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In-Vessel Resonant Communications

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ABSTRACT This paper presents a comprehensive performance estimation of enclosed volume (in-vessel) resonant communications. This type of communications can be used for measurements of pertinent parameters of liquids such as temperature, density, or viscosity within large, enclosed vessels, such as barrels, cisterns, or tanks. Extensive simulations and experimental work have been carried out to evaluate the feasibility of such communication. The efficiency of the excitation of cavity resonators filled with lossy liquids was analyzed. Further, the influence of antenna sizes and dielectric properties of liquids on the transmission characteristics between two antennas was investigated. Finally, measurements of monopole antennas located inside a tap water-filled barrel were performed. It is demonstrated that the determination of optimal antenna size providing communication links is one of the most important practical tasks for the development of an in-vessel communication system.

INDEX TERMS Cavity resonator, wireless communication, dielectric loss, monopole antenna

I. INTRODUCTION

Measurements of pertinent parameters of liquids such as temperature, density, viscosity or chemical composition within large, enclosed vessels, such as barrels, cisterns or tanks are important practical tasks used to control technological processes or storage conditions. Additional examples include control of the level or the degree of mixing of two or more liquids and ensuring that an adequate degree of mixing has been achieved, as is the case, for example, with hair and other cosmetic products. This type of measurement requires the establishment of reliable wireless communications links to convey relevant information among multiple sensors, preferably, but not necessarily uniformly distributed within the enclosed vessel. In order to obtain correct spatial information on the technological activity taking place inside an enclosed vessel (such as the extent of mixing of liquids and temperature measurements, as examples), the placement of communications equipped sensors inside the enclosed vessel is necessary. Such sensors will communicate vital information about the relevant parameters (exhibited at their own spatial locations inside the vessel) among themselves and, also, with the outside world. However, even though the measurement of pertinent characteristics inside an enclosed vessel, such as temperature, viscosity and density are relatively trivial tasks, effective communications among the sensors and the outside world is challenging. This is due to performance limitations of the existing traditional communication methods in the scenario of enclosed vessels filled with high-loss liquids.

As it is known, optical communication links are reliable under line-of-sight conditions, however, they are adversely affected by the opacity and turbidity of liquids [1]. Acoustic communications [2] is, also, a well-established approach for such scenarios but it is hampered by environmental factors like temperature, pressure, and influence of external interference. Radio Frequency (RF) communications can be an attractive solution to overcome the above-mentioned limitations of optical and acoustic in-vessel communications. A standard RF link is established by the interaction of transmitting and receiving antennas, which are traditionally equal to half or a quarter of the wavelength [3]. This means that the operational frequency has to be relatively high (GHz-frequency range) to be able to use small antennas in the limited space of the vessel. However, in that frequency range, losses related to the propagation of Electro-Magnetic (EM) waves through liquids are too high to establish a reliable communication link. Thus, a new approach for an enclosed volume or in-vessel communications is required to overcome these challenges. We propose an alternative approach that considers the use of an enclosed space as a low-frequency resonator and allows data transmission over resonant frequencies.

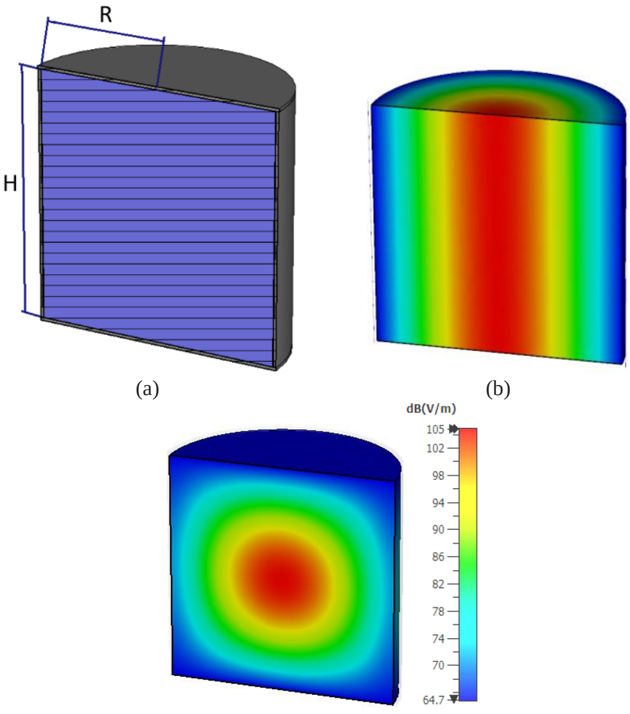
The problem of antennas placed inside the closed cavities was analytically solved in [4], where the self-impedance of two antennas as well as the mutual impedance were successfully calculated. It was shown that the mutual impedance of such antennas strongly depends on the absolute position of the antennas inside the cavity. This makes wireless communication in such conditions a challenging task. The same approach is also used for wireless power transfer inside enclosed spaces. For example, in [5] a similar concept was used to achieve optimal power transfer in cavity resonators and in [6] a novel wireless power and information transfer technique, employed in an enclosed space utilizing frequency selected surfaces was demonstrated. However, all of them fail to practically demonstrate communication limitations in space constrained scenarios. This paper investigates the possibilities and limitations of the proposed wireless in-vessel communications approach through theoretical and experimental parametric studies.

II. THEORY AND SIMULATIONS

To describe the interaction between transmitting and receiving antennas in a free space, the *Friis transmission formula* is widely used [7]. This equation allows to calculate power at the terminals of the receiving (RX) antenna under ideal conditions based on the operating frequency, parameters of both transmit (TX) and RX antennas and distance between them. However, the transmission of EM energy between antennas located inside an enclosed space (vessel) with conducting walls cannot be described by the classical antenna theory due to multiple reflections of EM waves from the walls and the absence of free-space radiation. Particularly, in the case of loss-free propagation medium and (Perfect Electric Conductor (PEC) walls, all EM energy remains inside the enclosed space, some part of the transmitted energy reaches the receiving antenna, and the rest reflects back to the transmitting antenna without any energy loss. In contrast, in the case of a very high-loss propagation medium, most EM energy radiated by the transmitting antenna will be fully absorbed by the medium and will not reach the receiving antenna. However, in reality, we observe the intermediate case, when the loss of the medium is not too high, and some transmitting EM energy reaches the receiving antenna with some loss. Such a scenario is most important for analysis from a practical point of view.

In this section, we perform a theoretical analysis including full-wave EM simulations in order to numerically evaluate transmission parameters between the antennas located inside the enclosed space. Special attention is paid to the influence of losses of a propagation medium on transmission characteristics and the quality of the communication channel.

As is well known, any enclosed volume with conductive walls can be treated as a cavity resonator. In this case, the distribution of EM fields inside the cavity can be calculated based on the shape and the dimensions of the cavity using the theory of resonators [8]. Moreover, any resonator has an infinite number of resonant modes or eigenmodes, which are characterized by their own resonant frequencies or eigenfrequencies and unique EM field distributions. Exceptions to this rule are the so-called degenerate modes, or modes which exist at identical frequencies but exhibit dissimilar distributions of the EM fields.



(a) (b)

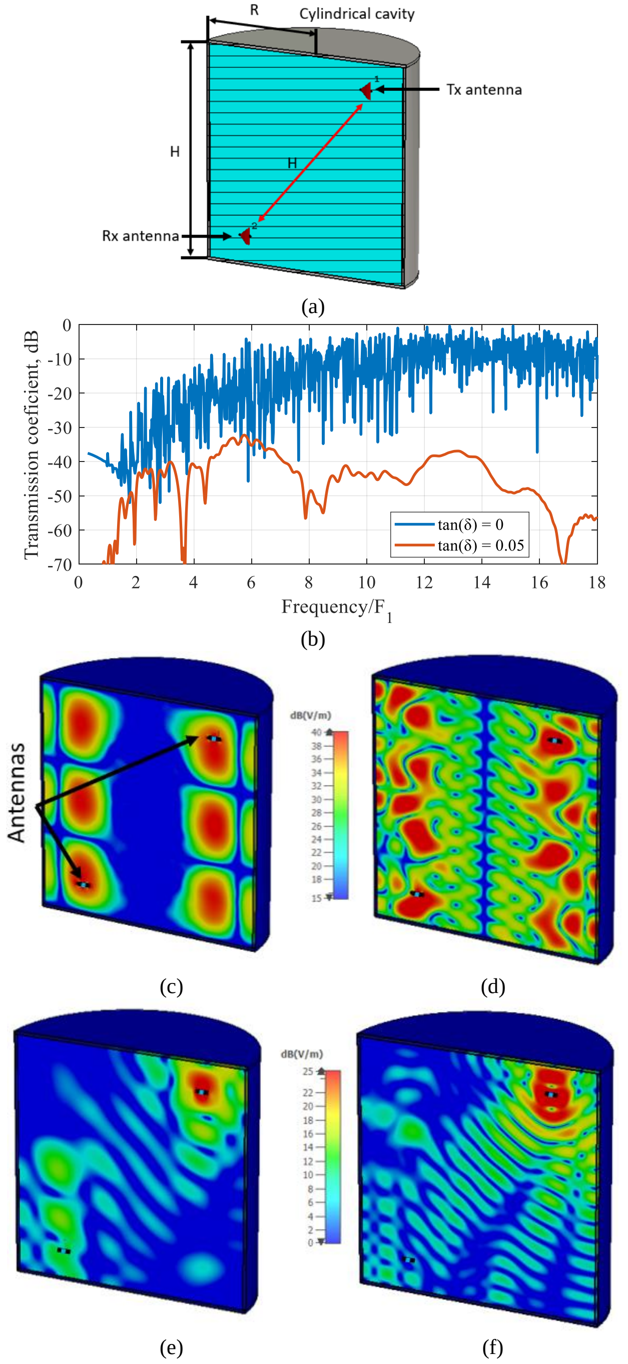
(c)

FIGURE 1. Cylindrical resonant cavity resonator filled with water (a); electric field distribution for: first eigenfrequency (b); second eigenfrequency (c).

For demonstration, let us analyse the electric field distribution at different eigenfrequencies inside a cylindrical cavity with PEC walls. The cylindrical cavity has a height H and a radius $R = H/2$, Fig. 1 a. This cavity is filled with a liquid with a relative dielectric permittivity of $\varepsilon_r = 80$ and $\tan(\delta) = 0.05$. As an example, the distributions of the EM field inside the analysed cylindrical cavity corresponding to the first (fundamental) and second eigenmodes are shown in Fig. 1 b and c, respectively. As can be seen, the electric field distribution for the case of the first and second eigenmodes is unique.

Using the described properties of the cavity resonator, a reliable communication channel between two antennas can be established. For that purpose, the design of the TX antenna (including its length, geometry, impedance, position inside the cavity, etc.) should allow efficient excitation of the corresponding eigenmode of the cavity. Also, if the antenna can efficiently excite an eigenmode, it will also efficiently receive energy from the mode, following the principle of reciprocity. Taking this into account, we can present the same requirements for both the RX and TX antennas.

To demonstrate the proposed method of in-vessel communications, let us analyse the transmission characteristics between two antennas inside the cavity, as described earlier. In this specific example, the two antennas are located at the opposite corners of the cavity and spaced distance H apart, as shown in Fig. 2 a. Both antennas are short



(a)

(b)

(c) (d)

(e) (f)

FIGURE 2. Cylindrical resonant cavity with two sensors placed inside it (a); transmission coefficient between two sensors as a function of frequency (b); cross section of the electrical field distribution at frequency of optimal transmission with tan(δ) = 0 frequency 6f_1 (c) and frequency 14f_1 (d); with tan(δ) = 0.05 frequency 6f_1 (e) and frequency 14f_1 (f).

dipoles of length $L = H/16$ (corresponding to $\lambda_1/20$, where λ_1 is the wavelength at the fundamental frequency of the cavity). The full-wave EM simulations of the described system were performed using CST Microwave Studio [9]. Here, two scenarios were analysed: when the liquid inside the cavity is lossy (tan(δ) = 0.05) and when it is loss-free (tan(δ) = 0). The simulated transmission coefficients between the TX and RX antennas for lossy and loss-free scenarios are shown in Fig. 2 b. The frequency axis was normalized to the fundamental eigenfrequency f_1 of the cavity.

The obtained results demonstrate that the optimum transmission coefficient between these two antennas is observed at the frequencies of around $14{\cdot}f_1$ and $6{\cdot}f_1$ for the case of loss-free and lossy scenarios, respectively. This means that in this particular case, low-loss transmission occurs at high-order eigenmode frequencies. Such a behavior of the transmission coefficient is caused by two main factors. Firstly, both TX and RX dipole antennas are electrically small, which makes the excitation of low frequency eigenmodes ineffective. The effect of antenna size on the transmission coefficient inside the cavity resonator will be investigated in more detail later in this section. Secondly, the positions of the TX and RX antennas strongly influence the extent of eigenmode excitation and, hence, EM energy transmission. It is interesting that, in the case of a lossy medium, lower frequency eigenmodes yield lower propagation losses. This will also be revisited later in this section.

As expected, the transmission coefficient strongly degrades as tan(δ) increases. In the considered example, the maximum transmission coefficient in a lossy medium is about 30 dB lower in comparison with the loss-free scenario. In addition, a lossy medium significantly changes the EM field distribution inside the cavity. Based on the analysis of the electric field distribution in loss-free and lossy media at frequencies 6f_1 and 14f_1, (Fig. 2 c - Fig. 2 f), it can be concluded that the introduction of losses attenuates the magnitude of the electric field. As can be seen from Fig. 2 e and Fig. 2 f the electric field inside the cavity consists of the regions with the standing electric field (in the areas where antennas are placed), and the region with the traveling wave propagating from one antenna to another. Moreover, electric field distribution in the case of a lossy medium strongly depends on the relationship between the size of the cavity and tan(δ) of the medium. To this point, increasing the size of the cavity while keeping tan(δ) constant, results in the increase of propagation losses, ultimately leading to further degradation of the magnitude of the eigenmode EM field distribution. In a similar manner, increasing the tan(δ) of the medium, while keeping the cavity size constant, also results in the increase of the propagation losses and, hence, degradation of the resultant magnitude of the eigenmode EM field distribution.

It can be concluded that efficient communications between transmitting and receiving antennas located inside the enclosed volume can be performed at optimal eigenfrequencies of the corresponding resonator. Such optimal eigenfrequencies are determined by the shape and dimensions of the cavity, dielectric permittivity and loss of the filling material, characteristics and positions of antennas as well. A more detailed analysis of the influence of antennas parameters on the transmission coefficient will be investigated in the following sections.

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A. OPTIMAL POSITIONS OF THE ANTENNAS

As it was mentioned earlier, the main task placed upon in-vessel communications lies with information exchange among the sensors placed in its interior. Such sensors can be used to measure a variety of parameters, such as temperature, density, viscosity or chemical composition and their spatial position within the cavity may not necessarily be fixed. This is particularly true if the medium inside the vessel, within which the sensors are distributed, is a liquid. In this case, the sensor's coordinates will no longer be constant, and therefore the transmission coefficients between any two sensors' antennas will be changing over time.

To evaluate the dependence of the transmission coefficient between antennas on their coordinates within the described cavity, a parametric study based on full-wave EM simulations was conducted. The analysis was carried out for three cavity eigenmodes (second, third and higher-order mode). The position and orientation of antennas are shown in Fig. 3. In order to maintain symmetry, antennas were moved symmetrically along the Z and Y axes. For this analysis, the dielectric properties of the liquid were kept the same as in the previous study-case for the lossy medium: a dielectric permittivity of $\varepsilon_r = 80$ and $\tan(\delta) = 0.05$. The length of each antenna is equal to $0.5*\lambda_1/4$ for better coupling with the fundamental eigenmode.

The simulated values of the magnitude of the transmission coefficient between two antennas as a function of their coordinates along the Y and Z axes for three different eigenmodes of the cavity are presented in Fig. 4. The Y-coordinate and the distance between the two antennas were

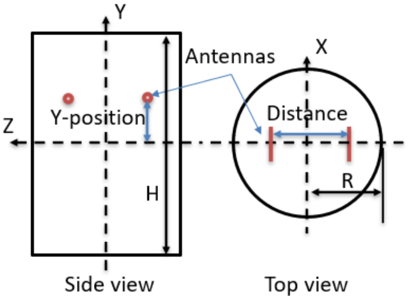
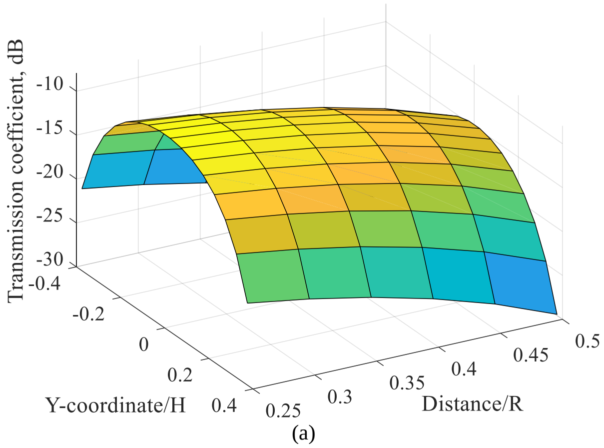
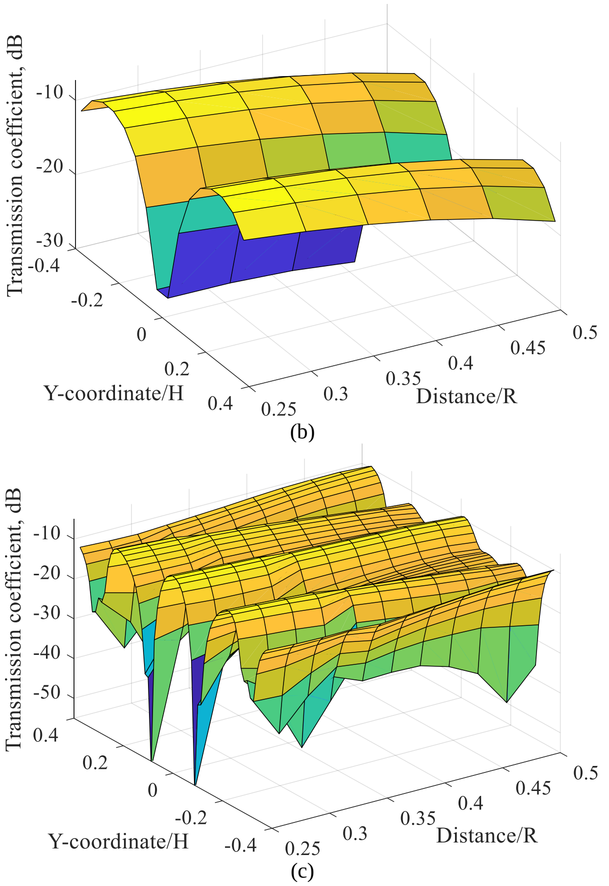


FIGURE 3. Cylindrical cavity model with two antennas.



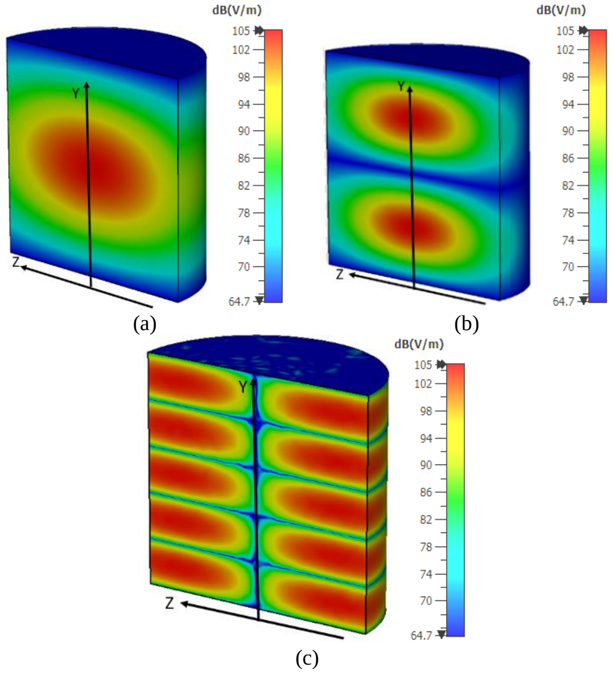
(a)



(b)

(c)

FIGURE 4. Magnitude of the transmission coefficient between two antennas as a function of Y-coordinate and distance between them: second mode (a), third mode (b), higher mode (c)



(a) (b)

(c)

FIGURE 5. Electric field distribution for: second eigenfrequency (d); third eigenfrequency (e); high eigenfrequency (f).

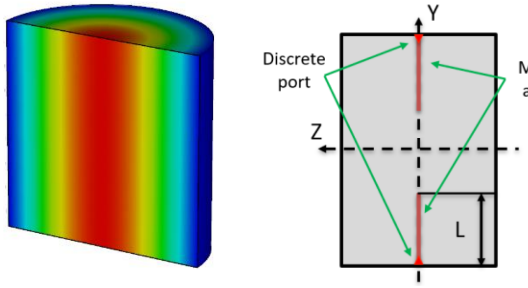
normalized to the height, *H,* and radius, *R* ($R = H/2$), of the cavity, respectively. The obtained results of the parametric study indicate that for the second eigenmode of the cavity, the maximum of the transmission coefficient is observed in the center of the cavity (Y-coordinate/H = 0), Fig. 4 a, which corresponds to the maximum of the electric field strength, Fig. 5 a. In the same way, the minimum of the transmission coefficient for the third eigenmode is achieved in the center of the cavity (Y-coordinate/H = 0), Fig. 4 b, where a minimum field strength is observed Fig. 5 b. The shape of the transmission coefficient curve for the higher-order eigenmode, Fig. 4 c, has a more complicated outline due to the corresponding field distribution, Fig. 5 c. Thus, for each eigenmode of the cavity, the value of the transmission coefficient between antennas depends on their coordinates and correlates with the EM field distribution. Moreover, antennas should be located close to the maximum magnitude of the corresponding EM field to achieve the maximum transmission coefficient. This means that in the case when antenna is not fixed and is floating in the cavity, the sensors must be able to adjust their operational frequency to the corresponding eigenmode of the cavity, whose maximum is the closest to the current antenna position, to maintain optimal data transmission.

B. SIZE OF THE ANTENNAS

Undoubtedly, the size of the cavity will limit the size of the antennas that can be used inside it. The small size of the antenna will allow it to move freely in the enclosed space, inferring that the size of antennas should be as small as physically possible. However, as the antenna size decreases relative to the cavity size, its operating frequency increases, leading to efficiency degradation at lower frequencies and it may result in the reduction of the transmission coefficient between antennas.

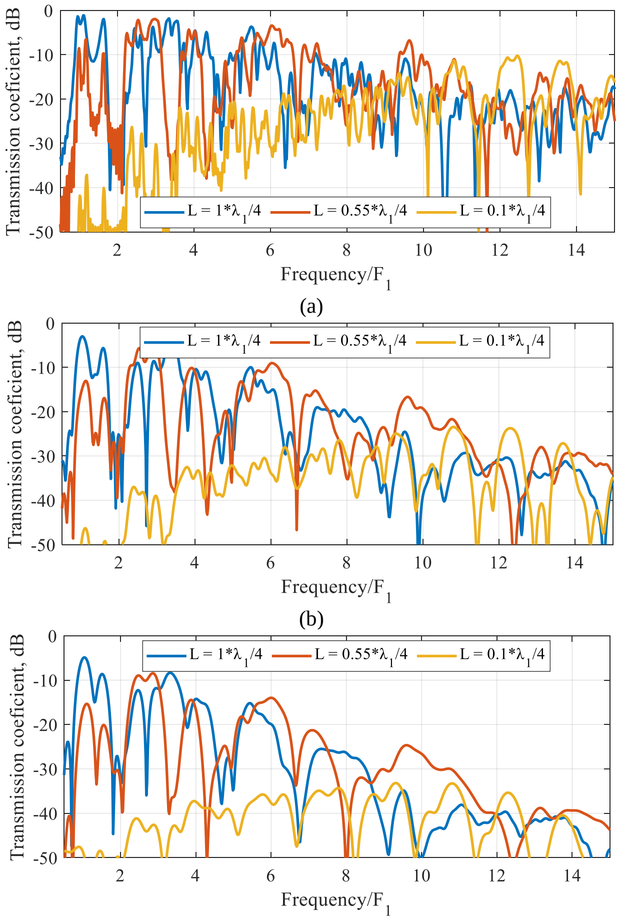
To investigate the dependence of the antenna's size on the transmission coefficient, full-wave parametric EM simulations were performed. To provide equal conditions for antennas with different lengths, the first eigenmode of the cavity was chosen with the field distribution shown in Fig. 6 a. In the present case, monopole antennas were placed on the top and bottom of the cavity, Fig. 6 b, so for the first eigenmode of the cavity, antennas will always be in the center of the maximum of the electrical field, regardless of their length. Moreover, the lengths of both antennas were always kept identical. In this parametric study, the length of each antenna was $L = n*\lambda_1/4$, where λ_1 is the wavelength at the fundamental eigenfrequency of the cavity, while *n* was varied, and allowed to attain values of 1, 0.55, and 0.1. For every antenna's length, three scenarios for three different values of the loss tangent of the medium: $\tan(\delta) = 0.01$; $\tan(\delta) = 0.03$; $\tan(\delta) = 0.05$ were analysed.

The simulated values of the transmission coefficient magnitude are plotted in Fig. 7 as a function of the frequency (normalized to the fundamental frequency, f_1, of the cavity) for each value of the antennas' length. Two main conclusions can be made based on the analysis of the plotted curves. Firstly, decreasing the size of the antenna reduces the efficiency of excitation of low frequency eigenmodes of the cavity. Secondly, regardless of the losses of the medium, the transmission coefficient corresponding to the smallest antenna ($0.1*\lambda_1/4$) is comparable to or superior to the transmission coefficient of longer antennas ($0.55*\lambda_1/4$ and $1*\lambda_1/4$) in the high frequency range (more than 12F$_1$). For example, in the



(a) (b)

FIGURE 6. **Electric field distribution for first eigenmode of the cavity (a); positions of the monopole antennas (b).**



(a)

(b)

(c)

FIGURE 7. **Transmission coefficients between antennas for different length of the antennas and loss of the filling material: tan(δ) = 0.01 (a); tan(δ) = 0.03 (b); tan(δ) = 0.05 (c).**

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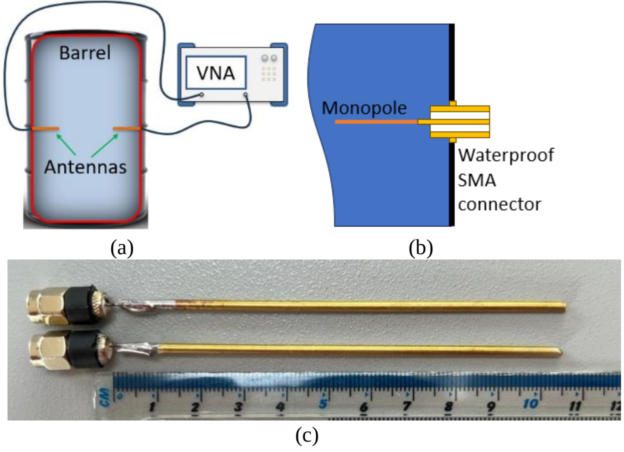
case of $\tan(\delta) = 0.01$, the maximum of the transmission coefficient for the shortest antenna ($0.1*\lambda_1/4$) is at least 10 dB higher than the maximum of the transmission coefficients for longer antennas ($0.55*\lambda_1/4$ and $1*\lambda_1/4$) across the frequency range between $12*f_1$ and $13*f_1$. In the case of $\tan(\delta) = 0.03$ and $\tan(\delta) = 0.05$ a difference of about 6.5 dB and 5 dB, respectively, is observed in the same frequency range. This implies that increasing the size of the antenna shifts the optimal operational frequency at which the maximum transmission coefficient is achieved, to a lower frequency range. This infers that in lossy media, electrically large antennas are preferable because using such antennas the data can be transmitted at lower frequencies, where propagation loss is significantly lower. However, using electrically large antennas in a space-constrained environment is impractical. Thus, determining the optimal size of antennas that provides the required transmission coefficient between antennas and a reliable communication link is one of the most important tasks to develop the in-vessel communication system.

III. EXPERIMETAL RESULTS

To experimentally confirm the theoretical analysis presented in the previous section, the measurement setup, which is shown in Fig. 8 a, was built. An oil barrel of radius $R = 30$ cm and height $H = 80$ cm was used as the enclosed vessel, which played the role of a cavity resonator and was later filled with tap water. Two monopole antennas, Fig. 8 c, were used as TX and RX antennas for further measurements. The monopole antenna consists of an SMA connector with a soldered piece of 1 mm diameter copper wire with a specific length. Waterproof SMA transitions were used to connect antennas located inside the barrel close to its wall, Fig. 8 b. A Vector Network Analyzer (VNA) was used to measure the scattering parameters (S-matrix).

The frequency dependency of the magnitude of the transmission coefficient between two identical monopole antennas with a length of 12 cm, located in the middle of the barrel wall (Fig. 8 a), is shown in Fig. 9. As one can see, the measured transmission coefficient is in a good agreement with the simulated one, which is presented on the same graph for easier comparison. Here it was assumed that the dielectric permittivity of water is $\varepsilon_r = 80$, and its loss tangent $\tan(\delta) = 0.05$. In this case, the first eigenmode of the barrel has a frequency of about $F_{b1} = 38$ MHz. It can be seen that the maximum of the transmission coefficient is observed at frequency around 125 MHz. Later in this section, an experimental-based approach to determine the optimal parameters of the in-vessel communication system for a fixed cavity size, such as antenna length and operating frequency range, is demonstrated.



(a)
(b)
(c)

FIGURE 8. Measurement setup (a); SMA connector placing (b); monopole antennas (ruler for comparison) (c).

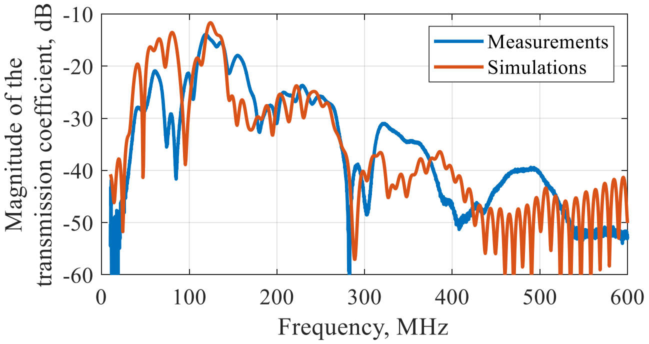


FIGURE 9. Measured and simulated magnitudes of the transmission coefficient between two antennas inside the barrel filled with tap water.

A. DIFFERENT SIZES OF THE ANTENNAS

As was mentioned previously, small-size antennas are preferred for in-vessel communications, due to their ability to move freely inside the enclosed space. However, as it was shown in Fig. 7, a small antenna cannot excite the low frequency eigenmodes of the cavity efficiently. To validate the simulation results, an experimental parametric study of the transmission coefficient versus the length of the monopole antennas was performed.

However, as was demonstrated in section II A, the transmission coefficient between antennas strongly depends on the location inside the vessel, and it should be taken into account during the analysis. Therefore, a set of measurements was carried out to investigate the transmission coefficient

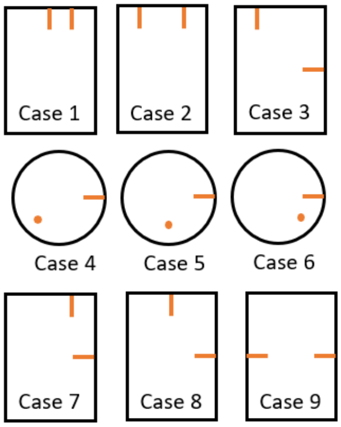


FIGURE 10. Schematic representation of the location of the antennas.

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between TX and RX antennas for different locations and orientations of antennas. For this purpose, several cases of antennas' mutual arrangements, which are shown in Fig. 10, have been analysed. During this parametric study, the length of TX and RX antennas were changed simultaneously from 2 to 22 cm with a 4 cm step. For each value of the antennas' length, the transmission and reflection coefficients were measured for all test cases presented in Fig. 10.

Due to the large number of data, for each frequency point the measured values of the transmission coefficient (Fig. 11 a) were averaged over all test cases for every antenna length to conclude its effect on the quality of in-vessel communication links. As can be seen, the tendency to decrease the averaged transmission coefficient (Fig. 11 a) with reducing antenna length aligns well with the results obtained via the simulations (Fig. 7 c) It confirms that the antenna size defines the optimal frequency band for data transmission.

In our specific case, at frequencies higher than 250 MHz the antenna length does not significantly affect the level of the transmission coefficient. However, at frequencies below 250 MHz, increasing antenna size results in an increase in the transmission coefficient. So, the larger the antenna used, the lower eigenmodes of the vessel can be exited, which will increase the efficiency of the data transmission. At the same time, a 22-cm-long antenna may not be convenient to use in the considered vessel because its size is comparable to the size of the vessel. In general, the antenna design must make a compromise between the level of the transmission coefficient and the usability of the antenna size in comparison to the size of the vessel.

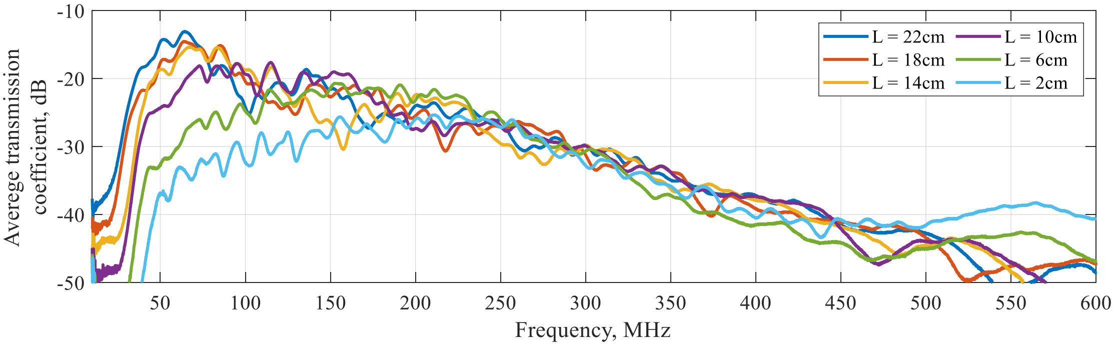
Therefore, it is necessary to evaluate the effectiveness of antennas in terms of their lengths. For this purpose, transmission coefficients for every particular length were normalized (Fig. 11 b):

$$norm|S21| = 10\log_{10}\left(\left(|S21|\frac{\lambda_{b1}}{L}\right)^2\right)$$

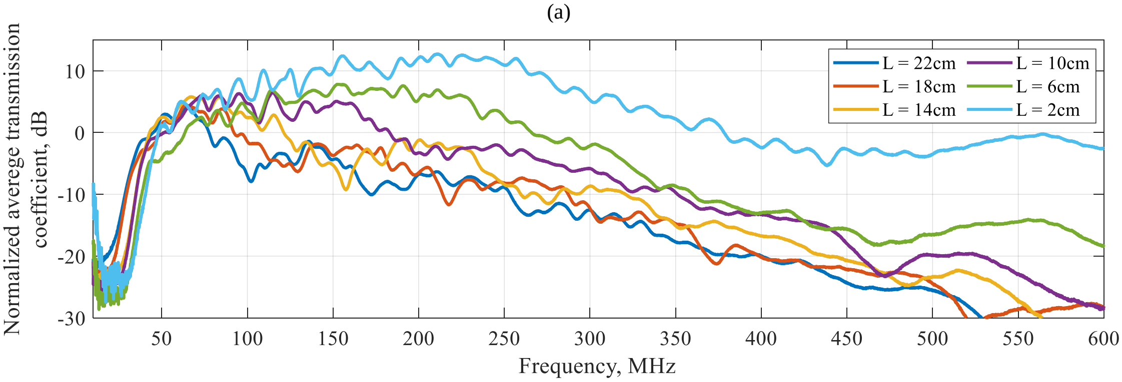
where L – is the antenna length, and λ_{b1} is the wavelength at frequency of the first eigenmode of the barrel F_{b1}. As can be seen from Fig. 11 b, level of the normalized transmission coefficient for short antennas is higher, which means that for a higher frequency range, the shorter antenna is more efficient in terms of length. This can be explained by the current level of loss, which makes the longer antennas less efficient at higher frequencies.

B. DIFFERENT POSITIONS OF THE ANTENNAS

The transmission coefficients for each test case of the antennas' arrangements inside the barrel (Fig. 10) were also analysed to evaluate trends in the change in transmission coefficient between two antennas when their length changes. For this purpose, the maximum value of the measured transmission coefficient was retrieved for each test case (Fig. 10). The obtained maximum values of the transmission coefficients in the frequency range from 10 MHz to 600 MHz are shown in Fig. 12 a and corresponding frequencies of

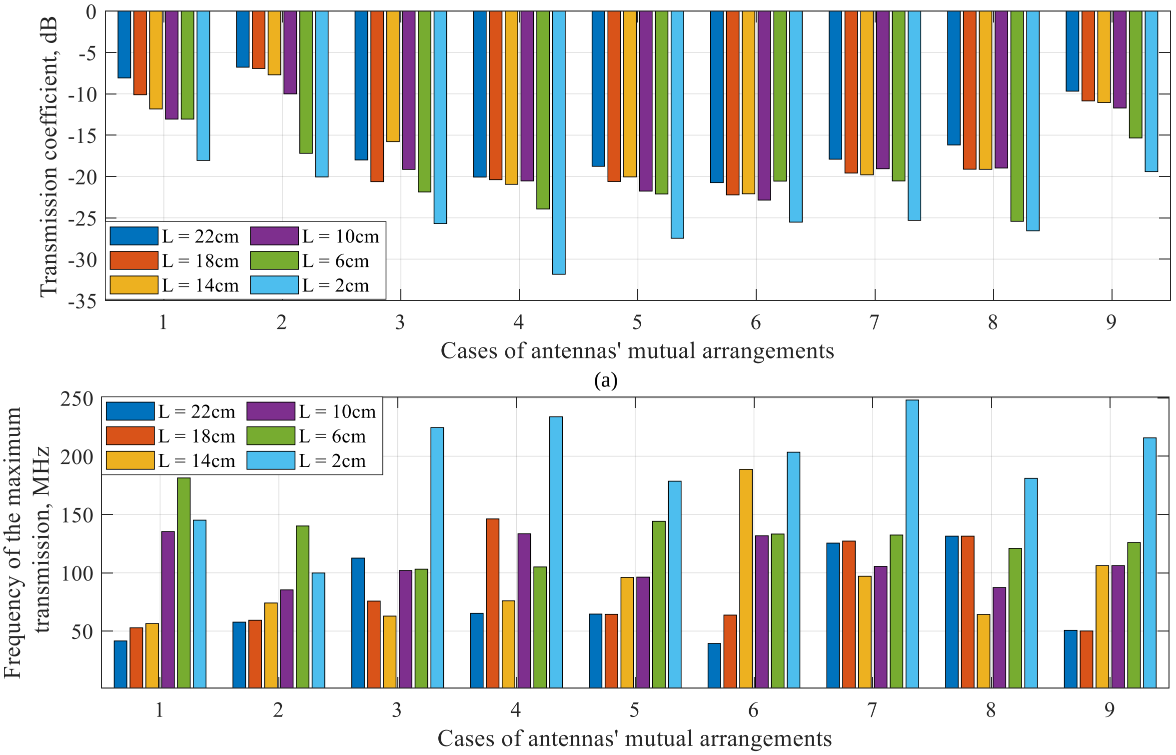


(a)



(b)

FIGURE 11. **Measurement results for two monopole antennas placed on the edges of the barrel: (a) averaged transmission coefficient; (b) averaged transmission coefficient normalized to the length of the antenna.**



(a)

(b)

FIGURE 12. **Measurement results for different antennas' mutual arrangements: (a) maximum of the transmission coefficient for every position of the antennas; (b) frequency of the maximum of the transmission coefficient.**

maxima are shown in Fig. 12 b. It can be concluded that the highest level of the transmission coefficient is achieved when antennas are located close to each other (test cases 1 and 2). In other test cases, (3–9) a lower level of transmission between two antennas is observed. Such behaviour is valid for all analysed lengths of antennas, but for the shorter antennas $L = 2$ cm, the level of the transmission coefficient is 10 dB lower on average compared to the larger antennas $L = 22$ cm. Combined with the sensitivity of the low-cost transceivers, which are usually not higher than -100 dBm [10], [11], and a standard power transceiver output of about 10 dBm, this leaves approximately 80 dB of additional link budget, which could be spent on reducing the transmit power, which reduces power consumption.

It should be additionally noted that the maximum level of the transmission coefficient is observed at different frequencies for each test case, Fig. 12 b. For example, in the case of 22 cm-long antennas the optimal frequency range lies between 42 MHz and 131 MHz (89 MHz bandwidth), while in the case of 2 cm-long antennas, it lies between 100 MHz and 248 MHz (114 MHz bandwidth). It can be concluded that when the length of the antennas decreases, the magnitude of the transmission coefficient reduces and the optimal operation frequency shifts to the higher frequency range. Moreover, in this case, the required operating bandwidth must be increased as well. Consequently, the length of the antennas will determine the operating frequency band and the data rate of the communication link.

IV. RESULTS DISCUSSION

Based on the obtained results, some recommendations on in-vessel communication system operation are discussed in this section.

First of all, it was shown that the transmitting (Tx) antenna should be placed at the location corresponding to the maximum field intensity of the eigenmode to perform communication at the frequency of interest. In this case, this eigenmode can be efficiently excited by the Tx antenna. At the same time, the transmission coefficient between Tx and Rx antennas will depend on the position of the Rx antenna as well. Ideally, the Rx antenna should also be located as close as possible to the position of the field maximum of the excited eigenmode. Moreover, the positions of the field maxima for different eigenmodes can overlap each other, and antennas will excite multiple eigenmodes simultaneously. It results in a complicated frequency dependence of the transmission coefficient between Tx and Rx antennas that is dependent on antenna placements.

The next parameter that should be designed is the antenna size. As it was demonstrated above, decreasing the length of the antenna reduces the efficiency of excitation of low-frequency eigenmodes of the cavity. It can be concluded that the optimal case for in-vessel communication is to design as long an antenna as possible to achieve lower transmission loss. However, taking into account that using electrically large antennas in a space-constrained environment is impractical, their size is a compromise between efficiency and practicality.

In addition, dielectric loss of filling liquid will affect the optimal transmission frequency, and it weakens the influence of the antenna size on the level of the transmission coefficient between antennas for high-order eigenmodes of the vessel. However, since changing the loss of the medium is a practically complicated task, for each particular scenario, the antenna size should be optimized, taking into account the loss of the medium.

In consequence, for in-vessel communication scenarios, the optimum operational frequency band is mainly determined by the size of the closed cavity, the dielectric characteristics of the liquids, and the antenna size. In practice, the operational frequency band can be defined by the simulation or measurement company. Meanwhile, the optimal transmission frequency is defined by the position of the antennas inside the vessel. In case when antennas can be static, their positions should be chosen by taking into account the field distribution at the frequency of interest. And vice versa, considering the system where antennas can move inside the cavity, the operational frequency should be an adjustable parameter in order to obtain minimum transmission loss. This can be done by performing a quick scan in a predefined frequency range, from which the frequencies exhibiting the lowest losses are selected.

IV. CONCLUSION

In this paper, a comprehensive feasibility study of resonant, enclosed volumed communications performance was completed. The study investigated the influence of several factors on the performance (transmission losses and frequency of operation) of enclosed (in-vessel) communications, such as antenna positions, their size and influence of the losses of the dielectric medium.

For this study, measurements were carried out using monopole antennas with lengths of 2-22 cm in 4 cm increment in a metal barrel with a radius of 30 cm and a height of 80 cm, filled with tap water. Estimates based on the simulations were fully confirmed by detailed experiments. In the present case examined in this paper, the maximum transmission coefficient for a 2 cm antenna occurs at a frequency of about 250 MHz and is equal to 30 dB. Given the fact that the power link budget is standard receivers is around -100 dBm, this provides scope for further reduction in the size of the antenna element.

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