Ultrasonic Wireless Sensor Network for Human Habitation in Deep Space Mission

Hendra Kesuma, Sallar Ahmadi-Pour,
University of Bremen Germany
hkesuma@uni-bremen.de, sallar@uni-bremen.de

Amber Joseph,
Founder of New Zealand Student's Space Association
josephambe@myvuw.ac.nz

Hans-Jürgen Zimmerman,
Software Engineer at Airbus Defence and Space
hans-juergen.zimmermann@airbus.com

Patrick Weis,
Electrical Engineering and AIT Support of Ariane Group
patrick.weis@ariane.group

Abstract—In this work we show the design and measurement of ultrasonic wireless sensor network in on-earth Columbus Module. The module is a copy of the original module attached on International Space Station (ISS) and it is usually used for testing any new hardware before launching them to the ISS. An analog mixed signal 350 nm technology Application-Specific Integrated Circuit (ASIC) was designed to handle ultrasonic modulation and signal conditioning. The sensor node comprises three pairs of ultrasonic transmitters and receivers. Smart sensors such as humidity/temperature sensor, air pressure sensor and visible/infrared light sensor are utilized to minimize power consumption, computational time and save weight. A low power micro controller ATmega238 is added to interface the smart sensors and ultrasonic ASIC. In order to achieve simple installation procedure for the astronauts, an innovative sensor node casing was designed to allow easy mounting and easy signal directing when attached to the wall. One access point and two sensor nodes were built for testing the signal range on various location in the module. During the test, the ultrasonic signal managed to propagate and received within the entire module. A constant speech signal was added (e.g. human conversation in the background) in order to simulate real mission condition. The power consumption of the sensor node in active/communication mode is less than 60 mW that ensures high durability. The total weight of the sensor node including 400 mAh battery, casing and sensor node holder is less than 50 g.

Keywords —Ultrasonic; Wireless Sensor Network; Space Mission; Human Habitat; International Space Station; analog mixed signal; Smart Sensor; Microcontroller;

I. INTRODUCTION

The development of orbital space settlements has been in vision since 1970s [1]. This endorses the realization of low orbit human settlement on ISS. The ISS has been since November 2008 continuously habituated until now [2]. Private space station developer such as Bigelow Aerospace also took part by successful attaching Bigelow inflatable module to the ISS. It has been tested over couple of years[3]. To push technological development, the ISS partners (ESA, NASA, JAXA, CSA, etc.) decided to develop deep space station to support human outpost around the moon [4]. This might increase the collaboration between commercial companies and state agencies to explore new technologies and to reduce development time. In addition, locating human habitat outside Van Allen belts poses new challenges for human health and space electronics integrity [5]. In order to increase safety, environment monitoring could be realized by deploying wireless network in various locations in the module. Some of the key benefits delivered by network are [6]:

- adaptable for various mission objectives
- scalable and extensible over time
- minimizing crew's maintenance time
- self-organizing

In various occasion, events which endangered ISS crews such as small air leak on August 2018 might be detected and located automatically if wireless sensor network were used effectively [7]. Heat source emitted from the inner wall could be also monitored by infrared light sensor for early warning.

Figure 1 illustrates gateway to the moon that opens up a cost-effective and sustainable path to the Moon [4].

Fig. 1: Deep Space Gateway illustration [4].

Ultrasonic technologies have been used in hydro location, underwater telecommunication, industry and medicine [8]. The human health issue poses by ultrasonic energy can be neglected due to the mismatch between acoustic impedance of air and human skin tissue which prevents penetration of ultrasonic energy in the human body [9].

Ultrasonic wave propagation in the air is selected in this work because of its advantages on Non-Line-of-Sight (NLOS)
signal propagation. This was demonstrated on ultrasonic communication for cordless earpiece application[10].

II. ULTRASONIC SENSOR NODE DESIGN

A. Ultrasonic Transducer Characteristic on Air

The ultrasonic wave is reflected well by solid materials such as metal, wood, concrete, glass, rubber and paper. Some soft material (cloth, cotton, wool, etc.) are disadvantages for wave reflection [11]. The velocity of sound wave propagation can be expressed by 1 [2].

\[ c = 331.5 + 0.607 \times T \]  \( [\text{m/s}] \) \hspace{1cm} (1)

Some measurement results of sound wave attenuation which depends on frequency is described in figure 2 [13]. The attenuation of sound wave in air can be approximated by 2 [14].

\[ A_{\text{air}} = 1.64 \times f^2 \times d \times 10^{-10} \]  \( [\text{dB}] \) \hspace{1cm} (2)

Where \( f \) is sound wave frequency and \( d \) is sound wave propagation distance. The 40 kHz frequency is selected for designing the ultrasonic transceiver due to its low attenuation which below -40 dB at 5 meters.

Fig. 2: Attenuation Characteristic of Sound Pressure by Distance at 20°C [13].

An open structure type of ultrasonic transducer is selected with its internal structure shown in figure 3 [13]. This type of ultrasonic transducer is preferable for its light weight (0.7 gr) plastic casing and its high sensitivity. Its diameter is less than 9 mm and it uses thin film piezoelectric ceramic material for optimal energy consumption.

The radiation characteristic of the receiver as shown in figure 4 was measured by placing a transmitter 30 cm from the receiver. The manufacture's calibration setup was by providing reference pressure of 20 \( \mu \text{Pa} \) at 0° for 0 dB attenuation. The characteristic show that at 60°, the attenuation is less than -20 dB which increases receiver coverage area at that angle.

Fig. 3: Construction of open structure type ultrasonic sensor [13].

Fig. 4: Receiver Radiation Characteristics [13].

In all cases, radiation characteristics were measured at 20°C and were performed in a non-echo chamber by the manufacture [13].
B. Sensor Node Mechanical Design

The sensor node was designed for simple installation in the space station. A vacuum holder was mounted below the casing to keep the sensor node sticks on the space-craft wall. All of the ultrasonic transducers are tilted 60° up-ward to optimized coverage area. Figure 6 shows sensor node mechanical design and its dimension.

![Ultrasonic Sensor Node Design Overview](image)

Fig. 6: Ultrasonic Sensor Node Design Overview.

The ultrasonic transducers in figure 7 are distributed with 120° angle from each other on the sensor node PCBs. This help better positioning by the crews during installation.

![Ultrasonic transmitter and receiver direction and wiring](image)

Fig. 7: Ultrasonic transmitter and receiver direction and wiring.

C. Sensor Node Circuit Design

A 3.7 V 400mAh lithium battery is used to power the sensor node. The Lithium battery is selected because it is light weight and it has higher energy density per weight. This has been demonstrated on numbers of planetary exploration spacecraft [15]. The voltage of the battery is stepped-up to 5V to drive the ultrasonic transmitters. A 3.3V voltage regulator is added to power the microcontroller, the smart sensors and the ultrasonic signal conditioning ASIC.

The ASIC requires 3.3V and it is designed for ultrasonic signal amplification and filtering. It also generates OOK signal for the ultrasonic transmitter driver. Figure 8 shows the building block of the ultrasonic sensor node. The smart sensor technologies are used to save weight and minimize sensor node size. Three types of smart sensor are selected and their characteristics are described as following.

The first is the SHT11 air humidity sensor which is intended for water leakage monitoring in space module. The sensor can measure humidity with ± 3% accuracy and it consumes only 3.3 mW in active mode. The sensor also has temperature sensor inside it. This is important for compensating humidity calculation data before read by the microcontroller [16].

The second is TSL 2561 and it is crucial for future space food cultivation. It measures visible light intensity as well as infrared light and suitable for light intensity control system. The infrared light sensing capability is also essential to detect inner wall heat source which can activate alarm system. The sensor maximum measurement range is 40,000 Lux and it requires only 2 mW to operate [17].

And the third is the MS5534A air pressure sensor. Air leakage detection is extremely important for detecting air pressure difference down to 0.1 mBar. The sensor has measurement range of 10 to 1100 mBar [18]. It has the lowest power consumption compare to all other sensors (165 µW).

In the next section, the measurement of ultrasonic signal and signal coverage in Columbus module will be presented.

III. ULTRASONIC SENSOR NETWORK MEASUREMENT

A. Sensor Node Signal Measurement

The on-off keying (OOK) modulation is selected because it is more power efficient and it has better accuracy than amplitude-shift-keying (ASK) modulation [19]. Figure 9 shows the transmitter's OOK signal shape. The signal on TX has period of 25µs with 5V amplitude.

At pre-amplifier output, the RX1 signal on figure 10 shows that the input signal of 450µV has been amplified 344 times. This signal can then be measured by oscilloscope and the...
signal voltage is 150 mV. This measurement was performed by locating the transmitter NLOS 4 meters from the receiver.

The OOK signal for bit '1' is constructed by sending an array of 20 OOK pulse groups separated by 0.980 ms interval. Each OOK group consist of ten 25µs pulses for energy saving. The total length of the array is 20 ms and is intended to reduce bit error. The output signal of RX1 shows that the polarity of the OOK signals are not uniformly distributed. This error might be caused by background voice or circuit noise. A deeper investigation of this issue will be presented in future work. During the transmission, the current consumption is less than 20 mA at 3.7V.

The distance $d_2$ is about 4 meters and the sensor node is located at $pos\ 2$. This is the maximum distance for testing signal coverage in Columbus. Lastly $d_3$ is about 2.7 m and sensor node 1 occupies $pos\ 3$.

The OOK was proved to have relatively minimum bit error at 5 m distance [20]. One of the advantages of OOK over FSK is its circuit simplicity and it allows the transmitter to be idle during transmission of bit '0' [21].

In order to achieve realistic measurement results, on-earth Columbus module is selected. This module is a copy of the real Columbus at the ISS. A test plan is required and is shown in figure 11 for later positioning of the access point and sensor nodes in the module.

$Pos\ 1$ is intended for testing the NLOS communication by expecting the TX signal to be reflected by the front, top and bottom walls. The distance $d_1$ between the transmitter and receiver at $pos\ 1$ is about 3 meters.

A. Sensor Node Signal Measurement

Figure 12 shows access point and two sensor nodes which were built to conduct the experiment. Each of the sensor node and access point is equipped with LEDs as signal received indicator.

Fig. 9: OOK signal measurement on TX pin.

Fig. 10: OOK signal at signal measurement on RX1 pre-amplifier output.

Fig. 11: Ultrasonic signal coverage measurement plan.

Fig. 12: Access point and sensor nodes preparation.
In the Columbus module, the access point and sensor nodes were mounted on the walls as depicted in figure 13. The room temperature was around 22°C with air humidity 55% to 70%.

The measurement setup for pos 2 is shown in figure 16. The results with \(d_2\) (4 meters) delivers minimum delay of 12.24 ms (sound distance ca. 4.22 meters) as shown in figure 17.

Although the LOS setup as shown in figure 18 is supposed to have less delay, but placing sensor node 1 on plant habitat that faces access point still deliver minimum delay of 12.03 ms (equivalent to 4.14 meters sound distance). This long delay shall be caused by the signal path reflected through the ceiling and floor.

In order to get an objective measurement result, the raw signals measured from RX outputs were not interpolated by the ultrasonic signal conditioning circuit. This makes it visible.
for calculating missing OOK pulses. Hence, the loss of OOK pulses is calculated less than 50% and therefore is sufficient for the signal conditioning unit to recover them. This configuration provides transmission rate of 50 bit/second.

The design and test of the ultrasonic wireless sensor network for future human habitat have been successfully performed on on-earth Columbus module. In next section, the summary of the work will be concluded.

CONCLUSION
The idea of implementing low power ultrasonic wireless sensor network has been realized on on-earth Columbus module. The results are summarized below:

- **The design offers optimal signal coverage**
  The measurement by distributing the sensor nodes in various locations in the module shows that all of the sensor nodes managed to receive the ultrasonic signal at least in one of their receivers with presence of background voice.

- **The mechanical design provides optimal mounting mechanism**
  In order to reduce crew's maintenance time, an innovative vacuum holder on rotatable sensor node casing was constructed. It took less than one minute to mount and to activate the sensor node including directing the receiver for optimal signal capturing.

- **The design offers low power, small size and less weight**
  The sensor node weights only less than 50 g with power consumption of less than 60 mW in transmission mode.

Further work to display sensor measurement data on smart phones and sensor anomaly data detection with Artificial Intelligence is required to increase safety and crew's awareness during the mission.

References