase by 180°.

The amplitudes and phases measured for the electrode configuration BA are presented in the second row in Fig. 8 (red lines). The highest amplitude was measured when the transmitter signal electrode was on the skin and ground electrode in the air, regardless of the order of the receiver signal and ground electrodes on the skin (GSGS and GSSG arrangements). When the transmitter ground electrode was placed on the skin, and signal electrode was in the air (SGGS and SGSG arrangements), the amplitude decreased by 25 dB. The difference between GSGS and GSSG arrangements amplitude (full and dotted lines) was below 0.8 dB, and the same as the difference and between SGGS and SGSG (dash-dot and dashed lines) arrangements amplitude. The phase was +90° up to 10 MHz for the measurements which resulted in the highest amplitude (GSGS and GSSG arrangements), and -90° for the measurements with the lower amplitude (SGGS and SGSG arrangements). Switching transmitter (configuration B) signal and ground electrodes positions changed the phase by 180°. Switching receiver (configuration A) signal and ground electrodes positions had no influence on the measured phase. Comparing the results obtained for the electrode configurations AB and BA, one can see that the measured amplitudes and phases were almost the same (the difference is below 0.8 dB) for the following configuration-arrangement pairs: AB GSSG, AB SGSG, BA GSGS, and BA GSSG, which resulted in higher amplitude and +90° phase, and AB GSGS, AB SGGS, BA SGGS, and BA SGSG, which resulted in lower amplitude and -90° phase. AB GSSG and BA GSSG match cases 1-2 and 2-1 in [21], for which the electric field intensities are theoretically identical.

Finally, the results measured for the BB electrode configuration, which is the configuration most discussed in the literature on capacitive intrabody communication [4-6, 9, 11, 12], are also in the second row in Fig. 8 (cyan lines). The GSSG electrode arrangement (dotted line) resulted in the highest gain of all sixteen measured electrodes combinations for this measurement setup. Switching signal and ground electrodes of either a transmitter (SGSG, dashed line) or a receiver (GSGS, full line), reduced the gain amplitude by 25 dB. Switching electrodes positions of both electrode pairs, i.e. placing both ground electrodes on the skin and both signal electrodes in the air (SGGS, dash-dot line) reduced the measured gain amplitude 50 dB in the whole frequency band. The phase was +90° up to 10 MHz for the electrode configuration GSSG, and changed by 180° when either transmitter or receiver signal and ground electrodes switched their positions.

Next, the results measured using the fixed electrode arrangement, i.e. same line types in Fig. 8, are analyzed. For the electrode arrangement GSGS (meaning that the transmitter signal and receiver ground electrodes are always on the skin, while the positions of the other two electrodes depend on the chosen electrode configuration; full lines) the measured gain amplitude was 20 dB higher for A configuration receiver than for a B configuration receiver, regardless of the transmitter electrode configuration. For a fixed receiver electrodes configuration (A or B), the gain was 6 dB higher for B transmitter than for A transmitter configuration. The phase was +90° up to 10 MHz for the measurements which resulted in the highest amplitude (BA and AA configurations), and -90° for the measurements with the lower amplitude (BB and AB configurations).

In the case of the GSSG electrode arrangement (dotted lines), which is the most common arrangement in the literature on capacitive intrabody communication [4-6, 9, 11, 12], both transmitter and receiver signal electrodes are placed on the skin. The highest gain amplitude was achieved in the case of BB electrode configuration. Amplitudes measured for AB and BA configurations were practically the same (the difference was below 1 dB at the highest frequencies) and 6.5 dB lower than BB configuration amplitude. AA configuration amplitude was another 6.5 dB lower than AB and BA configurations gain amplitude. The phase was +90° up to 10 MHz for all four tested electrode configurations, and decreased to –180° at 100 MHz frequency.

When transmitter and receiver ground electrode were connected to the skin (SGGS electrode arrangement, dash-dot lines), the highest gain was measured for AA electrode configuration. Gain amplitude for AB and BA configurations differed less than 3 dB. AA configuration gain amplitude was 16 dB higher than the BA amplitude, and AB configuration gain amplitude was 11 dB higher than BB configuration amplitude (above 30 MHz frequency this difference decreases). Also, in case of the BB electrode configuration the measured gain up to 1 MHz was below the noise limit of the measuring instrument, for the selected resolution bandwidth frequency (RBW). As this was the lowest gain amplitude measured for the selected sixteen configuration-arrangement combinations, for this particular measurement RBW was narrowed, since it obviously does not satisfy the practical IBC system requirements. The phase was +90° up to 7 MHz for the AA and BB configuration measurements, and -90° for the BA and AB configurations.

At last, the results for SGSG electrode arrangement are presented with dashed lines in Fig. 8. Measured gain amplitude was always higher for A configuration transmitter than for B configuration transmitter, regardless of the receiver electrodes configuration. The difference between the gain amplitudes was 7 dB for the same transmitter electrodes configurations (AB - AA and BB - BA), and 16.5 dB for the same receiver electrodes configurations (AB - BB and AA - BA). As for the GSGS arrangement, the phase was +90° up to 10 MHz for the measurements which resulted in the highest amplitude (AB and AA configurations), and -90° for the measurements with the lower amplitude (BB and BA configurations).

These results corroborate that the arrangement in which the signal and ground electrodes are connected to the body has a significant influence on the transmission characteristics measurement results when non-symmetric RF transformers are used for galvanic decoupling, [13, 25]. The change in the measured amplitude for different electrode arrangements is influenced by the transformer symmetry to the ground, and not the capacitive intrabody communication transmission characteristics. Not taking care of the electrode configuration and arrangement might lead to drastically different measurement results and their misinterpretation. Comparing the results in Fig. 8, one can see that switching the signal and ground electrodes of the A configuration transformer electrode pair has no influence on the measured phase, while switching the signal and ground electrodes of the B configuration transformer electrode pair changes the phase by 180°. Regardless of the electrode configurations, the highest gain is achieved for the GSSG electrode arrangement, when both signal electrodes are connected to the test subject's skin. In the GSSG arrangement case, the highest gain is achieved for the BB electrode configuration, configurations AB and BA have similar gains, and configuration AA has the lowest gain.

3.2 Decoupling using balun transformers

The other way of decoupling the instrument from the test subject's body is by using truly symmetrical balun transformers, like North Hills™ 0300BA transformers [19]. For this transformer from the practical point of view, the capacitances C_{bal1} and C_{bal2} can be considered equal, so they are drawn using the same color (blue) in Fig. 7 right. Differential measurements employing balun transformers were realized twofold: with secondary center tap connected to the ground potential (section 0; Fig. 7 right, position 1), and with center tap floating (section **Pogreška! Izvor reference nije pronađen.**; Fig. 7 right, position 2).

3.2.1 Center tap connected to the ground potential

S_{21} amplitudes and phases measured for four possible electrode configurations (AA, AB, BA, and BB) and four electrode arrangements (GSGS, GSSG, SGGS, and SGSG) are illustrated in the same graphs in Fig. 9.

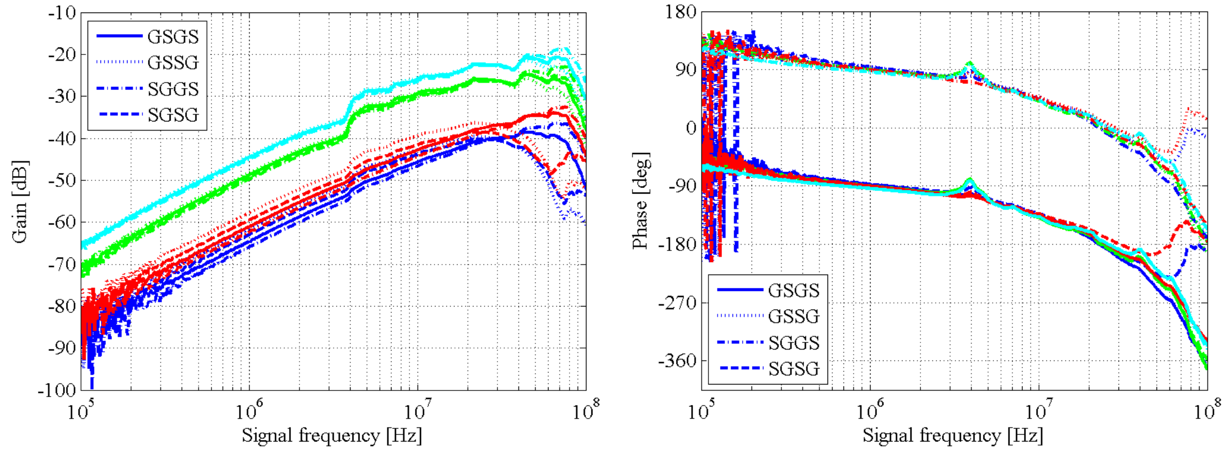

Figure 9.Amplitudes and phases measured using balun transformers with center tap floating for different electrode configurations (AA – blue line, AB – green line, BA – red line, and BB – cyan line) and arrangements

The results show that regardless of the transmitter and receiver electrodes configurations (A or B), the arrangement of signal and ground electrode has no influence on the amplitude of the measured gain, as expected, since symmetrical transformers are used for decoupling. Some differences are visible only at the highest frequencies, but at lower frequencies the differences are indistinguishable for practical purposes. When comparing measurements made with a fixed electrode configuration, one can see that the highest gain amplitude was always achieved for B configuration receiver, i.e. electrode configurations BB and AB, among which configuration BB had higher gain amplitude. Configurations with A receiver, BA and AA, have lower gains. All measured gain amplitudes are parallel, and the amplitude values at 1 MHz frequency are -22 dB, -26 dB, -31 dB and -35 dB for BB, AB, BA, and AA configurations, respectively. Switching signal and ground electrodes introduced 180° change in the measured gain phase. In the frequency range from 1 MHz to 10 MHz the phase was 0° when both electrodes on the skin were of the same type (GSSG and SGGS arrangements) and 180° when the electrodes on the skin were of a different type (GSGS and SGSG arrangements), in all 16 measurement scenarios.

However, on a closer look one can see that, although decoupled from the measuring instrument, in this measurement setup the signal path is closed through the center tap connected to the ground, and not capacitively through the environment. The human body and the center tap ground behave as a twin-lead transmission wire with losses. Therefore, using this measurement setup, only transmission characteristic of forward IBC path through the human body is measured.

3.2.2 Center tap floating

The S_{21} amplitudes and phases measured on the same test subject at 16 cm transmitter-receiver distance, for four possible electrode configurations (AA, AB, BA, and BB) and four electrode arrangements (GSGS, GSSG, SGGS, and SGSG) using the measurement setup as in Fig. 7 right, position 2, are presented in Fig. 10.

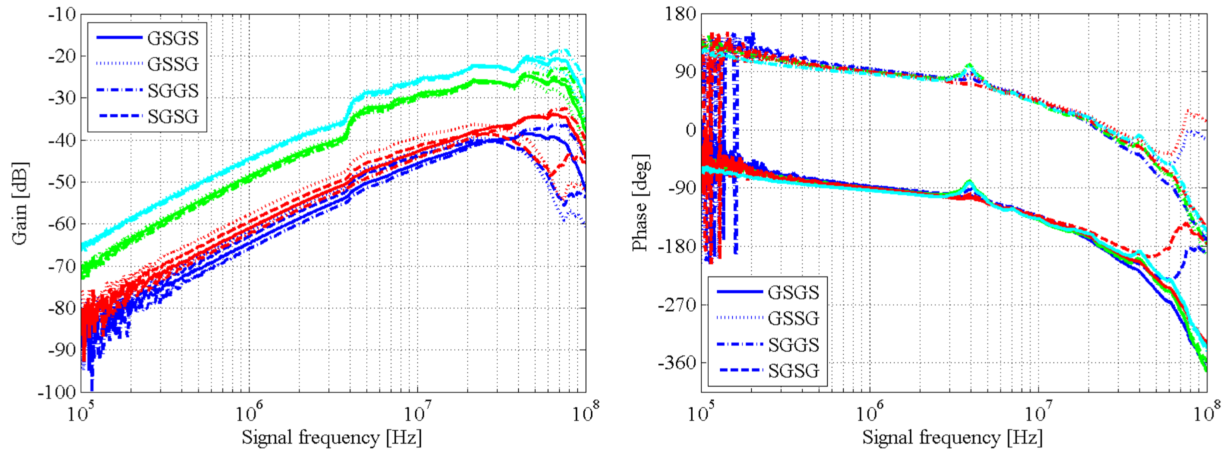

Figure 10. Amplitudes and phases measured using balun transformers with center tap floating for different electrode configurations (AA – blue line, AB – green line, BA – red line, and BB – cyan line) and arrangements

For a fixed electrode configuration AA (blue lines) switching either transmitter or receiver signal and ground electrodes introduces change of the measured amplitude below 1.2 dB, since this does not change the overall symmetry of the measurement setup. The greatest gain amplitude difference was between the GSSG and SGGS arrangements, and it was lower than 4 dB up to 40 MHz frequency. All four amplitude characteristics show the same trend: increase 20 dB/decade up to the maximal value and the decrease afterwards. Unlike the measurements with RF transformers as decouplers, the maximal frequency is not the same for all four electrode arrangements: it is at 25 MHz for the arrangements with the receiver signal electrode on the skin (GSSG, SGSG) and 70 MHz for the arrangements with the receiver ground electrode on the skin (GSGS, SGGS). This causes that above 30 MHz the order of the arrangements from the highest to the lowest amplitude becomes SGGS, GSGS, SGSG, and GSSG. Similar results were obtained for the other configuration with the A type receiver (BA configuration, red lines in Fig. 10), where change of the amplitude was below 1.7 dB for switching transmitter or receiver electrodes. The difference between the highest and lowest amplitude below 40 MHz frequency, was 4.5 dB, and the frequencies at which the maximal amplitude was achieved were the same as for the AA configuration.

The results obtained with the B type receiver (AB configuration, green lines; BB configuration, cyan lines in Fig. 10) are similar. Switching ground and signal electrodes introduced differences negligible for practical purposes. The difference between the highest and the lowest amplitude measured at the same frequency was below 1.5 dB for AB and below 0.9 dB for the BB electrode configuration up to 43 MHz, respectively. Switching signal and ground electrodes introduced the same 180° change in the measured gain phase, in all 16 measurement scenarios. Between 400 kHz and 4 MHz frequency the phase was constant +90° when both electrodes on the skin were of the same type (GSSG and SGGS arrangements) and -90° when the electrodes on the skin were of a different type (GSGS and SGSG arrangements).

Therefore, in the case of the B type receiver there was no difference for changing the positions of the signal and ground electrodes of the same transmitter/receiver electrode pair, while for the A type receiver there was some difference, but negligible up to 40 MHz. In the case of the A type receiver it is better to keep the transmitter signal electrode on the skin closer to the receiver, rather than the transmitter ground electrode. For all four electrode configurations the highest amplitude was measured in the case of GSSG electrode arrangement.

For a fixed electrode arrangement, the highest gain amplitude was measured in case of BB electrode configuration, followed by AB, BA, and AA configurations, respectively. In case of GSGS electrode arrangement, the difference between the B type receiver (BB - AB) gain amplitudes was 4 dB, and between the A type receiver (AB - AA) gain amplitudes was 3.4 dB in the whole frequency range. The difference between the A type transmitter (AB - AA) gain amplitudes was 15.8 dB, and between the B type transmitter (BB - BA) amplitudes it was 16.5 dB. For the electrode arrangements SGGS and SGSG the results are very much alike the results obtained for the GSGS arrangement: for a B type receiver, B transmitter configuration was 4.6 dB better than A, and for an A type receiver B transmitter configuration was 3.4 dB better than A. For a fixed transmitter electrode configuration, the gain amplitude difference BB - BA equalled 17.2 dB and 14.8 dB, and the difference AB - AA equalled 16 dB and 13.6 dB for SGGS and SGSG arrangements, respectively. As for the most common electrode arrangement, GSSG; the difference between the gain amplitudes of B type receiver (BB - AB) was the same as of the A type receiver (BA - AA), and was approximately 3.9 dB in the whole frequency range. The gain measured using the fixed transmitter configuration and changing the receiver electrodes configuration differed by 13.5 dB, in favour of the B type receiver configuration.

It can be seen that the configurations with a B type receiver yielded at least 13.5 dB higher gain amplitude than the corresponding configurations with an A type receiver. Consequently, AB and BB are preferred to the AA and BA electrode configurations. Although switching signal and ground electrodes of the same transmitter/receiver electrode pair is not as an important issue as in the case of asymmetrical RF transformers as decouplers (switching signal and ground electrodes has influence only at highest frequencies for A type receiver), in the measurements of the IBC transmission characteristic GSSG electrode arrangement is preferred, since it results in the highest measured gain.

4 Conclusion

We measured IBC system transmission characteristics using three types of galvanic decouplers: non-symmetric RF transformers, balun transformers with center tap grounded and balun transformers with center tap floating. Regardless of the electrode configurations and setups, the gain amplitude was the highest when both signal electrodes were connected to the skin, and the ground electrodes were floating (GSSG), which is also the configuration usually analyzed in the literature on capacitive IBC.

In the measurements employing non-symmetric RF transformers and the GSSG arrangement case, the highest gain was achieved for the BB electrode configuration, configurations AB and BA have similar gains, and configuration AA has the lowest gain. Switching the signal and ground electrodes of the same transformer electrode pair might result in drastically different measurement results (up to 50 dB difference) and their misinterpretation. In case symmetric balun transformers with center tap grounded are used, transmission characteristic of only forward IBC path through the human body is measured. For the measurements with symmetric balun transformers with center tap floating, the highest gain amplitude was measured in case of BB electrode configuration, followed by AB, BA, and AA configurations, respectively. The results for A type receiver (BA and AA) correspond to the results measured using non-symmetric RF transformers, and the results for the B type receiver (BB and AB) are 10 dB higher, which might be due to the different interwinding capacitance values of the two transformers.

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