Radio Channel Study for Colon Capsule Endoscopy with Low-Band UWB Multiple Antenna System

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***Abstract*— This paper presents a study of the radio channel characteristics between a colon capsule endoscope and a multiple on-body antenna system in ultra wideband wireless body area networks (UWB-WBAN). The main aim is to study the variation of the channel characteristics for the on-body antennas in different capsule locations throughout the whole colon area. The study is conducted with CST Studio Suite simulations and one of its anatomical voxel models. A simplified capsule model and directive on-body antennas designed for low-band UWB in-body communications are used. It is found that five of this type directive on-body antennas provide sufficient coverage over the whole colon are even in the most challenging capsule locations.**

Keywords—colon capsule endoscopy, directive on-body antenna, multiantenna system, ultrawideband, wireless body area networks

I. INTRODUCTION

Previously, capsule endoscopy has been targeted mainly on the detection of abnormalities in the small intestine area since the small intestine is not easily achieved with traditional endoscopes [1]-[3]. In recent years, interest on colon capsule endoscopy has increased remarkably since the majority of the intestinal tumors are located in the colon area [4]-[6]. In general, capsule endoscopy is remarkably more comfortable than the traditional endoscopy and hence, possibility of obtaining colon examination with capsule endoscopy instead of traditional endoscopy, lowers the threshold to seek in the medical examination [6].

Recently, it has been recognized that ultra wideband (UWB) technology could provide several advantages for capsule endoscopy, such as high resolution images, high data rate, low power, and reliability [3]. These are essential features especially for future's active capsules. However, one of the main challenges related to UWB based capsule endoscopy, or in general UWB implant communications, is the high propagation loss in the tissues [3], [7].

UWB propagation in the context of capsule endoscopy has been an actively studied topic recently [8]-[12]. There are only a few papers presenting UWB propagation studies with anatomically realistic voxel models. Previous UWB capsule channel modeling studies focus mainly on small intestine area.

This paper is continuation for [3] by presenting radio channel evaluations between the capsule endoscope and multiple directional receiving on-body antennas in different capsule locations in different parts of the colon area of a realistic voxel model. The novelty of this research is that, up to author's knowledge, other UWB capsule endoscope studies do not evaluate radio channels throughout the colon area using an anatomical voxel model and multiple directional on-body antennas.

This paper is organized as follows: Section II presents the study case describing the simulation model, on-body antenna, and the capsule endoscope model. Besides, locations of the on-body antennas as well as locations of the capsule in different parts of the colon are presented. Section III presents channel evaluations in different capsule locations. Summary and Conclusions are given in Section V.

II. STUDY CASE

A. Simulation Model

The study is carried out with Dassault Simulia CST Studio Suite [12], which is based on Finite Integration Technique (FIT). An anatomical voxel model Laura, illustrated in Fig. 1a, is used in the simulations to enable realistic radio channel evaluations. Fig. 1b presents the cross-section of the voxel model via the black line depicted in Fig. 1a. The simulation model includes also the use a simplified capsule model as well as a directional on-body antenna, which are described more in detail in the following subsections.

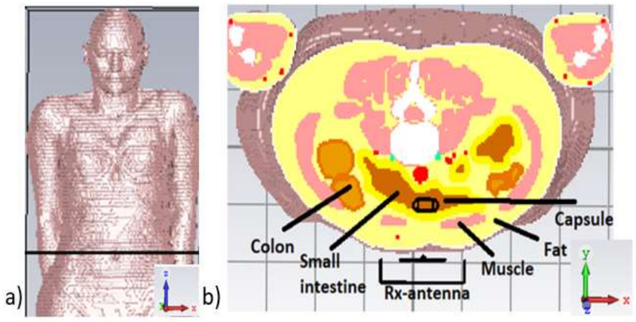


Fig. 1. a) Laura voxel model, b) cross-section of the voxel model.

This research is funded by Academy of Finland Profi6 funding, 6G-Future Sustainable Society (University of Oulu), which is greatly acknowledged. Work has been financially supported in part by the Academy of Finland 6G Flagship.

B. On-body Antenna

In this study, we use a directional on-body antenna designed for in-body communications for UWB frequency range 3.75 – 4.25 GHz according to IEEE 802.15.6 Wireless Body Area Networks (WBAN) standard [13]. The antenna structure is illustrated in Fig. 2a. The antenna has a cavity (grey area in the antenna) to enhance the directivity towards the body. Originally, the antenna was introduced in [14] and it has been later used in several in-body channel studies in [3], [11], [15]. Realized gains of the antenna as it is located on the body, are presented in Figs. 2b-d for frequencies 3.75 GHz, 4 GHz, and 4.25 GHz, which are the start, center and end frequencies of the range of interest, respectively.

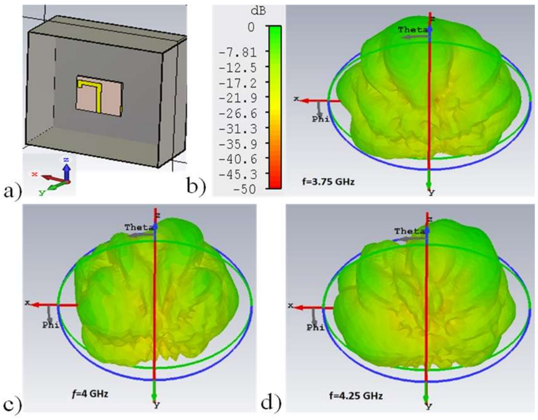


Fig. 2. a) The directional on-body antenna designed for in-body communications, b) realized gain at 3.75 GHz, c) realized gain at 4 GHz, d) realized gain at 4.25 GHz.

C. Capsule Model

This study uses a simplified capsule model, in which an omnidirectional dipole antenna is embedded in plastic capsule shell having realistic dimensions: 11 mm x 25 mm, corresponding to the size of the commercial capsules nowadays [1]. The scheme of the dipole antenna and the capsule shell are presented in Fig. 3a-b, respectively. The dipole antenna is designed to work at the frequency of 4 GHz inside the intestine. Details of the model can be found in [15].

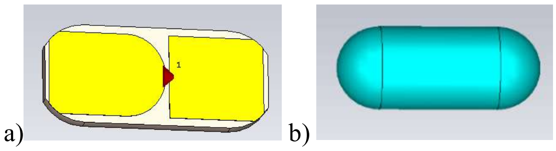


Fig. 3. a) Dipole antenna inside the capsule, b) and the capsule shell.

D. Locations of the On-body Antennas

The channel evaluations are conducted using five on-body antennas located on the voxel's abdomen area as shown in Fig. 4. Five directional on-body antennas have been depicted to provide full coverage over the *small intestine area* in [3] and now the aim is to evaluate whether the on-body receiver antenna setup is sufficient to coverage also *the large intestine area*, i.e. the colon. The antenna numbering is set according to the port numbering of the simulation model: the port number 1 is the capsule antenna port, and port numbers 2-6 belong to the on-body antennas. The on-body antenna – skin distance is approximately 4 mm, which corresponds to the thin cloth thickness. Due to the pixelization of the voxel models, size of the antenna and shape of the voxel model, the antenna-skin distance may slightly differ in some antenna locations which may have impact on the propagation depth as discussed in [3].

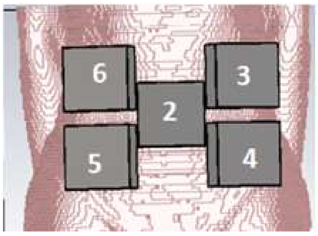


Fig. 4. On-body antennas on the voxel model's abdomen.

E. Locations of Capsule in the Colon

The channel characteristics between the capsule and the on-body antenna are evaluated throughout the whole colon area in seven different capsule locations A-F shown in Figs. 4a-g. The leftward of the Figs. 5a-g illustrate the capsule locations throughout the colon area at different cross-cut levels. The rightward of Figs.5a-g depicts the capsule location respect to the on-body antennas to visualize which of the on-body antennas are the closest in different capsule location.

The capsule location A is at the beginning of the colon part, in cecum, in which 20 % of the colonrectal cancers get developed [16]. It is noted that only the on-body antenna 5 is in the vicinity of the capsule at this location. The next closest on-body antennas are 2 and 6, for which the distance is several centimeters. This may cause challenges for reliable capsule localization, which typically requires reliable link at least for three on-body antennas [17].

The capsule location B in Fig. 5b, is less challenging than the capsule location A, since the location B is in the relatively close presence of three on-body antennas (2, 5, and 6).

The capsule location B2 is at the same vertical crosscut level as the capsule location B, but deeper inside the colon tissue.

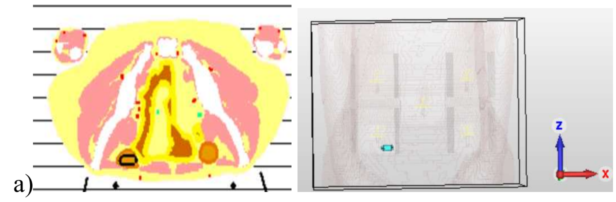
The capsule location C is in the highest part of the ascending colon, in the vicinity of the on-body antennas 6 and 2, as shown in Fig. 5d.

The capsule location D is in the middle of the transversal colon just above the on-body antenna 2. Due to the central location in the abdomen area, the distance to the other on-body antennas is moderate as well.

Capsule locations E is the highest part of the descending colon, as shown in Fig. 5f. This location is roughly a mirrored version of the locations C, and it is in the vicinity of the on-body antenna 2,3, and 4.

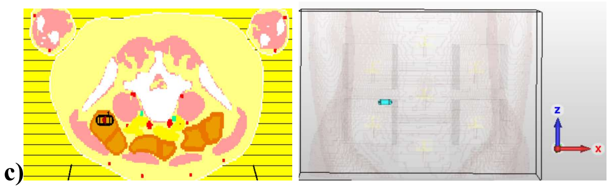
Capsule locations F is the lowest part of the descending colon. This location is roughly a mirrored version of the locations A. It is in the close presence of only one on-body antenna, 4, which may cause challenges in capsule localization - as in the case of capsule location A.

Location A

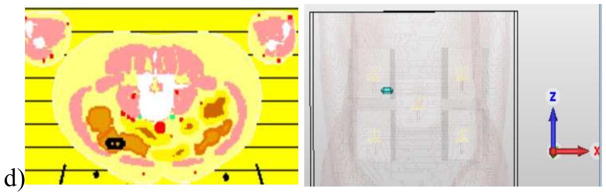


Location B

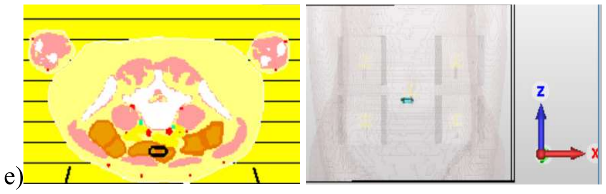
Location B2



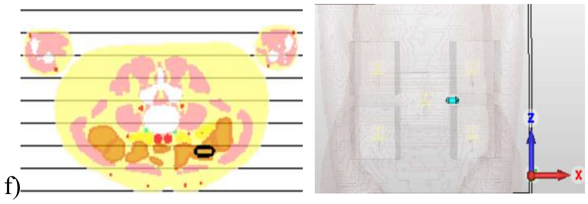
Location C



Location D



Location E



Location F

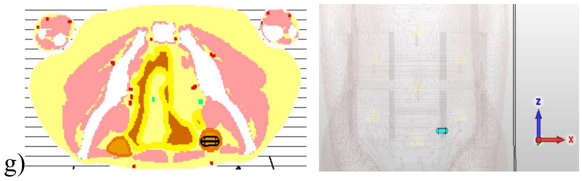


Fig. 5. a-g): Evaluated capsule locations A-G in the colon area. Leftward figures depict the location at different cross-cut levels (leftward figure) and rightward figures illustrate capsule location respect to the on-body antenna locations.

III. CHANNEL EVALUATIONS

In this section, channel characteristics between five on-body antennas and the capsule are evaluated in the capsule locations "A, B, B2, C, D, E, and F". Frequency domain results, i.e., channel parameters S21, S31, S41, S51, and S61 are presented at different capsule locations in Figs. 6-12, respectively. The channel attenuations in different capsule locations are evaluated regarding the possibility for capsule localization: For the successful capsule localization, it is essential to obtain at least three channels with moderate attenuation. In the literature, different WBAN link budget calculations have been presented with criteria for channel attenuation and receiver's sensitivity [17]-[19].

A. Capsule Location A

This capsule location is among the most challenging locations since only the on-body antenna 5 is in the immediate vicinity for the capsule. As it can be seen from the simulated frequency domain channel results (S-parameters) in Fig. 6, the channel attenuation is at the moderate level only in the case of S51. At 4 GHz, which is the center frequency of the frequency range of interest, the attenuation is 58 dB. The second strongest channel is obtained with the on-body antenna 6, with the channel attenuation 68 dB and the third strongest channel for the on-body antenna 2 with 70 dB attenuation. For the rest of the channels, the attenuation is 76 dB. Hence, the capsule can be localized also in the location A especially with receivers having higher sensitivity.

As it can be noted from rightward of Fig. 6a, the physical distance between the capsule and the on-body antenna 6 is slightly larger than that for the on-body antenna 2. However, the S61 is at slightly higher level than S21 with the frequency range of interest. This is due straighter fat connection (both visceral and outer) between the capsule and on-body antenna 5 since fat is known to be a good propagation channel in implant communications [21]-[22]. In this location, antenna radiation characteristics are somewhat similar to both directions as shown in Fig. 2.

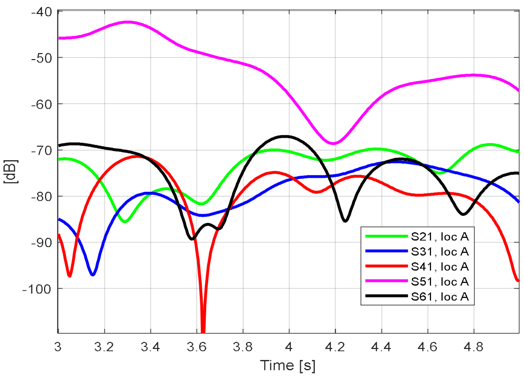


Fig. 6. Channel parameters between the capsule and five on-body antennas in the capsule location A.

B. Capsule Location B

The simulated channel parameters in the capsule location B are depicted in Fig. 7. As it can be seen, the location B is less challenging than the capsule location A since in the capsule location B, we can note three channels with moderate channel attenuation: S21, S51, and S61. At 4 GHz, the channel strengths for S21, S51, and S61 are -48 dB, -45 dB, and -51 dB, respectively. Additionally, the channel parameters to the on-body antennas 3 and 4 are also at reasonable level at -55 dB and -65 dB. Hence, in this capsule location, communications link for several on-body antennas is reliable and capsule localization feasible even with receivers having minor sensitivity.

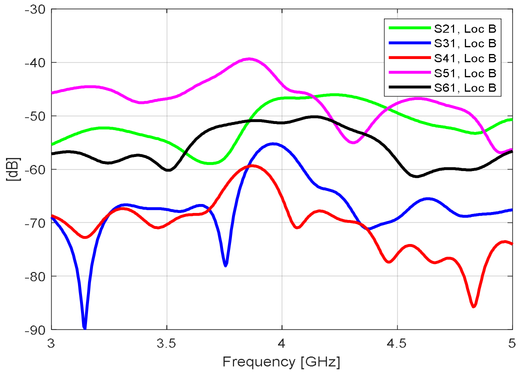


Fig. 7. Channel parameters between the capsule and five on-body antennas in the capsule location B.

C. *Capsule Location B2*

Fig. 8 presents the channel parameters in the capsule location B2, which is at the same vertical crosscut level as the capsule location B, but deeper inside the colon tissue. Now, the channel strengths are noted to drop remarkably due to deeper propagation depth in the colon tissue in which the power loss in remarkable due to the dielectric properties [ITIS]. The difference between the channel attenuations in B and B2 locations is 17-23 dB. For the on-body antennas 2 and 5, the channel attenuation is -65 dB which is still at moderate level. The channel attenuation for on-body antenna 6 is -70 dB, which is still at acceptable level with receivers having higher sensitivity. Hence, the capsule localization is feasible also in this location.

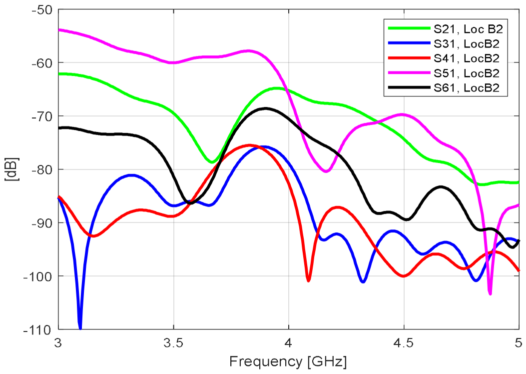


Fig. 8. Channel parameters between the capsule and five on-body antennas in the capsule location B2.

D. *Capsule Location C*

Fig. 9 presents the channel responses in the capsule location C. In these results, one can note clearly the impact of antenna gain changes in the radiation patterns: the channel between the capsule and its nearest on-body antenna is not always the strongest channel. For instance, the distance to the on-body antenna 4 is larger than to the on-body antenna 3, but still the S41 is clearly stronger than S31 at 3.75-4 GHz. At 4.25 GHz it is vice versa. This can be understood by studying the radiation patterns presented in Fig 2. For instance, at 3.75 GHz and 4 GHz, the lobe is stronger from antenna 4 towards the capsule than from the antenna 3 towards the capsule. However, the channel attenuation is moderate for all the capsule – on-body antenna links, which hence enables smooth capsule localization.

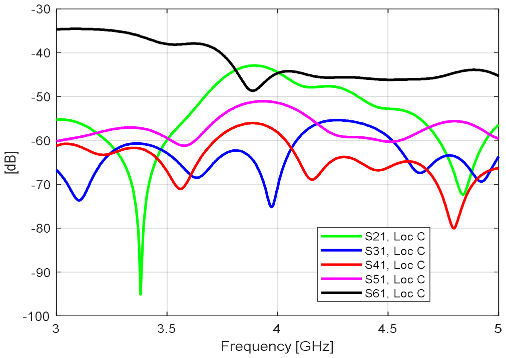


Fig. 9. Channel parameters between the capsule and five on-body antennas in the capsule location C.

E. *Capsule Location D*

At 4 GHz, the radiation patterns of on-body antennas are relatively symmetrical for left and right sides in the level of the capsule in the location D. This can be seen also in Fig. 10 where the channel attenuation is noted to be at the same level (60 dB) for the capsule on-body antenna links S31 and S61, i.e., for the antennas 3 and 6, which are located symmetrically respect to the capsule. This is valid at 4 GHz and 4.25 GHz, whereas at 3.75 GHz, clear differences can be seen both in the radiation patterns and in S-parameters. Similarly, channel attenuation is at the same level (53 dB) for the on-body antennas 4 and 5, which also are located symmetrically respect to the capsule.

Impact of the antenna gain lobes can also be noted from the comparison of the S-parameters for antennas that are oblique (3,6) and downward (4,5) to the capsule. The difference in the S-parameters is approximately 8 dB. Such a large difference further highlights the importance of understanding comprehensively the on-body antenna characteristics which also should be considered when determining the location of the on-body antennas. In the capsule location D, the localization of the capsule is straightforward due to multiple strong capsule-on-body antenna links.

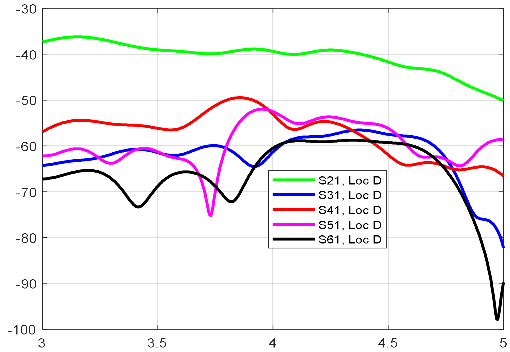


Fig. 10. Channel parameters between the capsule and five on-body antennas in the capsule location D.

F. Capsule Location E

The S-parameters obtained in the capsule location E are presented in Fig. 11. Also, in this case, the communications link and capsule localization is ensured since there is minimum three enough strong channels between the capsule and the on-body antennas. The levels of the S21, S31 and S41 are at -53 dB, -55 dB and -58 dB. This location is somewhat a mirrored version of the location B in the left side of the abdomen. When comparing the channel responses obtained in locations E and B, we can note that the channel responses in location E are at clearly lower level than in the capsule location B. Also, this phenomenon can be explained from the antenna radiation pattern dissymmetry seen in Fig. 2: the antenna gain towards the capsule is more favorable in the location B than in the location E. In general, the channel strengths in the capsule location E are sufficient to enable reliable communication link as well as capsule localization.

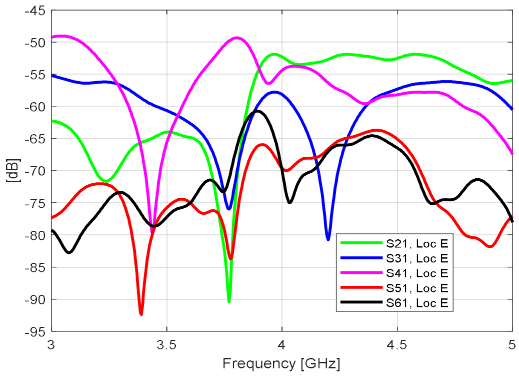


Fig. 11. Channel parameters between the capsule and five on-body antennas in the capsule location E.

G. Capsule Location F

Finally, the channel characteristics are evaluated in the capsule location F, at the end part of the ascending colon. The S-parameters are presented in Fig. 12. This location is challenging to due to vicinity of the only one on-body antenna (antenna 4), and this the situation is similar to the capsule location A. Channel attenuations are slightly more moderate than in the case of the capsule location A due to more favorable lobe directions towards the nearest on-body antennas. The channel attenuations remain minor than 65 dB for three of the capsule - on-body antenna links (S21, S31, and S41), which ensures also the capsule localization.

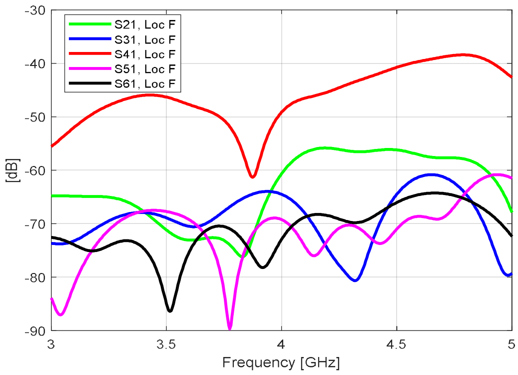


Fig. 12. Channel parameters between the capsule and five on-body antennas in the capsule location F.

TABLE I. CHANNEL PARAMETERS AT 4 GHZ IN DIFFERENT CAPSULE LOCATIONS.

Location	**Levels of S21, …S61 at 4 GHz [dB]**				
	S21	***S31***	***S41***	***S51***	***S61***
A	-70	-76	-76	-58	-68
B	-47	-55	-65	-45	-48
C	-45	-70	-58	-52	-45
D	-40	-60	-52	-52	-61
E	-52	-58	-55	-69	-69
F	-60	-64	-49	-69	-72

Table I summarizes the channel attenuations at 4 GHz in different capsule locations. As discussed earlier, successful capsule localization requires at least three channels with moderate attenuations. The presented results show that reliable communication links can be obtained with 5-multi antenna system in all the studied colon locations especially if receivers with higher sensitivity is used. For the locations B-F, the sensitivity criteria can less strict. In the case of the location A, the communication links could further be improved by using a mirrored version of the on-body antenna. This way the antenna gain lobes are directed towards more favorable directions and the channel attenuations could be decreased to the same levels as in the capsule location F.

IV. SUMMARY AND CONCLUSIONS

This paper presented a study of the radio channel characteristics between a colon capsule endoscopy and a multiple on-body antenna system in UWB-WBAN application, The main aim was to study the variation of the channel characteristics between the capsule endoscope and the on-body antennas in different capsule locations throughout the whole colon area.

The presented channel evaluations showed that the 5-on-body antenna system, proposed originally in [3] for capsule endoscopy communications for the small intestine area, is sufficient also for colon capsule endoscopy. Only the most outermost locations, like capsule location A and F are the most challenging since in those locations, there is only one on-body antenna in the vicinity of the capsule. However, since the fat is relatively good propagation channel [20], [21], the reasonable channel attenuation level is obtained for the next closest antennas as well. Additionally, the location B2, which is in the deepest part of the colon, is a challenging location since the propagation loss is high in the colon. Besides, colon is relatively thick tissue. Nevertheless, the localization of the capsule is found to be feasible also in these most challenging capsule locations especially if receivers with higher sensitivity is used.

When we compare channel evaluations in the colon area to the channel evaluations in the small intestine area (e.g. in [3], [11]), we can notice that the colon area is less challenging due to smaller propagation depth requirements. On the other hand, the small intestine has benefit of being thinner. Besides, visceral fat around the small intestine may help to get enough strong channel even in the deeper capsule locations [21]. Instead, the colon is remarkably thicker and thus, the capsule-on-body antenna link might become too weak if the capsule is located in the deepest corner of the colon with voxels having larger size than Laura-voxel. However, the use of more directional antennas or increasing number of antennas, is assumed to meet this challenge.

As future work, we plan to conduct comprehensive channel simulations with several different antennas and different voxel models having different sizes and body constitutions. Besides, we will prepare phantoms for abdominal tissues and carry out measurements to validate simulation results.

ACKNOWLEDGMENT

The authors would like Dr. Chaimaa Kissi for on-body antenna design and Dr. Markus Berg for capsule antenna design.

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