# Battery-free Wireless Communication for Video Capsule Endoscopy

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***Abstract*—Wireless capsule endoscopy is an advanced application of using ICT in healthcare and medicine. It is a non-invasive method to examine the gastrointestinal (GI) for early diagnosis and treatment. The capsule is equipped with a camera, light source, processing, control unit, and a transmitter to send the captured pictures or videos wirelessly to an external receiver system. The capsule is used to monitor small bowel diseases, esophageal diseases, and colonic diseases. The current data rate of the capsule endoscopes is limited to 1-2 Mbps with 2-3 frames per second and significant compression rates are applied to provide an operation time at least 8 hours inside the body. The data and frame rates might be sufficient for a capsule without locomotion, in which the capsule travels slowly, and the gastric wall movements mainly manage the speed. However, the next generation of the capsules will need remote locomotion and orientation control for fast and precise diagnosis. This application requests high data rate and low image or video compression rates with high frame rates for real-time navigation and control. Such a communication system becomes power hungry and limits the longevity of the device. Design of an ultra-low power wireless transmission scheme can assist the capsule device to save energy to handle the technology requirements. In this paper, we assess the communication systems of the capsule endoscopes and propose a battery-free high data rate backscatter wireless transmission scheme. The proposed system has been tested inside biological phantom in order to measure the path loss over different capsule depths. The average attenuation in a backscatter link inside biological phantom is 4.1 dB/cm in which is a linear function of capsule depth. According to link budget calculations, by using a 20 dBm transmitter at the outside of the body we can receive 8 Mbps data from the capsule at 10 cm depth. Our proposed system demonstrates superior performance compared to state-of-the-art systems in the literature.**

## I. Introduction

Wireless capsule endoscopy is a new emerging technology that not only reduces the cost of the digestive diseases diagnosing, but also it is easy to use for patients in comparison to the traditional methods. Generally, WCE consists of three main parts: the imaging system, wireless data link, and power management unit. The imaging system generally consists of a light source and image sensor. Image sensors are divided into two separate technologies, CMOS and CCD. The CMOS technology is more widespread because of its lower power consumption. The main goal of a WCE is collecting images from inside of the body for diagnostic purposes. Thus, several considerations should be taken into account for the design of the imaging part. For this aim, it is necessary to compromise between different image sensor parameters such as image quality, power consumption, image size and frame per second [1]. From the power rating point of view, the available commercial image sensors for biomedical applications typically consume tens of milliwatt. As an example, a biomedical specific image sensor from OmniVision (OVM6946) consumes 25 mW for the resolution of $400 \times 400$ pixels. The power handling to the capsule device is conducted by using battery or recently novel approaches in wireless power transfer (WPT) are proposed to handle the power with coupling link. In [2] a WPT system is proposed that uses Helmholtz coils and VLF signal for coupling the alternative current magnetically to the WCE. However, the coil size is significantly large and usually bends around the abdominal area, and high current flow is required to deliver approximately 100 mW of the power. The system is quite bulky and may not be appropriate to be carried by the patient. By reducing the power consumption of the capsule device, the transmitted power from outside of the body could be reduced in which increases the safety of the system and the size of the coils. In a battery-based WCE design, working hours is an important bottleneck that limits the duration of the clinical test. So one of the main challenges for solving this issue is reducing the power consumption of the different parts of the system. Another section of a WCE is the communication system. If the data rate increases, the better image quality of the malignant tissues can be delivered. However, high data rate requires larger power consumption, and thus further limitations are applied to the capsule. In this paper, we address the communication methods for a wireless capsule endoscope. We study the power consumption and data rates for the available active transmitter technics including radio frequency (RF), human body communication (HBC) and impulse radio. Then, we propose our novel technique using RF backscatter for deep implants in which the transmitter is removed from the capsule device, and all the communication system complexity and power consumption are moved to the outside body. Thus battery-free wireless communication becomes feasible. The paper is organized as follows: in section II, we present the examples of power consumption for active transmitter techniques and provide the power rating numbers. In section III the system design for an RF backscatter system is presented followed by our solution for efficient antenna design for the backscatter usage. Section IV presents the system implementation and measurement for high data rate communications in a phantom experiment. Section V, concludes this paper.

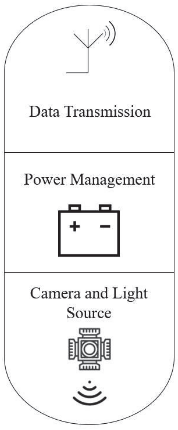



Fig. 1: Main blocks of a typical wireless video capsule endoscopy.

## II. Communication Systems for Capsule Endoscopy

In order to reduce the power consumption of a WCE, several solutions have been proposed in the literature. In [3] a subsample-based algorithm is used for the video compression part. The key idea of the proposed method is in the similarity of different parts of endoscope images in the spatial domain. In [4] a complete image processing unit for the WCE cameras is proposed. For the video compression, a digitized version of discrete cosine transform followed by an entropy-based encoding is used. After the data compression, a forward error correction (FEC) is applied for reducing the memory demand for the data re-transmission request in the case of burst and random errors. Regarding the wireless data transmission, the conventional approach is by using RF links for communications. The main reason is the already established technology and the wide availability of electronic components from the consumer market. However, RF technology is a power hungry approach for high data rates and is less efficient for communication inside the body due to the significant loss of RF in biological tissues compared to the free space. In addition, the antennas used in the implants are the scaled version of the antenna technology in free space, and less attention has been taken in the technology scaling to the implants. The small efficiency of implant antennas is a limiting factor for the communication link quality, thus the link performance and the quality of service requires a reasonable transmitter power. Using galvanic (conduction) coupling is promising for WCE, in which a baseband signal is used for communications. The method uses the conductivity of human organs to inject the transmit data directly to the tissues and capture the received data using on-body electrodes. A WCE device has been developed based on this technology [5]. The major advantage of galvanic communication is that the power-hungry parts of a typical RF system can be eliminated in which results in a highly efficient system. Also, the path loss through the organs is smaller compared to the RF due to using the low-frequency signal. The major concern with galvanic coupling is the possible interaction of the transmitted signals with the biological signals such as heart electrical activity and the requirement for continuous contact of the capsules electrodes with the surrounded medium. In [6] an ultra-wideband wireless data link is proposed that operates on the frequency range of 3-5 GHz. The main purpose for using UWB in the implantable devices is that the transceiver is active in a short period of the data bit duration. Thus the hardware will be more power efficient than the conventional architectures. The major disadvantage of UWB architecture is for the deep implants in which high attenuation is present using higher operating frequency. In [7] a human body communication-based link for WCE is proposed. The transmitter consists of two ring electrodes for inducing the desired signal into the body, and the receiver uses several electrodes at the different parts of the body. An algorithm is proposed for selection of the best receiving electrode at the receiver. In [8] a near-field based link with FSK modulation scheme is proposed. For the near-field purpose, the carrier frequency is selected 144 MHz. The disadvantage of the proposed method is that the RF carrier generator is a free running oscillator in which do not have frequency stability for high data rates. For the real-time and low power data transmission in [9], an RF data link is proposed. The method is based on traditional RF links with ASK modulation scheme. For reducing the power consumption, blocks of radio link have been optimized together for better power performance. Using the commercial off the shelf electronic components, the power consumption is higher than the state of the art methods. For example, ZL70103 RF transceiver chip from Microsemi support data rates up to 800 kbps in both 402 MHz  405 MHz and 2.4 GHz frequency band. It consumes 16.5 mW power in active mode. This module is designed for biomedical short range applications with high integration purposes [10]. For another example, CC1101 is a transceiver designed for very low-power wireless applications. It supports data rates up to 600 kbps and consumes about 20 mW [11]. In table I, a comparison between several states of the art data links for WCE and this work is depicted.

TABLE I: Comparison between available solutions and this work for wireless capsule endoscopy.

| | Data Rate | Frequency Band | Power Consumption | Method |
|---|---|---|---|---|
| [8] | 2 Mbps | 144 MHz | 2 mW | Near-Field |
| [6] | 10 Mbps | 3-5 GHz | 22.5 mW | IR-UWB |
| [5] | 6 Mbps | 8-16 MHz | 3.7 mW | HBC |
| [10] | 0.6 Mbps | 2.4 GHz, 402 MHz | 16.5 mW | RF (Commercial) |
| [11] | 0.9 Mbps | Multi band | 20 mW | RF (Commercial) |
| This work | 8 Mbps | 750 MHz | 3$\mu$W | Backscatter |

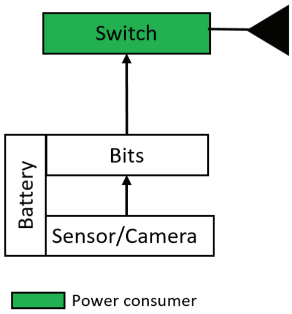



Fig. 2: Block diagram of a backscatter transmitter.

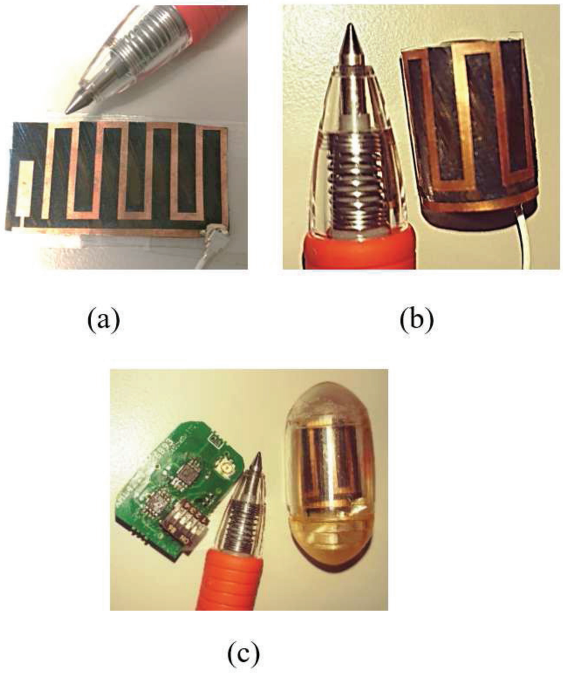


Fig. 3: (a) Backscatter antenna based on meander loop with capacitive coupling. (b) Conformal antenna with battery pack inside the cylinder. (c) Antenna inside colon capsule shell and selectable switch with different rates.

## III. System Design

One of the most power consuming part of a capsule device is the transmitter part. The carrier signal generator consumes a large part of the source energy. As the carrier frequency increases, the power consumption also increase. Roughly, for higher frequency bands, higher power consumption is needed. Thus, by considering this fact, if the carrier generator part of the link could be removed, the demand of power for the implant will decrease dramatically. This leads us to test the backscatter communication method for data transmission. In this method, the carrier generator is moved to the external side of the body where we do not have power limitation. For data transmission from the capsule, we need only an RF switch and appropriate backscattering antenna. The digital data from the image acquisition part is directly fed to the RF switch [12]. The RF carrier signal that transmitted from the external is received by the antenna, and the RF switch modulates the digital data into the received carrier signal by changing the impedance of the antenna between short and open states. There is not any circuit for power harvesting or energy saving for sequential communication. Therefore, real-time communication can be provided. The reflected signal is an amplitude modulated signal that propagates back in the environment and can be detected by an external receiver. If the radar cross section (RCS) of the implant antenna increases, we can receive a stronger signal at the receiver. By using this method, we have reduced the power consumption of the link at the in-body side dramatically. However, the link experiences forward and backward paths with larger path loss in which the external transmitter must compensate for the loss. The only part that needs power for operation in the capsule is RF switch which is ultra low power in comparison to the RF oscillators consumption. It can be in the order of nanowatts. In addition, by using the backscatter method, the design of the capsule becomes simpler, and there is no need to integrate an onboard transmitter. Fig.2 shows the block diagram of a backscatter system.

We have proposed an antenna design approach for providing high backscatter in the communication link [12]. The method is based on increasing the differential radar cross section between the data states and simultaneously provide large RCS. For this purpose, the antenna uses meander loop geometry and a capacitively coupled patch mechanism for the impedance tuning and adjusting the maximum RCS operation point. The antenna has been designed and optimized by using numerical electromagnetic simulation tool of CST Microwave Studio. The frequency domain solver is used to compute the antenna impedance characteristics as the antenna size compared to our intended frequency band at 600-750 MHz is very small. The physical size of the antenna is maximum 18 mm. The designed planar antenna is folded around a metallic cylinder of diameter 11.49 mm for simulating the loaded battery pack inside the antenna cylinder space. Thus, the maximum space is used. A foam dielectric of thickness 0.8 mm is placed on top of the antenna to guarantee a short gap to the antenna surrounding and the capsule shell. The antenna is placed inside a colon capsule shell of thickness 1.2 mm [see Fig.3].

The antenna is measured for the return loss in free space and inside the liquid phantom. Fig.5 shows the measured S-parameters in the free space and inside the liquid phantom. As shown, the antenna becomes wideband inside the phantom due to the induced loss from the environment. The antenna can be used in the frequency range of 580-680 MHz as an active transmitter antenna with appropriate matching to the source 50 ohms impedance. Using the antenna for the backscatter requires maximum reflection and maximum differential radar cross-section. For this purpose, the antenna impedance on a Smith chart is plotted [see Fig.4]. An active switch is used at

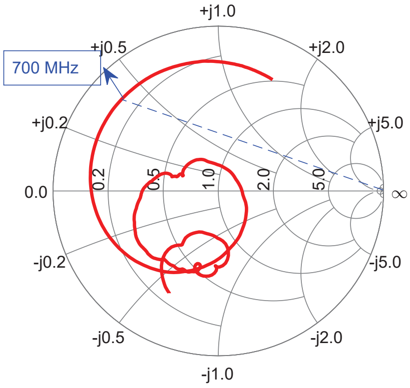



Fig. 4: Smith chart of the capsule antenna inside liquid phantom. The operating frequency is selected in the way that maximum distance between the antenna impedance at two states of RF switch could be achieved.

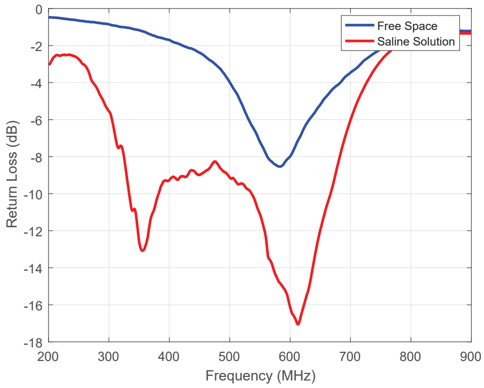



Fig. 5: The measured return loss for the capsule antenna at the free space and liquid phantom.

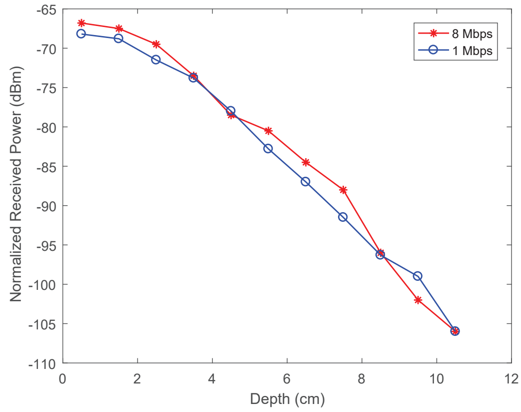
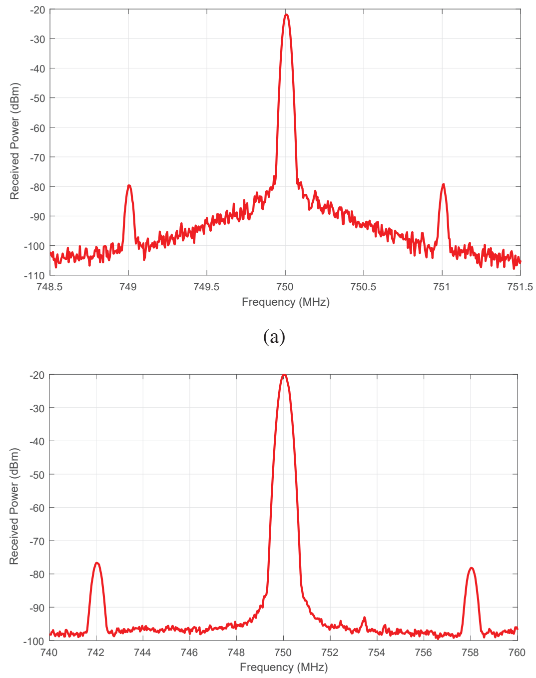



Fig. 6: Measured backscattered signal level for two different data rate (1 Mbps, 8 Mbps). It can be seen that the signal attenuation is a linear function of the capsule depth.




(a)

(b)

Fig. 7: Received power spectrum for 1 Mbps data rate (a), 8 Mbps (b). The transmitted carrier leakage appears in the center of the spectrum and the sidelobes indicate the backscattered data from the capsule.

the meander endpoint to make the switching task. The switch is placed at the resonance line of the antenna between the meander endpoint and the antenna ground. The load distance between the switching modes of the antenna is calculated and shown in Fig.4. In the short circuit (SC) mode the antenna is used at self-resonance mode, and the antenna reflection is maximum. In the open circuit (OC) mode, the antenna is in the structural mode, and minimum reflections occur. These two states are used to modulate the antenna reflections. Fig.4 shows the optimum operating frequency range with maximum backscatter signal in the frequency band of 650-750 MHz. We have used the frequency at 750 MHz which can provide about 3 dB better data signal link in the backscatter tests. The switch is an ultra-low power device ADG 902 with an integrated data source of selectable rates. We are using a periodic binary sequence of $\{0, 1\}$ to control the switch. The reason is that in the measurement process the spectrum of a periodic signal can be easily clarified from the random data. So the periodic data are used for the link measurements.

## IV. Prototype Test Inside Biological Phantom

Two different data rates of 1 and 8 Mbps are measured for the feasibility demonstration of backscatter. Fig.7 shows the measured spectrum of the backscatter signal for both rates. The main peak is the reader leakage to the receiver which is stationary and can be eliminated using RF techniques of filtering at the receiver. The spikes around the central peak are related to the data signal. The separation from the main coupling is related to the data rates. We have measured the data signal peak level for different depths inside the liquid phantom using an on-body reader antenna. For this purpose, the power of the sidelobes is considered as the measurement parameter. In order to estimate the required transmitter power for successful decoding the transmitted data at the receiver, the link budget should be calculated. Thus, by assuming the OOK demodulation scheme and $BER = 10^{-6}$, the required SNR for the received signal is 14 dB. By assuming 25 MHz for the receiver bandwidth for 1 Mbps and 8 Mbps data rate, and using a raised cosine data filter with a roll of factor of 0.5 and also by assuming the noise figure of 5 dB for a typical receiver, the minimum received power is -92 dBm for 1 Mbps data rate and is -83 dBm for 8 Mbps [12]. It can be seen from Fig.6 that by transmitting 0 dBm of the RF power, we can receive the backscatter data of 1 Mbps from 8 cm depth and for 8 Mbps from 6 cm. By increasing the transmitter power, the maximum achievable distance also will increase. It is essential to say that, by adding a typical external low noise amplifier with the noise figure of 2 dB, the sensitivity of the receiver will be improved by 3 dB and thus less transmitter power is required for communications.

## V. Conclusion

In this paper, an ultra-low power communication scheme based on backscatter technique is proposed for wireless video capsule endoscopy. An efficient antenna is designed for having maximum RCS in order to reflect the incident power as much as possible. The data source is a periodic binary sequence of $\{0, 1\}$ in which controls the RF switch for backscattering binary data toward the receiver. All parts of the system are placed in a capsule. The proposed system also has been tested inside biological phantom in which mimicking the material properties of human tissues in operating frequency. According to the measured results, the backscatter technique not only is a power efficient solution for wireless capsule endoscopy but also it can be used in ultra-low power deep implants in which the replacement of the implants is not possible for a long period of time. For future work, the periodic binary sequence can be replaced by a digital camera signal and channel coding techniques can also be used in the transmitter for reducing the bit error rate at the receiver.

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