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Design and Comparative Evaluation of Two Low-Cost Analog RF Transmission

Approaches for a Wireless Capsule Endoscopy Prototype

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Abstract Capsule endoscopy provides a pain-free, non-surgical alternative to conventional gastrointestinal (GI) tract examination, yet its high commercial cost restricts adoption in resource-constrained healthcare environments. This paper presents the design and comparative evaluation of a low-cost wireless capsule endoscopy prototype built entirely from commercially available analog components. Two radiofrequency (RF) transmission solutions are implemented and compared: Solution 1 employs the MC1373 TV modulator integrated circuit (IC) configured as a 67.25 MHz carrier generator, while Solution 2 uses a discrete-component NPN transistor (2N2222) Colpitts-type oscillator circuit tuned to 61.2 MHz. Both solutions share a common miniaturized analog CMOS camera (8×8 mm, 600 TVL, CVBS output) and a custom-wound 0.1 μ H air-core inductor forming the LC tank resonator. Breadboard prototyping, Proteus-based PCB design, and physical fabrication were performed for both solutions. Solution 1 produced a stable RF carrier confirmed on an oscilloscope but encountered video reception failure on available digital television receivers due to PAL/NTSC format incompatibility. Solution 2 successfully delivered

clear real-time wireless video on an analog PAL television receiver, with a fabricated PCB footprint of 25×25 mm satisfying the esophageal lumen size constraint. The work provides a documented engineering baseline for low-cost capsule endoscopy development in developing-country contexts and identifies PAL/NTSC format incompatibility as a critical design constraint not previously reported in the prototype literature for this region.

Keywords Capsule endoscopy · Wireless video transmission · RF modulator · CVBS · Analog CMOS camera · PAL television · MC1373 · LC tank circuit · Biomedical prototype · Pakistan

1 Introduction

Gastrointestinal (GI) tract disorders — including intestinal bleeding, ulceration, polyps, and Crohn's disease — represent a significant global health burden. Effective management depends on timely and accurate diagnosis. Conventional endoscopy allows visualization of the upper 4 feet (gastroscope) and lower 6 feet (colonoscope) of the approximately 30-foot GI tract, leaving roughly 20 feet of the small intestine beyond reach [1, 2]. In addition, conventional endoscopy requires sedation and local anaesthesia, causes patient discomfort, and carries a risk of adverse reactions, rendering it unsuitable for a substantial proportion of patients.

Wireless capsule endoscopy, first commercialized in the early 2000s, addresses these limitations. The patient swallows a pill-sized capsule containing a miniaturized wireless camera; as the capsule traverses the GI tract passively through peristalsis, it transmits images to an external receiver worn on the patient's body. No

1 sedation is required, cross-infection risk is eliminated, and patient acceptance is high
2 [2, 3]. Commercial systems — notably the PillCam SB (Given Imaging) and the
3 EndoCapsule (Olympus) — have demonstrated clinical viability [1].

4 Despite these advantages, commercial capsule endoscopy systems remain
5 prohibitively expensive for widespread deployment in developing countries. In
6 Pakistan, the technology has yet to achieve broad clinical uptake and access to
7 diagnostic endoscopy is concentrated in large urban centers. The WHO estimates that
8 over 70% of GI-related cancers in low- and middle-income countries are diagnosed at
9 an advanced stage due to limited access to endoscopic screening, highlighting the
10 critical need for affordable diagnostic alternatives [16]. There is therefore a compelling
11 need to investigate low-cost prototype implementations that establish engineering
12 feasibility and provide a basis for future affordable system development.

13 This paper presents the design and comparative evaluation of two analog RF
14 transmission solutions for a wireless capsule endoscopy prototype, constructed
15 exclusively from commercially available components at low cost. The two solutions
16 differ in transmitter architecture: Solution 1 employs the MC1373 TV modulator IC,
17 while Solution 2 uses a discrete-component NPN transistor oscillator circuit. Both
18 solutions interface with the same miniaturized analog CMOS camera.

19 The primary contributions of this work are: (i) a systematic comparison of IC-
20 based versus discrete-component analog RF transmission in a PAL-standard
21 environment; (ii) a custom inductor design enabling LC tank operation without
22 commercially unavailable components; (iii) a PCB layout achieving a 25×25 mm
23 transmitter footprint compatible with the esophageal lumen; and (iv) identification of
24 the PAL/NTSC format incompatibility as a critical design constraint for capsule

endoscopy prototype development in South Asian markets, not previously highlighted in the prototype literature.

2 Literature Review

2.1 Anatomical constraints on capsule size

The GI tract extends approximately 9 m (30 feet) from mouth to anus and encompasses the esophagus, stomach, small intestine, large intestine, and rectum. Table 1 summarizes the dimensions of key GI segments, which directly constrain the maximum permissible capsule cross-section.

Table 1 Dimensions of key GI tract segments

Body part	Length (mm)	Width (mm)	Reference
Stomach	304.8	152.4	[8]
Large intestine	1500	76.2	[9]
Small intestine	6700	50.8	[9]
Esophagus	250	30	[10]
Rectum	200	25	[11]

The narrowest segment is the esophagus, with an internal lumen of approximately 25–30 mm [10]. Commercial systems such as the PillCam SB operate at 11 mm diameter and 26 mm length, well within this limit [1]. The present work therefore adopts 25×25 mm as the maximum transmitter PCB footprint constraint.

2.2 Commercial and prototype capsule endoscopy systems

A number of commercial and research-grade capsule endoscopy systems have been documented in the literature. Table 2 summarizes the specifications of the most widely referenced commercial devices.

Table 2 Specifications of representative commercial capsule endoscopy systems [1]

Manufacturer	Product	Size (mm)	Resolution	Battery (h)
Given Imaging	PillCam SB	26×11	CMOS 256×256	8
Olympus	EndoCapsule	26×11	CCD 1920×1080	8–10
IntroMedic	MicroCam	24×11	CMOS 320×320	11
Chongqing Jinshan	OMOM	24×11	CMOS 640×480	7–9

In the prototype research domain, Chan et al. [2] established a foundational architecture using an analog CMOS camera with CVBS output interfaced to a TV modulator for RF transmission in the 20–800 MHz range — the approach directly adopted in the present work. Khan et al. [3] subsequently demonstrated an FPGA-based digital system achieving improved image quality at the cost of substantially higher circuit complexity and power consumption. Xie et al. [6] investigated low-power IC designs for bidirectional digital capsule systems. Chen et al. [15] developed a custom ASIC achieving low-power wireless capsule control. More recently, Bandari et al. [17] reviewed advances in wireless capsule endoscopy from 2014 to 2021, noting that miniaturization, power efficiency, and data transmission rate remain the three primary open challenges. Moglia et al. [18] surveyed the state of the art in capsule endoscopy and identified RF transmission reliability in lossy biological tissue as a persistent engineering challenge. These observations directly motivate the present comparative investigation of low-cost RF transmission architectures.

2.3 Camera selection: analog versus digital

The image capture subsystem is the most critical component of any capsule endoscopy system. Analog CMOS cameras produce a single-pin CVBS output that interfaces directly to an analog RF modulator without additional signal processing. Digital cameras offer superior miniaturization and resolution in modern implementations, but require complex parallel interfaces and dedicated image signal processors, substantially increasing system complexity, power consumption, and cost [2]. Table 3 compares both approaches.

Table 3 Comparison of analog and digital camera options for capsule endoscopy

Characteristic	Analog camera	Digital camera
Primary application	Surveillance	Mobile / capsule systems
Typical module size	12×12 mm	6×6 mm
Resolution	High (600–1200 TVL)	Variable (CMOS sensor)
Output interface	Single-pin CVBS	4- or 8-pin parallel digital
Interface complexity	Simple	Complex; needs ISP/FPGA
Power consumption	Low	Moderate–high

For a low-cost prototype targeting proof-of-concept, the simplified interfacing of the analog camera is compelling, consistent with Chan et al. [2]. The camera selected for this prototype is an 8×8 mm analog CMOS module (PC2209 sensor) with 600 TVL horizontal resolution, PAL format output at 25 frames per second, and 80 mA power consumption operating at 5–12 V DC.

2.4 Wireless transmission: analog versus digital

The wireless transmission subsystem must up-convert the camera's CVBS baseband signal to an RF carrier for transmission to an external receiver. Table 4 compares analog and digital approaches.

Table 4 Comparison of analog and digital RF transmission for capsule endoscopy

Characteristic	Analog transmitter	Digital transmitter
Bandwidth	Large (>30 MHz for raw video)	>2.4 GHz for uncompressed video
Circuit complexity	Simple; few components	Complex; digital interface required
Size	Small (miniaturizable)	Medium
Receiver	Standard analog TV	Dedicated digital receiver
Cost	Low	Higher

Digital transmitters for ISM bands (e.g. the Chipcon CC1100) have maximum data rates of 500 kbps — insufficient for uncompressed video — and require dedicated compression hardware [2]. More recent work has explored ultra-wideband (UWB) transmission for capsule endoscopy, offering higher data rates with lower tissue absorption [19], but at significantly greater circuit complexity and cost. Analog RF transmission using a TV modulator remains the simplest viable approach for a low-cost prototype, with the resulting RF signal received directly by a standard television set, eliminating custom receiver circuitry. Two analog transmitter architectures are evaluated in this work: the MC1373 TV modulator IC and a discrete-component transistor oscillator.

2.5 Television standards and regional design constraints

A critical but frequently overlooked design constraint in capsule endoscopy prototype development is the compatibility of the RF transmission system with the local television standard. The two dominant analog television standards are NTSC (National Television System Committee), used primarily in North America and Japan, and PAL (Phase Alternating Line), used in Europe, South Asia, and most of the developing world including Pakistan, India, Bangladesh, and Sri Lanka [20]. The MC1373 TV modulator IC, widely cited in the capsule endoscopy prototype literature, is an NTSC-

only device. Work conducted under NTSC standards — including the seminal prototype by Chan et al. [2] — cannot be directly replicated in PAL-standard environments without modification. This incompatibility has not been previously documented in the capsule endoscopy prototype literature and constitutes a practically significant finding for researchers in PAL-standard regions.

2.6 Antenna and housing

The helical antenna is widely used in capsule endoscopy due to its compact form and near-omnidirectional radiation pattern, important because the capsule moves in random orientations within the GI tract [4]. A short copper wire antenna serves as a simplified substitute appropriate for bench-top prototype testing.

2.7 Research gap

While the fundamental analog prototype architecture has been established [2], a systematic comparison of IC-based versus discrete-component transmitters under PAL television standards has not been previously reported. Furthermore, no published work has specifically documented the practical component availability and television standard compatibility constraints relevant to prototype development in Pakistan or other South Asian countries. The present work addresses these gaps.

3 Methods

3.1 System architecture

The overall system follows the architecture established by Chan et al. [2] and consists of four subsystems: (i) illumination (LED array), (ii) image capture (analog

CMOS camera), (iii) wireless RF transmission (either Solution 1 or Solution 2), and (iv) video reception (analog PAL television). The camera produces a CVBS baseband video signal which is fed to the transmitter subsystem. The transmitter up-converts this signal to an RF carrier, which is radiated by a short wire antenna and received by the television set tuned to the corresponding channel. Figure 1 shows the complete system block diagram, common to both solutions — the only difference between them is the internal implementation of the RF transmitter block.

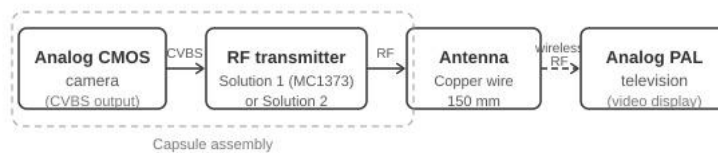


Fig. 1 System block diagram common to both solutions (adapted from Chan et al. [2]): analog CMOS camera (CVBS output) → RF transmitter (Solution 1 or Solution 2) → antenna → (wireless RF signal) → PAL television receiver.

For prototype validation, an artificial body model was constructed from a rubber hot-water bottle connected to plastic tubing to approximate the GI tract geometry, as shown in Fig. 2. This model was developed as the intended test environment since direct testing on human subjects was not possible. The proposed testing procedure involved placing the capsule assembly inside the model and evaluating the received video on the television receiver. The artificial body construction approach is consistent with the bench-top testing methodology described by Chan et al. [2].



Fig. 2 Artificial body model: rubber hot-water bottle connected to flexible plastic tubing, used to simulate the GI tract during prototype testing

3.2 Camera subsystem and CVBS characterization

An 8×8 mm miniaturized analog CMOS camera module (Fig. 3) was sourced from an online supplier. The camera was first characterized by interfacing its RCA-female output port to a digital oscilloscope via an RCA-to-BNC adapter. Table 5 lists the camera specifications.



Fig. 3 Miniaturized analog CMOS camera module (8×8 mm, PC2209 sensor, 600 TVL) used in both solutions

Table 5 Specifications of the analog CMOS camera module

Parameter	Value
Image sensor	PC2209 CMOS
Horizontal resolution	600 TVL

Minimum illumination	0.5 LUX
Signal-to-noise ratio	≥ 48 dB
Frame rate	PAL 25 fps
Video output	CVBS (1.2 V _{p-p} , 75 Ω)
Operating voltage	DC 5–12 V
Power consumption	80 mA
Lens	3.6 mm, 78° wide-angle
Module dimensions	8×8 mm

The oscilloscope analysis (Fig. 4) confirmed the expected PAL CVBS waveform structure: each frame begins with a negative-going sync tip pulse used by the television to synchronize frame rate, followed by a color burst subcarrier reference signal, followed by luminance signal lines encoding pixel brightness values. The measured frame rate of 57.8 Hz is consistent with the PAL 25 fps (50 Hz field) specification within oscilloscope measurement uncertainty. When the camera lens was covered (Fig. 5), the luminance signal collapsed to a uniformly low level, confirming correct sensor response.

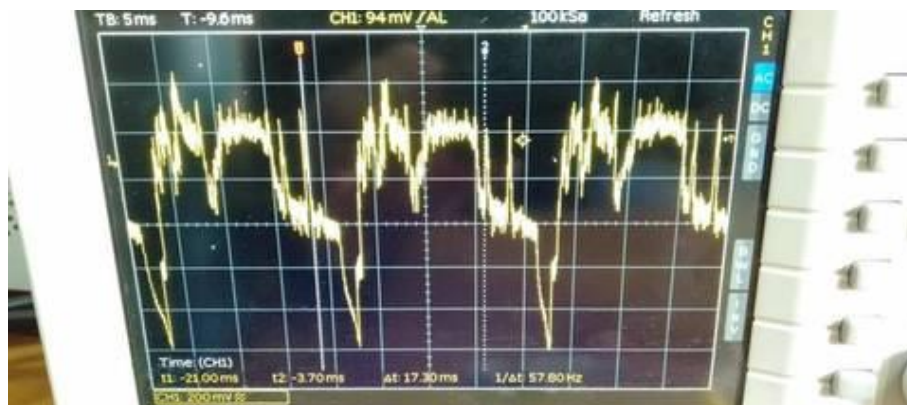


Fig. 4 CVBS output of analog camera on oscilloscope, showing sync tip, color burst, and luminance values (TB: 5 ms/div, CH1: 94 mV/AL, 1/Δt: 57.80 Hz)

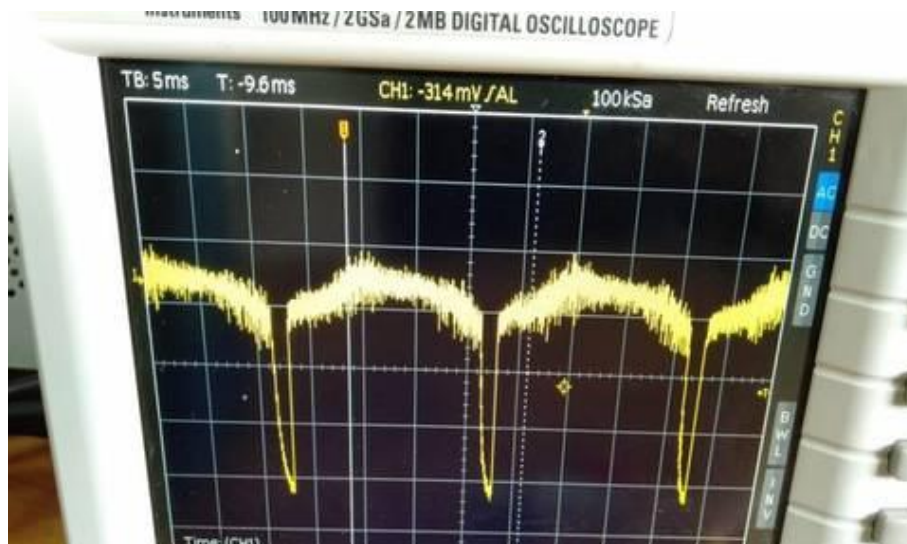


Fig. 5 CVBS signal with camera lens covered, showing collapsed luminance — confirming correct sensor response (CH1: -314 mV/AL)

3.3 Custom inductor design for Solution 1

Solution 1 requires a 0.1 μH air-core inductor for the LC resonant tank circuit of the MC1373 IC. This value is not commercially available as a standard through-hole component in Pakistan and was therefore custom-wound. Using the solenoid inductance formula and rearranging to solve for number of turns N , with wire diameter 1 mm (18 AWG) and coil diameter 5 mm:

$$N = (L \times \text{wire diameter}) / ((r^2 \times \pi) \times 1.26 \times 10^{-6})$$

$$N = (0.1 \times 10^{-6} \times 1 \times 10^{-3}) / ((2.5 \times 10^{-3})^2 \times \pi \times 1.26 \times 10^{-6}) = 4.04 \approx 4 \text{ turns}$$

Resulting inductor specification: coil diameter = 5 mm, $N = 4$ turns, wire diameter = 1 mm (18 AWG), coil length = 4 mm. Solution 2 uses a separate inductor value of 0.19 μH wound by the same method, selected empirically during breadboard tuning to achieve the 61.2 MHz operating frequency — no formal calculation was

required as the variable capacitor allowed fine tuning of the carrier frequency. The MC1373 internal schematic is provided in Fig. 6 for reference.

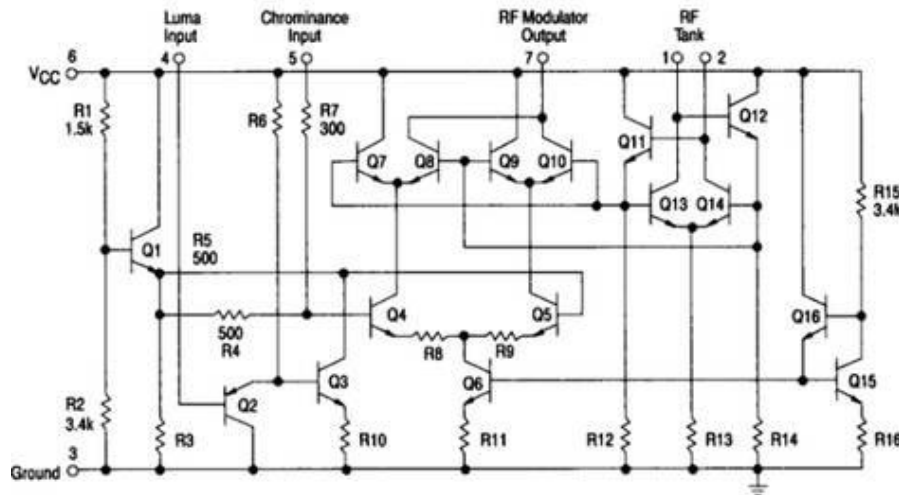


Fig. 6 Internal schematic of the MC1373 TV modulator IC showing RF oscillator, RF modulator, and pin assignments (Luma Input: Pin 4; RF Tank: Pins 1–2; RF Output: Pin 7)

3.4 Solution 1: MC1373 TV modulator IC

The MC1373 (Motorola) is an 8-pin RF oscillator IC designed for video games, computer displays, and video recorders. The CVBS output of the camera is applied to Pin 4 (luminance input). Pins 1 and 2 connect to the LC tank circuit, which determines the carrier frequency according to:

$$f = 1 / (2\pi\sqrt{LC}) = 1 / (2\pi\sqrt{(0.1 \times 10^{-6} \times 56 \times 10^{-12})}) = 67.25 \text{ MHz (Channel 4, VHF)}$$

Resistors R2 and R3 (240 Ω each) provide adequate switching voltage amplitude; R4 (240 Ω) lowers the maximum DC level below VCC to prevent IC saturation; R1 (75 Ω) provides standard TV line impedance matching. The application circuit for Solution 1 is shown in Fig. 7. The circuit was first implemented on

breadboard (Fig. 8, Fig. 9) and verified on the oscilloscope. It was then laid out as a PCB in Proteus software (Fig. 10) and physically fabricated (Fig. 11, Fig. 12). Four PCB copies were produced to allow comparison of layout variants.

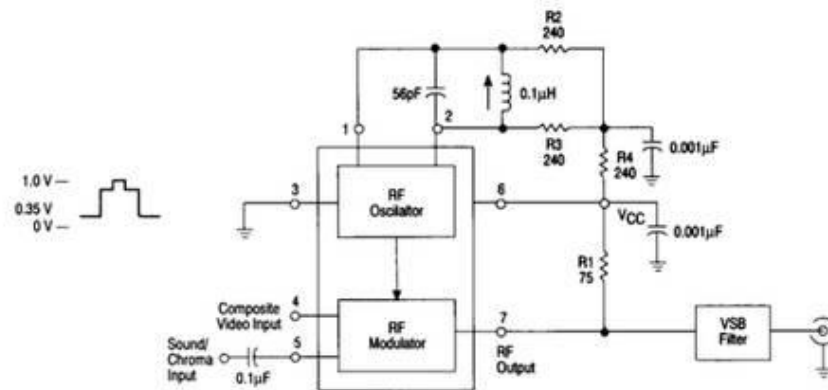


Fig. 7 Solution 1 application circuit for the MC1373 IC: LC tank (56 pF, 0.1 μH) on Pins 1–2 sets carrier frequency to 67.25 MHz; CVBS applied to Pin 4; R1 = 75 Ω line matching

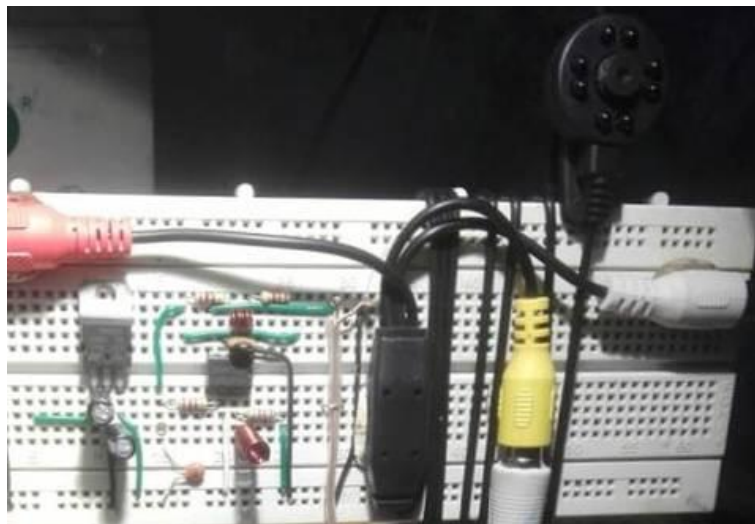


Fig. 8 Solution 1 breadboard implementation — MC1373 IC (centre), custom-wound inductor, and camera connected at left

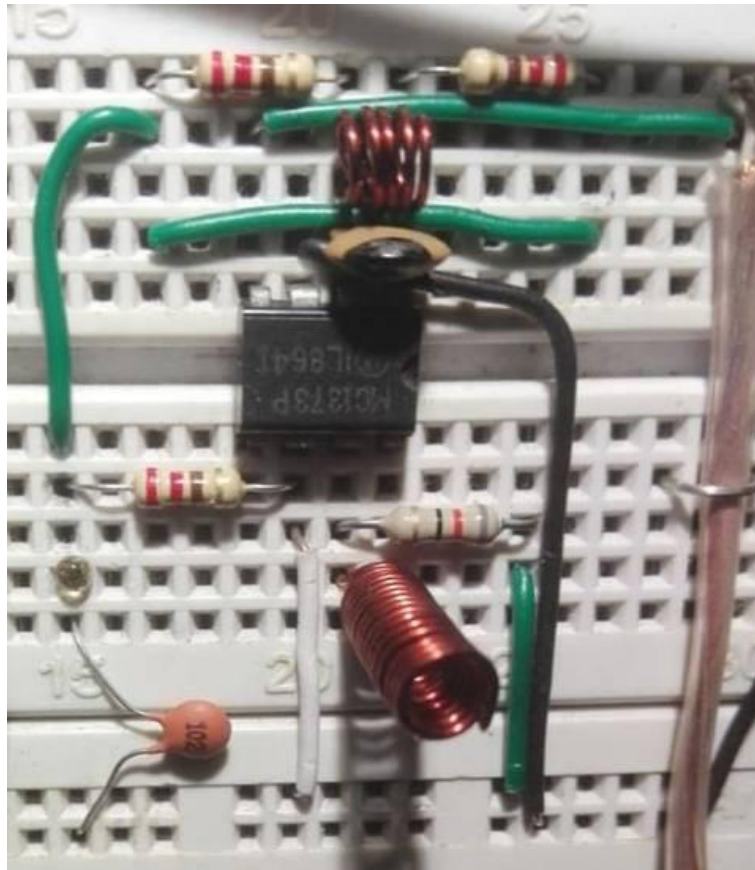


Fig. 9 Solution 1 breadboard close-up showing the MC1373 IC and two custom-wound copper inductors

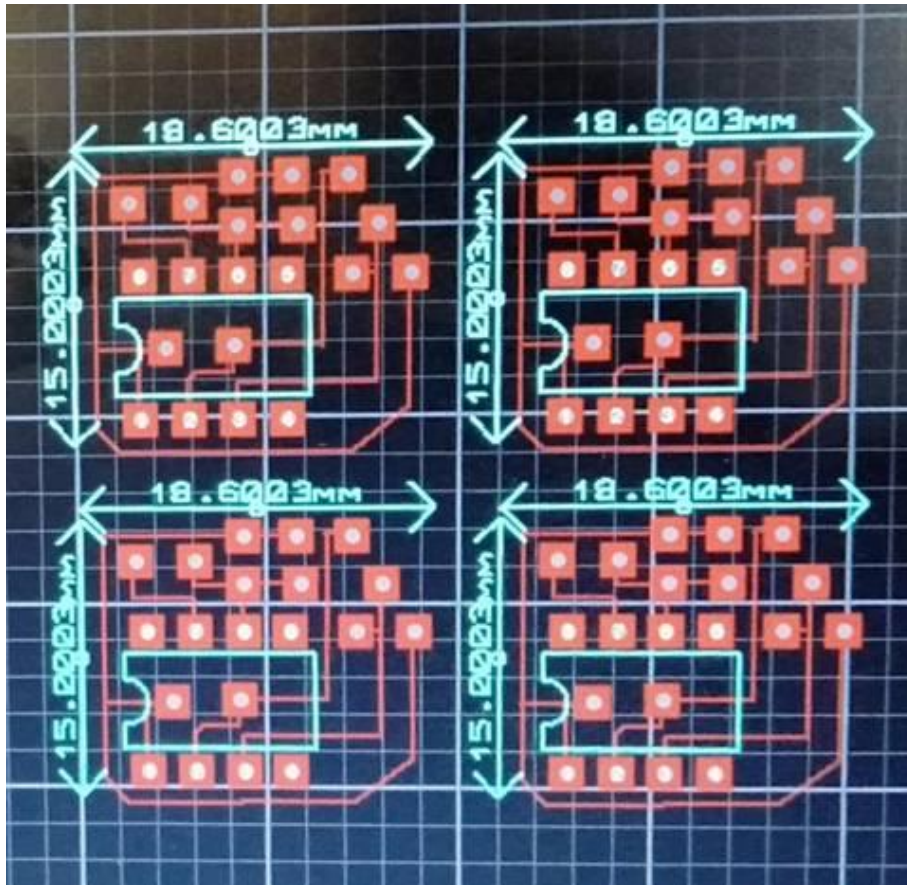


Fig. 10 Solution 1 PCB layout designed in Proteus — four copies shown, each 18.6×15.0 mm

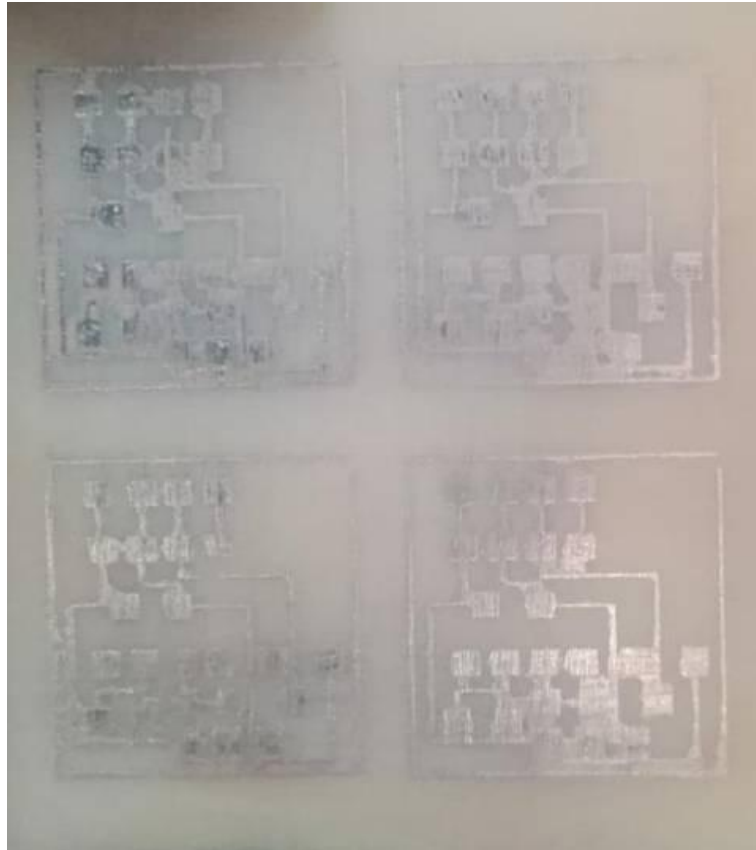


Fig. 11 Solution 1 PCB etched and fabricated — four copies on a single copper board

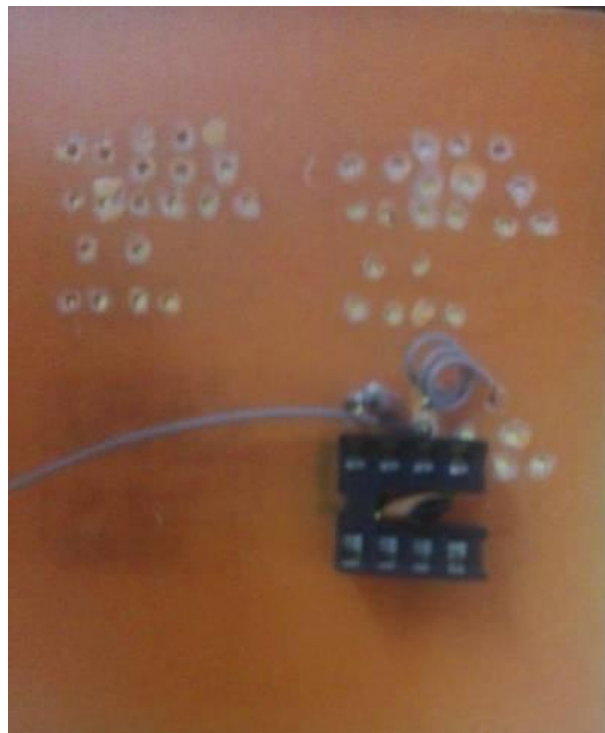


Fig. 12 Solution 1 fabricated PCB with IC and antenna wire — assembled and ready for testing

1

2 **3.5 Solution 2: Discrete-component transistor transmitter**

3 Solution 2 uses a 2N2222 NPN transistor configured as a Colpitts-type RF
4 oscillator. Key component values are: variable capacitor (16–56 pF, operating at 35
5 pF for 61.2 MHz tuning); custom-wound inductor (0.19 μ H); coupling capacitor (47 pF
6 across antenna); input coupling capacitor (1 μ F); 75 Ω load resistor for TV line
7 impedance matching; 500 Ω potentiometer for over-modulation control; and 1N4148W
8 diode for bias stability. Unlike the MC1373, this circuit has no inherent TV standard
9 restriction and is compatible with both PAL and NTSC receivers. The variable
10 capacitor allows continuous tuning, enabling alignment to the exact channel frequency
11 of any receiving television set.

12 The carrier frequency at the 35 pF operating tuning point is approximately 61.2
13 MHz (Channel 3, VHF). The circuit schematic is shown in Fig. 13. It was implemented
14 on breadboard (Fig. 14), then laid out as a PCB in Proteus (Fig. 15, Fig. 16), and
15 physically fabricated (Fig. 17, Fig. 18). The final PCB dimensions were verified against
16 a precision caliper (Fig. 19).

17

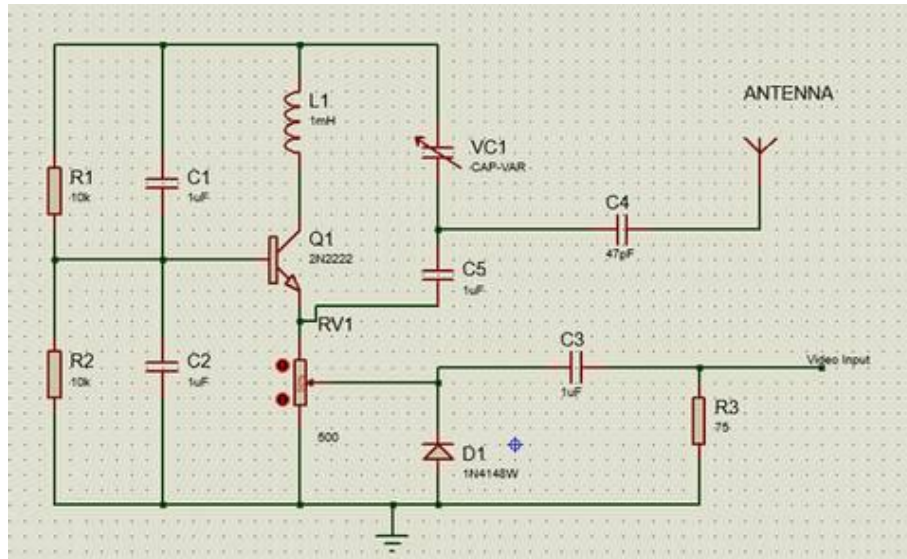


Fig. 13 Solution 2 schematic: Colpitts-type oscillator using 2N2222 NPN transistor, variable capacitor (VC1), custom-wound inductor (L1), 75 Ω load (R3), and 1N4148W bias diode (D1)

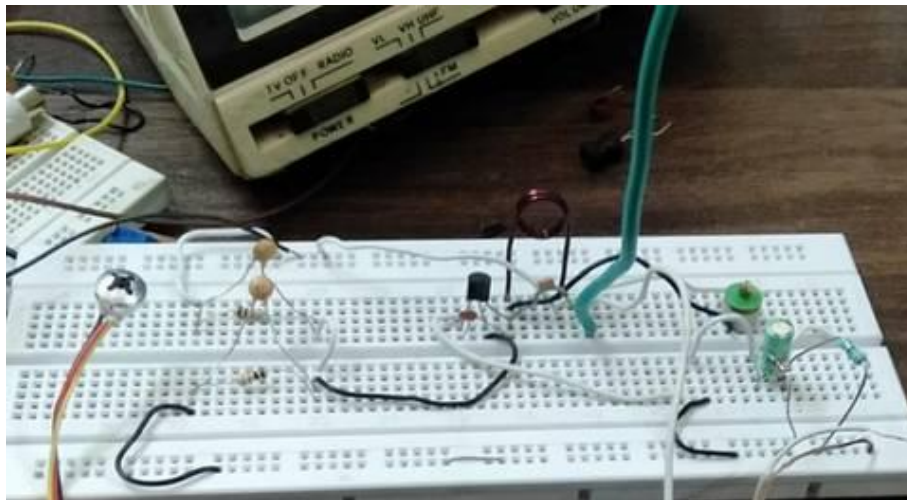


Fig. 14 Solution 2 breadboard implementation showing 2N2222 transistor, variable capacitor (green, right), and custom-wound inductor (centre)

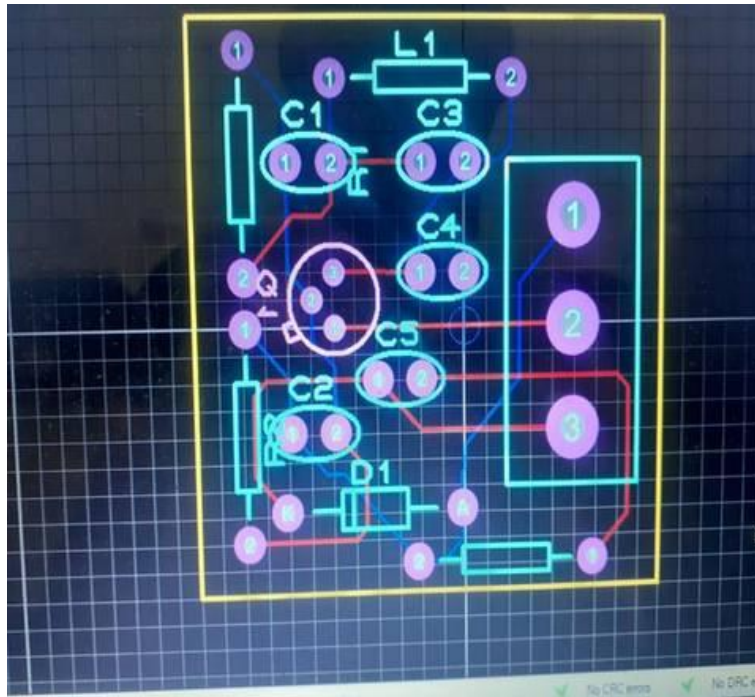


Fig. 15 Solution 2 PCB schematic view in Proteus showing component placement

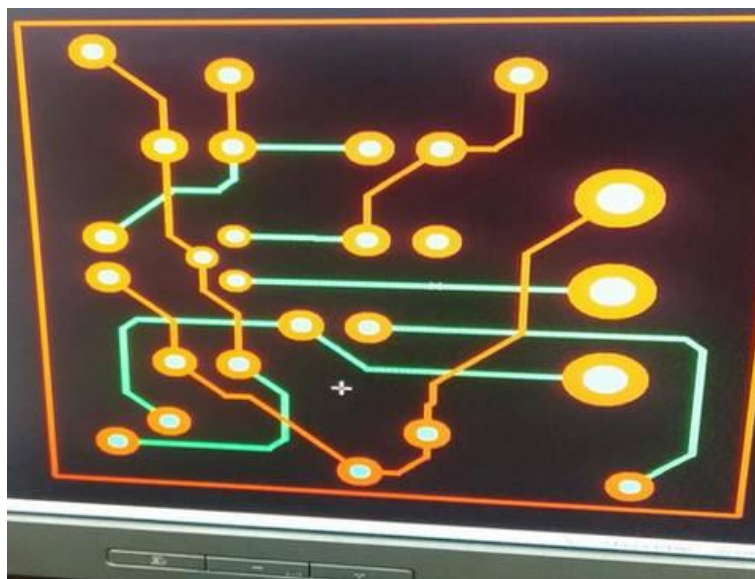


Fig. 16 Solution 2 PCB routing in Proteus showing track layout for the Colpitts oscillator circuit



Fig. 17 Solution 2 PCB etched and drilled — bare copper board before component population



Fig. 18 Solution 2 PCB fully populated with all discrete components including variable capacitor (blue, top-left) and custom-wound inductor (bottom-left)

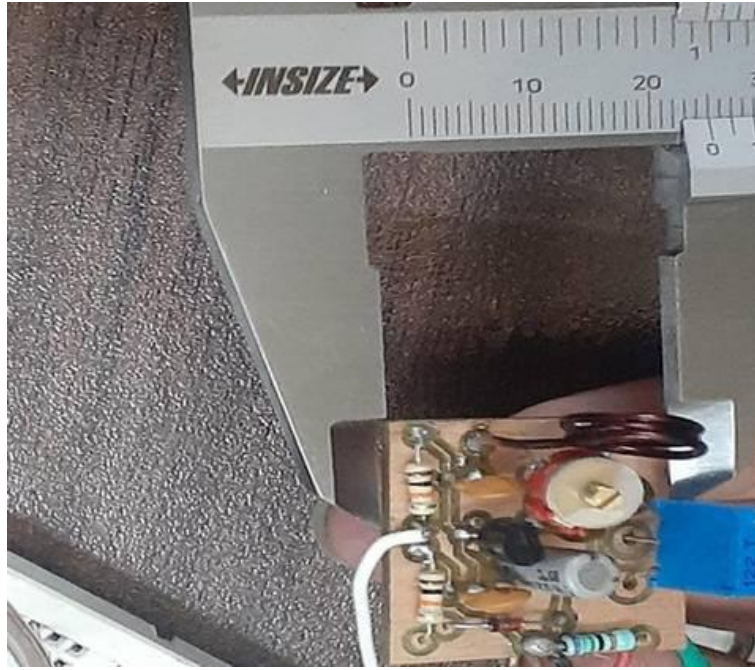


Fig. 19 Solution 2 PCB verified at 25×25 mm with precision caliper — satisfying the esophageal lumen size constraint of ≤ 25 mm

3.6 Artificial body model

To evaluate prototype operation without human subject testing, an artificial GI tract model was constructed following the approach of Chan et al. [2]. A rubber hot-water bottle was connected to flexible transparent plastic tubing to approximate the stomach and intestinal segments. Placing colored stones of varying hue inside the bottle as distinguishable imaging targets was proposed as the verification procedure. However, full in-model testing of the complete capsule assembly was not carried out in the present work due to hardware access constraints at the time of writing. The artificial body model represents the intended next step for prototype validation, and the RF transmission results obtained on the bench demonstrate that the core wireless video functionality is operational and ready for this evaluation.

4 Results

4.1 CVBS signal characterization

The CVBS output of the analog camera was successfully characterized on a 100 MHz digital oscilloscope. The waveform exhibited the expected PAL composite video structure: a negative-going sync tip at the start of each line, a color burst reference signal, and a continuous luminance signal encoding pixel brightness. The measured frame rate of 57.8 Hz is consistent with the PAL 25 fps specification. When the camera lens was covered, the luminance signal collapsed to a uniformly low level, confirming correct sensor response.

4.2 Solution 1 results

The LC tank circuit with $C = 56 \text{ pF}$ and $L = 0.1 \text{ }\mu\text{H}$ produced a measured carrier frequency of 67.25 MHz on the oscilloscope, consistent with the theoretical value of 67.225 MHz ($< 0.04\%$ error). The RF carrier waveform was clean and stable as shown in Fig. 20, confirming correct operation of the MC1373 IC and the custom-wound inductor. The PCB footprint measured $18.6 \times 15.0 \text{ mm}$, satisfying the 25 mm size constraint.

However, when the RF output was applied to available television receivers, only partial, heavily distorted video was obtained. Investigation established that the MC1373 IC modulates the video signal in NTSC format only, whereas Pakistan uses the PAL television standard. Available digital television receivers use DVB-T/T2 digital reception and have no analog RF tuner compatible with the transmitted signal. This PAL/NTSC format incompatibility prevented stable video display from Solution 1.



Fig. 20 Solution 1: stable 67.25 MHz RF carrier on oscilloscope (right); analog television shows static due to PAL/NTSC incompatibility (left)

4.3 Solution 2 results

The discrete-component transmitter, tuned to Channel 3 (61.2 MHz) using the variable capacitor, produced clear real-time video on an available analog PAL television set (Fig. 21, Fig. 22). Two observers were visible in the received images, confirming functional end-to-end wireless video transmission. Residual flickering was observed, attributed to instability in the analog television's demodulator circuitry rather than the transmitter — identical flickering appeared on broadcast television channels (e.g. PTV) on the same receiver. The fabricated PCB measured 25×25 mm as verified in Fig. 19, satisfying the esophageal dimension constraint.



Fig. 21 Solution 2: clear real-time video on analog PAL television — two observers visible, confirming successful end-to-end wireless video transmission



Fig. 22 Solution 2: second video frame demonstrating sustained image clarity during wireless transmission

Tables 6, 7, and 8 summarize the design parameters and comparative results of both solutions.

1 **Table 6 Solution 1 (MC1373 IC) design parameters and results**

Parameter	Value
IC	MC1373 (Motorola)
Oscillator stability	Excellent at 100 MHz
Intermodulation distortion	−50 dB
Over-modulation protection	Built-in
Supply voltage	−5 V DC
LC tank capacitance	56 pF
LC tank inductance	0.1 μH (custom wound)
Carrier frequency achieved	67.25 MHz
PCB footprint	18.6×15.0 mm
TV format compatibility	NTSC only

2

3

4 **Table 7 Solution 2 (discrete transistor circuit) design parameters and results**

Parameter	Value
Active device	2N2222 NPN transistor
Topology	Colpitts-type oscillator
Variable capacitor range	16–56 pF
Operating tuning capacitance	35 pF
Inductor	0.19 μH (custom wound)
Carrier frequency achieved	61.2 MHz (Channel 3)
Antenna	Copper wire, 150 mm, 1 mm dia.
Load resistance	75 Ω
PCB footprint	25×25 mm
TV format compatibility	PAL and NTSC

5

6

7 **Table 8 Comparative evaluation of Solution 1 and Solution 2**

Criterion	Solution 1 (MC1373 IC)	Solution 2 (Discrete circuit)
Carrier frequency	67.25 MHz (stable)	61.2 MHz (tunable)
RF signal confirmed	Yes	Yes
Video reception	Partial glitches; PAL incompatible	Clear real-time video on PAL TV

PAL compatibility	No	Yes
PCB footprint	18.6×15.0 mm	25×25 mm
Size constraint met (≤ 25 mm)	Yes	Yes
Tuning flexibility	Fixed (LC tank only)	Variable capacitor allows tuning
Component count	Low (IC-based)	Moderate (discrete)
Implementation complexity	Low	Moderate

1

2 **5 Discussion**

3 **5.1 IC-based versus discrete-component transmission**

4 The comparative results demonstrate a clear trade-off between the two
5 solutions. Solution 1 (MC1373 IC) offers lower component count, superior oscillator
6 stability ($< 0.04\%$ carrier frequency error), built-in over-modulation protection, and a
7 smaller PCB footprint (18.6×15.0 mm). However, its fundamental limitation — NTSC-
8 only modulation — renders it incompatible with PAL-standard markets including
9 Pakistan, India, and the United Kingdom. This is a critical finding for researchers in
10 these regions seeking to replicate or extend the Chan et al. [2] approach: the MC1373
11 IC cannot be used as a direct drop-in solution in PAL environments without significant
12 RF front-end modification.

13 Solution 2 (discrete transistor circuit) eliminates the format constraint entirely,
14 producing clear PAL-compatible video. Its variable capacitor provides continuous
15 frequency tuning, enabling alignment to any VHF channel — practically important
16 given variability in available analog television sets. The trade-off is a slightly larger
17 PCB size (25×25 mm versus 18.6×15.0 mm) and moderate additional circuit
18 complexity. Both PCB footprints satisfy the 25 mm esophageal constraint, but further

miniaturization using surface-mount device (SMD) components would be required to achieve the 11 mm diameter of commercial systems.

5.2 Carrier frequency and signal path analysis

Both solutions achieve carrier frequencies within the VHF television band (54–216 MHz), appropriate for short-range bench-top transmission. For Solution 1, the custom-wound inductor design is a notable practical contribution: the 0.1 μH inductance required for the MC1373 LC tank is not commercially available as a standard discrete component in Pakistan. Winding 4 turns of 18 AWG wire on a 5 mm former provides this value at negligible cost, with a measured carrier frequency error of less than 0.04% from the theoretical value. For in-vivo application, tissue attenuation must be considered — biological tissue at VHF frequencies presents a relative permittivity of approximately 40–60 and conductivity of 0.4–0.8 S/m [21], which would reduce effective transmission range and may require frequency reoptimization or the use of the MICS band (402–405 MHz) for regulatory compliance in clinical deployment.

5.3 Video quality and demodulator limitations

The residual flickering in Solution 2 output was attributed to the analog television demodulator rather than the transmitter, based on the observation that identical artifacts appeared on broadcast channels on the same receiver. This is an important distinction: it indicates that the RF transmission chain (camera → transmitter → antenna → propagation) is functioning correctly, and that video quality improvements should target the receiver subsystem. The transition from analog to digital television in Pakistan — driven by DVB-T2 adoption — has made obtaining well-maintained analog PAL television sets increasingly difficult, representing a practical

constraint for prototype researchers in the region that has not been previously documented.

5.4 Comparison with prior work

Chan et al. [2] demonstrated successful video transmission using an analog CMOS camera and TV modulator at approximately 60–70 MHz — consistent with the frequencies achieved in the present work. However, their work was conducted in a NTSC-standard environment and did not address PAL compatibility. Khan et al. [3] moved to a fully digital FPGA-based system with significantly better image quality but at the cost of substantially higher power consumption and circuit complexity. Bandari et al. [17] and Moglia et al. [18] have both identified low-cost transmission reliability as an open challenge in capsule endoscopy. The present work occupies a complementary position: it extends the Chan et al. analog approach to a PAL environment, directly documents the MC1373 PAL incompatibility, and provides a comparative evaluation of alternative transmitter architectures not previously reported.

5.5 Limitations and future work

Several limitations of the present work should be acknowledged. First, quantitative RF performance metrics — including transmitted power, link budget, signal-to-noise ratio, and transmission range — were not measured due to the absence of RF measurement equipment beyond a basic oscilloscope; future work should include spectrum analyzer characterization. Second, the prototype was evaluated under bench-top conditions using a rubber bottle model; validation in a tissue-equivalent phantom or ex-vivo porcine colon [2] represents a necessary next step. Third, the CMOS camera module (8×8 mm) significantly exceeds the 11 mm diameter of commercial systems; SMD redesign of all subsystems is required for

clinical-scale integration. Fourth, battery life and power management were not addressed — a silver-oxide or lithium coin cell with a full system power budget is required for a standalone prototype. Fifth, no polycarbonate dome was fabricated; a biocompatible outer housing is required before any in-vivo or phantom testing. These limitations define a clear and tractable development roadmap for future work.

6 Conclusions

This paper has presented the design and comparative evaluation of two low-cost analog RF transmission solutions for a wireless capsule endoscopy prototype. Three key findings emerge. First, the MC1373 TV modulator IC produces a stable RF carrier at 67.25 MHz with high frequency accuracy but is incompatible with PAL television standards, making it unsuitable for direct use in Pakistan and other PAL-standard markets. This incompatibility has not been previously highlighted in the capsule endoscopy prototype literature and constitutes a practically significant finding for researchers in these regions. Second, a discrete-component Colpitts oscillator using a 2N2222 NPN transistor successfully delivers clear real-time wireless video on a PAL analog television receiver, with a fabricated PCB footprint of 25×25 mm that satisfies the esophageal lumen size constraint. Third, the 0.1 μ H air-core inductor required for the Solution 1 LC tank — unavailable as a standard component in Pakistan — was custom-wound using 4 turns of 18 AWG wire on a 5 mm former, achieving less than 0.04% carrier frequency error at negligible cost, directly addressing a component availability gap in resource-constrained development environments.

The work establishes a documented engineering baseline for low-cost capsule endoscopy prototype development in resource-constrained environments such as

Pakistan. The primary pathway toward clinical capsule dimensions is miniaturization using SMD components. Future work should incorporate spectrum analyzer characterization of RF output, tissue-equivalent phantom testing, power budget analysis, and polycarbonate dome fabrication via 3D printing.

Declarations

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

A.A. and M.A. jointly designed and implemented both prototype solutions and performed all experiments. A.A. led the RF circuit design and inductor calculations. M.A. led the PCB layout design and fabrication. Both authors drafted and approved the final manuscript.

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List of Abbreviations

CVBS Composite video baseband signal
DVB-T Digital video broadcasting — terrestrial
FPGA Field-programmable gate array
GI Gastrointestinal
IC Integrated circuit
ISM Industrial, scientific and medical (radio bands)
LC Inductor–capacitor
MICS Medical implant communication service
NTSC National television system committee
PAL Phase alternating line
PCB Printed circuit board

- 1 RF Radiofrequency
- 2 SMD Surface-mount device
- 3 TVL Television lines
- 4 UWB Ultra-wideband
- 5 VHF Very high frequency
- 6

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