Int J Wireless Inf Networks (2012) 19:326–340
DOI 10.1007/s10776-012-0195-z

RF Localization for Wireless Video Capsule Endoscopy

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Received: 1 April 2012 / Accepted: 25 September 2012 / Published online: 14 October 2012

Abstract RF localization science and technology started with the global positioning systems for outdoor areas, and it then transformed into wireless indoor geolocation. The next step in the evolution of this science is the transformation into RF localization inside the human body. The first major application for this technology is the localization of the wireless video capsule endoscope (VCE) that has been in the clinical arena for 12 years. While physicians can receive clear images of abnormalities in the gastrointestinal tract with VCE devices, they have little idea of their exact location inside the GI tract. To localize intestinal abnormalities, physicians routinely use radiological, endoscopic or surgical operations. If we could use the RF signal radiated from the capsule to also locate these devices, not only can physicians discover medical problems, but they can also learn where the problems are located. However, finding a realistic RF localization solution for the endoscopy capsule is a very challenging task, because the inside of the human body is a difficult environment for experimentation and visualization. In addition, we have no-idea how the capsule moves and rotates in its 3D journey in this non-homogeneous medium for radio propagation. In this paper, we describe how we can design a cyber physical system (CPS) for experimental testing and visualization of interior of the human body that can be used for solving the RF localization problem for the endoscopy capsule. We also address the scientific challenges that face and the appropriate technical approaches for solving this problem.

Keywords Capsule endoscopy · In-body radio propagation · Localization algorithms · Security and reliability · Virtual visualization · Gastrointestinal tract · Body area networks · Sensor networks

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1 Introduction

Many of the profound innovations in science and engineering start with metaphors presented in science fiction. The wireless information networking industry was motivated by the Captain Kirk's communicator in the 1960s science fiction series "Star Trek". The idea was formed in the early 1980s; the Federal Communications Commission (FCC) released the Industrial, Scientific and Medical (ISM) bands; the IEEE 802.11 standardization committee created the WLAN standard in 1997 [1, 2, 3] and, after almost half a century, modern smart phones are what the evolution of the "Star Trek" communicator fantasy brought to us. Recently, another 1960s science fiction, the "Fantastic Voyage", in which a space craft with its crew were shrunken to become a micro-device capable of traveling inside human body to remove a brain clot, has stimulated a new wave of innovations science and engineering for the body area networking (BAN). That space craft lost its navigation capabilities and went through an unguided dramatic travelling experience within the human body before it exits through tears from the eye of the human subject. Today, endoscopy capsules [4] are traveling inside the digestive system in the same way as the space craft in the fantastic voyage travelled and one can envision emergence of a number of other similar applications for micro-robots inside the human body [5, 6].

Wireless video capsule endoscope (VCE) has been in the clinical arena for 12 years. The latest VCE devices appearing in the market are evolving into micro-robots with mechanical legs that can stick to specific location for closer observations, precision medical delivery or other missions [7]. An endoscopy capsule provides a non-invasive wireless imaging technology for the entire gastrointestinal (GI) tract with the unique feature for medical applications in terms of observing abnormalities in the small intestine. The small intestine is a "long" curled tube with an average length of six meters (see Fig. 4). While physicians can receive clear pictures of abnormalities in the GI tract with capsule endoscopy, they have little idea of their exact location inside the GI tract [8]. As a result, when surgical intervention to excise a lesion is indicated, localization of the lesion can be very challenging. Exploratory clinical procedures include computed tomography (CT), planar X-ray imaging, magnetic resonance imaging (MRI). Ultrasound, laparoscopy or surgery. Radiological imaging procedures such as CT and MRI are not easily combined with capsule endoscopy because of the requirement for continuous imaging over several hours. Therefore, if we could use the RF signal radiated from the capsule to also locate these devices, not only can physicians detect lesions, but they can also locate them efficiently.

RF localization science and technology started with the global positioning systems (GPS) for outdoor areas, then it transformed into wireless indoor geolocation [9]. The next step in the evolution of this science is the transformation into RF localization inside the human body [10]. However, RF localization of micro-robots inside humans is not trivial. Compared to outdoor and indoor environments, the inside of the human body is a complex environment making engineering design and visualization a formidable task. The inside of the human body is an extremely complex medium for RF propagation because it is a non-homogeneous liquid-like environment with irregularly shaped boundaries and severe path-loss. When the signals are used for RF localization of micro-robots, things become more complex since the road map for the movements of the micro-robot is blurry and the body mounted sensors used as references for localization are also in motion [5, 6]. More importantly, reliable designs need testing the hardware implementation, but we cannot easily test devices inside the human bodies. Like maps for outdoor and indoor navigation, we need a "3D map" of the human body for virtual visualization of the location of the micro-robots to observe the uncertainty in location for a medical application. To overcome these difficulties, we need to design a cyber physical system (CPS) as a testbed for performance evaluation and virtual visualization of the interior of the human body to be used for advancements in in-body RF localization science and technology.

The existing principles of science and technology for engineering design of RF localization systems for micro-robots traveling inside the human body are in their infancy and there is a need for multi-disciplinary research in this area. As far as we know attempts to deploy such systems have not been successful and to date there are no clinically available systems for this purpose.

The RF localization inside the human body is a fertile area for seminal scientific research with a broad impact on a number of engineering designs for the future of the wireless health industry. From a scientific point of view, by solving the localization problem for micro-robots, we will shed light on 3D RF localization of devices with irregular patterns of motion in a non-homogeneous and non-stationary medium such as the human body. The results of this research may have a considerable impact on the evolution of navigation technology and understanding of fundamentals of localization science. From an engineering design point of view, solving the RF localization problem inside the human body will enable a number of applications ranging from localization of the endoscopy capsule, precision drug delivery, localization of the intrusive devices during surgery and localization of micro-devices to open blood clots, which are emerging in practice. One can also envision that many more will appear as the enabling navigation and visualization technologies open the path for micro-robotic surgery inside the human body. Further advancement in research in this area requires a CPS for performance evaluation and visualization to allow design of realistic algorithms and analysis of the effects of RF radiations.

2 A CPS for RF Localization Inside the Human Body

In this paper we describe the architecture and the challenges for the design of a CPS for performance evaluation and visualization of RF localization algorithms for micro-robotic applications inside the human body, and suggest how we can use this CPS as a testbed to solve the problem of localization of endoscopy capsules inside the GI tract. To implement a CPS for RF localization experiments inside the human body we need the following elements:

- Models for the movement of video capsule inside the GI tract

- Models for the RF signal propagation from the video capsule to the body-surface and beyond for the design of localization algorithms and the analysis of reliability and security aspects
- A real-time hardware platform for emulation of the radio propagation channel between the transmitter in the video capsule and the receivers on the body-mounted sensors
- A virtual reality visualization platform to inspect and demonstrate the actual movements and the estimated distance from fixed points as the video capsule moves along the tract

Implementation of this CPS requires integration of several existing facilities and results of fundamental research in RF localization inside the human body. Figure 1 provides an overview of the CPS elements and the general concept behind this idea. There are large database of capsule endoscopy videos and follow-up clinical “explorations” of locations inside the GI tract, through the observation of abnormalities, which could be used to model the movements of the VCEs inside the human body. The movement model could then be mapped to a RF channel simulation software. Results of simulations could be validated by measurements inside phantoms and body surface measurements. Massive empirical measurements of the received waveforms could be used for modeling the wideband channel characteristics between the VCEs and body mounted sensors. These wideband channel characteristic models could be mapped on to a multi-port real-time RF channel emulator, for example PROPSIM C8 that is connected to the actual transmitters and receivers of devices. This environment could then be used for understanding the security and reliability and design of RF localization algorithms for the video capsule. The physical and the estimated location of the capsule along with the 3D images of the organs could be imported into a virtual visualization platform. The use of this CPS may allow comparative performance evaluation necessary for design and analysis for an optimal solution to the problem.

The significance of such a CPS testbed is that it transforms the way people interact with engineered systems moving inside the human body. Therefore, such a CPS system is able to foster advancing research in CPS and to transferring the resulting CPS science and technology into engineering practice. To implement such a CPS we depend on successful collaboration and synergistic multi-disciplinary efforts among medicine and engineering researchers to collect meaningful databases, computational facilities, RF simulation software, and hardware elements of the testbed. Previous experience in the implementation of similar performance evaluation hardware for indoor geolocation [11–15] and in-body visualization [16, 17] are reported in the literature and that testifies the practicality of the design of such a complex CPS testbed. A successful design for such a CPS to emulate the RF environment inside the human body faces certain scientific challenges that demands basic research in the field.

3 Challenges for Implementation of the CPS

There are a number of fundamental multi-disciplinary scientific and technological challenges facing the RF localization of the VCEs inside the human body. To design a CPS hardware and visualization platform to explore these fundamentals of the science and technology that is needed for enabling RF localization of VCEs inside the human body we need to consider the following:

3.1 Modeling of the VCEs Movements Inside the GI Tract

The first challenge for meaningful analysis of RF localization inside the human body is to use clinical databases and clinical procedures performed by GI specialist, to model the movements of the endoscopy capsule inside the GI tract. Previously acquired and stored databases of patients with approximately 55,000 images per patient could be examined for detection of landmarks or fixed points such as the pylorus and the ileo-cecal valve [18]. Using the location of these landmarks, the number of images that observes the landmark, and the fact that the images are taken at a rate of two images per second, we should design a model for the movements of the capsule in the GI tract to be mapped into the CPS hardware and visualization platform. In the future, inertial sensing units that are small enough to be embedded in a pill size device could be used to provide real time information about pitch and roll angles of the endoscopic capsule. This information could be used to enhance the movement model provided by examining the images reported by the capsule. The improved model for the movements of the VCE using inertial sensors would enhance the RF localization result. The feedback controlled inertial sensors have been already used to monitor the robotic end luminal system using magnetic field to efficiently perform diagnostic and surgical medical procedures [19].

3.2 Modeling of the Wideband RF Propagation from Inside the Human Body

The second challenge is to model the wideband characterization of the RF propagation channel between an endoscopy capsule and body-mounted sensors. We could use measurements inside phantoms and on the human

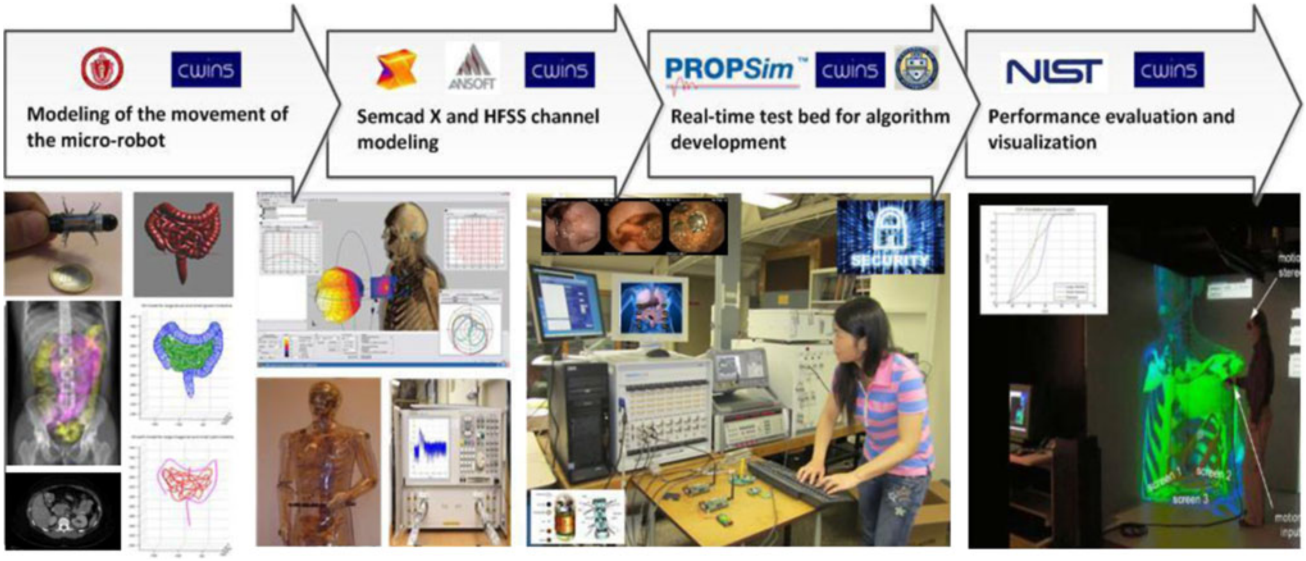

Fig. 1 The CPS for RF localization of micro-robots inside the human body

subject's body surface to calibrate existing software simulation tools for direct solution of Maxwell's equations inside the human body. We then could use the software to determine the waveforms observed by a body-mounted sensor used as a reference point for localization or another endoscopy capsule inside the tract that could be used for cooperative localization purposes. Finally, it should be possible to design models for the temporal and spatial features of these waveforms (that are extracted for localization techniques) as capsules travel along the GI tract, to be used by the CPS for performance evaluation and visualization.

3.3 Design of Algorithms for Localization Inside the GI Tract

The third challenge would be the design and comparative performance evaluation of alternative localization algorithms and discovery of methods for visualization of the results. For this part one needs to consider the use of channel models for spatial and temporal variation of the signal, the model for the track of physical movement of the capsule inside digestive system, and landmarks detected from video frames of the endoscopy capsule camera. In addition to the RF localization features, we may expect that these algorithms could exploit the knowledge of pattern of movements and the visual data observed by the camera inside the tract. The Cramer-Rao lower bound (CRLB) for the performance of basic received signal strength (RSS) and time-of-arrival (TOA)-based localization algorithms for capsule endoscopy are already available in the literature [20, 21]. We can use these bounds as a guideline for the expected performance of the designed algorithms.

3.4 Security and Reliability Issues

One last challenge in RF localization for VCEs would be to examine and where possible quantify the security, reliability, and privacy of implantable VCEs in human bodies. Here, there is an impending need to understand and analyze radio propagation of signals from VCEs outside the human body at larger distances where they may (a) cause interference (accidental or malicious) to the localization of VCEs and or devices inside a human body (b) recovered by more powerful devices towards identifying existence of such VCEs in specific patients. The former impacts the reliability of localization of the VCEs inside the human body while the latter impacts the privacy of patients and the medical procedures that may be conducted on the patients. We elaborate on these in the last section of the paper.

4 How Can We Meet the Challenges?

The common scenario for RF localization of VCEs inside the human body, shown in Fig. 2, is to install a number of body-mounted sensors to monitor the transmitted waveform on the surface of the human body [10, 22, 23]. The received waveforms at the body-mounted sensors can then be analyzed to extract the RSS, TOA and direction of arrival (DOA) of the received signal. The static value of these features of the signal at any given time or location

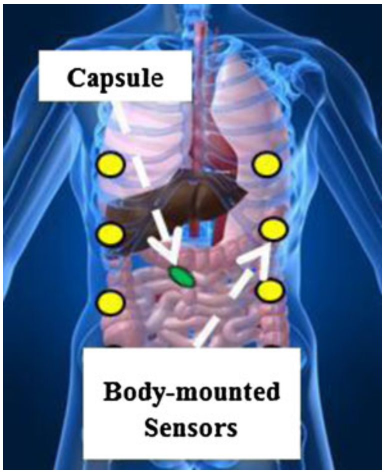

Fig. 2 Localization scenario

provides a means for estimation of the relative distance/direction of the signal source to the body-mounted sensor, which is commonly used for absolute localization [3, 9]. The sequencing of these features in time and space of the signal is used to refine the location estimate as the device is moving along a path in 3 dimensions. The current generation of capsules uses the Medical Radio communication Services (MedRadio) band at 401–406 MHz [24]. The IEEE 802.15.6 standards for BANs also considers the ISM bands at 902–928 and 2,400–2483.5 MHz as well as Ultra Wideband (UWB) frequencies from 3.1 to 10.6 GHz for general BAN applications [25]. To implement these systems we need to focus on the MedRadio bands for practicality and we should consider the ISM and UWB spectra that support wider bandwidths, which is useful for more accurate TOA-based localization. The desired localization accuracy for the existing capsules is within a few centimeters. More accuracy and precision are necessary for envisioned futuristic applications such as intrusive surgery.

4.1 Modeling of the VCE Movements Inside the GI Tract

A model of the movements of the VCE inside the GI tract is needed for the simulation and the analysis of the temporal and spatial variation of the observed signals by body mounted sensors, design of algorithms for localization, and the emulation of the channel characteristics for performance evaluation and visualization of locations of VCEs in a CPS platform. GI specialists localize these abnormalities in the GI tract that are reported by the capsule by clinical procedures such as endoscopy, colonoscopy, CT scan or surgery. We can use these abnormalities as landmarks in the GI tract and by counting the number of images observing these landmark estimate the velocity of the VCEs in a particular section of the GI tract.

4.2 Modeling the Movement of VCE Inside the Human Body

Unlike the movement of vehicles on roads or human beings in indoor areas, the movement of VCE inside the human body is very inconsistent and varies with the type of organs. While we cannot develop completely generalized models, we should be able to develop empirical movement models for these movements. These models can primarily employ videos augmented by information obtained from CT scans, deep enteroscopy, and surgery where available [4].

The basic idea for developing the movement models is as follows. Some pre-defined landmarks are detected by image processing techniques or identified by a GI specialist through the video source taken by VCE [18, 26]. These landmarks include entrance and exit of each of the four organs traversed by the endoscopy capsule: esophagus, stomach, small intestine and large intestine as well as tumors and bleeding identified in the tract. Figure 3 shows pictures of landmarks inside the GI tract associated with pictures of duodenum, bleeding, tumor and cecum.

Since the videos are taken at a fixed frame rate, the average speed of the video capsule can be obtained by dividing the typical distance between known landmarks and the average length of the organs by the elapsed time periods. This speed estimation can be further improved by analyzing the correction between the consecutive frames. Other movement features such as rotations and flips of the capsule can be also estimated based on the captured video source [27]. Another key point is to find the location of the tumors or bleedings that occurs in different locations of the GI tract. Those abnormalities can be used as new landmarks to reveal the knowledge on speed of the VCEs in different locations of the GI tract and distance of the abnormalities away from fixed point. This way, we can emulate the movement of the capsule moving inside the GI tract and associate the video frames to the location inside the tract. A GI specialist can provide data to an engineering team from pre-existing clinical studies. In a typical hospital about 500 video capsule procedures are performed per year, of these, about 15 % of the patients have CT scans performed of the abdomen and pelvis to provide additional localization data on the position of a pathological lesion. Of these, about 40 % of patients have exploratory surgery for resecting of a source of bleeding or tumor from the small intestine. At operation the surgeon can accurately measure the position of the lesion with respect to the length of the small intestine. This database can be searched for those patients who have had all of the above procedures. Once the most useful patient population has been identified, interpretation of the VCE studies can be provided by the medical team so that accurate and meaningful data can

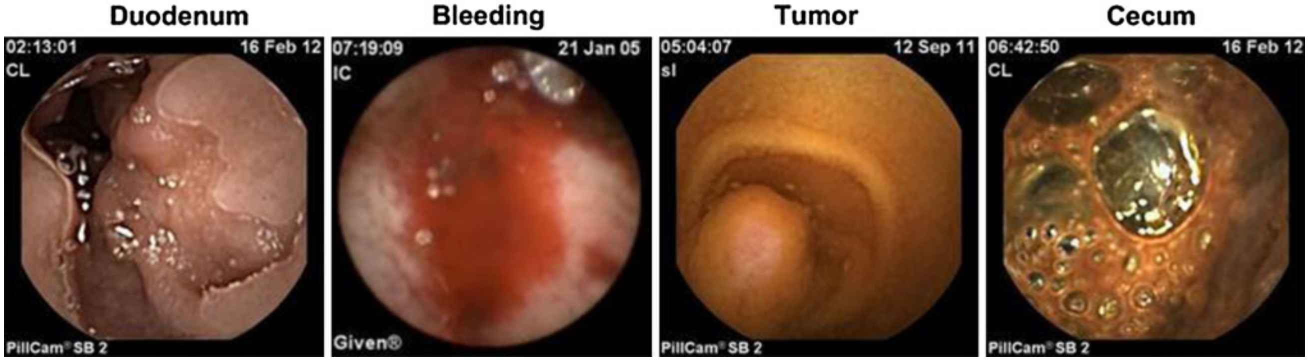

Fig. 3 Sample pictures of landmarks for localization taken by the capsule

then be linked to the models and simulations developed by the engineering groups.

4.3 Available Data for Model Validation

Using the database from a number of patients who have undergone varying tests for localization of lesions within the small intestine it is possible to validate models for movements of the VCE. There are four techniques that can be used to validate the position of a VCE within the abdominal cavity.

Firstly, the VCE provides up to 55,000 images in JPEG format at 2 frames per second. These images are transmitted to a recording device in real time attached to the patient's body. These images are then processed into a video that can be read by a trained observer at varying speeds from single frame to full video speed. Since each image is associated with a timestamp, it is possible to identify the exact time when either a fixed point (landmark) such as the pylorus or ileocecal valve or an abnormality such as a tumor or vascular lesion is reached. In this way, the relationship of an abnormality can be related to the landmarks. However, this observation alone is inadequate since as mentioned above the movement of the video capsule is inconsistent within the GI tract.

Secondly, patients who are thought to have tumors by the VCE usually undergo a CT scan. A CT scan is able to provide a three-dimensional view of the entire small intestine, and is helpful in the further analysis of the lesion's characteristics, including localizing its position inside the small intestine, measuring its size and determining whether or not there is metastatic spread of a tumor. This technique can be further enhanced by the presence of oral and intravenous contrast. Oral contrast provides delineation of most of the length of the small intestine whereas intravenous contrast provides for imaging of the blood supply of tumors or vascular abnormalities.

Thirdly, the positional information measured from the previous steps can be further validated by the deep enteroscopy. Deep enteroscopy is a new technique that employs two balloons or a spiral device [28] placed over a flexible endoscope which, when deployed in the small intestine, allows for pleating the small intestine on to the endoscope, thereby shortening it, and allowing deeper penetration of the endoscope [29]. It is usually possible to advance the scope up to 250 cm beyond the pylorus when it is inserted orally and up to 200 cm when inserted through the anus in a retrograde fashion. As the scope reaches a point of interest it can be marked with India ink to facilitate localization at subsequent surgery. It is also possible to deploy a metallic clip at the point of interest to enhanced radiological detection. Such a clip attached to the mucosa eventually will drop off and be passed in the fecal stream.

Lastly, if the patient requires surgical resection, this can be performed by laparoscopy or open surgery. The point at which the lesion is found at surgery can be physically measured with respect to the landmarks of either the pylorus or ileocecal valve.

The techniques described above, can be used alone or in combination, to permit the development of movement models and the validation of simulation, modeling and development of localization algorithms with enhanced use of radiofrequency tracking of small objects within the abdominal cavity.

4.4 Modeling of Wideband RF Propagation from Inside the Human Body

The main challenge for the design of accurate algorithms for RF localization of the VCEs inside the human body is the lack of wideband wireless channel models for in-body localization applications. These models are also needed for emulation of radio propagation inside the human body for the CPS testbed used for performance evaluation and visualization. Since it is not practical to make RF measurements inside the human body, researchers resort to using phantoms, dead body animals or computational techniques to measure the RF characteristics inside the human body. It is very difficult to emulate complex paths such as those of inside the small intestine, in a phantom or a dead animal body and computational techniques may be perceived as less accurate and un-realistic. However it should be possible to use limited measurements on phantoms and the surface of human volunteers to validate and calibrate software simulation of RF propagation for direct solutions to Maxwell's equations.

In the literature, there are three software simulation tools for RF propagation inside the human body: the commercially available SemCAD X used in [30, 31] and Ansoft HFSS used in [17, 32, 33] as well as our proprietary FDTD software on MatLAB developed at CWINS/WPI [34, 35] Noe11, [36]. The SemCAD X and Ansoft HFSS have fancy collection of waveforms, diversity of models for human bodies and organs, and simpler proprietary and faster FDTD solver [34–36]. A detailed comparison of these three approaches for in-body radio propagation analysis is available in [37].

We need to develop wideband radio channel models for general analysis and a set of simulation tools that will simulate the radio propagation characteristics when the VCEs are at various points in the GI tract and the fixed receivers are at various points on the surface of the human body. Towards this, we have the following tasks: importing the movement models of the capsule into the RF channel simulator CAD software, validating the results of software simulations with actual measurements, and modeling of the wideband characteristics of RF propagations pertinent to localization inside the human body.

4.5 Importing the Movement Model Into the CAD

If we have a 3D CAD model of the GI tract with which we can find the path of the movement of the capsule, we can import this path into the software simulation tool for RF propagation modeling. An important and challenging part of this process is the import related to the intestinal tract. Given a 3D CAD model of the intestinal tract, shown in Fig. 4, we need to trace the center of the intestine volume that is similar to a curled tube, so that we can model the movement of the capsule inside the intestine tract. The 3D image processing techniques can be applied to accomplish this goal.

In the case of the large intestine, since it already has a very clear pattern, which looks like a big hook, we can apply the 3D skeletonization technique [38] to extract the path. Since the shape of the small intestine is much more complicated, the same technique does not work well. In this case, need to resort to an element sliding technique [27] to trace the path. The basic idea behind this technique is to define an element shape with its radius automatically adjustable to the radius of the small intestine. As the element shape goes along the small intestine, the center of the element shape is recorded and this approach gives us a clear path inside the small intestine. The preliminary result of the path extracted from the 3D CAD model is shown on the right side of Fig. 4 [27]. This technique can be used with the models of the movement of the capsule, discussed in the previous section, to simulate the movements of the capsule in different RF propagation simulation software.

4.6 Validity of the RF Propagation Simulations

To discover the validity and limitations of RF propagation simulation software, we have performed some preliminary experiments. We used a hollow phantom to show that the Finite Difference Time Domain (FDTD) computational method can simulate results that closely match the results of actual wideband measurements. The wideband measurements are taken by a network analyzer inside our anechoic chamber built with absorbing material covering the inside walls (Fig. 5). We have simulated this environment using our fast and simple FDTD software in MatLAB. The boundary conditions of the simulation are absorbing walls similar to those of the chamber. Figure 5a shows wideband measurements on the network analyzer on a hollow phantom inside the chamber. Figure 5b shows the results of FDTD simulation of the RF propagation using the CT scan of the same phantom. Figure 5c shows the results of waveform simulation using FDTD and the actual wideband measurements inside the chamber for a transmitted signal with a bandwidth of 70 MHz [36]. These preliminary results justify the validity of software simulation for wideband measurements inside the human body. Our preliminary results also reveal that the computational techniques have bandwidth limitations that are a function of the distance between the transmitter and the receiver and the grid size used for simulation of the environment. For practical distances and 12.5 mm grids with reasonable computational time, we found that we can have accurate measurements for bandwidths up to 100 MHz that is enough for the CPS implemented on the PROPSIM channel simulator with a bandwidth of 70 MHz. Additional research using more complex phantoms with organs and real human bodies is needed to validate and understand the results of simulation inside the human body using computational techniques.

4.7 Modeling of the Wideband Characteristics

To measure the statistics of the temporal and spatial behavior of the signal, we used computational techniques for direct solution of Maxwell's equations for extensive measurements of wideband characteristics of RF signals inside the human body. We have used these techniques to

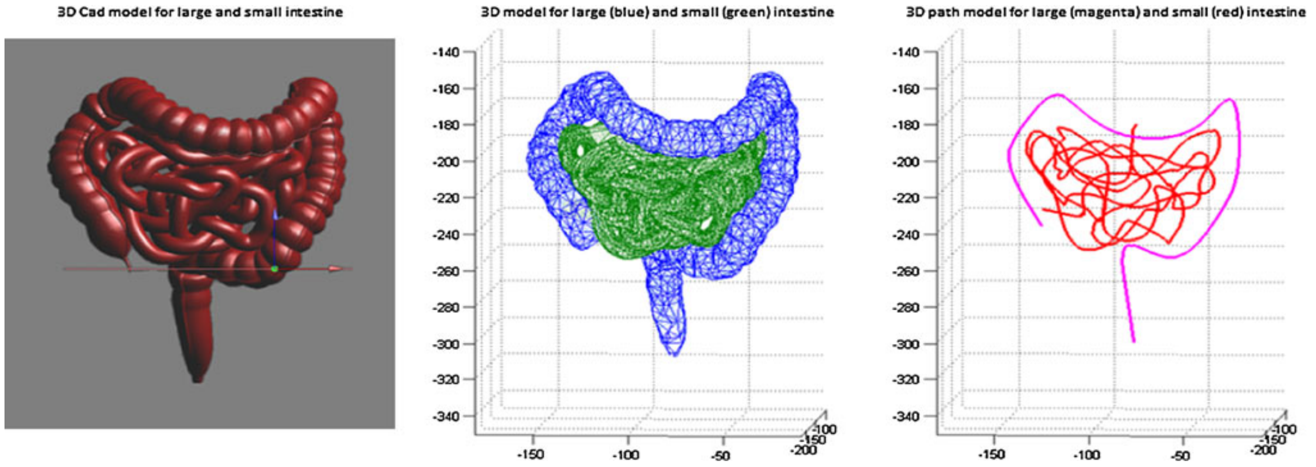

Fig. 4 The 3D CAD model of the small and large intestine, the 3D digitized model and the 3D model for the path of movement of the capsule

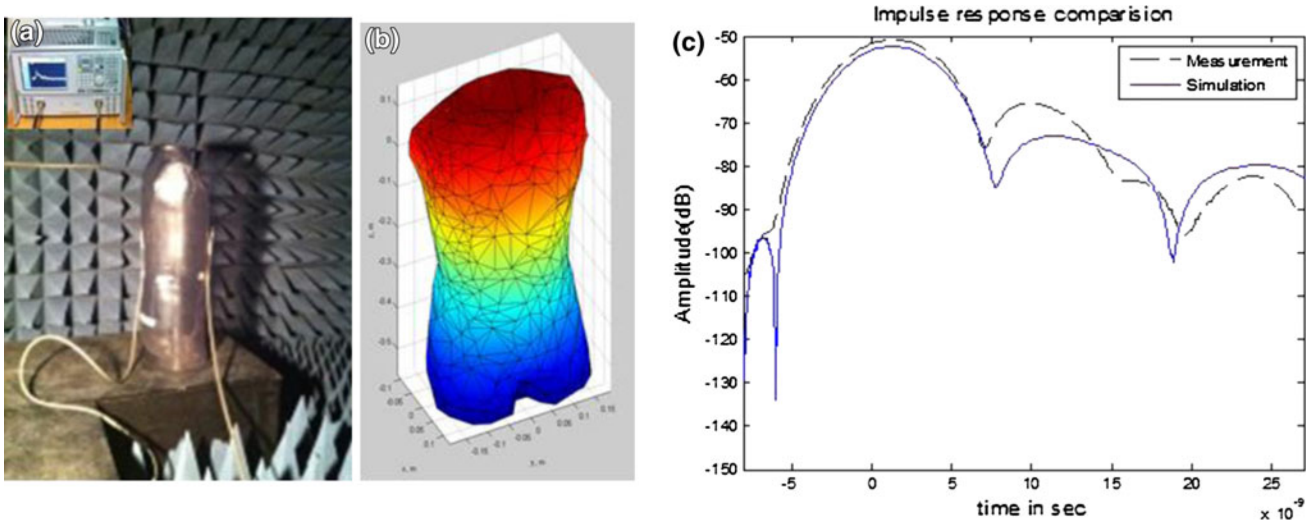

Fig. 5 **a** Measurement set up inside the anechoic chamber **b** simulation of the same environment using FDTD **c** matching the waveforms from measurements and computation

find the wideband received signal at body mounted sensors and other VCEs when a waveform is transmitted from a VCE in a specific location inside the GI tract. Then we extracted the RSS, TOA and DOA of the received wideband signal by other capsules or by body-mounted sensors to model them for use in RF localization algorithm design.

For RSS based localization techniques, we need a path-loss model that relates the statistical behavior of the power to the distance to calculate the estimated distance of the capsule from the body-mounted sensors used as the reference point. For TOA-based localization algorithms, we need a model for the multipath arrival and the relationship between distance measurement error and the bandwidth of the system to account for the measurement noise and various biases in distance estimation from TOA measurements [39, 40]. The current body of literature only provides a few path-loss models for implant communication applications [17, 33]. Modeling of the effects of multipath on TOA- and DOA-based localization is at its infancy and new models for these purposes are needed.

4.8 Design of Algorithms for Localization Inside the GI Tract

The current body of literature is very rich in algorithms designed for localization outside the human body for GPS and indoor geolocation applications. However, because of the lack of knowledge of movements of the VCEs inside the human body and the availability of channel models to relate the locations to RF propagation, these algorithms have not been verified for the use in localization process inside the human body.

Localization inside the human body not only demands the (*x, y, z*) coordinates, it also can rely on the relative distance travelled from fixed landmarks. These landmarks include pylorus at the entrance of the small intestine or the ileocecal valve at the entrance to the large intestine or location of a tumors or bleedings that are identified by the images reported by the capsule. This is a challenging problem and it gets more complex as human body moves and changes its posture. We need a fixed reference point for localization, such as location of the pylorus, to measure the locations and the distances among them inside the human body that is constantly in motion. The research methodology to solve this problem could use channel models for spatial and temporal variation of the signal from Sect. 4.2, the models for tracking the physical movement of the capsule inside digestive system Sect. 4.1, and the landmarks detected from video frames of the endoscopy capsule camera to design RF localization algorithms both in 3D and relative to the distance travelled from the major landmarks. Three classes of algorithms are suitable for the localization inside the human body:

- Cooperative localization algorithms using relative location of reference points and multiple capsules inside the human body to determine the location.
- Algorithms using the movement models of endoscope capsules and imaging landmarks to refine the precision of tracking.
- Super-resolution algorithms that are used to refine the bandwidth resolution of the signal to determine the TOA of the signal.
- Algorithms that use antenna design to refine the estimation of the DOA of the signal.

4.9 Cooperative Localization Algorithms

Cooperative algorithms are widely used for localization in challenging environments such as indoor areas [22, 41, 42]. These algorithms use the relative location of a number of reference points with a few targets with less accurate location estimates and use location of targets with each other to determine an optimum location for all targets. Since endoscopy using multiple capsules has been examined for clinical purposes [8], these are a very important class of algorithms that should be considered. Using CRLB, the limits of RSS-based localization accuracy with a certain topology of body-mounted reference-point and a number of VCE devices in cooperation are analyzed in [21]. Figure 6 shows some of the results for RSS-based localization relating the accuracy achievable in different organs in the GI tract to the number of body-mounted sensors and cooperative capsules [20, 21, 43]. For the TOA-based localization we need to analyze the influence of non-homogeneity of the human body tissue on propagation and distance estimation which causes TOA ranging error in TOA based localization techniques. Some preliminary results on this research topic is reported in [21]. More research is needed to design actual TOA-based algorithms, which can handle the effects of non-homogeneity of the human body.

4.10 Algorithms Using Movement Models and Landmarks

It should be possible to employ Kalman filter and particle filter to combine the information from the RF localization system using RSS or ToA and capsule movement model information to enhance the accuracy of the localization. Kalman filter and particle filters have been widely used in outdoor and indoor RF localization and navigation applications to incorporate movement models into the TOA-based systems such as GPS and RSS-based localization systems such as WiFi-localization. In our previous work [20], we have used both filters to combine RSS-based Wi-Fi localization and movement models from inertial sensors for cooperative robotic applications in indoor areas. The results are promising since this method shows the potential to smooth the localization results while reducing the error by several orders of magnitude. In the localization literature, there is trend to use Kalman filter or particle filters to incorporate imaging landmark information to improve the performance. These classes of algorithms are known as simultaneous localization and mapping (SLAM) algorithms [44]. In the capsule application, since an endoscopic capsule continually takes pictures inside the GI tract, we can also use the image information to aid the RF localization system.

4.11 Super-Resolution Algorithms to Refine TOA-based Ranging

For TOA based localization using capsule endoscopy, another challenge is to estimate the TOA of the direct path between the transmitter and the receiver with limited bandwidth, because the FCC's MedRadio band, currently used in capsule endoscopy devices, only spans 5 MHz. In our previous seminal research work in indoor geolocation, we have shown that super-resolution algorithm [45] has the potential to resolve the multipath components in a bandwidth limited situation through advanced spectrum estimation techniques. Figure 7 shows the effectiveness of super-resolution algorithms to resolve the multipath components in a typical indoor environment. There is a need for research to examine the effectiveness of super-resolution algorithm to reduce the bandwidth requirements, yet provide sufficient accuracy and precision for localization of the VCE.

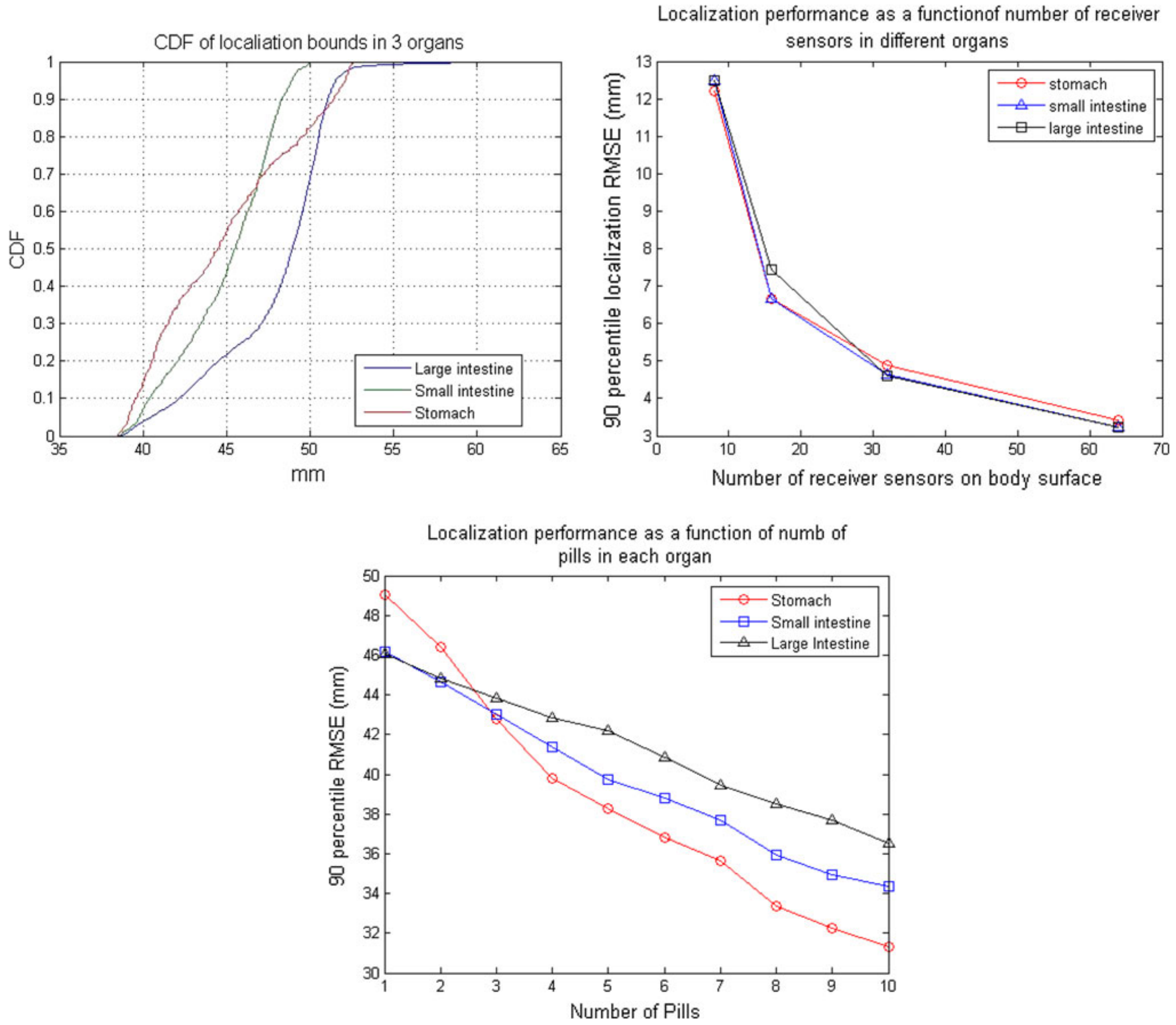

Fig. 6 Localization bounds for RSS based cooperative capsule endoscopy

4.12 Small Antennas Design for DOA Localization

The new concept of a small directional receiving antenna array intended for localization purposes on a human body could be used in the Fresnel region [46–48]. Figure 8 illustrates the basic concepts behind this approach. The array element is composed of two small orthogonal coils (magnetic dipoles). These coils are to be driven/acquired in quadrature, for both continuous wave and pulse signals. As a result, the array element becomes quite directional, with a relatively high-gain (about 8 dB) beam pointing into the body. An array of such radiators makes it possible to develop a simple yet effective localization algorithm within the body using RSS estimates for every individual radiator. The observed array performance in a complicated dielectric environment is derived based on the previous theoretical models [49–51] and may be explained as follows. To a certain degree, the array still utilizes near-field behavior of magnetic antennas, which is weakly affected by variable dielectric properties. On the other hand, every individual orthogonal-coil antenna forms a directional beam already in the Fresnel region, which significantly improves RSS estimates as compared to ordinary coil antennas (magnetic dipoles). Numerical simulations have shown that the directional beam is formed at distances greater than quarter wavelength in the body (~2.5 cm at 400 MHz) from the orthogonal-coil radiator [46–48].

4.13 Tackling Security and Reliability Issues

A final challenge in localization of VCEs inside the human body relates to reliability and security. The implantable

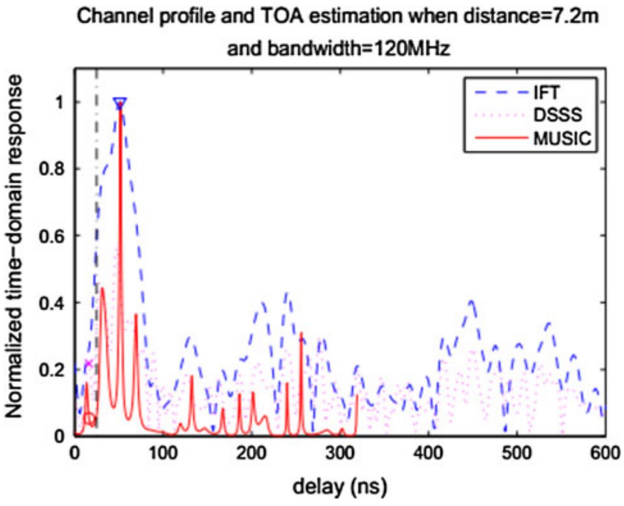

Fig. 7 The effectiveness of super resolution algorithm

VCEs inside the human bodies can be thought of as mobile sensors (or actuators) although the mobility is constrained to within the human body. These devices communicate with the outside world for presumably short distances and can also be manipulated from the outside with commands to perhaps release drugs at the appropriate locations. The propagation of wideband signals from the inside to the outside of a patient's body and the propagation of interfering signals to the body-mounted sensors allow for reliability, security and privacy problems with localization of VCEs. The challenges in the former case are related to the lack of understanding and need for analyzing how far signals can propagate outside the human body and what information can be recovered from them at larger distances. In the latter case, the challenges are related to whether the localization of an implanted VCE scan be tampered with or accidentally rendered unreliable due to interference or signals generated from larger distances during critical operational phases.

Security issues in sensor and ad hoc networks have received significant attention in the last decade (see for example [16] for a survey). Threats in such networks have focused on aspects such as denial of service (through jamming) [52–54], attacks against routing, attacks for identification of sources and destinations [55] in sensor networks, security with cooperative communications [56] and more sophisticated attacks such as Sybil and wormhole attacks. Security solutions have considered key distribution, authentication and encryption in general, use of timing and location against wormhole attacks, using random walks and fractal propagation to enable privacy in sensor networks, localization of nodes against Sybil attacks and challenge-response methods for a variety of selfish and fabricated reporting. The previous work in this area described above does not consider the special circumstances and constraints of wearable networks or VCEs inside the human body. These circumstances include the fact that such devices are used primarily in physically secure locations such as hospitals for fairly complicated medical procedures. Multi-hop routing is unlikely to be the networking scenario (which is most commonly assumed in previous work). Recently, the authors in [57] have outlined the security and privacy issues for implantable medical devices. Other work in this area has focused on key generation using physiological values or access control for patient data (that has left the implanted device). Very little work exists on reliability of localization in the presence of interference.

We briefly describe below some needed work towards understanding and examining the reliability and security

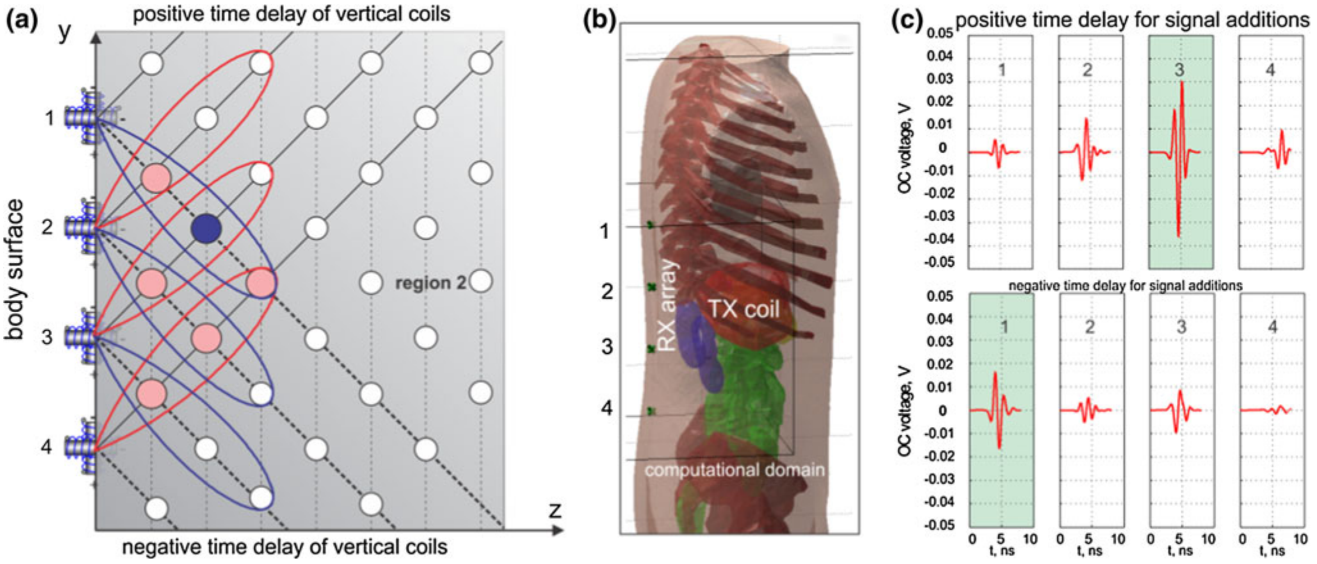

Fig. 8 Small directional receiving coil antenna array

problems related to localization of VCEs. Here, we consider a priori potential security and reliability risks that may exist due to accidental or malicious activity rather than to consider the various security problems previously considered and our focus will be on the impact on localization accuracy. For example, if there is an interfering signal, could it stop the delivery of a precision drug at the correct location in the GI tract?

4.14 Measurement, Modeling, and Simulation of Radio Propagation for Reliability and Security

Towards understanding the reliability and security threats for implanted VCEs, there is an imminent need model (a) the propagation and detectability of the wideband signals transmitted by an implanted VCEs at distances far beyond the human body and (b) impact on localization if multiple VCEs are present in a close physical area (e.g., two patients). Although VCEs are supposed to operate with low power, it is not clear how the radio signals will actually propagate. Measurements of radio signals on body-mounted sensors from a different phantom are needed to determine what the sensors detect.

4.15 Assessment of Reliability and Security

There is a need to determine (a) how localization accuracy is impacted under interference and (b) if crude localization of the device or a patient is possible externally using powerful receivers and/or with directional antennas. By this, for example, this may mean that it may be possible to discover that "some" device (device exists) is operating in a particular room in a hospital or it may even be possible to identify the device itself (identifying device type and correlating it with patient data). Measurement data and the models for RF signal propagation described earlier may be employed to determine the distances at which signals can be reliable detected by receivers with different capabilities. Analytically characterizing the bounds on a privacy "region" for a patient in terms of distance from the patient may help in careful deployment of VCEs in different environments. Finally, there may be a need to consider more sophisticated attacks wherein adversaries may employ long range communications in conjunction with local low-power devices as extreme cases of potential security threats.

5 Conclusions

RF localization of the endoscopy capsule is a challenging scientific and engineering problem with a very important application in wireless healthcare. A systematical solution to this problem can be achieved through design of a CPS testbed that emulates the behavior of the RF propagation inside the human body and provides a visualization platform to observe the interior of the human body. To design this CPS we need fundamental research in modeling the movements of the capsule inside the GI tract and modeling of the wideband characteristics of the radio propagation inside the human body.

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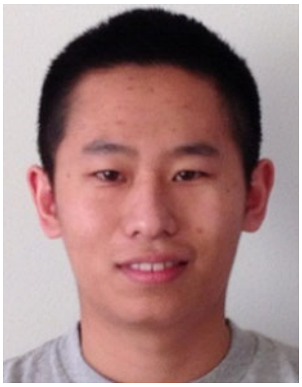

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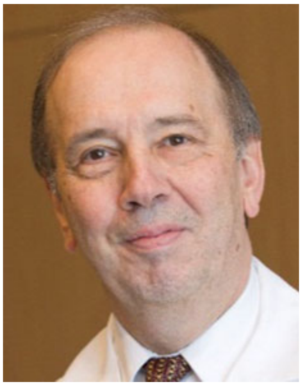

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