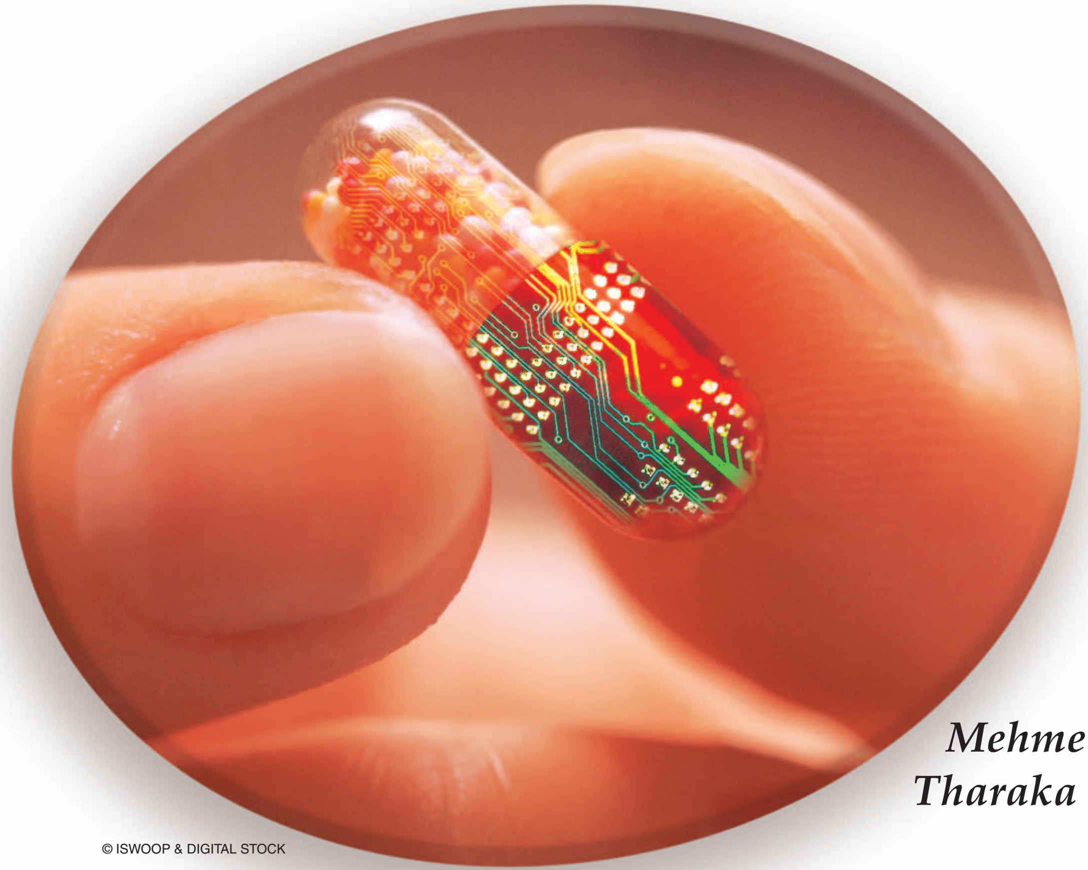

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Mehmet R. Yuce and
Tharaka Dissanayake

# Easy-to-Swallow Wireless Telemetry

Many countries will experience the effects of an aging population, resulting in a high demand of health-care facilities. Development of novel biomedical technologies is an urgent necessity to improve diagnostic services for this demographic. Electrocardiogram (ECG) and temperature recording have been used for more than 50 years in medical diagnosis to understand various biological activities [1], [2]. A more recent development, electronic pill technology, requires the integration of more complex systems on the same platform when compared to conventional implantable systems. A small miniaturized electronic pill can reach areas such as the small intestine and can deliver real time video images wirelessly to an external console. Figure 1 shows an electronic pill system (i.e., wireless endoscopy) for a medical monitoring system. The device travels through the digestive system to collect image data and transfers the data to a nearby computer for display with a distance of one meter or more. A high resolution video-based capsule endoscope produces a large amount of data, which can then be delivered over a high-capacity wireless link.

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A recent article [3] gives a good history of capsules from their early development to clinical implementation. The design of wireless capsules began in the 1950s. Since then, they have been called "endoradiosondes," "capsules," "smart pills," "electronic pills," "radio pills," "wireless capsules," "wireless endoscopy," "video capsules," and so forth. Herein we will use the term "electronic pill" when referring to this technology. Since its early development [4]–[7], electronic pill designs have been based on narrow-band transmission and thus have a limited number of camera pixels. Commonly used frequency values have been ultra-high-frequency (UHF) around 400 MHz. One of current state-of-the-art technologies for wireless endoscope devices is commercially available by the company Given Imaging [8]. The pill uses the Zarlink's radio frequency (RF) chip [9] for wireless transmission in the medical implant communication service (MICS) band (402–405 MHz). The allowable channel bandwidth for this band is 300 kHz. It is difficult to assign enough data rate for the high-quality video data at the moment for real-time monitoring. It is quite obvious that future electronic pills will target higher-bandwidth data transmission that could facilitate a better diagnosis.

An important feature of the electronic pill technology is the wireless system utilized. This article reviews recent attempts in the design of the wireless telemetry unit for the electronic pill technology and also discusses challenges and developments for successful implementation of high-resolution video-based electronic pills.

## Wireless Telemetry Methods Used in Eletronic Pills

The design of swallowable radio transmitters for use in diagnosis of the digestive organ system first appeared in the literature in 1957 by two different groups almost simultaneously [4], [10]. These early attempts were based on low-frequency transmission and with simple structures. A basic transmitter, using either Colpitts or Hartley oscillator topology connected to a sensor was used to send the signal from inside the body to external devices for tracking the physiological parameters of inner organs. Despite their simplicity, early systems were bulky because of the physically large electronic components and batteries at the time, in addition to the targeting of several diagnostic measures such as temperature, pH, and pressure [2], [10], [11]. Table 1 summarizes the recent attempts in electronic pill technology. The electronic pill device is placed deeply inside the body, which makes the wireless communication interesting due to its surrounding environment. Many designs have preferred lower-frequency transmissions [UHF-433 industrial, scientific and medical (ISM) or lower] [12]–[19]. Low-frequency transmission is easy to design and is attractive due to its high efficiency of transmission through layers of skin. A low-frequency link, however, requires large electronic components such as capacitors and inductors, which makes it difficult to realize a fully integrated system.

Recent significant technology improvements have enabled the design of small-size cameras and batteries. Thus, in the last ten years, some research projects looking at developing electronic pills have concentrated mostly on the visual sensor system. As a result, a high-frequency telemetry link is required for better resolution and a miniaturized system. Recent telemetry systems for the electronic pill technology given in Table 1 are still at prototype levels [12]-[20], [36]. In [12], a wireless endoscope system uses a commercial RF transceiver operating at 433 MHZ ISM with a 267 kb/s data rate. The electronic pill includes a passive wireless link used for wake-up to reduce power consumption. The wake-up system recovers energy from a 915 MHz RF modulated signal with some sort of identification code. This capsule uses image compressing techniques with an application specific integrated circuit (ASIC) to enable a higher transmission rate of images for low–data rate systems. The pill in [13] uses a simple on-off keying (OOK) wireless system. Similar to early developments, this device transfers physiological data, including pH and temperature. Another such device was developed by Valdastri et al., in [14] with a multichannel feature to cover a few different physiological parameters. It was tested in vivo in

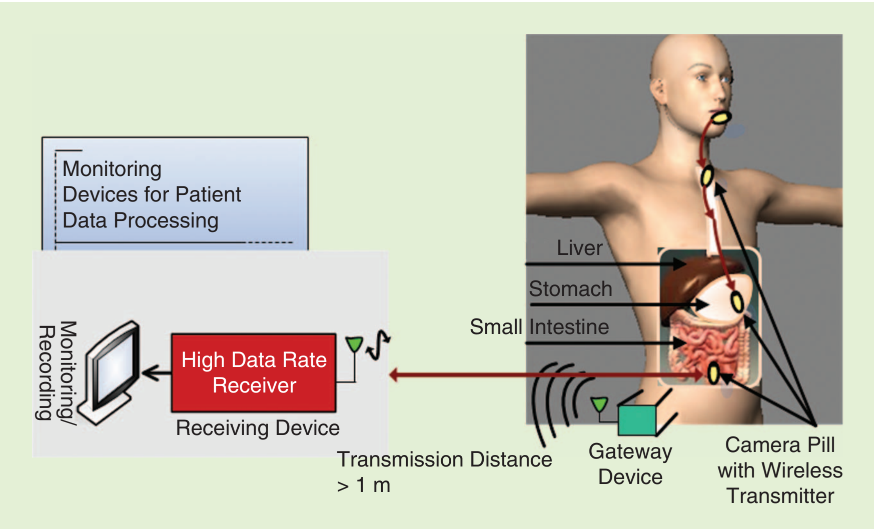


**Figure 1.** *A wireless endoscope monitoring system.*

**TABLE 1. Recent research project outcomes on electronic pill.**

| Reference | Image / Physiological Sensor | Image Resolution | Frequen. | Data Rate | Modulation | Trans. Power, Distance | Physical Dimension | Power Supply/ Battery | Current Power |
|---|---|---|---|---|---|---|---|---|---|
| (Chen, 2009) [12] | VGA, 0-2 frames/s | 307,200 pixels | 433 MHz | 267 kb/s | FSK | NA | 11.3 × 26.7 mm × mm | 2 × 1.5 V silver-oxide | 8 mA (24 mW) |
| (Wang, 2008) [15] | PO1200 CMOS | 1600 × 1200 pixels | NA | NA | AM | High (variable) | 10 × 190 mm × mm | 3 V, wireless | 405 mW |
| (Kfouri, 2008) [19] | CCD ICX228AL | 768 × 494 pixels | UHF | 250 kb/s | — | NA | 20 × 100 mm × mm | Li-ion battery | — |
| (Itoh, 2006) [20] | 2-frames/s | On-chip CMOS 320 × 240 pixels | 20 MHZ | 2.5 Mb/s | BPSK | 48 cm | 10 × 20 mm × mm | 2 V coin cell (CR1025) | 2.6 mW |
| (Park, 2002) [17] | OV7910 CMOS | 510 × 492 pixels | 315 MHZ/ 433 MHz | NA | AM | NA | 11 X 7 mm × mm | 5 V | NA |
| (Yu, 2009) [36] | NA | NA | 915 MHz | 2. 5 Mb/s (400ns) | OOK | –25 dBm | 8 × 23 (00-sized) | Wireless power | NA |
| (Moon, 2007) [18] | Stimulation | — | 434 MHz | 4 kb/s | ASK | 5.35 dBm | 11 mm × 21 mm | silver-oxide cells | 4.6 mA |
| (Johannessen, 2006) [13] | pH and temperature | — | 433 MHz | 4 kb/s | OOK | NA, 1m | 12 × 36 mm, 8 g | 2 × 1.5 V SR48 Ag2O | 15.5 mW |
| (Valdastri, 2004) [14] | Multichannel | — | 433 MHz | 13 kb/s | ASK | 5.6 mW 5 m | 27 × 19 × 19 $mm^3$ | 3-V coin cell (CR1025) | — |
| (Farrar, 1960) [35] | Pressure | — | | 3 kb/s | FM | | 7 mm × 25 mm | Wireless power | |
| (Mackay, 1957) [4] | pH, temp., oxygen level | — | 100 kHz | — | FM | — | — | — | — |

The highlighted section is for visual-based electronic pill systems.

pigs using pressure sensors and a transmission range of 5 m was reported. These devices do not require a high data rate when compared to the video based pills highlighted in Table 1; this is because physiological parameters, such as pH and temperature, are slowly varying and hence low-frequency signals. Simple modulation schemes like OOK and amplitude shift keying (ASK) with a low data rate are desired for low power consumption and miniaturization. Another type of capsule is the robotic endoscope, which has features such as locomotion and the energy transmission using electromagnetic (EM) coupling. Wang et al., adopted earthworm-like locomotion for their design [15]. The device size is quite large when compared with other proposed systems because of this locomotion function. Similar to smartpill technology, this device can also be used for precise drug delivery in the human gastrointestinal tract. Real-time wireless energy transfer via magnetic coupling is necessary for these types of endoscopes to provide mechanical function, as they require a large amount of power for continuous movement.

A recent study [16] demonstrated a prototyping system to achieve a high data rate transmission (2 Mb/s) for higher image resolution. This systems enabled an image resolution up-to 15–20 frames/s using a compression technique similar to Joint Photograpic Experts Group. It uses a transmitter based on a Colpitts oscillator consisting of a small number of components and consuming little power. The device operates at 144 MHz, lower than most of the systems that are operating at UHF, but requiring a larger antenna that, in turn, will increase the physical size. In [17], Park et al., also uses a simple amplitude modulation (AM). It is designed with a mixer and an oscillator circuit together with a CMOS image sensor and loop antenna to form a capsule-shaped telemetry device. This device uses an external control unit to control the capsule within the human body. The same group later developed a different version of their device that uses an electric stimulation technique to move the capsule up and down inside the small intestines [18]. The stimulating electrical voltage was controlled externally by adjusting the amplitude of the stimulating pulse signal and, thus, allowing movement of the capsule in the human gastrointestinal tract. This new system uses an ASK modulated signal at 434 MHz.

Another category of electronic pill technology uses fluorescence spectroscopy and imaging, similar to those that are commercially available (see Table 4). Kfouri et al., studied a fluorescence-based electronic pill system that uses UV light with illumination LEDs to obtain clearer images [19], similar to flash-based digital cameras in widespread use. Due to the use of power hungry LEDs, such a device consumes more power than the other systems. An alternative power source, together with a battery, is required to support the electronics.

As seen in Table 1, current systems use UHF frequencies as the transmission frequency. At these frequencies, the wireless telemetry systems should be based on antenna-transmission rather than inductive links. Using an inductive link is also a possible wireless link for electronic pills. Its drawback is the short-range wireless link provided by weak inductive coupling. Inductive link based designs use a frequency transmission, typically 20 MHz or lower, to obtain a high coupling between primary and secondary coils and therefore improved transmission efficiency. In addition, when the primary and secondary coils are not aligned correctly, the received signal will be very weak and may cause the wireless communication to fail. A system described in [20] uses an inductive link for data transfer. The device uses a 2 V coin battery, but is not tested in the biological environment. The communication distance is 38 cm with a receiving coil diameter of 20 cm for the carrier frequency of 20 MHz and the bit rate of 2.5 Mb/s. It is important to note, however, that communication regulators around the world do not allow a transmission bandwidth of 2.5 MHz at 20 MHz for medical applications. This is a very large bandwidth for a low-frequency transmission. To use a bandwidth as high as this, designers will need to move their system to a higher transmission frequency.

It is important to select the right transmission frequency band for wireless electronic pill applications. This is crucial for medical data transmission to ensure the patient's safety and to convey accurate information. Unlicensed ISM and MICS medical bands, such as those shown in Table 2, are often used for wireless telemetry in electronic pills. Some of these bands are internationally available (2.4 GHz for example) whereas others are only available regionally (such as the 900 MHz band in North America and Australia). Lower frequency unlicensed ISM bands, especially the 13.56 MHz frequency band, are widely used for RFID, security system smart cards and inductive links for implantable systems. Below approximately 20 MHz, bandwidths are limited to only a few KHz, limiting the use of a multiaccess technique that might allow several implantable devices to work in the same environment. For example, the maximum bandwidth in the 13.5 MHz ISM band is limited to 14 KHz. Thus, for electronic applications, a more advanced wireless technology will be required to accommodate better radio links for enabling safe and reliable data communications. Higher frequencies should be used to increase the range and also dedicate enough spectrum for reliable communication and high data rates. International communications authorities have allocated the 402–405 MHz band with 300 kHz channels for communication between an implanted medical device and an external controller. The intent of this band is to deliver a high level of comfort, better mobility, and better patient care while providing for improved device telemetry [9]. Today, the MICS band is being extended from 402–405 to 401–406 MHz in some countries. Introducing the additional 2 MHz within the band increases the number of channels in the band, enabling more patients to be monitored in a hospital setting. The wireless medical telemetry service (WMTS) is used in the United States and Canada but not in Europe. There are three different WMTS frequency bands in the United States: 608–614 MHz , 1395–1400 MHz, and 1427–1432 MHz. In Japan, WMTS frequencies are 420–429 MHz and 440–449 MHz. For the mid-ISM range, countries in Europe, New Zealand, and Hong Kong use the 865–868 MHz band. Australia, Korea, Taiwan, Hong Kong, and Singapore use a frequency range within the 902–928 MHz, while the United States and Canada use the whole band between 902–928 MHz. Japan has a 950–956 MHz ISM band that has widely been used for cordless headphones and microphones.

Though advances in high frequency and high bandwidth communication technologies for wireless systems have been significant in the commercial domain, these technologies are not directly applicable to biomedical implants or ingested systems because of the differing power, size, and safety related radiation requirements. As an example, in [21], an implant prototyped with a ZigBee compliance (one of the low-power, less complex, and small size commercially available wireless standards) occupies an area of $26 \times 14 \times 7\,mm^3$ without being integrated with other required blocks of an electronic pill. Existing advanced wireless systems such as ZigBee (IEEE 802.15.4), wireless local area networks (WLANs), and Bluetooth (IEEE 802.15.1) operate in the 2.4 GHz ISM band and suffer from strong interference from each other when located in the same environment [22]. Therefore, the electronic pill should use a different transmission band or more sophisticated modulation protocol suitable for the environment for an interference free wireless system. Existing wireless modules contain complex multiaccess communication protocols such as orthogonal frequency-division multiple access (OFDMA) and time division multiple access (TMDA) that increase the power consumption

**TABLE 2. Available unlicensed wireless frequencies.**

| Wireless Frequency | Frequency | BW | Country/Region | Current ePill Projects | Comment |
|---|---|---|---|---|---|
| MICS | 402–405 | 300 KHz/ channel | United States, Australia, Europe, Japan | [8]—Given Imaging | It can be used from the pill to an external receiver |
| WMTS | 608–614<br>1395–1400<br>1427–1432 | 1.5 MHz<br>5-6 MHz | U.S., Canada | None | It is used in some hospitals in the USA for telemetry systems. It is not available for in body communication. |
| High Freq. ISM | 2400–2483<br>5725–5875 | 20 MHz,<br>40 MHz | Worldwide | [21] | It can be used for electronic pills. This band is very crowded as it is occupied by many other applications. |
| Mid-ISM | 433–434 MHz<br>315 MHz | kHz range | Worldwide | [12]–[14],<br>[18]—433 MHz<br>[17]—315 MHz | The high-bandwidth channels are not available internationally. 433 MHZ ISM allocate a very small bandwidth. Thus it is difficult to use it for high definition video data transmission. |
| | 865–868 MHz | 200–500 kHz/10–15 channels | Europe | | |
| | 902–928 MHz | MHz | USA, Canada, Australia | [36] | |
| Low ISM | 13.55–13.567<br>26.95–27.283<br>40.66–40.70 | kHz range, 14 kHz for 13 MHz | Worldwide | None | These frequencies can be used for the wireless power link. They have been common frequency bands for RFID applications and implantable electronics such as Cochlear and Retinal implants |
| UWB | 3.1–10.6 | >500MHz | International | [26] | It provides a high bandwidth. However due to the penetration loss, the signal can only be received when the receiver is close to skin. |

and size of the wireless chip [23]. Unless these chips are miniaturized to levels that can be inserted into a capsule size of 11 mm × 30 mm, the telemetry link will still be based on simple communication modulations such as ASK, OOK, frequency shift keying (FSK), FM, and AM (as seen in Table 1). An easy way to implement these modulation schemes is to use Hartley- or Colpitts-based oscillators. Two different configurations of the Colpitts oscillator are shown in Figure 2.

EM interference (EMI) is another source of interference that may limit the use of wireless in certain environments, especially in medical applications. There already have been incidents where the telemetry devices have affected the available medical systems in the hospitals [24].

In addition to the above wireless bands, ultrawideband (UWB) can also be used for electronic pills. High data rate transmission, as commonly known, is not the only unique property of an UWB-based monitoring system. Some other advantages of a wideband technology are its low transmitter power; the physical size, which can be extremely small because of the design in the gigahertz range; the simplicity of transmitter design; and the fact that the band is not crowded when compared to the other available bands [25]. The maximum transmission power is limited to –41 dBm/MHz. Such a low signal level will have an insignificant EMI effect on medical equipment in the medical environment. The current drawback of UWB technology is that there are not a large number of devices currently available in the market that can be used in a fully integrated or complete system. Experimental results have shown that the UWB communication can achieve a data rate equal to or higher than 100 Mb/s for electronic pill applications [26].

Besides EMI, one must also ensure that EM radiation from electronic pill devices located inside the body does not cause any harm to the human body. There have been studies reporting biological effects such as changes in blood pressure, DNA damage, and effects on nerve cells due to exposure of EM radiation [27]. Thus, the EM and RF exposure levels should not exceed the RF/microwave safety standards established by communication authorities (e.g., the U.S. Federal Communications Commission) [28].

The MICS band has been regulated for a low emission power (25 μW, comparable to UWB) and, thus, low EM radiation. UWB and MICS bands will provide the

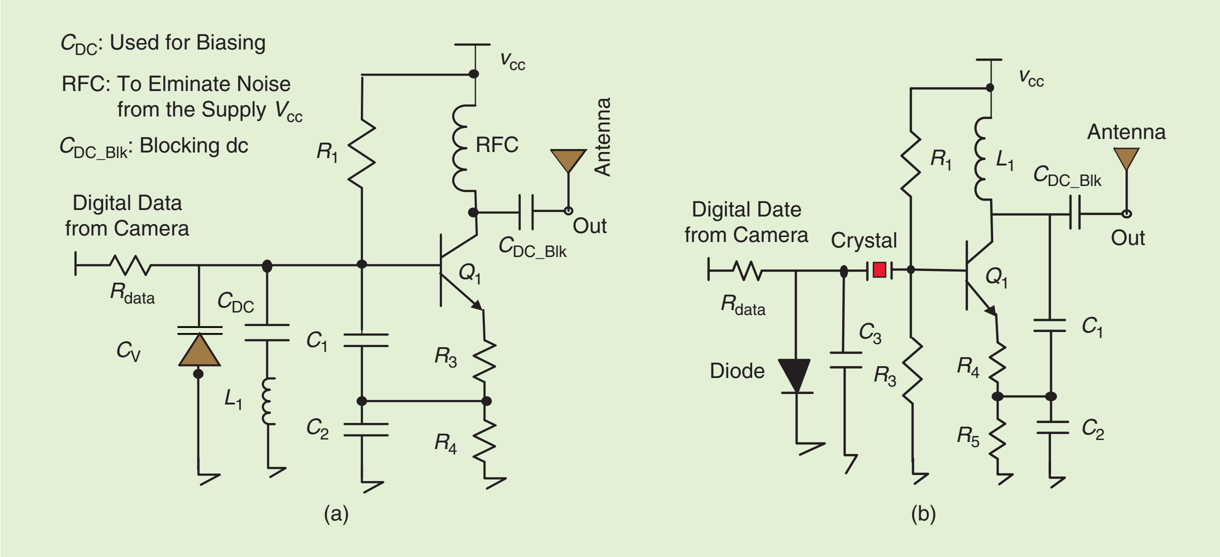


**Figure 2.** *E-pill transmitters based on RF Colpitts oscillator: (a) a common collector Colpitts oscillator and (b) a common base Colpitts oscillator with crystal.*

most suitable telemetry designs in medical environments and, most likely, will continue to be the choice of designers.

## Hardware Designs for Electronic Pills

The earliest electronic pills [5], [2] and even more recent ones [29], [16] use a transmitter circuit similar to those shown in Figure 2 [Figure 2(a) is schematic of a low-power transmitter that can be used for electronic pills]. The operation frequency of these transmitters is established by the frequency selection filter consisting of $L_1$, $C_1$, and $C_2$ as

$$\omega_0 = 1/\sqrt{L_1 C_1 C_2/(C_1 + C_2)}. \quad (1)$$

To measure pressure inside the body with early electronic pills, a diaphragm was used to move an iron core inside the oscillation coil ($L_1$ in the Figure 2). As the induction changes, the amount of the frequency change was dependent on the pressure change. In the case of video imaging in modern electronic pills, digital data converted from image signals are applied to the input, as shown in Figure 2 [16]. The transmitter in Figure 2(a) uses a varactor (variable capacitor; *Cv*) to generate FSK or FM modulated signals for wireless transmission of medical data or images. The value of the variable capacitor changes with respect to the amplitude of the input signal, which could be image data from a camera, or a physiological signal such as temperature or pH level in electronic pill applications.

In a real implementation, the values of inductors and capacitors will have tolerance variations that will result in potential offsets in the transmission frequency, making it difficult to recover the transmitted signal at the receiving site. One way to overcome this issue is to use a crystal to maintain the oscillator frequency at the desired transmission frequency. The electronic pill system presented in [29] uses this technique for the transmitter. As depicted in Figure 2(b), when the input signal is one, the diode conducts and $C_3$ is short circuited. When the input signal is zero, the diode does not conduct. This binary switching either keeps capacitor C3 in the circuit or shorts C3 out, modifying the output frequency according to the bit pattern. As a result, two different frequencies will be generated for bit 0 and bit 1, forming an FSK modulated signal. The receiver circuits for the transmitters given in Figure 2 are easily constructed from the radios available in commercial domain. As it is outside the body, the size and power consumption of the receiver is not critical.

When a number of similar types of electronic pill systems are used in the same environment, these simple transmitters face the problem of interference and packet collisions and, therefore, lack the multiuser (i.e., multiaccess) capability. The packet collisions occur when more than one user transmits information at the same time; as a result, the required information from each user may be lost. In order to distinguish signals from two electronic pills given to two patients located in the same room, each telemetry should use a pseudo noise (PN) code for identification so that the receiving device can identify the individual electronic pill. Based on an extensive search on the electronic pills in the literature, to our knowledge, none of the systems has provided any information regarding multiuser capability of their electronic pills. The lack of this feature should be resolved in future electronic pill developments. From Table 1, current attempts in the design of electronic pill hardware do not consider multiaccess, as the modulation technique used is simple and the data rate is low. This multiaccess issue will become more critical when more advanced medical implants such as wireless implantable cardioverter defibrillators and pacemakers are operated together with electronic pills in the same clinical environment. Advance communication standards, especially low-power wireless personal area network (WPAN) standards, use communication protocols [carrier sensing multiaccess (CSMA), TDMA, and OFDMA] to avoid data packet collision among multiple users. The communication protocols mentioned above will require a receiver and a microcontroller in the electronic pill to provide bidirectional communication to accommodate control signals, increasing the electronic pill complexity and potentially increasing the size of the pills.

An example of a hardware design for an electronic pill that has the capability of multiaccess protocol is shown in Figure 3. In addition to image data, detection and subsequent transmission of physiological signals are usually necessary to improve patient diagnosis. The image data is obtained from a CMOS camera and is in a digital format. Physiological signals obtained from inside the human body are initially analog and thus go through an amplification/filtering (A/F) process to increase the signal strength and to remove the unwanted signals and noise. A multiplexer is used to switch between each data. An analog to digital conversion (ADC) stage is required to convert the analog body signals into digital for digital processing. The microcontroller will then pack and code the data before the data is sent to the wireless transceiver. The multiaccess protocol to enable a multiuser function is implemented in the microcontroller.

In addition to these data blocks, there is also battery and its power management circuitry. The power management circuit is usually a voltage regulator chip used to distribute the power source to the individual blocks. It is advised to keep all the sensor blocks' power supply level the same so that the regulator should not consume a large amount of power. In the past few years, there have been significant advances in sensor node technology. An electronic pill is similar to a wireless sensor node except in this case, the sensor could be a camera or another sensor that can detect signals such as temperature and pH level. Among sensor network applications, short-range WPAN systems, such as Bluetooth or Zigbee, are the most suitable ones for use in electronic pills as they are designed to be low power and small in size. Some commonly used wireless sensor platforms (as a complete sensor board) in the commercial domain are shown in Table 3. Mica2DOT and T-node are the smallest sensor nodes available on the market that can be used in an electronic pill (see Figure 4). The Mica2DOT sensor node can operate at 868/916 MHz and 433 MHz ISM frequencies and uses the ATmega128L microcontroller (4k SRAM, 128K Flash, 8 MHz). Total power consumption of this board with a 3.3 supply, including the radio and microcontroller, is 135 mW.

Another small node for sensors is the T-node which operates in the same bands as Mica2DOT. The board uses a separate chip for the microcontroller with 10-bit ADC, memory of 128 k flash memory and 4 kB static RAM (SRAM). The sensor node consumes 80 mW at 3 V supply voltage [31] and is similar in size to that of Mica2DOT (23 mm). Although the physical sizes of these two sensors are small enough to be used in electronic pill hardware, their data transmission rates are low and cannot accommodate a high-quality video-based system. However, companies are continuously developing new sensor nodes and, in the near future, small-size sensor platforms, similar to those in Figure 4 with high data rate capability, will be available to biomedical engineers for use in electronic pill applications.

Table 4 gives the details of commercially available electronic pill technologies that are already being used in clinical environments. Due to the limited transmission bandwidth used for the electronic pills that are currently being developed or those commercially available the image transfer rate has been limited to 0–10 frames/s. As high-definition cameras continue to be developed, they will become more attractive for use in electronic pills. A higher pixel camera will require a higher image transfer rate, however. Currently, all video-based commercial systems use LED illumination. Sayaka, by RF System Lab (previously known as RF Norika), has both wireless power transfer and localization capabilities. This battery-free capsule contains three rotor coils for posture control and four LEDS for focus

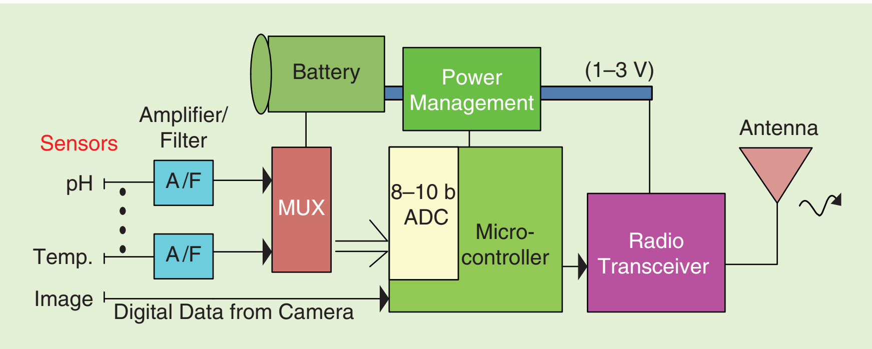


**Figure 3.** *An example of advanced hardware design for an electronic pill.*

**TABLE 3. Various hardware sensor nodes configurations.**

| Model | Company | Frequency | Data Rate | Transmission Power (dBm) | Physical Dimension (mm) | Power Consumption Tx | Power Consumption Rx | Micro Controller |
|---|---|---|---|---|---|---|---|---|
| Mica2 (MPR400) | Crossbow | 868/916 MHz, 433 MHz, 315 MHz | 38.4 kb/s | −20 to 10 | 58 × 32 × 7 $mm^3$ 18 g | 25 mA at 3.3 V | 8 mA at 3.3 V | 8 mA at 3.3 V |
| MicAz | Crossbow | 2400 MHz to 2483.5 MHz (IEEE 802.15.4) | 250 kb/s | –24 to 0 | 58 × 32 × 7 $mm^3$ 18 g | 17.4 mA at 3.3 V | 19.7 mA at 3.3v | 8 mA at 3.3 V |
| Mica2DOT | Crossbow | 868/916 MHz, 433 MHz, 315 MHz | 38.4 kb/s | –20 to 10 | 25 × 6 $mm^2$ 3 g | 25 mA at 3.3 V | 8 mA at 3.3 V | 8mA at 3.3 V |
| Tmote Sky node | Sentilla (Moteiv) | 2.4 GHz (IEEE 802.15.4) | 250 kb/s | –25 to 0 | 66 × 32.6 × 7 $mm^3$ | 17.7 mA at 3 V | 20 mA at 3 V | 1.8 mA at 3 V |
| T-node | SOWNet | 868, 433, 915, or 315 MHz | 52.2 kb/s | –20 to +5 | Diameter of 23 mm | 25 mA at 3 V | 12 mA at 3 V | ~6.2 mA at 2.4 V |
| Sensium | Toumaz | 868/915 MHz | 50 kb/s | –23 to –7 | 90 × 45 × 10 $mm^3$ | 2.6 mA at 1.2 V | 2.09 mA at 1.2 V | 0.03 mA at 1.2 V |

adjustment. This capsule with posture and orientation control has the ability to stay in a specific area of the intestine to obtain higher-quality images. Another endoscope, EndoCapsule, developed by Olympus, was mainly used in Europe but, in 2007, received marketing clearance from the U.S. Food and Drug Administration (FDA). The device contains six LEDs with adjustable illumination to maintain optimal imaging. The electronic pill by SmartPill is designed to measure pressure, pH, and temperature as it passes through the gastrointestinal (GI) tract. A receiving device worn by the patient collects data and is later examined by a physician. Another commercially available capsule for endoscopy is MiroCam. This system has a different wireless transmission compared to other capsule technologies. Instead of using RF signals to transmit images, MiroCam uses natural electrical impulses in the human body as the transport medium] [32].

## Batteryless Electronic Pills

Currently, the battery, one of the essential components in electronic pills, provides the power source to the active electronic components in the device. Although small miniature rechargeable battery technologies are available, the lifetime they provide may not satisfy the desired operation time for detecting and transmitting enough useful data from inside the body. As given in Table 4, current electronic pills have limited operational time as a result of the battery technology used. One way to enhance this operational lifetime is to charge the battery wirelessly. Alternatively, a completely wireless power system could also be used. In batteryless systems, it is necessary to bring the charging transmitter very close to the patient's skin to charge or energize the electronic pill. Unlike conventional implant systems [33], longer-range wireless power transfer is required for electronic pills, which needs to transfer energy efficiently through the 15–20 cm thick skin in order to reach the device inside the body [34]. Wirelessly energizing electronic pills was studied early in the development of the first electronic pills [2], [11], [35]. One of the first electronic pills [35] used an inductive link for

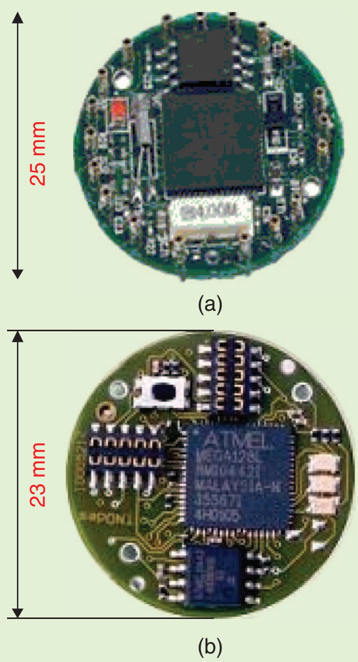


**Figure 4.** *Commercial sensor node examples: (a) a Mica2DOT board and (b) a T-node sensor node [31].*

**TABLE 4. Comparison of commercial electronic pills, www.givenimaging.com, http://www.olympus-europa.com/endoscopy/, www.rfsystemlab.com, www.smartpillcorp.com.**

| Model | Company | Camera (Sensor) | Freq. (MHz) | Data Rate | Power Source | Physical Dimension | Image Rate and Resolution | Operation Time |
|---|---|---|---|---|---|---|---|---|
| PillCam (SB) | Given Imaging | Micron, CMOS | 402–405 & 433 (Zarlink) | 800 kb/s (FSK) | Battery | 11 mm × 26 mm, < 4 gr | 14 images/s, or 2,600 color images | 8 hr |
| EndoCapsule | Olympus Optical | CCD camera, 1 920 × 1080 | – | – | Battery | 11 mm × 26 mm, 3.8 gr | 2 images/s | 8 hr |
| Sayaka | RF System Lab | CCD Image sensor | – | – | Wireless Power | 9 mm × 23 mm | 30 images/s | 8 hr (870,000 images ) |
| MiroCam | IntroMedic | Camera (320 × 320 pixel) | Body as transmitted channel | – | Battery | 11 mm × 24 mm 3.4 gr | 3 images/s | 11+ hr (118,800 images) |
| OMOM capsule | ChongQing JinShan Science & Technology | – | – | – | Rechargeable battery | 13mm × 27.9mm < 6 gr | 2–15 frame/s | 8 hr |
| SmartPill | SmartPill Corp. | Acidity (pH), pressure, temperature | – | – | Battery | 13 mm × 26 mm | Only sensor discrete data | – |

wireless power transfer. The cylindrical shaped pill was 0.7 cm in diameter and 2.5 cm in length. A large circularly shaped coil connected to an external source was placed around the body to energize the capsule while inside the body. The batteryless pills in [2] and [11] operate based on passive telemetry. They utilize a resonant circuit whose characteristic frequency is sensed from the outside. This capsule operates in a similar fashion as current reflective RFID technology. Electronics pills with wireless power sources are generally smaller in size than a battery-powered capsule, with the further advantage of the virtually unlimited device life they provide.

Another study [36] used 13.56 MHz for the wireless power link. In this study, testing was been done with a phantom solution used to represent the human body, with the wireless power link put very close to the prototype device (approximately 2 cm [37]). The wireless power link also provided downlink command functions to the pill. A receiver antenna was placed very close to the set-up container for receiving data from the phantom solution. The autonomous robotic electronic pill in [15] also used a wireless energy-based supply, which successfully provided 400 mW of wireless power to the pill. A very-low-frequency 10 KHz transmitting frequency was used for wireless power to reduce human body absorption. A recent study implements a multicoil technique for inductive powering of an endoscopic capsule [38]. The system consists of two external Helmholtz coils transmitting energy to a 9-mm three-dimensional (3-D)-coil power receiver. The link is able to transmit power of around 300 mW at 1 MHz, sufficient for use in electronic pills with locomotion function.

## High-Speed Wideband Technology for Electronic Pills

Although the image-based electronic pill systems listed in Tables 1 and 4 can provide an image rate up to 30 images/s, for some diseases, detailed images with higher-resolution cameras may be required [39]. In order to monitor high-quality images in real time, a wideband radio link is desired for the high capacity data transfer and, therefore, improved image resolution [16], [40]. A wideband, high-frequency technology would be useful for high-definition images exceeding 2 Megapixels (i.e., $> 1920 \times 1080$).

In order to accommodate the high bandwidth to make the high data rate feasible, some researchers have investigated the use of a telemetry link over GHz frequency links. As an example, in [41], a research group from Korea used a transmitter in the capsule with a carrier of 1.2 GHz and 20 MHz bandwidth to provide a data rate of 20 Mb/s. However, a frequency band of around 1.2 GHz is not available internationally for use in medical applications. In addition, there could be strong interference to GPS receivers, as they also work within this frequency range. Another high frequency link has been presented using the new unlicensed UWB wireless technology band 3.1–10.6 GHz [26], [40]. The potential benefits of a UWB link are an increased battery life due to lower-power transmitters, higher data rates, which increase resolution and performance, and less interference effects on the other wireless system in medical centers. A small antenna is also possible with a wideband high-frequency technology. To make a UWB transmission feasible for electronic pills, because of the strong attenuation through the body tissue, higher transmitted signal levels at the transmitter must be accommodated [26] but keeping the signal output less than the regulatory limit of −41 dBm/MHz. The UWB signal power can be arranged so that when the signal is radiated through the skin, the power level should meet this FCC mask without violating safety requirements.

## Future Developments

Although low-frequency transmission has commonly been used in electronic pills, high-frequency links can also be used and offer such advantages as physically small electronics and antennas and high data rate transmission. These improvements with high-frequency links are partially offset by higher path and tissue penetration loss. Thus, in order to provide good wireless communication performance, the receiver should be placed very close to the human body (i.e., wearable) to reduce the impact of these losses. In the future, multiple antenna array connected to a wearable receiver could be used to receive images from all directions, as well as to increase the sensitivity of the received signal for a better signal transmission.

Another important area for study is reduction of the pill size and associated antennas. The overall length and width of commercially available electronic pills is usually 26 mm x 11 mm, which is barely smaller than the average diameter of the adult upper esophagus.

Electronic pills travel within the body unlike stationed implants. Because of this movement, increasing transmit power levels from the pill will not increase the heat much at the tissue of a certain body part. Thus higher transmitted signal levels can be used at the transmitter side of the electronic pill inside the body if it can be ensured that the pill does not lodge in a certain location. The only section of the body that the device will stay is the stomach, a watery environment, full of acidic material that can reduce the effect of localized heating. Considering the strong attenuation through body tissue, the transmitter power level can be adjusted in the system without violating power levels of regulations (i.e., FCC regulations) [25]. Of course, the power levels should not reach above regulated in-body tissue specific absorption rates (SAR); this is especially important for UWB-based electronic pill designs.

Small batteries are used or are being considered to supply the energy to the electronic pills, but even the smallest batteries still take a considerable amount

**Another important area for study is the reduction of the pill size and associated antennas.**

of space. Wireless power transmission or wirelessly charging an electronic pill is another research area that should be investigated to enable long-term medical monitoring. Wireless power can substantially reduce the overall size and weight since the need for batteries is removed. To transfer enough energy, inductive links require the external unit be very close to the implanted/ingested device, so ideally the external unit should be placed on the body for an efficient wireless power (care must be taken to protect the patient from high power operation in close proximity to the body). A wireless power mechanism can also be used to recharge the battery of the electronic pill if a rechargeable battery is used.

Figure 5 shows the basic building blocks of a potential electronic pill medical system for the future. The system contains a wireless power mechanism and two wireless links to enable remote monitoring. The external signal for powering the pill is received and regulated to provide the power for the on-board electronics: the wireless data transmitter, the sensors and the signal acquisition unit which processes and amplifies the sensors' data. The external unit contains a second wireless link that will control the communication between the monitoring station and the electronic pill. A remote receiver can be connected directly to a workstation for monitoring, analyzing, and displaying images. The external unit acts as a gateway and transfers the received image data to the remote monitoring station wirelessly, using a high-speed wireless link. This wireless link can easily be constructed using the commercially available wireless platform such as Bluetooth or, Wi-Fi. This additional wireless link will provide more patient freedom of movement in the hospital environment. With this scenario, it is also possible for a health professional to see the data online through the Internet [42]. For the system in Figure 5, the patient would wear the external unit close to the skin and, therefore, in close proximity to the swallowed electronic pill.

Future pill systems should be developed that incorporate the following significant design requirements:

- *Multiaccess communication techniques* should be developed to allow the operation of multiple pill devices, as well as monitoring a group of patients within the same environment.
- *Wireless Power:* For commercial pills, small batteries are used or are being considered to supply the energy to the electronics of the device, taking a considerable amount of space. As a result, a wireless power source, either charging a battery

externally or directly powering from an external wireless source, would be a significant development for the targeted application. Moreover, wireless power can substantially reduce overall the device size and weight.

- *The need of a high frequency link.* Considering the advantages of high-frequency transmission such as small electronic components and high data rate capability, a high-frequency link can provide a number of advantages. Moreover, a wearable receiver operating at high frequency could be easily incorporated in a hospital environment without causing any interference to other existing medical devices since higher-frequency links are in less crowded and rarely used frequency bands.
- *Small size antennas.* One challenge observed in the literature for implanted/injected antenna design is the variation of the antenna resonant frequency due the layers of skin, as well as in-body environment conditions. One approach to tackling this is to design the antenna for broadband matching, of which any shift in the 10 dB return loss bandwidth of the antenna is still within the operating frequency of the radio system.
- *The external unit:* This unit should also be miniaturized so that it can be easily wearable by patients.

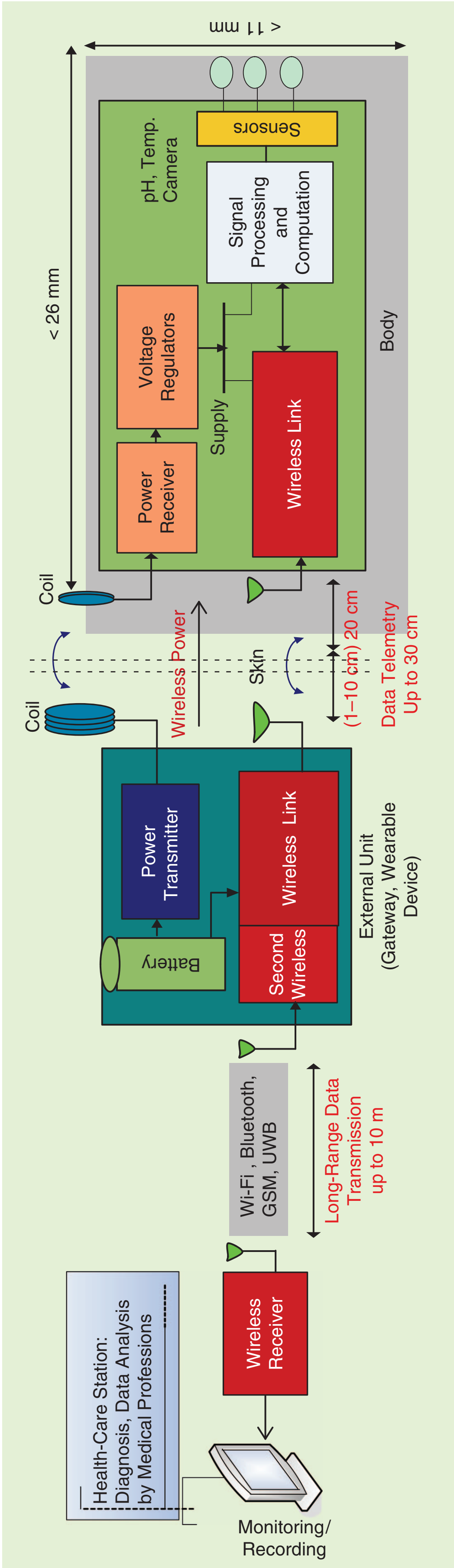


**Figure 5.** *An electronic pill technology with wireless power embedded and wireless gateway for long-range data transmission. The available electronic pill devices have a dimension of 26 mm × 11 mm.*

## Conclusions

This article has reviewed the systems proposed and currently commercialized for electronic pills. The article illustrates some of the challenges and design issues related to the implementation of a video-based pill. Electronic pills must operate and co-exist with other network devices operating in similar frequency bands to ensure an interference-free, reliable wireless link. Although the design of electronic pills has a long history, current designs show the technology is still in its infancy, mainly due to the small size requirement, which prevents designers from including complex design techniques. As the feature size of integrated circuit technology is further reduced and functionality increased, future electronic pills designers will use these new technology and techniques, leading to completely self autonomous micro-robots that will contain sufficient functionality to go to designated areas within the patient. A high-capacity radio system is currently necessary for electronic pill technology in order to visually examine the digestive tract wirelessly with more detailed images. Although it is known that tissue imposes strong attenuation at higher frequencies, it may be necessary to use high frequency technologies, such as UWB, to increase the data rate transmission of electronic pills. Due to the high data rate capacity (e.g., 100 Mb/s), a wideband electronic pill can transmit raw video data without any compression, resulting in low-power transmitters, less of a delay in real-time, and increased picture resolution. With a high definition camera, such as 2 Megapixels, UWB telemetry can send up to 10 frames/s.

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