Wireless Telemetry System for Long-term Real-time Subsurface Monitoring

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***Abstract*— Carbon capture and storage (CCS) is an effective technique to mitigate the global climate change by storing the CO_2 underground permanently. Therefore, the techniques to monitoring the CO_2 sequestration status and the potential leakage are crucial. In this paper, a novel real-time underground monitoring and wireless communication system has been developed. The system will include an array of toroidal transceivers winding around the highly conductive casing string for wireless data transfer between surface and deep subsurface, and energized casing technique is utilized to charge the toroidal transceivers and subsurface sensors. This novel wireless telemetry system will help to maintain well integrity and reduce potential leakage by eliminating the needs for perforated casing or an umbilical in the cement annulus since no direct path of fluid leakage is induced by this wireless system. The wireless signal and energy transfer rate are both enhanced significantly by the metal casing amplification. The available bandwidth and the corresponded channel capacity are calculated based on numerical simulation.**

I. Introduction

Fossil fuels, including coal, petroleum, and natural gas, have been playing, and will continue to play a dominant role to power the global and US economy. The overwhelming majority of energy consumed in our modern society comes from the burning of these fossil fuels which provides us with electricity, heat, and power for manufacturing and transportation [1]. However, carbon dioxide (CO_2) generated by fossil fuel combustion can have serious consequences for humans and the environments. In 2016, global CO_2 emission from fuel combustion is 32.3 Gt CO_2 (gigatons of equivalent carbon dioxide). This large amount of greenhouse gas emissions is increasingly recognized as the most dangerous environmental challenge posed by human activity. Therefore, the technology advances are desperately needed to reduce the carbon dioxide emissions from fossil fuel usage

Carbon capture and storage (CCS) is a key technological approach to slow down the CO_2 accumulation in atmosphere. The sequestrated CO_2 needs to be safely stored in the underground geological structure for at least thousands of years. The leaked CO_2 will affect the environment, and endanger human lives. Therefore, measuring and detection of CO_2 leaks at sequestration sites are extremely important. Currently, the deep subsurface monitoring data are sent to surface via an umbilical placed either inside or outside of the well casing. The method requires perforation on the casing and will impair well integrity; the umbilical running up the outside of the casing in the cement annulus can potentially be a pathway to CO_2 leakage [2].

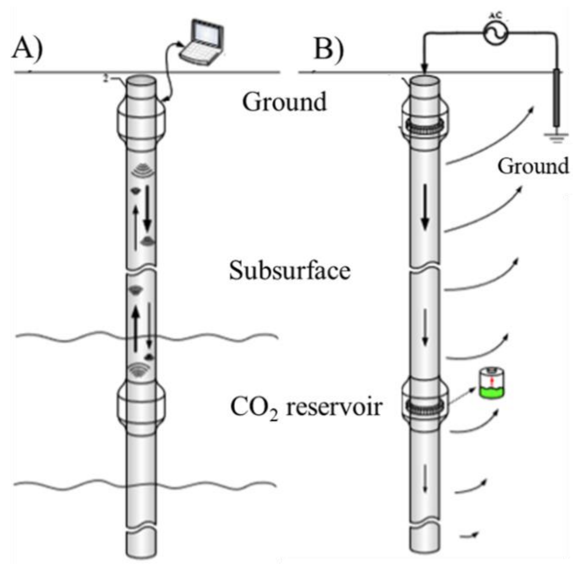

Fig. 1. (A) Schematics of wireless data transfer using toroidal antennas, and (B) wireless power transfer from surface to subsurface.

In this paper, we will develop a reliable and cost-effective wireless telemetry system to send the real-time monitoring information of CO_2 sequestration to surface. The system will deploy at least two toroidal transceivers, and might be an array of toroidal transceivers winding around the steel casing string for wireless data transfer if the well is too deep, and utilize energized casing to charge the toroidal transceivers and subsurface sensors at the surface due to the monitoring should last hundreds of years. The concept of transferring data through this system has been discussed for underground communication. The schematic drawing of geometry model of telemetry communication from subsurface to surface has shown in Fig. 1A, and the charging schematic figure from surface to subsurface is in Fig. 1B. In this paper, we have performed numerical calculation of the "uplink" data transfer with COMSOL Multiphysics.

This paper is structured as follows. Section II provides numerical analysis of the system, and the best coil configuration is obtained. The ideal channel characteristics such as channel capacity are calculated in section III, and more characteristics will be evaluated in the further research. The paper is concluded in section IV.

II. NUMERICAL ANALYSIS

The system includes data transfer (uplink, Fig. 1A), and energy transfer (downlink, Fig. 1B). Note that, although the uplink and downlink are two separated processes, they share the same transmitters and receivers. The schematic drawing of the data transfer function (uplink, left) is shown in the Fig. 1A, in which the toroidal coil near the ground is the receiver and the bottom toroidal coil is the transmitter. The toroidal coil can be regarded as magnetic current source. Therefore, the toroidal circuit transmitter with a casing inside is TM mode, and only the H_Φ component of the magnetic field propagates in the surrounding medium. The induced voltage signal [3] in the transmitter can be evaluated by the integral of magnetic flux change rate in equation (1),

$$Emf = -\int_A j\omega N \vec{H}_\phi \mu_0 \mu_r \hat{\phi} dA \qquad (1)$$

where A is the effective section area, N is the turns of receiver and μ_r is the relative permeability of ferrite.

The curves in Fig. 2A show the predicted magnetic field of tangential component near the metal pipe at different frequency and depth. An oscillating 10 mA current source with some specified working frequency is used to drive the toroidal antenna. In this case we assume a 200 m long vertical metal pipe surrounded by a homogenous 10 ohm-m underground formation. At a given frequency, the intensity of magnetic field decreases with the increase of the transmitter depth. At a given depth, the intensity of magnetic field decreases with the increase of the frequency due to the skin effect in lossy medium. Simulation parameters are list in Table I.

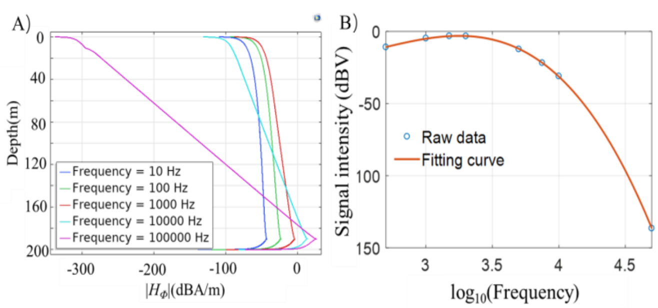

Fig. 2. Estimated H_Φ (A) and signal intensity (B) received on the surface w.r.t. working frequency

III. CHANNEL CHARACTERISTIC

The estimated voltage signal intensity of receiver has been simulated with the COMSOL Multiphysics and the fitted curve is shown in Fig. 2B. The channel frequency response can be estimated from the curve. Notice that the channel is frequency selective and can be modeled as a band-pass filter. The channel capacity can be computed with the equation [4]

$$C = B\log_2(1+\frac{S}{N}) \qquad (2)$$

where C is capacity, B is the bandwidth, and S/N is the signal-to-noise ratio. In this case, we assume the noise level is -70 dBm. We evaluate the single carrier system by utilizing the maximum channel response with 3dB bandwidth. The transmitter current in Fig. 2B is 10 mA, and the corresponding channel capacity is 16.4 kbps. Furthermore, the channel capacities could vary with different transmitter current density, which has been clearly shown in Table II.

TABLE I. SIMULATION PARAMETERS

Symbol	Properties		
	Description	***Value***	***Unite***
I.R.	Inner radius of metal pipe	6	cm
O.R	Outer radius of metal pipe	7	cm
L	Length of the pipe	200	m
σ_s	Conductivity of surrounding medium	0.1	S/m
μ_r	Relative permeability of ferrite	10000	1
N	Turns of transceivers	1000	1
r	Radius of ferrite	0.5	cm

TABLE II. CHANNEL CAPACITY OF DIFFERENT CURRENT SOURCE

Noise(dBm)	Current(A)	Capacity(kbps)
-70dBm	1A	32.7
-70dBm	0.1A	24.5
-70dBm	0.01A	16.4
-70dBm	0.001A	8.5

IV. CONSLUSION

A novel using the electromagnetic waves real-time monitoring and wireless underground communication system has been developed. The toroidal transceivers are coaxial with the metal pipe and has larger radius. The magnetic field of tangential component is simulated, and the voltage signal on the toroidal receiver is evaluated with this certain case. Then channel capacity for that case with metal pipe is evaluated. It is found that the ideal data rate up to about dozens thousand bps can be achieved for this wireless energized casing telemetry system.

ACKNOWLEDGEMENT

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