Temperature Sensing and Data Transmission Mechanism for High Temperature Applications

Kuruparan Shanmugalingam*, Dulanjana Liyanagama†, Rubisha Rubanathan‡ and Subramaniam Thayaparan§
Department of Electronics and Telecommunication Engineering, University of Moratuwa
Colombo, SriLanka
Email: *kuruparan4@gmail.com, †140346D@uom.lk, ‡140534D@uom.lk, §thayapran.ent.mrt.ac.lk

***Abstract*—Most of the electronic devices do not perform well in high temperature.In wafer fabrication, data propagation through thick metallic chamber walls need more transmitting power for successful data transmission. Measuring and transmitting temperature in closed metallic high temperature environment is a challenging issue. In this paper, a scheme to sense, process and transmit the data through fully closed and thick Aluminum chamber is proposed. The system is capable of sensing high temperature while handling for power fluctuations. Temperature is measured using tiny RTD resistors placed in different 7 locations up to 350 degree Celsius. The data is transmitted as radio-waves using ASK and FSK modulation techniques at the rate of 1 kbps. Processed demodulated data at the receiver-end provides the power supply voltage level, RTD locations ID, and the temperature in different locations of the IC inside the chamber real-time. Re-transmission technique is proposed to reduce the propagation loss. It ensures possibility of the the transmitter to work in low power environment. Experimental results show the effectiveness of the proposed system to over come the limitations of measuring and transmitting real-time data.**

***Index Terms*—ASK, Envelope detector, Frequency counter, FSK, High temperature, Re-transmitter, RF-transmission, Ring oscillator, RTD sensor, Wireless communication**

I. Introduction

There are number of communication technologies to transmit data in between far points. Optical fiber, wired coaxial and wireless wave propagation technologies are used in several scenarios based on its suitability. In this research, the environment which is fully closed by metal chamber with higher temperature is considered for analysis. Several applications need wireless communication for fully closed metal chambers such as space exploration, industry automation and controlling and Silicon (Si) wafer fabrication etc.

In wireless communication electromagnetic rays propagate through air influenced by line of sight (LOS), absorption, diffraction, refraction [1]. When it comes to metals, skin depth of the metal attenuates the signal power which leads to unavailability of data. Therefore, high power amplification is necessary in the transmitting. When a closed metallic chamber is thick, the mechanism of the wireless communication to receive data outside to a computer system for real time analysis is still a challenging issue. In Integrated Circuits (IC) fabrication process, expensive wafers are treated in high temperature inside the metallic chambers. There are money loss due to temperature variations because of the imperfections occurred in wafers. It emphasizes the need fr developing a solution for sensing higher temperature variation inside the metallic chamber

In this paper a method to retrieve the data from outside to fully closed and thick metallic chamber is proposed and analyzed with various parameters. The design of a transmitter, a receiver and a re-transmitter is considered in this paper. The transmitter generates electromagnetic waves using low power Voltage Controlled Oscillator (VCO) [2], [3], inside the metallic chamber. The receiver which is kept outside the metallic chamber receives and processes the data from the body of the metal chamber. It is capable of sensing data for the fluctuation of the VCOs frequency [4], [5]. Finally, the re-transmitter again transmits the received data for 80 m range. While solving the harsh environment issues temperature variation play a major role.

II. Literature Review

Devices made by Silicon Carbide(SiC) have been demonstrated operating at more than 600°C [6]. A two-day repeatability test was performed up to 500°C on 4H-SiC ring oscillators and the oscillator fundamental frequency changed by only 1 percentage [7]. A SiC wireless transmitter processes the pressure signal from the sensor head, applies it to modulate a RF carrier and transmits it wirelessly to the receiver [8]. From higher temperature testing, the pressure signal was successfully recovered from the receiver side from 250°C to 450°C. The literature review fully characterizes the SiC Junction gate Field-Effect Transistor (JFET) [9], N-type Metal Oxide Semiconductor (NMOS) [6] technologies in harsh environment mentioning the variation of the frequencies with temperature sweep.

High temperature RF wireless pressure sensing system was designed by *Jie Yang*. In his paper [8], a 450°C capable RF wireless pressure sensing system was designed and developed based around the commercial Kulite XTEH-10L-190 pressure sensor head. The core of this system is a SiC wireless transmitter, which processes the pressure signal from the sensor head, applied it to modulate a RF carrier and transmits it wirelessly to the receiver. From high temperature testing, the pressure signal was successfully recovered from the receiver side from 250°C to 450°C.

Ruchi Gupta researched on high temperature MEMS (Micro Electrical Mechanical System) based transmitter for wireless sensor and communication network. In his research paper [14] temperature characteristics of diodes are experimentally proved. He mentioned that Silicon-tunnel-diode based-oscillator transmitter with an on board optical power converter is attractive for stand alone, low power high temperature MEMS sensing and data telemetry application. The prototype wireless sensing and communication module achieves high temperature operations up to 250°C over a telemetry distance of 1.5 meters with a transmitter power consumption of 60W. His architecture involves tunnel diode, photo diodes for wireless transmitting.

Suster, Young, and Wen Ko proposed an architecture that can also serve as a low-power telemetry platform for general sensing and wireless communication applications. The prototype wireless sensing and communication module in his paper Micro-Power Wireless Transmitter for High-Temperature MEMS Sensing and Communication Applications achieves high-temperature operations up to 290°C over a telemetry distance of 2.5 meters with a total power consumption of 110W [15]. The low supply voltage and power dissipation make it feasible to potentially operate the system using thermo electric generator, converting temperature gradients available from a high-temperature environment to DC power, or RF inductively powering techniques, thus enabling the realization of a stand-alone high-temperature wireless sensor communication module.

Brown in his book Silicon Carbide metal oxide semiconductor field effect transistor (MOSFET) Integrated Circuit Technology [16] compared the operating properties including band gap, thermal conductivity, saturated electron drift velocity, electron mobility, hole mobility, breakdown electric field and dielectric constant of SiC, Si and Gallium Arsenide (GaAs). He provided the graphs for SiC properties with the change of temperature up to 400°C. 1MHz ring oscillator with simple temperature compensation circuit dedicated to MEMS sensor application was developed and tested [17]. The circuit is realized using 0.35m CMOS technology at a 5V supply. The frequency variation of the compensated oscillator over the temperature range of -40°C to +90°C is -0.1 percentage to +0.19 percentage. For worst case process, the frequency deviates from -1.5 percentage to +1.9 percentage for the stated temperature span and it deviates from -1.2 percentage to +1.2 percentage at 10percentage supply variation under 1 MHz oscillation frequency. Electrical characterization up to 573K is performed on integrated inverters with different ratios and 17-stage ring oscillators based on SiC NMOS technology [6]. The 17-stage ring oscillators, driven by a 5.5 V power supply, show an oscillator frequency of 625 kHz at 303K, which corresponds to a 47ns delay per inverter stage. This time constant increases only to 59 ns at 573K.

The research on developing the robust receiver for frequency variations of ring oscillator by the supply power variation and temperature variation can be used in harsh environment as well. Frequency of 11 stage ring oscillator varies from 881.5 kHz to 234.2 kHz while increasing the temperature 25°C to 500°C [1]. 8-bit data receiving up to 400bps is checked for different frequencies. This research analyses the chambers behavior on handling the frequency attenuation of the signal using different stages of ring oscillators.

Section III of this paper elaborates the the circuits used in this proposed method.The section IV illustrates about the heating experiment. The section V of this paper includes the results from experimental data and discussion. Final section VI contains the conclusion from the results.

III. Circuits and System

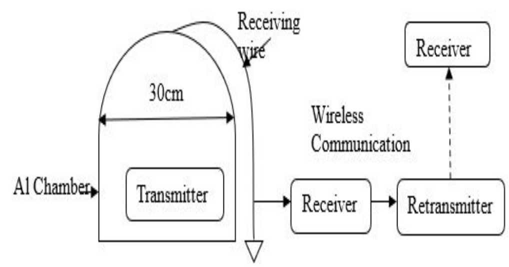

Fig. 1. Overall architecture

This section illustrates the proposed method to retrieve the data outside to the fully closed thick metallic chamber. Fig. 1 shows the overall picture of the proposed Architecture.

A. Fully Closed thick Metallic Chamber

The transmitter is kept inside the fully closed thick Al chamber which is hardly possible for the wireless communication. The Al chamber has diameter of 25 cm, thickness of 2 cm and has a spherical shape in the middle. Top and bottom parts are flat and covered.

B. Resistance temperature detectors

Resistance temperature detector (RTD) element technologies are constantly enhancing the quality of the temperature measurement. RTDs are the most accurate, linear and stable temperature sensing element over time [18] and temperature. Typically, a data acquisition system uses RTD sensors for high temperature applications.

$$RTD_T = RTD_0 * (1 + \alpha * T) \tag{1}$$

here RTD_T, RTD_0, T denotes the RTD elements resistance at T, the RTD elements resistance at 0°C, the RTD elements temperature (°C) respectively and the temperature constant α = 0.00385 $°C^{-1}$ (European curve, ITS-90). An approximation to the platinum RTD resistance change over temperature can be estimated by using the temperature constant mentioned in the equation (1), that can be simply used to calculate the absolute resistance of the RTD at temperatures between -100°C and +200°C (with a nominal error smaller than 3.1°C).

If a higher accuracy temperature measurement is required, or a greater temperature range is measured, the standard formula below (Calendar-Van Dusen Equation) can be used as mentioned in equation (2) in a calculation in the controller engine of PT100 RTD sensor or be used to generate a look-up table [19].

$$RTD_T = RTD_0 * (1 + A * T + B * T^2 + C * T^3 * (T - 100)) \quad (2)$$

here RTD_T, RTD_0, T denotes the RTD elements resistance at T, the RTD elements resistance at 0°C, the RTD elements temperature (°C) respectively and A, B, C are constants derived from resistance measurements at multiple temperatures. RTD_0= 100Ω ,A = 3.9083 10^{-3} °c^{-1}, B = -5.775 10^{-7} °c^{-2}, C = -4.183 10^{-12} °c^{-4} for T <0°C and 0 for T>0°C according to the ITS-90 standard values.

C. Transmitter

The transmitter which is kept inside the Aluminium (Al) chamber transmits data at a low data rate to the receiver which is kept outside to the chamber. Basic architecture of the transmitter is shown in Fig. 2. The VCO in transmitter generates frequency which can be transmitted through the copper coil. Hex inverter IC -SN74LS04N is used to develop the

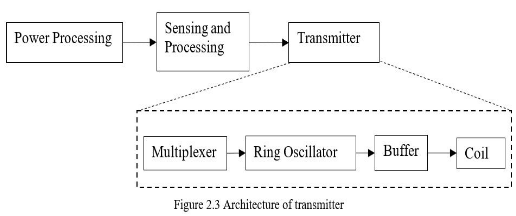

Fig. 2. Transimitter

voltage controlled oscillator. Output frequency is controlled by number of inverters and input power supply to the IC. Voltage controlled oscillator output connects to the copper coil and it induces the voltage in the Al chamber wall. Buffer is used in between ring oscillator circuit and coil to reduce probing effect. Induced voltage is detected by the receiving part which is kept outside to the chamber.

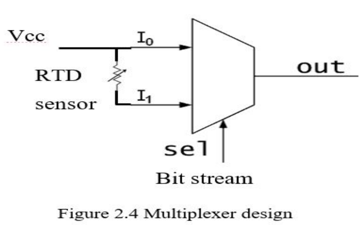

Fig. 3. RTD connected multiplexer

Resistance temperature detectors (RTD) resistors are placed in different locations to measure the temperature values. RTD resistors's resistance is mapped with temperature for analysis.

The 8 channel analog multiplexer IC, CD4052B is used as multiplexer. The bit stream is given as On-Off keying in the selection pin of the multiplexer. The two inputs given to the multiplexer are the direct voltage and the voltage through the

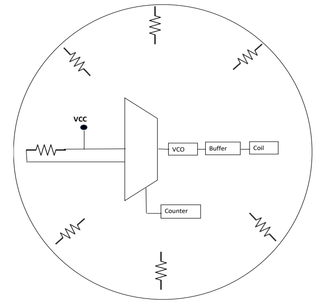

Fig. 4. Transmitter placement

resistance temperature detector (RTD) sensor. The difference of the two voltages gives different output voltages based on the selection bit. Since the RTD sensor changes its resistance based on the temperature, for different temperature values the multiplexer outputs different voltages.

D. Receiver

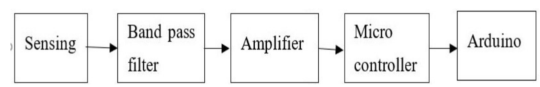

Fig. 5. Receiver architecture

The receiver depicted in Fig. 5 should be kept outside to the fully closed metallic chamber. It is designed and coded to detect the bits.

Since the 50Hz AC noise is a main interference for measurements, a high pass filter with an approximate cut off frequency 160Hz is used.

Since, the voltage induced on the outside of the Al chamber is very small, the signal needs to be amplified with more gain. TL072CN is selected as the most suitable operational amplifier. The receiver is tested with a mechanism to detect the transmitted binary bits. There are high and low levels needed to differentiated by a margin of detection. Envelope detector is utilized to detect the voltage levels of binary bits.

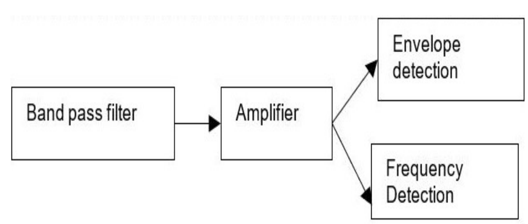

Fig. 6. Receiver workFlow

Micro controller is used for frequency counting and amplitude detection. Teensy 3.2 [20] is a micro controller that counts 10 HZ to 65000 KHz frequency range. After frequency counting ,received signal is sent through envelope detector. GPIO analog pin is fed with the processed signal for identifying the digital envelopes (1,0) . Availability of Frequency is taken as 1 and no frequency is taken as 0 by the frequency Counter for the sequence of received signal. Both GPIO input and Frequency Counting Input is processed to identify the RTD ID.

Teensy and Arduino embedded with ESP8266 module are communicated by serial communication to transfer between each other.

E. Modulation Schemes

Different modulation schemes can be used for transmitting signals for long distance in a specific frequency ranges. Typically these techniques can be categorized as analog modulation and digital modulation based on the input signal type. Amplitudes, frequencies, phases of signals are changed with the variations of input signal's symbols; leads to amplitude modulation (AM), frequency modulation (FM), Phase modulation(PM).

1) Amplitude Shift Keying: Amplitude Shift Keying (ASK) represents the digital data by varying the amplitude of the carrier signal. It is a form of AM, in this paper on-off shift keying is used a a simpler form of ASK. When data represents 1 signal is transmitted with full amplitude. When the data represents 0, signal amplitude is set to null.

2) Frequency Shift Keying: Frequency Shift Keying is a form of FM where carrier signal's frequency is changed according to the input signal. In this paper , voltage drops by RTDs creates different frequencies that can be mapped with a lookup table to estimate the temperature of the RTD. Even though input signal is varying continuously because of the temperature variation and the modulation scheme looks like analogue FM, the idea of the imputing data into frequency is inferred from the concept FSK.

F. Retransmitter

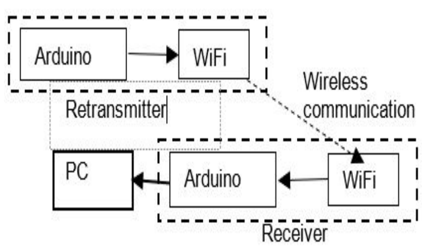

Fig. 7. Retransmitter architecture

The received data need to be transmitted to another location for real time analysis. The detected signal in envelope detector is sent to Arduino Nano and then transmitted to another location by WIFI module. At the end point another WIFI module receives the signal. Through Arduino Nano the PC detects the data as binary bits and use those data for further analysis. The overall architecture of the re-transmission and receiving is presented in Fig. 7.

IV. Heating Environment

Heating experiment was done for the circuits in a closed environment. Engine Oil with High vaporizing point is heated. RTD Resistors are kept directly inside the oil. Multiplexer and VCO are coated with temperature high gradient materials and Teflon tapes. Heating experiment was done for 40 minutes while changing different voltage levels of power supply for differed stages of inverters while ensuring the steady temperature inside the oil.

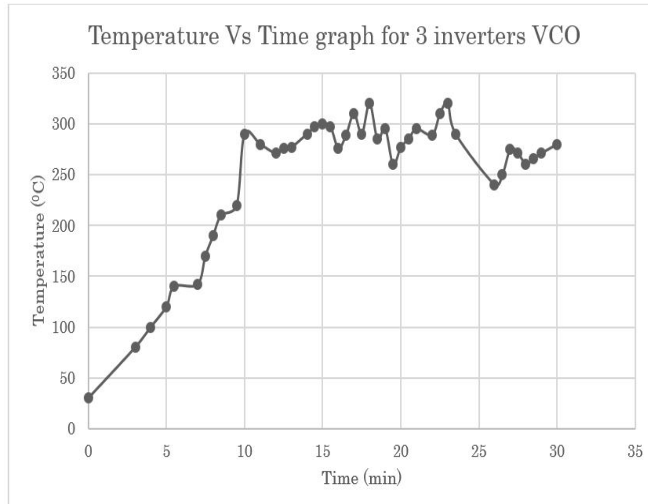

Fig. 8. Temperature with time

V. Results And Discussion

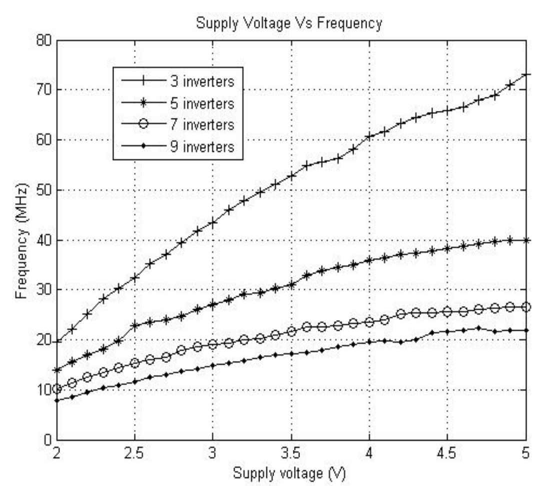

Fig. 9. Frequency with temperature and different inverters

The transmitter circuit (i.e. ring oscillator) is checked for different supply voltages and different number of inverters at room temperature. This experiment was done to find out the min number of transistors needed for designing transmitter because of the temperature dependency of transistor characteristics. Tested results are shown in Fig. 9. From the graph on Fig. 9 it can is proven that, with the increase of supply voltage the frequency of the ring oscillator increases. It also shows that when the number of inverters are increased, the frequency decreases for a specified range of supply voltage. It can be concluded that the required number of inverters and the required frequency for the transmitter circuit can be selected based on the bandwidth of the data signal. Frequency increases with number of inverters used in the VCO due to the delay created in the circuits.

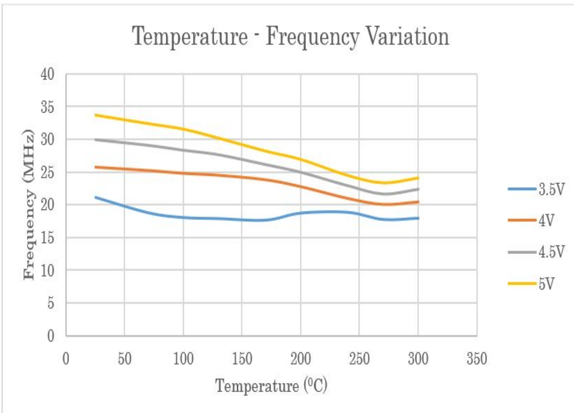

Fig. 10. Frequency with temperature

In Fig. 10, 5 stage inverter VCO is heated and the frequency of the VCO for different supply voltage are modelled to identify the operational range of the frequency. when supply is given between 3.5 to 5 v, VCO exhibits 17 MHz to 35 MHz frequency for the temperature variation upto 300. Frequency decreases with increasing temperature.

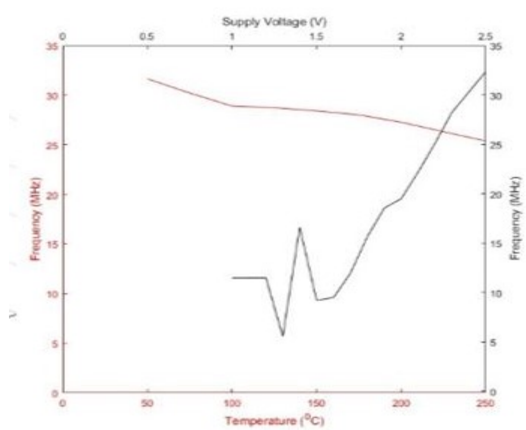

Fig. 11. Frequency variation with temperature and supply 2D

Fig. 10 and Fig. 12 compares the effect of supply voltage and the temperature on frequency. It is clearly proven that for the given 5 stage VCO, frequency decreases with drop of supply voltage comparatively larger percentage than the temperature effect.

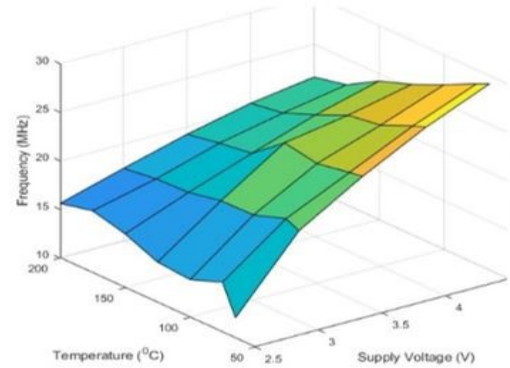

Fig. 12. Frequency variation with temperature and supply 3D

10

From the heating experiment up to 300°C, it is observed that the frequency varies by 5 MHz. Supply voltage is changed from 2.5 V to 1.5 V by 0.5 V interval reduction at each time. It reduced the frequency by nearly 12 MHz for each interval.

We are solving the effect of voltage fluctuations and the temperature variations in the circuit. One input of the multiplexer is fed by the supply voltage of the VCO. By the frequency generated from the this voltage we identify the voltage level of the supply. Similarly multiplexer is fed by the voltages, that are the calculated as the reduction of RTD resistor voltage drop from supply voltage. The frequency generated from these voltage is also read by the receiver. Finally we compare the difference between periods of signals generated by these two voltages and map it to temperature. Fig. 13 shows the difference between periods of transmitted frequency and the mapped to the temperature as a range for different supply voltages.

Supply Vol	5.52v		5v		4.51v		4v	
	Delay							
Temperatu	Ranges (ns)		Ranges (ns)		Ranges (ns)		Ranges (ns)	
46	52.6	52.2	53.6	53.2	54.3	54.8	55.6	55
47	52.72786	52.32622	53.71967	53.33514	54.43533	54.93514	55.74935	55.9391
48	52.85535	52.45215	53.83936	53.46999	54.57046	55.06999	55.89837	56.0782
49	52.98248	52.57778	53.95907	53.60455	54.70538	55.20455	56.04704	56.2172
50	53.10924	52.70312	54.07879	53.73881	54.84011	55.33881	56.19539	56.3562
51	53.23563	52.82817	54.19852	53.87277	54.97463	55.47277	56.3434	56.4951
52	53.36167	52.95293	54.31828	54.00645	55.10896	55.60645	56.49107	56.6339
53	53.48734	53.07741	54.43805	54.13983	55.24309	55.73983	56.63842	56.7727
54	53.61264	53.20159	54.55783	54.27292	55.37702	55.87292	56.78543	56.9114

Fig. 13. Frequency difference mapped with temperature

In Fig. 14 the Envelope detector outcome is shown in blue color for the transmitted data in yellow color.

Figure. 15 shows the final temperature from 7 different locations, imparted in the sequence of signal with their corresponding location IDs. It depicts the output signal directly

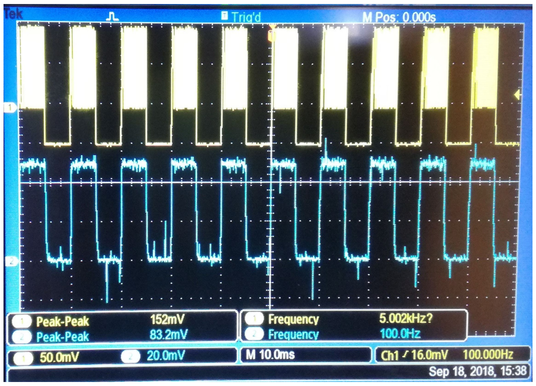

Fig. 14. Envelope detection

from the transmitter in blue color. The induced signal from the aluminum chamber followed by the band pass filter and the amplifier is denoted by yellow signal. Still there small glitches and noise are observable even after filtering. These noise are induced by the chamber from the environment. But micro controller can distinguish the noise and the data by the threshold values.

Fig. 15. Transmitted bits and the received signal

VI. Conclusion

In this paper, the mechanism of retrieving the data out of the closed metallic chamber using wireless communication techniques is discussed. The result is concluded from various frequencies and power levels using 3, 5 and 7 stage ring oscillators. Receiver sense the data through wire and processes the received data in a micro controller to re transmit to another location through WIFI. It is deduced that frequencies in range of 17MHz to 35 MHz can be sensed with 1 Hz accuracy and 0.1 percentage of input peak voltage from the body. When supply voltage reduces, the frequency of ring oscillator decreases non-linearly. By analyzing the graphs, VCO with low number of transistors for preferred frequencies can be chosen from different stage ring resonators. 5 stage ring oscillator with 2.5 to 5 V voltage supply is used to generate frequency, tested that 60mV to 200 mV can be measured from body directly, 2 V while amplifying. The period difference between transmitted frequencies are mapped to temperature. Frequencies are directly mapped to the voltage level to predict the supply voltage and temperature. Counter is used create a sequence ASK pattern to impart the position ID of each RTD resistors. Re-transmission technique after sensing the voltage from the body of the chamber reduces required the supply power level transmitter. Temperature information and supply voltage information are embedded inside the frequency. RTD locations are imparted in the ASK sequences. The data will be used for further research experiments of high temperature data retrieving out of the chamber.

Acknowledgement

We thank Swissranks (Pvt) Ltd for funding the project and arranging testing environments. This project was developed as a co-solution of the product led by Swissranks (Pvt) Ltd, 9 Tagore Lane 01-15, Singapore 787472.

References

[1] Tse, David, and Pramod Viswanath. Fundamentals of wireless communication. Cambridge university press, 2005.

[2] Michal, Vratislav. "On the low-power design, stability improvement and frequency estimation of the CMOS ring oscillator." In Radioelektronika (RADIOELEKTRONIKA), 2012 22nd International Conference, pp. 1-4. IEEE, 2012.

[3] Eken, Yalcin Alper, and John P. Uyemura. "A 5.9-GHz voltage-controlled ring oscillator in 0.18-/spl mu/m CMOS." IEEE Journal of Solid-State Circuits 39, no. 1 (2004): 230-233.

[4] Docking, Stephen, and Manoj Sachdev. "A method to derive an equation for the oscillation frequency of a ring oscillator." IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications 50, no. 2 (2003): 259-264.

[5]] Macken, Peter, Marc Degrauwe, Mark Van Paemel, and Henri Oguey. "A voltage reduction technique for digital systems." In Solid-State Circuits Conference, 1990. Digest of Technical Papers. 37th ISSCC., 1990 IEEE International, pp. 238-239. IEEE, 1990.

[6] Schmid, Ulrich, Scott T. Sheppard, and Wolfgang Wondrak. "High temperature performance of NMOS integrated inverters and ring oscillators in 6H-SiC." IEEE Transactions on Electron Devices 47, no. 4 (2000): 687-691.

[7] Scardelletti, Maximilian C., Philip G. Neudeck, David J. Spry, Roger D. Meredith, Jennifer L. Jordan, Norman F. Prokop, Michael J. Krasowski, Glenn M. Beheim, and Gary W. Hunter. "Novel High Temperature Capacitive Pressure Sensor Utilizing SiC Integrated Circuit Twin Ring Oscillators." In Electronic Components and Technology Conference (ECTC), 2017 IEEE 67th, pp. 197-205. IEEE, 2017.

[8] Yang, Jie. "A high temperature RF wireless pressure sensing system." In Wireless for Space and Extreme Environments (WiSEE), 2014 IEEE International Conference on, pp. 1-6. IEEE, 2014.

[9] Yang, Jie, John Fraley, Bryon Western, Marcelo Schupbach, and Alexander B. Lostetter. "Characterization of SiC JFETs and its Application in Extreme Temperature (over 450 C) Circuit Design." In Materials Science Forum, vol. 645, pp. 949-952. Trans Tech Publications, 2010.

[10] J. J. L. U. Robert F. Cleveland, "Questions and Answers about Biological Effects and Potential Hazards of Radiofrequency Electromagnetic Fields," Office of Engineering and Technology Federal Communications Commission, Washington, D.C. 20554, August 1999.

[11] Pletcher, Nathan Michael, and Jan M. Rabaey. Ultra-low Power Wake-up Receivers for Wireless Snesor Networks. University of California, Berkeley, 2008.

[12] Kucukkomurler, Ahmet. "Thermoelectric powered high temperature wireless sensing and telemetry." In Industrial Electronics and Applications, 2009. ICIEA 2009. 4th IEEE Conference on, pp. 1080-1086. IEEE, 2009.

[13] Chang, Chun-hsiang, Li Xu, and Marvin Onabajo. "A low-power RF receiver front-end chip designed with methods to reduce third-order intermodulation distortion." In Circuits and Systems Conference (DCAS), 2016 IEEE Dallas, pp. 1-4. IEEE, 2016.

[14] Gupta, Ruchi. ”High Temperature MEMS Based Transmitter for Wireless Sensor and Communication Network.”

[15] Suster, Michael, Darrin J. Young, and Wen H. Ko. ”Micro-power wireless transmitter for high-temperature MEMS sensing and communication applications.” In Micro Electro Mechanical Systems, 2002. The Fifteenth IEEE International Conference on, pp. 641-644. IEEE, 2002.

[16] Brown, D. M., E. Downey, M. Ghezzo, J. Kretchmer, V. Krishnamurthy, W. Hennessy, and G. Michon. ”Silicon carbide MOSFET integrated circuit technology.” physica status solidi (a) 162, no. 1 (1997): 459-479.

[17] Wang, Yanmei, Pak Kwong Chan, and King Ho Li. ”A compact cmos ring oscillator with temperature and supply compensation for sensor applications.” In VLSI (ISVLSI), 2014 IEEE Computer Society Annual Symposium on, pp. 267-272. IEEE, 2014.

[18] Hyde, Darrell. ”Evaluating Thin Film RTD Stability.” Sensors-the Journal of Applied Sensing Technology 14, no. 10 (1997): 79-81.

[19] Baker, Bonnie. ”Precision temperature sensing with RTD circuits.” AN687, Microchip Technology Inc (1998).

[20] TRKDOAN, SUNAY. ”Design and Implementation of a Cost Effective Quartz Crystal Microbalance System for Monitoring Small Changes on any Surface.” Balkan Journal of Electrical and Computer Engineering 7, no. 3 (2019): 213-217.