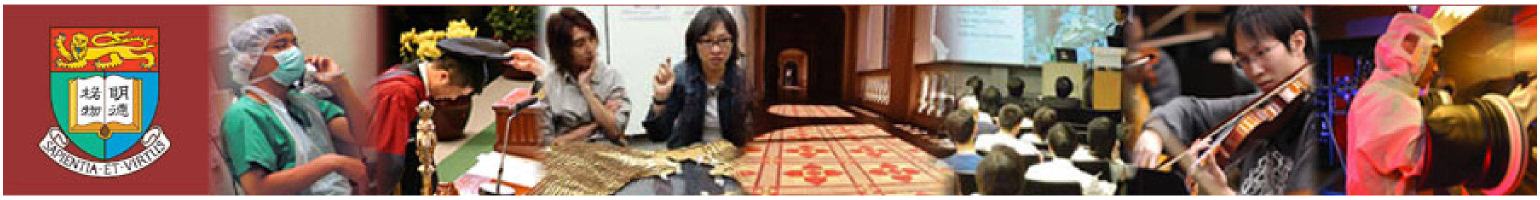

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A New Low Radiation Wireless Transmission System in Mobile Phone Application Based on Magnetic Resonant Coupling

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A novel two-stage transmission system for short range data exchange between cell phone and headset is proposed. The signal transfer is realized by non-radiative magnetic resonant coupling at an extremely low radiation level, rendering it a safe technique for the human body. Compared with Bluetooth technology, the proposed method also avoids electromagnetic interference with other radio transmissions at 2.4 GHz band as it operates at a much lower frequency band in the MHz range. Numerical analysis and simulation are conducted to study the transfer characteristics of the system and to demonstrate the advantages in terms of efficiency and SAR level.

***Index Terms*—Magnetic resonant coupling, specific absorption rate (SAR) level, wireless signal communication.**

I. Introduction

THERE is an increasing concern on the exposure of human subjects to radio frequency (RF) electromagnetic (EM) radiation produced by mobile phones, in particular after World Health Organization (WHO) has classified EM radiation as possibly carcinogenic to humans [1] recently. The amount of radiation that human body absorbs is measured by the specific absorption rate (SAR), which is subject to serious regulations. The SAR limits for U.S and Europe are summarized in Table I. Methods to reduce the SAR values mainly fall into two categories. The first type of methods employ special materials (e.g., ferrite sheets) to shield human head from the EM radiation generated by cell phone antennas. Most shielding methods, however, cannot dramatically reduce EM radiation and may cause undesirable interferences with the antenna. The other category uses headsets to prevent the main body of cell phone from being too close to the human head. The communication between the headset and the main body is typically realized, wirelessly, by the Bluetooth technology. Nevertheless, Bluetooth operates at the same 2.4 GHz band as several other co-existing RF transmission protocols like Wi-Fi. The EM interference (EMI) therefore becomes an issue, which downgrades the quality and performance of the affected transmissions. Existing remedies, e.g., [2], can only mitigate but not eliminate the EMI problem.

In this work, we propose a new two-stage transmission system featured with extremely low SAR level near human head. The system separates the headphone and the main body of cell phone with antenna as Bluetooth does, but transmits signal between the two parts by a recently developed magnetic resonant coupling (MRC) technique [3], where power is transmitted over a short- to mid-range through resonant coupling of magnetic fields at MHz range. Since human body is generally transparent to magnetic fields, and the frequency is too low to form RF EM radiation, the EM power absorbed by brain and other tissues in head is substantially reduced. The much lower operational frequency (< 20 MHz) also eliminates to a large extent the problem of interference with other RF transmissions.

TABLE I
SAR Limits for Cell Phone Radiation

Country	SAR limit	Averaging mass
Unite States	2 W/kg	10g
European	1.6 W/kg	1g

This work aims to set up the conceptual model of the proposed system and analyze the energy transfer characteristics and the SAR level. A succinct review the MRC transfer is given in Section II. The proposed transmission system is detailed in Section III. Numerical simulations and comparisons with a GSM antenna are provided in Section IV followed by a conclusion in Section V.

II. Background on Magnetic Resonant Coupling

MRC [3], [4] is a short- to mid-range wireless energy transfer technique, wherein energy can be efficiently transmitted between two objects via *non-radiative* magnetic fields when they resonate at the same frequency. Despite its significantly high power transfer performance, MRC is shown to be safe to human body because it operates at a much lower frequency (MHz range vs. GHz range for the data transmission process between mobile phone and base station) and its energy carrying fields are primarily in the magnetic form, to which human body is generally transparent. In addition, MRC is insensitive to general (non-metallic) objects located between the resonant objects and also relatively robust to misalignment.

The working principle of MRC can be conceptually illustrated by a four-coil system shown in Fig. 1. Differing from the traditional inductive coupling, the MRC system has a drive loop at the bottom layer and a load loop on the top layer, which constitutes the transmitter and the receiver with the TX coil and the RX coil in the middle, respectively. The source generator is connected to the drive loop, from which power is transferred to the TX coil via normal (non-resonant) inductive coupling. The receiver side functions in a similar manner. The load is connected

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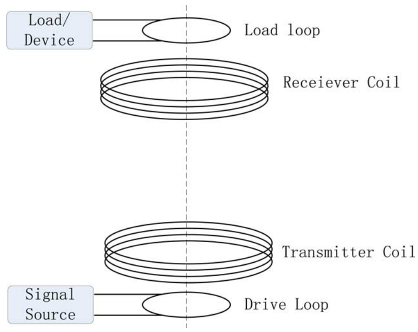
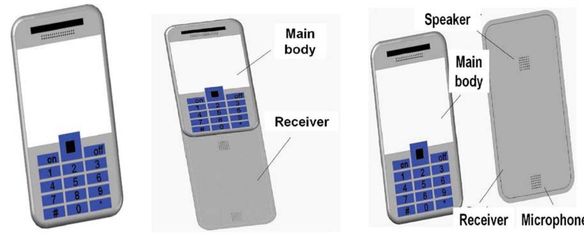


Fig. 1. Four-coil system for MRC.



(a) (b) (c)

Fig. 2. Three operation modes of the proposed system. (a) Idle mode, (b) Slip-out mode, (c) Slip-away mode.

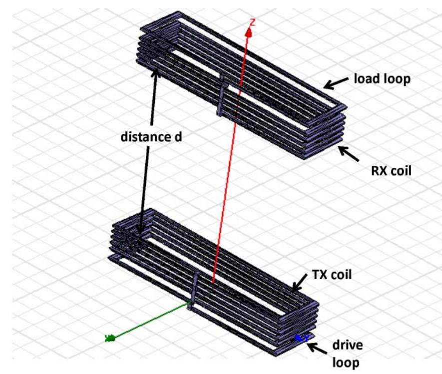


Fig. 3. Four-coil system model in HFSS.

to the load loop, which extracts energy from the RX coil inductively. The TX and RX coils are both RLC resonant circuits, between which energy can be transferred in high efficiency when they resonate at the same frequency.

By isolating the drive (load) loops and the TX (RX) coils, the source (load) resistance can be transformed into a much higher effective resistance in parallel with the RLC resonant tank of the TX (RX) coil, hence providing a higher quality (Q) factor [5]. This "resistance amplification" favors a large turn-ratio between the TX (RX) coil and the drive (load) loop, which, however, should be used with caution so as not to introduce excess self-resistance to the TX and RX coils which degrades their Q factors. The high Q factor of TX and RX coils is the key of the high power transfer efficiency of MRC, which compensates the low coupling coefficient between the TX and RX coils when distance becomes large. Instead of being a *power* transfer technology, MRC in this work is exploited as a short-distance *data* transmission technology between headset and mobile phone. Since wireless signal transfer can accept a much lower efficiency, the effective transfer distance can therefore reach tens of coil radii, which is sufficient for common connection between the headset and the main body.

III. Proposed Two-Stage Transmission System

The proposed transmission system consists of the main body of cell phone and a detachable receiver with speaker and microphone. The receiver is attached to the main body in waiting mode (Fig. 2(a)), and can be slip out (Fig. 2(b)), or slip away (Fig. 2(c)) from the main body with certain distance d. The receiver has its own power supply provided usually by a battery. The communication between the receiver and the main body is realized by the MRC technique. In practical implementation, the transmitter coil can be wound on the upper part of the main body and the receiver coil on the lower part of the speaker. Considering the typical rectangular cross-section of cell phone, the coils are wound in a rectangular helix form using round wires, as visualized in Fig. 3.

Fig. 4 depicts the equivalent circuit of the MRC system in Fig. 3, for which the analytical transfer function is available in [10]. The parameter values in the circuit model can be determined by the physical parameters of the structure.

- The AC coil resistances $(R1 - R4)$ are calculated by the common round wire resistance formula taking into account the skin effect

$$R_{AC} = \frac{2\rho N(w+l)}{2\pi r\delta} \tag{1}$$

where ρ is the metal resistivity, N is the number of turns, w and l are respectively the width and length of the coil, r is the radius of the winding wire and δ the skin depth. Since the frequency interval of interest is relatively narrow, the resistances are calculated at the central frequency and fixed throughout the interval for circuit simulation.
- The self-inductances $(L_1 - L_4)$ are determined analytically by the Niwa's inductance formula for multi-turn rectangular winding coils [6]. Since we are not just interested in the power efficiency at the resonant frequency, all six magnetic coupling coefficients $(k_{12}, k_{23}, k_{34}, k_{13}, k_{24}, k_{14})$ need to be taken into account. In practical implementation, the relative position of the TX (RX) coil and the drive (load) loop is usually fixed, so is k_{12} (k_{34}). The other four cross-coupling coefficients are strong functions of the communication distance and the coil geometry. To determine these coefficients based on physical parameters, we employ the technique in [7], which calculates numerically the mutual inductance between two rectangular coils with arbitrary axial and angular misalignments. The coupling coefficients are then defined by $k_{xy} = M_{xy}/\sqrt{L_x L_y}$, where M_{xy} denotes the mutual inductance.
- Two lumped, adjustable capacitors C_2 and C_3 are connected in series with the TX and RX coils to tune the resonant frequency. In principle, to achieve a high Q

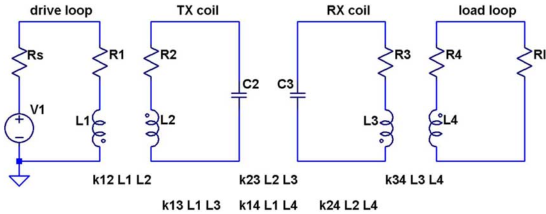


Fig. 4. Equivalent circuit model.

TABLE II
GEOMETRIC SPECIFICATIONS OF THE TESTING STRUCTURE

Number of turns (N)	5 (TX, RX), 1 (drive, load)
Rectangular coil length (l)	50mm
Rectangular coil width (w)	10mm
pitch between turns (p)	1mm
total helix height	7mm (drive+TX)
Radius of wire cross-section (r)	0.5mm
distance between TX and drive coils	5mm

TABLE III
EQUIVALENT CIRCUIT PARAMETERS FOR THE STRUCTURE USING THE SPEC. IN TABLE II

R_1, R_4	0.038Ω	R_2, R_3	0.19Ω
L_1, L_4	$0.073\mu H$	L_2, L_3	$1.06\mu H$
R_S, R_L	50Ω	C_2, C_3	$100pF$
k_{12}, k_{34}	0.38	k_{23}	0.00018
k_{13}, k_{24}	0.00013	k_{14}	0.00010
f_r	15.46MHz	Q_2, Q_3	542

factor, smaller capacitors should be used. Nevertheless, the resonant capacitors should be larger than the self-capacitances of coils by sufficient amount to keep the resonant frequency for power transfer sufficiently lower than the self-resonant frequency of the coils. Since the typical self-capacitances of our coils are several pF, the resonant capacitances are recommended to be >50 pF

IV. NUMERICAL SIMULATION

A. Power Transfer Efficiency

The four-coil system shown in Fig. 3 is simulated by Ansoft HFSS. The geometric specifications of the structure are given in Table II, which are intended to fit typical dimensions of wide-screen smart phones. The communication distance is 200 mm. For simplicity, the system is defined to be symmetric, e.g., $k_{12} = k_{34}$ and $k_{13} = k_{24}$. The circuit parameters derived from these physical specifications are listed in Table III.

The simulated $|S_{21}|$ (which measures the power transfer efficiency) is shown in Fig. 5, with the input and output ports defined with the drive and load loops, respectively. The peak transfer efficiency is -36 dB. In the specifications of Bluetooth technology, the minimum sensitivity level of the receiver is -70 dBm [8]. With the maximum transmitted power of 2.5 mW (4 dBm) for class 2 devices (for a range of 10 m), Bluetooth actually accepts a -74 dB lower bound of transfer efficiency. Therefore, the power transfer efficiency of the proposed MRC system in the neighborhood of the resonant frequency is comparable with that of Bluetooth and thus sufficient for short range data exchange.

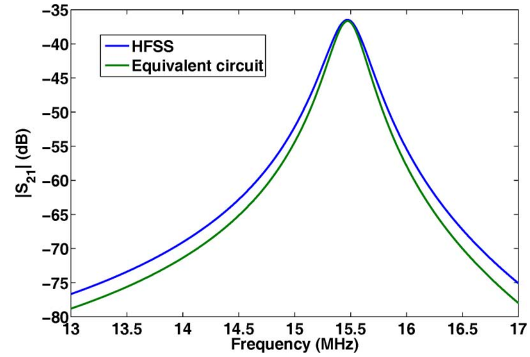


Fig. 5. $|S_{21}|$ simulated by HFSS and equivalent circuit model.

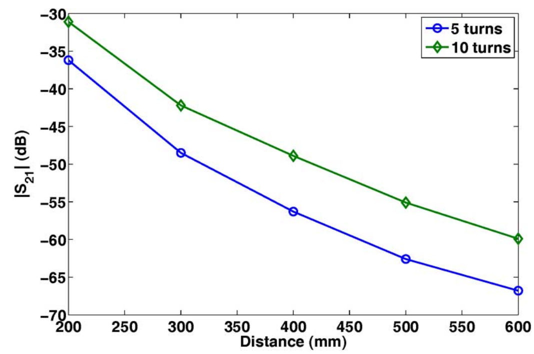


Fig. 6. Peak $|S_{21}|$ w.r.t distance using 5-turn and 10-turn coils.

TABLE IV
-70 DB BANDWIDTH W.R.T. DISTANCE OF MRC

Distance (mm)	200	300	400	500	600
Bandwidth (kHz)	2400	1150	700	430	330

The dependence of the peak transfer efficiency on the communication distance is shown in Fig. 6, which is predicted by the equivalent circuit model with the coupling coefficients extracted by the method in [7]. It can be seen that for up to 600 mm distance, which is the common separation between the headset and the cell phone, the efficiency of MRC system using the 5-turn coils remains higher than the -74 dB lower threshold. If we improve the coupling coefficients by increasing the number of turns of the TX and RX coils to 10 (with the other specifications unchanged), even higher transfer efficiency can be achieved to allow more margin for the reduction in coupling coefficients arising from misalignments.

B. Bandwidth

Frequency bandwidth is another concern in wireless communication. The typical bandwidth required for audio signal transfer is 4 kHz. The absolute -70 dB bandwidths with different distances is reported in Table IV for the MRC system with 5-turn coils, all of which are all well above the required bandwidth. The MRC system also has good out-of-band blocking and spurious emission suppression owing to the high selectivity of frequency, as evident in the steep curve shown in Fig. 5.

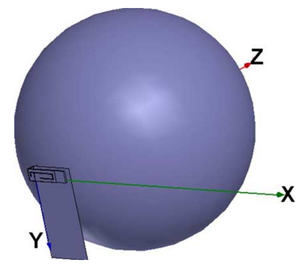


Fig. 7. Cell phone antenna and head model in HFSS.

TABLE V
PEAK SAR VALUES OF GSM ANTENNA AND MRC SYSTEM

SAR level (W/kg)	1g	10g
GSM antenna	4.94	3.01
Bluetooth (class II)	NA	2.1×10^{-3}
Propsed MRC system	6.92×10^{-5}	4.99×10^{-5}

C. SAR Level

The SAR of the proposed system is also simulated in HFSS. A two-layer head model is placed 5 mm away from the RX coil, on/inside which the SAR is calculated. A dual-band GSM planar inverted F-antenna [9] is also simulated for comparisons as shown in Fig. 7. The SAR is calculated with the same head model.

The peak SAR values from the proposed system and the GSM antenna averaged over 1 g and 10 g tissues are compared in Table V. A 2 W input power is used to model the max power operation of the antenna. It is seen that the SAR level of traditional antenna violates the safety requirement indicated in Table I. The SAR from the MRC system is generally negligible, since human body has very weak interactions with magnetic fields and the frequency is too low to form radiation.

Some remarks regarding the commonplaces and differences between the MRC and Bluetooth are given below.

1) The main features of the proposed system is being an alternative for short-range wireless data communication to reduce the EM radiation of cell phone absorbed by users. Compared to the traditional inductive-coupling approach, the new MRC-based system trades bandwidth, which is less demanded in audio communication, for transfer efficiency to allow larger communication distance. Compared to the mainstream Bluetooth technology, the proposed system avoids using the highly occupied 2.4 GHz band, so as to avoid interference with other RF transmissions.
2) For a short communication distance < 1 m, MRC is able to maintain a comparable power transfer efficiency with Bluetooth. The bandwidth of MRC is generally smaller than the typical bandwidth of 80 MHz of Bluetooth (which is reduced to only 20 MHz in some countries). In addition, a higher receiver sensitivity may be required in MHz range than in GHz due to the more significant man-made noise the receiver would perceive, to maintain a sufficient signal-to-noise ratio. This further lowers the available bandwidth of the MRC system. Yet given the low bandwidth requirement of audio signal transfer ($\sim$4 KHz), the bandwidth of the system proposed suffices for common wireless control and communication in which Bluetooth is being applied. Further analysis on this issue would be carried out in follow-up work.
3) Bluetooth has better omni-directional property so no deliberate alignment between transmitters and receivers is required. The MRC technique, on the other hand, is more sensitive to misalignment, and will experience serious efficiency drop when the transmitter and receiver are nearly perpendicular to each other. Special shaped inductors (e.g., L-shaped), however, can be exploited to avoid complete decoupling between inductors.
4) In terms of device sizes, the transmitting and receiving antennas for MRC are usually larger than that of Bluetooth, due to the requirements of high Q factors and sufficient coupling strength among coils. As a result, the MRC technique is generally more applicable for scenarios where the desired communication distance is no greater than 50 times the transmitter diameter.

V. CONCLUSION

In this paper, a new wireless communication system for mobile phone application based on MRC is proposed. The new technique features an extremely low SAR level and can avoid the EM interferences with other radio transmissions. The characteristics of the MRC system have been analyzed by numerical simulation and the SAR reduction has been verified by comparing with normal cell phone antenna. It has been demonstrated that the proposed MRC technique can be a promising substitute for Bluetooth in a number of application involving short distance cordless data exchange.

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