Downhole Wireless Communication Using Magnetic Induction Technique

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***Abstract*—This paper presents a novel method utilizing magnetic induction (MI) for wireless data transmission in oilfield borehole systems. Compared with conventional techniques, MI telemetry can achieve massive data transmission with low cost. Three coil configurations in borehole system are investigated, and most effective one is selected out based on numerical simulations. Through equivalent circuit model analysis, path loss and channel capacity are derived.**

I. INTRODUCTION

In oilfield drilling, telemetry refers to a system which converts the information recorded by measurement while drilling (MWD) tool into a suitable form for transmission to the surface from downhole sensors. Drilling operator can exploit information such as pressure, formation, or drilling direction to accurately control the drilling rig towards desirable position. Taking advantage of this capability, the drilling efficiency will be greatly increased and the operation cost is to be largely reduced. Various techniques have been used for data transmission, including mud pulse and electromagnetic (EM) telemetry. Mud pulse telemetry is severely limited by low data transmission rate which is only several bps. On the other hand, EM telemetry suffers from short range due to heavy attenuation in lossy formation.

In this paper, we propose a high data rate telemetry using array of magnetic induction (MI) antennas. Distinguished from EM radiation, MI accomplishes transmission by coupled magnetic fields. The concept of transferring data through MI has been discussed for underground communication [1], and further validated by experiment [2]. Fig. 1 illustrates how the MI telemetry is going to work in borehole system. Transmitter in downhole excited by time-varying current generates alternative magnetic fields, which then induces current in an adjacent MI coil. Signals are transferred one by one in this way, until they reach receiver on surface.

This paper is structured as follows. Section II provides numerical analysis of MI telemetry, and the best coil configuration is obtained. Channel characteristics are derived based on equivalent circuit model in section III. The paper is concluded in section IV.

II. NUMERICAL ANALYSIS

As shown in Fig. 1, three coil arrangements are available in drilling fluid. We name them as option A, option B, and option C, respectively. It should be noted that MI telemetry can take place in steel casing (scenario 1), or in open hole (scenario 2), or near the casing shoe with one coil in the casing and the other outside of the casing string (scenario 3). Simulation parameters are listed in Table I.

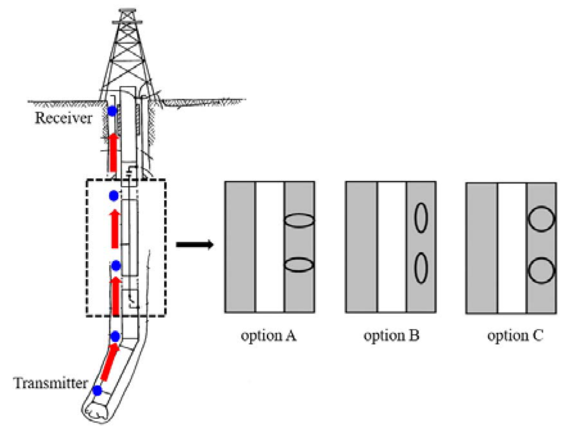


Fig. 1. Schematic diagram of MI telemetry system. (Red arrow represents the direction of signal flow; blue dot stands for coil antenna)

Fig. 2 shows simulation results for all three scenarios. Evidently, option C provides the configuration which can induce strongest magnetic field compared with option A and B. Such a result is reasonable since borehole system is equivalent to a coaxial line, in which TEM mode is the dominant mode. For TEM mode, magnetic field forms circular loop around drill string, so option C gives the largest effective area for flux line going through. In addition, ferrite cores play a significant role in boosting filed at receiver. The intensity has been improved about 15 dBT when relative permeability is 500. This phenomenon can be interpreted by the fact that a magnetic core with high permeability can confine and guide magnetic fields.

III. CHANNEL CHARACTERISTICS

The equivalent circuit model of MI communication system is presented in Fig. 3. M represents mutual inductance, and its value can be obtained by simulation for complex situations. C is the resonant capacitor. Z_L stands for the load impedance. Impedance Z_{rt} refers to the influence of receiver on transmitter, and impedance Z_{tr} represents the influence of transmitter on receiver. L_t and L_r are self-inductance of transmitter and receiver. To maximize the receiving power, load impedance should satisfy conjugate matching condition, $Z_L = \overline{Z_r + Z_{tr}}$. All relevant formulas can be found in [3].

The receiving power and transmitting power can be obtained after circuit analysis, as shown in (1) and (2). Path loss is defined as the difference between P_t and P_r in dB.

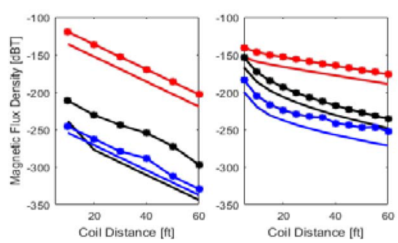
$$P_r = \mathrm{Re}(\frac{Z_L U_M^2}{(Z_{tr} + Z_r + Z_L)^2}) \quad (1)$$

$$P_t = \mathrm{Re}(\frac{U_s^2}{Z_t}) \quad (2)$$

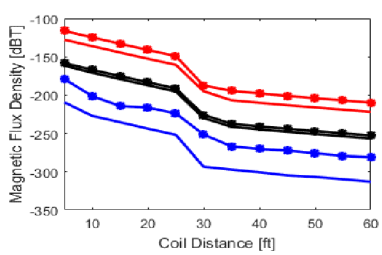
$$PL = -10\lg\frac{P_r}{P_t} \quad (3)$$

Shannon theorem gives the channel capacity as (4). If the date rate of transmission is less than channel's capacity, digital information can be sent over a noisy channel without error. S/N denotes the signal to noise ratio, and $SNR = P_t - PL - P_n$, P_n refers to noise level.

$$C = B\log_2(1+\frac{S}{N}) \quad (4)$$



(a) Scenario 1 (b) Scenario 2



(c) Scenario 3

Fig. 2. Magnetic field at receiver as a function of transceiver distance, for scenario 1, 2, 3, respectively. (Black line: option A; blue line: option B; red line: option C; dot line: with ferrite core)

As an example, the bandwidth and channel capacity are evaluated for the second scenario where drill-pipe has no casing. Results are provided in Fig. 4. For different distances, bandwidth is almost the same, and equals to 400 Hz. Here we assume the noise level is -100 dBm and transmitting power is 10 dBm. Based on (4), we can plot the channel capacity as a function of transmission range. For distance within 4 feet, the data rate reaches 1000 bps, which is much larger than present telemetry techniques.

TABLE I. SIMULATION PARAMETERS

Symbol	**Properties**		
	Description	***Value***	***Unit***
f	work frequency	100	kHz
R1	Inner radius of drill string	6.75	inch
R2	Outer radius of drill string	8	inch
t	Thickness of casing	0.1	feet
N	Number of coil turns	10	1
ε_r	Relative permittivity of fluids	80	1
σ	Conductivity of drilling fluids	1	S/m

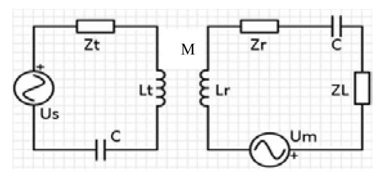
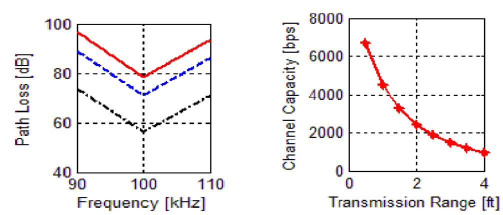


Fig. 3. Equivalent circuit model.



(a) (b)

Fig. 4. (a) Frequency response of path loss; (b) Channel capacity as a function of coil distance.

IV. CONCLUSION

A novel method based on magnetic induction for borehole wireless data transmission is investigated in this paper. Three configurations are considered, and the most promising configuration is chosen based on theoretic analysis and numerical experiments. The channel capacity for second scenario where drill-pipe has no casing is evaluated. It is found that high data rate up to several thousand bps can be achieved for a MI borehole telemetry system.

REFERENCES

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