

Wireless power and data transfer through carbon composite using a common inductive link

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ABSTRACT

This paper presents the design and development of an integrated wireless power transfer and data communication system. The power and data transfer share a common inductive link that consists of two identical Helical coils placed on both sides of a carbon composite barrier. Power and data are transferred simultaneously through a 5-mm thick carbon composite barrier without any physical penetration or contact. Power transfer measurements show that the system can deliver 9.7 AC power to the receiving coil with a power transfer efficiency of 36% through the carbon composite barrier. The system achieves a bidirectional half-duplex data communication with the data rate of unit 1.2kbit/s.

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1. INTRODUCTION

Design and optimization of wireless power transfer (WPT) systems have been well studied over the last decades to charge cell phones and electric vehicles as well as to power up sensors over a short distance [1–6]. In recent years, there has been a great demand for wirelessly powered sensors to support structural health monitoring (SHM) for industrial applications containing carbon composite barriers and enclosures (e.g., naval vessel, aircraft and chemical vat). Drilling holes for feeding wires reduces the integrity of the structure. Specifically, practical issues include higher probabilities for the leakage of toxic chemicals and the loss of pressure or vacuum. The SHM systems typically require embedded sensors for data acquisition inside a sealed container, wireless communication, and energy harvesting. The sensors need to be powered and controlled wirelessly through a barrier without any physical penetration through mechanical structures.

Several methods have been proposed to transfer power and data wirelessly using a common inductive link. The concept of inductive power transfer (IPT) is similar to the principle of transformers in which an alternating magnetic field in the primary coil induces a load voltage on the secondary coil when the two coils are tightly coupled [7-9]. In low-power applications, the inductive link for power transfer is also used for data transmission, where the data is directly modulated on the power carrier [10-14]. However, these techniques have low data rates and low power transfers.

Several methods using multiple inductive links with multiple carriers have been proposed to increase the data rate while maintaining the power transfer efficiency [15, 16]. In these methods, power and data are transferred via independent physical channels, where the power signal is delivered through one inductive

link and the data signal is transmitted through another. However, multiple links will cause extra magnetic interferences between the two channels, thereby decreasing the signal-to-noise ratio (SNR) in a communication channel. Multiple inductive links also lead to larger device size, which is undesirable for confined space applications. The method with multiple carriers in a single inductive link is another candidate for WPT systems. Conventional systems feed both power and data signals through two terminals of the inductive coil [17, 18] or use strong couple inductors to mix them before driving those signals to the coil [19]. However, these approaches cause direct interference of high power leakage into the data communication band at multiple harmonics. As a result, sharp-response filtering circuits or high power data transmission (well above harmonics levels) is required for a successful data communication. The main challenge of this approach is to achieve a reliable communication link in the presence of a strong interference from the power link.

In this paper, a novel system for simultaneous power and data transfer through a 5-mm thick carbon composite barrier using a common inductive link will be presented [20, 21]. The block diagram of the proposed system is shown in Figure 1. In this system, power is applied two terminals of the transmitting coil while the data is fed through the coil's center tap. By doing this, the power and data signals are isolated by means of the half-coil impedance. This feeding configuration can help to reduce the data signal power being transmitted to only 1.5. Consequently, it significantly releases the amount of power that needs to be harvested on the sensing side for sensing and communication operation. A complete system prototype is built to demonstrate that it can deliver 9.7 AC power to the sensing side and achieve wireless communication at the data rate of 1.2.

2. SYSTEM OVERVIEW

As demonstrated in Figure 1, the system is divided into two parts: the primary side and the sensing side. On the primary side, a power amplifier (PA) delivers power to two terminals of the transmitting coil while the data is applied via the coil's center tap. The power and data mixed signals are captured across two terminals of the receiving coils. A rectifier is employed on the sensing side to convert the harvested energy into DC power. This DC power is then used for sensing and communication operation on the sensing side, which does not have any batteries. The frequency of the power carrier is set at 300 while the data carrier is set at 8. The data-carrier frequency should be at least an order of magnitude higher than the power-carrier frequency so that the crosstalk interference of data communication from power transfer is suppressed. This facilitates the design of demodulation circuit and guarantees the reliability of communication. Low frequency was chosen for the wireless power transfer to isolate high power leakage at multiple harmonics into the data communication band. Conversely, for the wireless data transfer, high frequency had to be chosen to have large bandwidth for high data rate. However, the frequency of data carrier cannot be too high because data signals may experience significant loss through the inductive link.

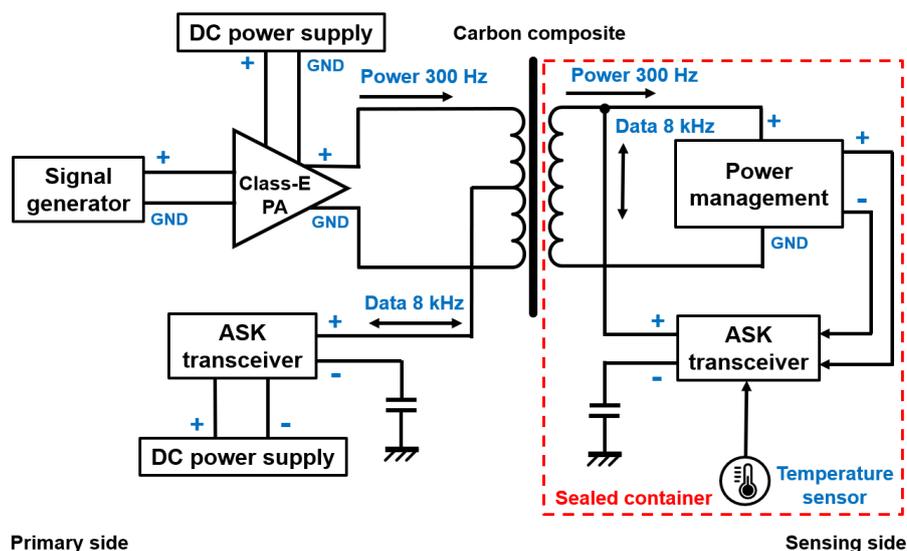


Figure 1. Proposed system for power and data transfer through carbon composite

2.1. ASK transceiver

In the proposed system, bidirectional half-duplex communication between the primary side and the sensing side is implemented using amplitude-shift keying (ASK) modulation. The proposed ASK transceiver shown in Figure 2, is adopted in both sides. In forward communication, the primary side is set to a transmitter mode while the sensing side is set to a receiver mode. In backward communication, the primary side is set to a receiver mode while the sensing side is set to a transmitter mode. The ASK transceiver can operate in two modes: transmitter mode and receiver mode, which are controlled by a bidirectional electronics switch TPS2080 from Texas Instruments. On the transmitter mode, digital data from an Arduino microcontroller (uC) is mixed with an 8-kHz carrier frequency generated by a local oscillator (LO) on a printed circuit board (PCB). The ASK modulated signal is then amplified by a commercial audio PA TDA7391 from STMicroelectronics and employed as a signal source to transmit data. On the receiver mode, the incoming data is demodulated and read by the same Arduino microcontroller. The ASK demodulator includes an active high-pass filter (HPF), a squarer, a low-pass filter (LPF) and a comparator. The active HPF consists of a second-order RC HPF followed by an op-amp amplifier. The strong power carrier signal and its harmonics that may interfere with the baseband data signal are suppressed by 40 by the active HPF. The filtered signals are then amplified and demodulated by the following sub-blocks in the receiver chain.

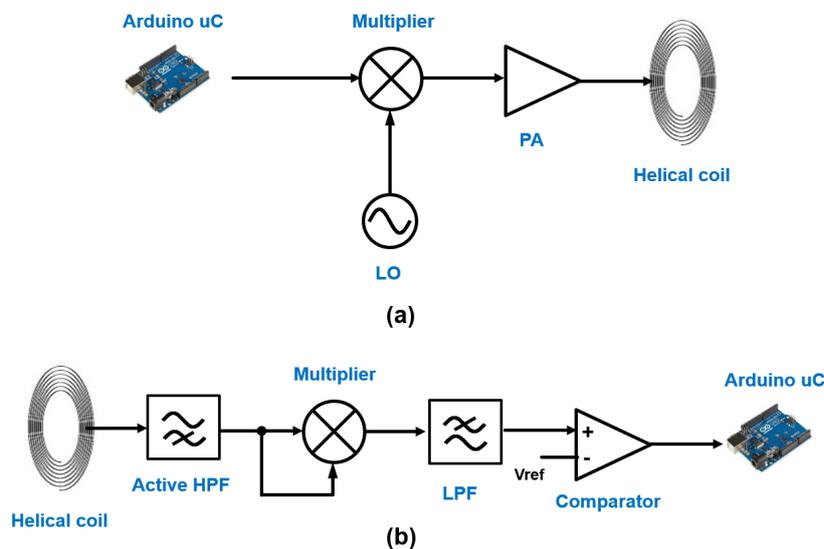


Figure 2. Proposed ASK transceiver, (a) ASK modulator, (b) ASK demodulator

2.2. Class-E power amplifier

A class-E PA is co-designed with the inductive link for power transfer. Class-E PAs achieve significantly higher efficiency than their conventional class-B or -C counterparts. The efficiency is maximized by minimizing power dissipation, while still maintaining a desired output power. The insulated-gate bipolar transistor (IGBT) STGW15S120DF3 from STMicroelectronics was used as the power transistor. This IGBT family has been specifically optimized for low switching frequencies. The complete circuit of the 300 class-E PA with all component values are given in Figure 3. The PA design is obtained by the Sokal-Raab approach [22, 23] is the coupling capacitor at the input of the PA. R_1 and R_2 form a voltage divider for gate biasing. The DC-feed choke, L_0 provides the connection to the DC power supply. L_1 and L_2 represent the coil inductances. In this design, the IGBT operates as an on/off switch and the load network shapes the voltage and current waveforms to prevent simultaneous high voltage and high current in the transistor. The load network is designed considering effects of the inductive link. The inductances of the transmitting and receiving coils become a part of the load network. C_1 and C_2 ensure that the collector voltage and collector current switching transitions are time-displaced from each other. Consequently, the power dissipation is minimized, especially during the switching transitions. L_2 and C_3 form a series-parallel resonant circuit. The IGBT is driven with a gate voltage of 8 and a supply voltage of 15. Measurement results show that the designed PA achieves a high collector efficiency of 54.2% when delivers 27 power at 300 to the transmitting coil.

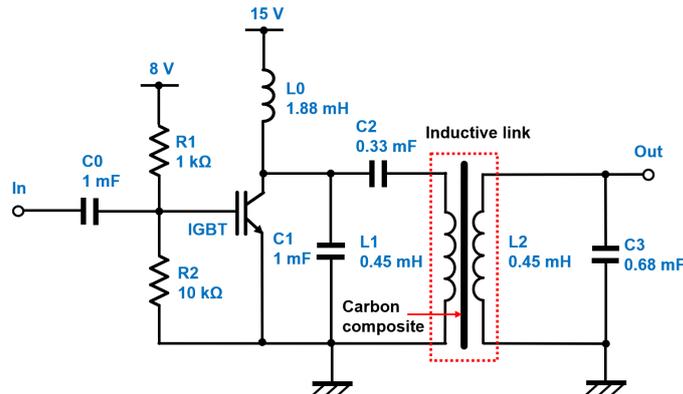


Figure 3. Schematic diagram of the class-E power amplifier

2.3. Power management

The power management module consists of an impedance transformer followed by several voltage regulators. Since the impedance of the coil is approximately 1 at 300, the AC power is harvested on the receiving coil in form of low voltage and high current. The series-L parallel-C impedance transformer is used to boost up the harvested AC voltage. The AC voltage is then converted into the DC voltage by a full-bridge rectifier GBPC3502W from ON Semiconductor followed by several smoothing capacitors. The DC voltage is distributed to several voltage regulators to generate stable voltage supplies for powering different sub-blocks of the ASK transceiver and sensors on the sensing side.

2.4. Helical coil

The power and data carrier share a common inductive link using a pair of identical Helical coils whose inductances are 0.45. Analysis and design of Helical coil were presented in [24-27] By co-axially aligning a pair of coils, the wireless IPT channel is formed without any physical penetration through the carbon composite barrier. The Helical circular geometry results in a more uniform magnetic field distribution that significantly improves the efficiency of energy transfer compared to that of the conventional Solenoid counterpart. The Helical coils are constructed using American Wire Gauge (AWG) 16 magnet wire. They have 63 turns with inner and outer radius of 22 and 108, respectively. Measurement results demonstrate that the power transfer efficiency is 36% for transferring power at 300 through the 5-mm thick carbon composite barrier.

3. EXPERIMENTAL RESULTS

A complete prototype was built to demonstrate the effectiveness of the proposed system. Figure 4 illustrates the measurement setup for power and data transfer through a $400 \times 400 \times 5$ carbon composite barrier. The other Helical coil cannot be seen in the figure since it is covered by the carbon composite barrier. For the practical demonstration of the proposed system, the prototype performances were verified in two experiments as shown in Figure 5. The first experiment verifies backward communication in which the sensing side sends data to the primary side. A temperature sensor TMP36 connected to the Arduino microcontroller on the sensing side continuously collects information on the temperature of the surrounding environment. The Arduino microcontroller is programmed to read this data and then the ASK transceiver sends the data to the primary side at a rate of 1.2. The temperature values are displayed on the monitor of a computer connected to the Arduino microcontroller board for further verification. In the second experiment, bidirectional half-duplex data communication is established when two ASK transceivers exchange one thousand bytes of data. The data is enclosed by the user-defined start and stop bytes. The ASK transceiver on the sensing side starts the communication at a data rate of 1.2 by sending the start byte followed by one thousand bytes of data and then the stop byte. After sending the stop byte, the transceiver is switched to receiver mode. On the primary side, as soon as the ASK transceiver detects the start byte, it is switched to the receiver mode and starts receiving the data in the backward communication. Alternatively, whenever the ASK transceiver on the primary side detects the stop byte, it is switched to the transmitter mode and starts sending the data in the forward communication. For both experiments, the ASK transceiver on the sensing side was powered by the rectified AC power that was harvested simultaneously while the data was received properly without any bit error.

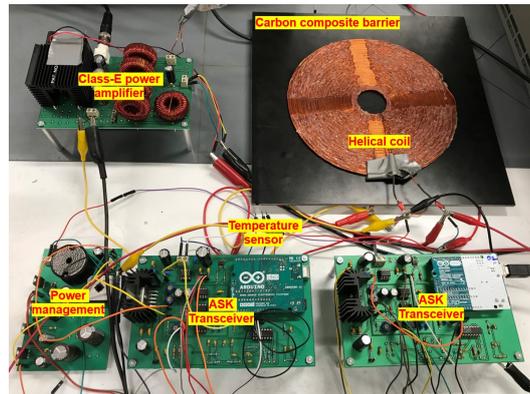


Figure 4. Measurement setup

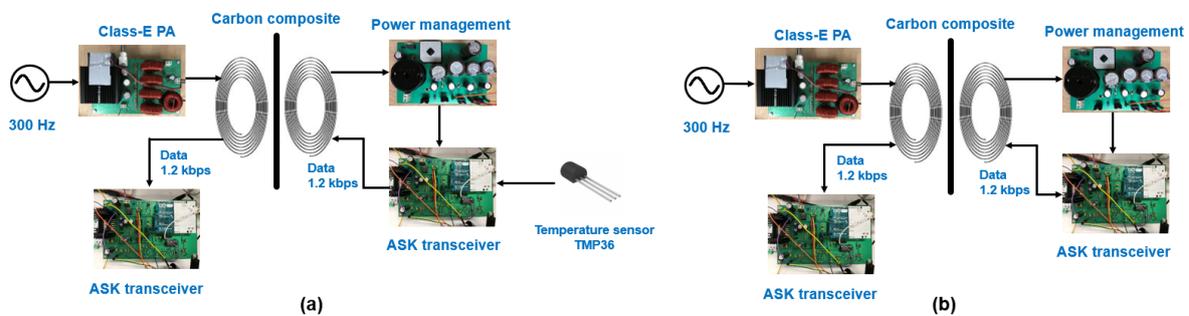


Figure 5. Experiment setups: (a) Real-time measurement of environment temperature; (b) Bidirectional half-duplex data communication.

Figure 6 (a) shows a typical spectrum of measured power and data mixed signals in the frequency domain captured by a vector signal analyzer. As seen in this figure, the modulated data signals exhibit lower side band (LSB) and upper side band (USB) symmetrically at the data-carrier frequency of 8. At this data rate, the channel bandwidth needed for data communication is 2.4. The power of the data signal at the carrier frequency and LSB/USB are 14.6 and 6.1, respectively. At the fundamental frequency of 300, the power of transmitted signal is 30.3 while the second and third harmonics are 22.6 and 11.2, respectively. Although the power signal is much higher than the data signal, they are still separated when the data-carrier frequency is chosen to be much higher than the power-carrier frequency. Consequently, the modulated signal is not interfered with the high-order harmonics of the power-carrier signal. Figure 6 (b) shows the mixed signals in the time domain captured by an oscilloscope. The low frequency corresponds to the power-carrier signal of 300, which is used to transfer power to the sensing side. The high frequency signal corresponds to the data-carrier signal of 8, which is used for ASK modulation.

Figure 7 shows a measured signal waveforms in backward communication at a data rate of 1.2. The backward communication is more challenging due to the limited power budget that can be harvested on the sensing side. The demodulation of the weak reception data signals on the primary side is critical to have data received properly. Figure 7 (a) and 7 (b) show the transmitted digital data from the Arduino microcontroller and the ASK modulated signal after the data signal is mixed with the 8-kHz carrier frequency generated by the local oscillator, respectively. The strong power-carrier signal at 300 and its harmonics are suppressed by the active HPF; thus, only data signals are available for demodulation. Figure 7c plots the baseband signals after downconversion and low-pass filtering. Depending on the received signal strength, the reference voltage of the following comparator is set accordingly. The digital data coming out from the ASK demodulator is plotted in Figure 7 (d). Comparing Figure 7 (a) with Figure 7 (d), it is demonstrated that the transmitted and received data are exactly the same with 0.24 delay time in transmission. The received digital data is read by the Arduino microcontroller on the primary side and displayed on a computer monitor for verification. The signal-to-noise

ratio (SNR) of approximately 18 for a bandwidth of 2.4 could be obtained. Using the proposed system, sensors and communication circuits enclosed in sealed containers can be powered up and communicate with exterior devices without any physical penetration for wire feed-throughs.

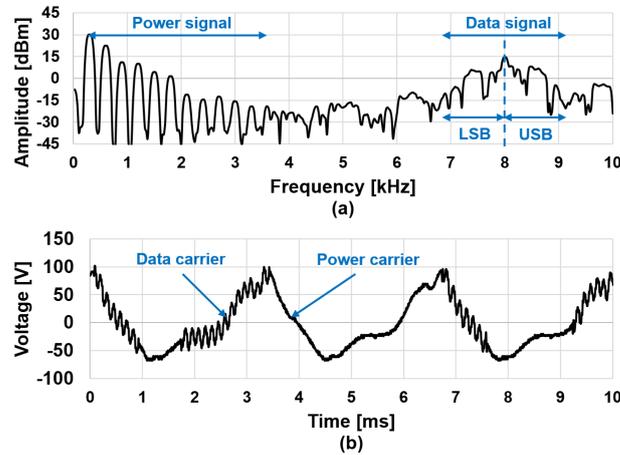


Figure 6. Measured transmitting mixed signals in, (a) frequency domain and (b) time domain

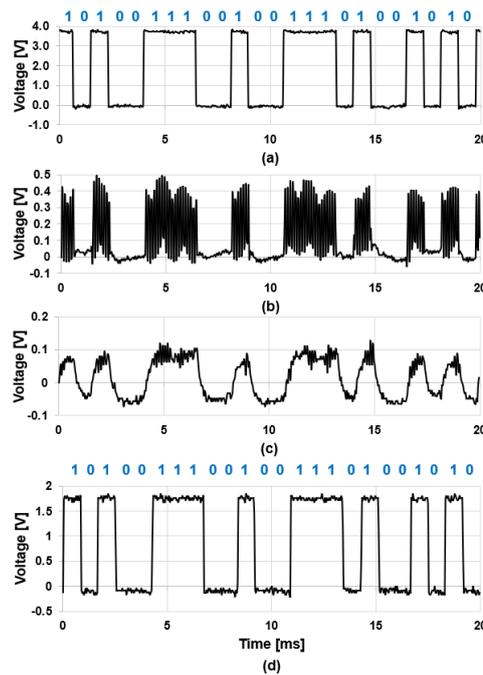


Figure 7. Measured signal waveforms in backward communication at data rate of 1.2, (a) Transmitted digital data, (b) ASK modulated signals before power amplification, (c) Received signal after low-pass filtering and (d) Received digital data after thresholding

4. CONCLUSION

In this paper, we have presented a novel system using multiple carriers in a single inductive link for wireless power and data transfer through the 5-mm thick carbon composite barrier. The proposed system exploits the center tap architecture enabling high power transfer and data communication at the same time. Measurement results demonstrate that the system could achieve wireless communication at a data rate of 1.2 while the sensing side was powered up using 9.7 AC power that was harvested simultaneously.

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