Wireless Capsule Video Endoscopy For Population-Based Colon Cancer Screening Using 5G network

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***Abstract*— We develop a battery-free communication system for a wireless video capsule endoscope with potential video streaming of a rate of up to 15 Mbps. We apply our innovative approach using backscatter for implants, a RADAR approach that remotely reads the information from the deep implants, such as the video capsule endoscope. We use the 5G deployed network with edge computing and slicing to transmit the video data from the capsule to a high-performance computing platform in a secure way with guaranteed end-to-end latency to perform polyp detection and localization. This way, the energy-intensive inference using deep learning neural networks for polyp detection and localization can be completed in the edge where control signals are sent back to the pill to increase the spatial and temporal resolution of the video, to obtain high-quality images for further analysis. The paper provides a system-level description, demonstrating the capsule data streaming to the network.**

***Index Terms*— Antennas, Backscatter communication, Capsule endoscopy, Implant communication,**

I. Introduction

Colorectal cancer (CRC) is the third most common cancer mortality for both men and women globally and the second leading cause of cancer-related death for both genders combined [1]. Thus, early detection and removal of subclinical polyps in the colon are crucial for the prevention. CRC usually does not cause symptoms until the disease is advanced; therefore, regular screening for individuals is highly recommended to prevent CRCs, starting from the age of 50 [2]. The screening aims to find pre-cancerous polyps before turning into malignant tissues. Population-based screening has been introduced in many western countries [3]. Norway aims to start with such a program in 2022 - 2025.

Colonoscopy is still the most sensitive method for colon screening due to its advantages. It is more effective to detect lesions and polyps of any size, allowing the surgeon to remove them during the same procedure. Colonoscopy has, however, several limitations: 1) it is a human-dependent operation, meaning it is prone to human errors, reported to be up to 22%-28% for the case of flat and small size polyps [4], 2) it is rather unconformable, risks inherent, and expensive procedure for patients [5], 3) it is a demanding procedure requiring a significant amount of time by specialized endoscopists [5]. These limitations make colonoscopy suboptimal for screening purposes, resulting in low uptake among the population in screening programs.

Wireless Capsule Endoscopy (WCE) has been available for small bowel visualization for more than ten years [6], while more recently, a colon capsule has been introduced for selective colon visualization. This may be an alternative to colonoscopy and has been compared favorably in terms of polyp detection in recent studies [7]. However, the use of capsule cameras for colon diagnosis requires similar or even more aggressive bowel cleaning than colonoscopy. Moreover, experts spend considerable time analyzing the video recordings captured by the capsule [8]. Although Pill Cameras hold promise as an accurate and convenient screening tool, several challenges exist. The cost of the capsule will likely go down as volumes increase. However, the cost of staffing required for analysis will remain; therefore, simplifications of the capsule reading are highly demanding, e.g., in the form of automated pre-reading the video footage by advanced image analysis, computer vision, and machine learning tools [9].

To make capsule endoscope effective and efficient for automatic polyp detection in both terms of hardware and software, one can modify momentarily the operative parameters of cameras, such as frame rate (from 3-5 fps up to 35 fps) or lighting spectrum just as they are needed to improve the diagnosis and save battery for the entire session. It is impossible to maintain a constant high frame rate for the whole procedure, as it would drain the onboard battery. However, using our recently developed technology, the capsule system can communicate to a remote reader on the body surface without using any communication system electronics or transceivers. Our previous publications have demonstrated the feasibility [10-13]. Having a quality video is a requirement for analyzing the data in a computer and applying the detection algorithms. However, using the automatic diagnosis of the video footage by a software algorithm is very computationally expensive and requires significant investments for the processing, which will be much more complex if screening of thousands of people is performed simultaneously. Using the potential of 5G network and Cloud or Edge computing can share the resources in an efficient approach. Consequently, 5G will enable real-time usage of such computing resources for the screening purpose.

Fig.1 shows the overall vision of the project in which a capsule endoscope is controlled and moved inside the colon, and a worn array antenna on the body surface collects the video data using backscatter communication technique and transmits the data via a local area network (LAN) interface using User Datagram Protocol (UDP) to the 5G modem where the gateway in the edge contains the required processing hardware to analyze the videos in real-time and give feedback to the capsule reader, and the capsule endoscope to alter the capsule position, change the light intensity, change video quality or the frame rate, or use hyperspectral imaging sensor to closely and seamlessly analyze the detected polyps. The Edge is in interaction with the Cloud to store the patient-specific data, apply machine learning algorithms and use cloud computing together with AI to improve the network capacity in detection and processing of the video data.

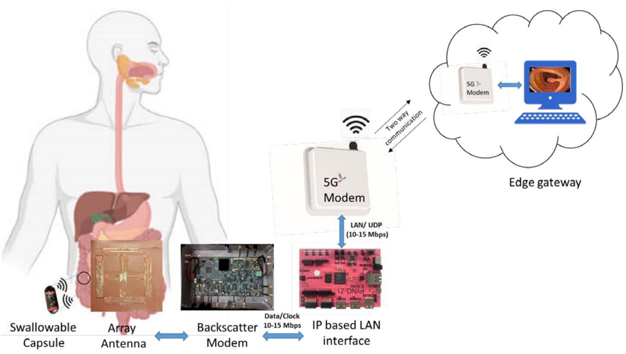

Fig. 1. The overall vision of the project with an endoscope capsule that operates using the backscatter communication technique, the reader interface and antennas, the protocol exchange and 5G modem interaction, and edge computing in a feedback loop is shown.

In this paper, we aim to provide a system-level description, key performance indicators, and test scenarios to make WCE more efficient for population-based screening. Our ambition is to use a 5G network to establish a secure link for a real-time transmission with feedback control between a deep learning model running in the Cloud and a WCE that is active and moving in the colon. The deep learning mode is to automatically analyze the video recordings sent by the capsule via the 5G link, looking to detect and localize polyps and tumors with minimum allowable latency for a real-time session. To gain the life of the onboard battery of WCE longer, the deep learning mode must be implanted in the cloud because it requires a massive amount of energy and time.

Section II presents a short description of the whole system and expected requirements from 5G network. Section III describes WCE in backscatter mode with some technical details, The processing system is expressed in Section IV. Section V concludes this paper.

II. System Description and 5G Network Requirements

The setup of our proposed system is depicted in Fig.1. It includes a gateway that handles the bridging between two physical layers, PHY1 and PHY2. PHY1 is related to the backscatter communication that operates at 434 MHz. The backscatter implements in-house designed PHY1 to simplify the capsule tasks. In brief, the backscatter is a kind of RADAR communication technique that uses the RF wave reflections from a capsule where the wave reflections are controlled by the data streamed from the capsule's camera sensor. Using this approach, the capsule's onboard communication system is reduced to a single switching gate that in principle consumes near to zero power (10 pJ/bit). Using this approach, the capsule's price becomes exceptionally cheap, making it a good case for mass production for a low-cost screening, a low power system that can be operated for a longer time. By saving power, the image quality and the illumination can be improved by allocating the battery resources; also, other types of sensors can be used in the capsule. The system-level development is illustrated in Fig.1, where a capsule is manufactured that can stream a pre-recorded video to the capsule's internal backscatter switch system. An antenna array can be worn to realize the near-field radar system with multiple transmitters and receivers to support the capsule localization and diversity antenna. The array antenna can combat signal fading that would occur due to different rotations and orientations that the capsule would take place in the pathway inside the colon. The capsule of length 2.5 cm and diameter less than 1 cm is considered in the demonstration process. An in-house backscatter radio system is developed to support the high data rate system up to 16 Mbps, where we test it for 8 and 10 Mbps. The backscatter reader is a quite complicated subsystem with controlling units for antennas, received signal sensing, RF power controlling, coupling reduction circuits, etc. The system is working at 434 MHz, and the transmitter emits a maximum power of 250 mW single tone signal that is mainly directed to the biological medium using the designed planar patch antennas. The antennas shape a dipole with loaded patches that couples EM wave using the capacitive technique to the internal body [11-13]. The antenna in the free space has a maximum gain of -20 dBi. This way, the radiation in the free space considering the transmitted maximum power becomes ERP= +6 dBm; since the signal is a single tone, and the level is below the defined standards that are maximum +10 dBm for non-modulated signal thus the radiation is limited by the SAR values. The SAR for this system has been computed that is below 10 W/kg.

Using the backscatter system, the data spectrum spreads around the carrier signal that is reflected from the capsule thus the reader receiver requires a bandwidth of multiple two of the data rate, considering simple BPSK or OOK. The spread signal is detected on the body surface has a level of about -75 dBm, in 10 cm depth from the body surface, the level is much above the theoretical noise level of about -100 dBm. So, the spectral emission limitations that are applied for active radio systems with data transmission does not consider here. This permits transmission data rates up to 32 Mbps using our system. However, the channel distortion due to the use of the antennas and the system nonlinearity must be considered that limits the data rate. The communication depth inside the body depends on the capsule size, where a length of 30 mm can provide a depth of 15 cm inside the body. Using the diversity antenna, or multi-antenna scheme, the coverage region can be improved. Figure 2 shows the measured spectrum of the video signal of rate 8 Mbps and the corresponding Eye diagram and constellation.

Fig. 2. Measured spectrum of the backscatter signal with video streaming of 8 Mbps and 10 frames per second. The time-domain detected data signal in a phantom test (the EYE diagram) also the constellation diagram is shown.

A backscatter reader is developed and manufactured that can control the antenna diversity to find the best combination among six (two receive and four transmitters) antennas. The system provides a sophisticated clock and data recovery.

The output of the system can be arranged to display on a screen, or it has the main feature to connect to an in-house FPGA/SOC based system to stream the video data via UDP LAN protocol to any wire-based network receiver or wireless interface to a WiFi or 5G modem with LAN input. Using 5G the data can be processed at the network edge, and the related polyp detection algorithms can be applied. The current system has not the feedback from the network side, but the next developments will include this option. We aim to design, implement and test an infrastructure that will use WCE where the recorders can transmit videos to an access point or a gateway that can upload the data and user ID in a secure manner to a cloud server at Oslo University Hospital (OUH) for an automatic assessment of the recordings. The latency of the backscatter system is only 5 microseconds in which the network and processing are the dominant latency factors. Figure 3 shows the demonstration setup of the system on a non-human basis. The setup uses a phantom prepared to simulate the average material properties of the human body. An endoscope capsule mockup is made that receives the preceded data stream from a microcontroller that reads a pre-recorded endoscopy video file from a computer and streams the data to the capsule. The capsule has its own switch-controlled backscatter reflector option and integrated antennas that reflect the reader signal on the body surface. The backscatter system feeds the data to a protocol exchanger and a standard 5G modem. The data can be processed locally to debug the system or can be switched to the 5G network for examination purposes.

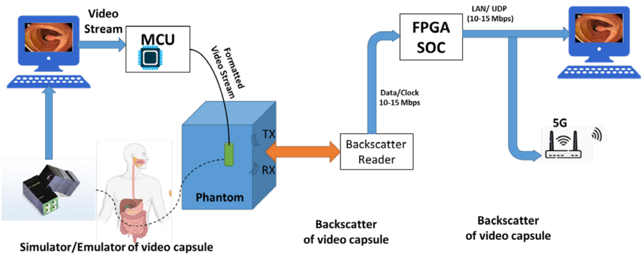

Fig. 3. Demonstration of video streaming via backscatter WCE to a remote computer or 5G network.

The goal is to bridge between the backscatter system and 5G network for real-time (low latency) data transmission to a medical cloud and feedback control loop to program the implant's features for targeted and personalized diagnosis and treatment plans. 5G and deep learning technologies are the keys for the creation of an effective infrastructure to reduce the time a clinician stares at long video sequences and simplify the whole process. A 5G network can be used to automatically transmit videos from the WCE recorders to a secure cloud. In the cloud, a deep learning-based model can perform real-time video assessment and provide feedback to the pill camera to optimize image capturing.

The 5G-VINNI [14] test network is used in this project as the 5G network platform. The 5G-VINNI accelerates the uptake of 5G in Europe by providing an end-to-end (E2E) facility that lowers the entry barrier for vertical industries to pilot use cases and supports the pilots as the infrastructure evolves [14]. The Network Key Performance Indicator (KPI) and requirements for the Pill Camera use case are summarized in Table I.

TABLE I. THE NETWORK KPIS AND REQUIREMENTS FOR THE WCE

Network KPI	*Estimated min/max value*
Roundtrip or E2E latency	*1-3 ms*
Downlink throughput	*1 Mb/s*
Uplink throughput	*10Mb/s*
Edge computing	*WCE video analytics at the edge to reduce latency – requirements to be explored*

III. EDGE COMPUTING AND DATA PROCESSING

AI research in medicine is growing rapidly due to the increase in computer hardware and software applications in medicine [14]. In the past decade, AI technologies, especially deep learning and convolutional neural networks (CNN), have been very successful in advancing computer vision, and image processing on databases of natural images [10]. AI has the potential to automate many tasks that require human intervention, including tasks in medicine. It has already been applied to analyze a diverse array of health, clinical, behavioral, drug data, etc. [14]. Recent studies [15], including ours [16-19], have shown that the CNN technology can be a promising technique to understand and analyze GI tract recordings, including the colon. Over the past decade, there has been a dramatic increase in the number of publications related to the application of CNN techniques for automatic polyp detection and segmentation [15]. This rise is due to a combination of factors, including advances in algorithm development, enhanced computational power, and the availability of annotated endoscopic imaging datasets, which has been facilitated primarily by increasing the interest of clinicians in deep learning technology.

Our group has been developing convolutional neural network (CNN) based models, achieved excellent results, and proven the capability and potential of deep learning for automatic detection and segmentation of pre-cancerous polyps in colonoscopy images and videos. We can further improve the models and adapt them for automatic review of videos of WCE to produce control feedback if anything suspicious comes to sight. The experiments have been implemented using the Keras, Tensorflow, and Pytorch libraries. We have been training different CNNs at the intervention center (IVS) at OUH. The automatic detection segment of the experiment has been designed to happen in 2 setups or stages. The first one envisions the polyp detection algorithm being performed in real-time at a remote location, while the second one is designed to perform the automatic polyp detection on edge using embedded computing boards that are specifically designed to deploy machine vision applications to the edge. Integrated with ARM architecture central processing units accelerated machine learning architectures, and low-power consumption, these edge devices allow us to deploy our deep learning application with less than 30W consumption while delivering top performance on the experiment's location.

Low latency transmission of the capsule video stream is essential to enable the control of the imaging parameters of the Pill cameras online. With the help of a feedback loop from the deep learning model, it is possible to generate high-quality frames for reliable detection of gastric disease such as polyps, bleeding, etc. It is also possible to alternate the stream rate of the WCE based on the received frames and the processed data to save energy of the implant sensory system. This is a perfect case for Mobile Edge Computing (MEC). Once the data package sent by the WCE is received at the edge, our polyp detection algorithm commences the detection and localization in real-time. If a polyp or a suspicious region has been identified, a signal with instructions is sent back to the WCE through the same end-to-end virtual network. The WCE adjusts its parameters according to the instructions sent by the deep learning model in order to obtain frames with the best lighting and resolution possible.

IV. CONCLUSION

Using battery-free backscatter communication implemented in a WCE can provide a large potential for low-cost cancer screening of the colon. The system in conjunction with the 5G network that is developed in this paper and by using the secure control protocols in the 5G network loop with low latency, opens several opportunities for various applications, including remote surgery, real-time feedback loop implant control, targeted localized treatment, drug delivery, and Internet of medical implants for future medicine. The realization of real-time video streaming from WCE may be the first step towards a much more precise diagnosis and less painful examination for colon cancer screening. Further enhancements are seen as the development of a controllable capsule is ongoing where the capsule can be moved and rotated while in the colon. Connecting the medical implant devices to a cloud using backscatter wireless technology reduces the healthcare cost and improves the patient lifestyle with a significant impact on treatment plans based on patient's specific information, intelligent monitoring, and control of the devices.

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