Signal Processing Techniques in Wireless Capsule Endoscopy Systems

Riya Vijayanand Naik[1], Sujani LN[2], Narendra Kumar S[3]
[1,2] Student, Department of Electronics and Communication Engineering, RV College of Engineering, Bengaluru, India
[3]Assistant Professor, Department of Biotechnology, RV College of Engineering, Bengaluru, India

***Abstract*— Wireless Capsule Endoscopy (WCE) has transformed gastrointestinal diagnosis with a minimally invasive, patient-friendly method to conventional endoscopy. This technology allows physicians to use a small, swallowable capsule with an imaging camera, light source, and wireless transmitter to acquire real-time images of the gastrointestinal tract. WCE systems are highly reliant on signal processing modules to achieve high-quality image acquisition, compress the data, provide reliable wireless transmission, and utilize low power consumption. This paper discusses the key signal processing techniques applied in WCE, their effect on the overall performance of the device, and the issues that arise when working in a restricted size, bandwidth, and energy environment. A MATLAB-based simulation using an actual WCE image is provided to demonstrate recognized image degradation and enhancement approaches, supporting the use of lightweight enhancement and robust error correction. WCE has the potential to improve both non-invasive diagnostics and patient outcomes, especially today with the rapid improvement of microelectronics and embedded signal processing.**

***Keywords*—Wireless Capsule Endoscopy, Biomedical Signal Processing, Image Compression, Non-invasive Imaging, RF Communication, Medical Electronics**

I. INTRODUCTION

The human gastrointestinal (GI) tract is a complex and vital organ system responsible for the digestion and absorption of nutrients. Accurate diagnosis of GI disorders is essential for effective treatment and long-term health. Traditionally, visual inspection of internal GI structures has been performed using conventional endoscopy, a procedure that involves inserting a flexible tube equipped with a camera into the digestive tract. While effective, this method is invasive, often uncomfortable for patients, and limited in its ability to access the entirety of the small intestine.

To overcome these limitations, Wireless Capsule Endoscopy (WCE) has emerged as a groundbreaking innovation in the field of gastroenterology. WCE uses a swallowable, pill-sized capsule embedded with a miniaturized camera, light source, transmitter, and power supply to capture thousands of images as it naturally traverses the digestive tract. These images are wirelessly transmitted to an external receiver worn by the patient, allowing physicians to analyze the data non-invasively. The procedure requires no sedation, causes minimal discomfort, and significantly expands diagnostic coverage—particularly in regions of the small intestine that are hard to access through traditional means.

Despite its clear advantages, the clinical success of WCE is highly dependent on the performance of its embedded signal processing systems. The capsule must operate under extreme hardware constraints—limited power, memory, bandwidth, and processing capability—while still delivering high-quality, diagnostically useful images. As a result, advanced signal processing techniques are essential for image acquisition, noise reduction, compression, transmission, and onboard optimization.

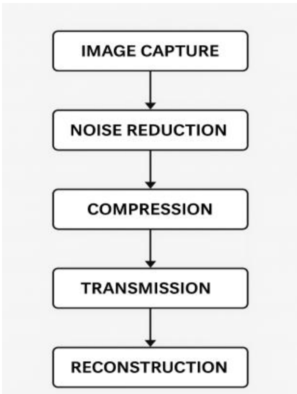

Fig 1. block diagram of image processing pipeline in WCE system

This paper explores the key signal processing techniques used in WCE systems, evaluates their trade-offs, and discusses the challenges of implementing them within such tight constraints. In addition, a MATLAB-based simulation using a real WCE image is presented to demonstrate the practical effects of noise degradation and wireless corruption, and how lightweight denoising and error correction methods can improve image quality. With continued advances in microelectronics, low-power design, and intelligent processing, WCE is poised to become even more efficient, accurate, and accessible—reshaping the future of non-invasive gastrointestinal diagnostics.

II. BACKGROUND

A. Evolution of Endoscopic Technology

The development of endoscopic tools has significantly evolved over the past several decades. Conventional endoscopy, which involves inserting a long, flexible tube with a camera into the body, has long served as the gold standard for gastrointestinal imaging. However, it has several drawbacks including patient discomfort, the need for sedation, limited access to deeper regions of the small intestine, and potential procedural complications.

To overcome these limitations, wireless capsule endoscopy (WCE) was introduced in the early 2000s. The first commercially available system, PillCam, provided a groundbreaking alternative by enabling a non-invasive, full-length visualization of the gastrointestinal tract through a small, ingestible device. This marked a paradigm shift in gastroenterology by providing an accessible and patient-friendly diagnostic approach.

B. Architecture of Wireless Capsule Endoscopy

A typical WCE device includes a CMOS camera, white LED light sources, a battery, and a wireless transmitter enclosed within a capsule measuring approximately 11 mm × 26 mm. Once ingested, the capsule moves through the gastrointestinal tract via natural peristalsis, capturing 2–6 frames per second. These frames are transmitted wirelessly to a receiver unit worn by the patient, which stores the data for further analysis by physicians.

Given the size constraints of the capsule, efficient power consumption, real-time image acquisition, and lossless or near-lossless transmission are critical requirements. This is where signal processing becomes integral to the system's operation.

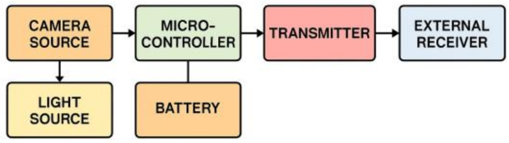

Figure 2: Block diagram of the internal components of a Wireless Capsule Endoscopy (WCE) system, showing the data acquisition and transmission fl-ow from camera source to external receiver.

Fig 1. block diagram of WCE system

C. Role of Signal Processing in WCE Systems

Signal processing techniques are crucial in enabling the wireless capsule to function effectively within its physical and power limitations. These techniques allow for:

- Noise reduction and image enhancement, especially in low-light environments
- Data compression to reduce transmission bandwidth without compromising diagnostic quality
- Synchronization and error correction during wireless transmission through biological tissues
- Real-time decision-making for intelligent frame selection and prioritization

These processes ensure that high-quality diagnostic data is captured, transmitted, and interpreted accurately, despite the challenges of operating in a constrained environment like the human gastrointestinal tract.

III. SIGNAL PROCESSING IN WCE SYSTEMS

A. Image Acquisition and Enhancement

The quality of diagnostic output from Wireless Capsule Endoscopy is primarily influenced by the quality and uniformity of the images acquired as it moves through the gastrointestinal tract. However, there are difficulties from the internal environment - light variations, variable peristaltic motion, and obstruction of the view by fluids or particles can negatively impact image quality. Therefore, image enhancement capabilities are employed to improve the characteristics of the images. These include adaptive illumination control with white LEDs, dynamic range compression, and spatial filtering to increase the contrast and decrease image artifacts. Edge-preserving smoothing filters can be used to decrease noise, while preserving important key diagnostic features of interest in the image. Additionally, motion compensation algorithms may be employed to

stabilize the captured sequence of images and deal with capsule rotation and erratic movements.
These enhancements can be processed in real-time, despite the limited computing power and energy capacity available onboard the capsule hardware.

B. Image Compression Techniques
Due to limited memory and low bandwidth wireless links, wireless capsule endoscopes (WCE) require compression of images. The essential issue is how to reduce the file size while maintaining the information necessary to allow a doctor to make an accurate diagnosis.

Lossless image compression schemes (Huffman coding, Run-Length Encoding (RLE)) are useful because they maintain all the original image information, but they do not reduce file size very much. Lossy transmission, which allows small amounts of quality loss for better compression ratios, is predominantly used by various systems.

Graph or image compression schemes include:

- The JPEG standard is the simplest to use of all the above, and gives a relatively good trade-off between image quality and file size. The JPEG standard is primarily based on Discrete Cosine Transform (DCT).
- JPEG2000 is a newer standard, and is based on Wavelet Transform, and provides better image quality than JPEG at a lossy compression ratio of 100:1 or higher. JPEG2000 is especially useful for medical images.
- SPIHT (Set Partitioning in Hierarchical Trees) is another wavelet based scheme that allows for very high compression ratios (typically > 20: 1), as well as allowing for adaptive quality scaling of images, based on the bandwidth capacity of the communication link.

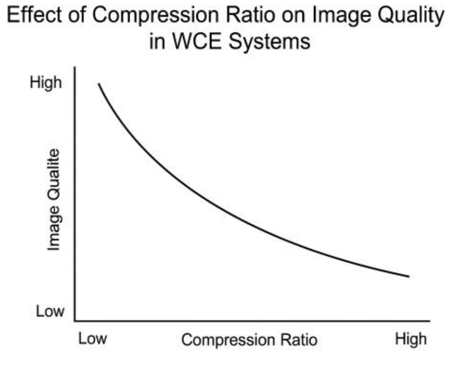

Fig 4. compression vs quality graph

C. Wireless Data Transmission and Reconstruction
Transmitting data wirelessly from inside the human body is a difficult task. Radio signals tend to be weakened by body tissues, so the effect causes data loss during transmission or the signal becomes corrupted, which leads to distorted data being transmitted.

To achieve this, WCE systems use the lower RF frequency range, typically working between 400 and 450 MHz, as they can penetrate tissue more effectively than frequencies above 1 GHz. Using techniques, such as Forward Error Correction (FEC) and Automatic Repeat Request (ARQ), the WCE system implements ways to fix or resend pieces of the data that may have been lost or corrupted.

It is important to keep everything synchronized. Signal synchronization methods exist to allow individual image frames to arrive in the correct sequence for reconstruction of the data at the receiving end.

Image files have significant large data sizes and are broken down using packet segmentation and reassembly. Packet segmentation will make it easier to transmit the data from the human body in short bursts of data and will ultimately lead to fewer delays and lost packets. You can use packet interleaving in addition to GMSK modulation (Gaussian Minimum Shift Keying) to improve transmission stability with respect to noise.

D. Power Management and Processing Efficiency
One of the primary factors that WCE systems must address is power efficiency because the capsule operates on a small coin-cell battery which is required to run an optimal experience for up to 8 hours while traveling the digestive tract. Therefore, every subcomponent of the system must be power efficient because the component that uses the most energy is most likely the signal processing.

To operate on low power, common techniques are: clock gating, dynamic voltage scaling and hardware accelerators (for low voltage tasks such as compression and filtering). In general, these techniques will lead to a system that can do more work and will operate at a lower energy level. Another intelligent strategy is selective image capture, whereby the capsule captures additional frames when it discovers areas of interest, thereby reducing the amount of unnecessary data processed and/or transferred.

Researchers are making advances in the area of ultra-low power chipsets and energy-aware scheduling algorithms. These types of systems could apply the scheduling algorithm to allow real-time energy management, assigning execution to the task with the greatest battery capacity, as a result, the capsule will be able to endure a little longer without sacrificing the quality of the data it is ultimately capturing.

IV. CHALLENGES AND LIMITATIONS

Even though Wireless Capsule Endoscopy (WCE) has transformed how we diagnose issues in the gastrointestinal tract, it still comes with a number of technical and practical hurdles. These challenges mostly stem from the fact that the device has to function inside the human body, all while being small, wireless, and battery-powered.

A. Limited Battery Capacity

Because the capsule is so tiny, there's no room for a large battery—which makes power a major limiting factor. Most WCE capsules use small coin-cell batteries that last around 8 to 10 hours. That might sound like a lot, but it has to power everything: high-res image capture, bright LED lights, wireless data transmission, and real-time signal processing.

As a result, battery constraints limit not just how long the capsule can operate, but also how detailed the images can be, how often they're captured, and how much processing can be done onboard. All of these are crucial for spotting small or subtle abnormalities, so any compromise here can directly affect diagnostic accuracy.

B. Uncontrolled Movement and Incomplete Visualization

The capsule's movement relies solely on natural peristalsis, which is passive and unpredictable. This can lead to:

- Uneven image coverage (e.g., rapid transit through certain segments),
- Poor orientation during image capture,
- Missed areas due to capsule rotation or blockages.

Unlike traditional endoscopy, wireless capsule endoscopy (WCE) cannot be steered or repositioned, making it difficult to target or revisit suspicious regions, potentially leading to missed lesions or incomplete diagnostic coverage.

C. Wireless Transmission Vulnerabilities

The WCE system transmits image and sensor data wirelessly to an external receiver. However, this wireless transmission is susceptible to:

- Signal attenuation caused by body tissues and movement,
- Data loss or corruption due to electromagnetic interference,
- Limited transmission bandwidth restricting resolution or frame rate.

Such vulnerabilities can degrade the quality of transmitted data, affecting diagnostic accuracy and necessitating robust error correction techniques in signal processing.

D. Limited Onboard Processing and Storage

Due to stringent limits on both size and heat, WCE capsules cannot accommodate large or powerful processors as well as sizable, high-capacity memory banks. Consequently, WCE systems are limited to running low-power or lightweight algorithms in real-time on the capsule.

More advanced tasks (like lesion detection or classification of abnormalities) typically must occur outside of the real-time procedure after the patient is finished and the images have all been reviewed externally, which eliminates any real-time insights or alerts that could help support a clinical decision at the time of the procedure.

E. Diagnostic Interpretation Burden

A single WCE session can generate in excess of 50,000 images and each image needs to be reviewed by a clinician. This represents a major workload, and the sheer number of images means that the chances for human error or missed findings are increased.

There is some good initial work on post-processing tools and AI-based algorithms that can help to sort, flag and/or label important frames, but a lot of these systems are in their early stages of development and very few of them are fully integrated into clinical workflows and/or certified for broad-based use.

V. SIMULATION RESULTS AND DISCUSSION

To evaluate the practical implications of signal degradation and recovery in Wireless Capsule Endoscopy (WCE) systems, a MATLAB-based simulation was conducted using an actual image captured by a WCE device. This real clinical image reflects the visual and structural complexity of the gastrointestinal environment. The simulation had two main aspects: noise reduction and correcting errors caused by noisy signals.

A. Real Image and Noise Simulation

The original WCE image was resized to fit processing size. Gaussian noise was added to the image to make it more realistic in terms of what might happen inside the gastrointestinal tract due to motion artifacts, available light, visual obstructions etc. A Gaussian filter was then applied to the image to diminish background noise and clarify to a degree defined structure, therefore increasing visibility.

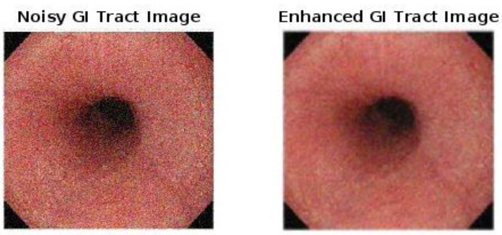

Figure 5.1: (a) Noisy image simulating internal GI conditions, (b) Enhanced image after applying Gaussian filtering.

B. Error Correction with Triple Redundancy

To simulate wireless transmission errors, image data was intentionally corrupted with random bit errors (2%). A basic error correction scheme—triple redundancy with majority voting—was applied to recover the original signal. This method helped restore image quality by selecting the most common value across three independently corrupted versions of the data.

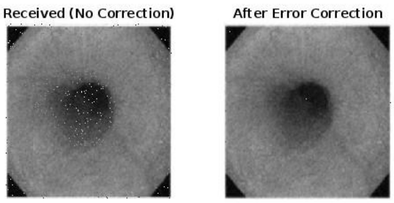

Figure 5.2: (a) Corrupted image after simulated wireless transmission, (b) Recovered image after applying error correction..

C. PSNR evaluation

The Peak Signal-to-Noise Ratio (PSNR) was used to quantitatively compare and assess the level of error correction performed to the compressed reference image against the corrupted and corrected images:

Stage	PSNR(dB)
After wireless transmission	18.74
After error correction	27.83

These values show that significant quality recovery can be had using even a rudimentary error correction strategy.

F. Discussion

This simulation illustrates two key challenges in WCE systems: image degradation under physiological conditions and data corruption during wireless transmission. The results emphasize the importance of lightweight denoising and resilient error correction techniques, particularly when operating under constraints of power, size, and bandwidth. The improvements observed in both visual output and PSNR scores reinforce the potential of simple signal processing strategies in enhancing diagnostic accuracy and reliability.

VI. FUTURE SCOPE

As technology continues to evolve, Wireless Capsule Endoscopy is poised to become more intelligent, efficient, and clinically impactful. The integration of advanced signal processing with emerging fields like artificial intelligence and low-power computing offers numerous opportunities to overcome existing limitations and expand WCE capabilities.

A. AI-Powered Image Interpretation

Artificial Intelligence—especially deep learning—will change the game with respect to the analysis of WCE images. Essentially, if the convolutional neural networks (CNNs) can be trained on a large data set of annotated (abnormal) images, future systems will be able to interpret images by automatically identifying and classifying abnormal findings, such as bleeding, ulcerations, and polyps.

Some more advanced ideas even propose that lightweight AI models could be implemented directly into the capsule. These models will enable the capsule to prioritize images or frames to send back to the physician based on clinical relevance to the patient,while other models will also have the ability to at least pre-filter the images for the physician with automated triage examination and annotations. If physicians could receive pre-filtered results, it could reduce data load as well.

B. Ultra-Low Power Processing Chips
Power efficiency is a key consideration, and new hardware is being developed to address this issue; custom ASICs (Advanced Semiconductor Integrated Circuit) and SoCs (System-on-Chip) continue to evolve to perform capabilities such as image enhancement and compression more efficiently and with less energy.

New semiconductor technologies, like FD-SOI (Fully Depleted Silicon-On-Insulator), are allowing for more energy-efficient chips, and chips that are capable of functioning inside the body for extended periods without generating heat.

C. Real-Time Cloud Connectivity and Remote Monitoring
Connecting WCE systems to the cloud will unlock real-time streaming capabilities and remote diagnostic capabilities. Encrypted Internet of Things (IoT) protocols could allow images to be streamed directly to a central server and something that gastroenterologists can read virtually anywhere, even in remote or underserved areas.

This infrastructure would not only enable telemedicine, but the large datasets would continually improve AI models and provide the possibilities of studying larger population data in gastrointestinal health.

D. Multi-Sensor Capsule Designs
Future capsules will not only take pictures; they could also assess other variables such as pH, temperature, pressure, and/or chemical markers, simultaneously. Merging visual and physiological data creates a much more complete understanding of what is happening in the body.
For example, if a temperature rise or pH decrease is paired with visible inflammation, it could help improve the accuracy in the diagnosis of diseases like Crohn's disease or stomach ulcers.

E. Magnetic Steering and Controlled Navigation
One area of research which is particularly exciting involves the ability of physicians to exert magnetic control from outside the body to steer the capsule, or at least to be able to perform some form of controlled navigation. If magnetic materials can be embedded in the capsule then it would allow the capsule to be navigated towards certain areas or slow down so that better images can be captured.

This shifts the technology from a "ride-along" passive diagnostic tool, into an actively navigating diagnostic tool and decreases blind-spots and ultimately chances of missing important pathologies.

VII. CONCLUSION

Wireless Capsule Endoscopy is a major development for non-invasive diagnostics in regard to the gastrointestinal tract with a friendly approach to patients, and is certainly a step towards diagnosis of diseases that were once hard to diagnose. It allows for viewing the whole GI tract while being minimally invasive. This could further lead to diagnosing diseases and allowing for particular treatment starting at a much earlier point in time.

Operationally, signal processing is key, and affects many of the capabilities of WCE, including capturing high-quality images, encumbered by the physiological circumstances of the patient, compressing and transmitting information, on a large scale, in real-time, while simultaneously recording real-time data! Within the WCE apparatus/self-contained miniature diagnostic systems, signal processing algorithms, fundamental to the apparatus, allow for the margination of these conditions.

The simulation in MATLAB used a real image from a WCE and reiterated the idea; that WCE must consider the effects of noise, compression, and wireless degradation on image quality. The amount of data that WCE transmits and ultimately saves, means either passive navigation (bio-absorbable, electronic small robotic capsule, with unknown diet consistently occurring through theorem proposal), even now fundamentally and practically is conceivable with light-weight images used for enhancement and error correction by the patient with anxiety, more readily adaptable.

Though there are current barriers such as limitations caused by the battery, only being a passive navigation platform, and the burden of reviewing thousands of images for the medical professionals and health-related professionals, the integration of AI and real-time cloud continues to enhance future WCE systems. I could imagine these devices being totally autonomous within the lifetime of current usage of WCE and even continuously monitoring patients and treatment, ultimately improving and establishing better standards to access care, and consequently patient care.

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