Available online at www.sciencedirect.com

ScienceDirect

Journal of Magnetic Resonance 186 (2007) 358–363

JMR
Journal of
Magnetic Resonance

www.elsevier.com/locate/jmr

Communication

A realization of digital wireless transmission for MRI signals based on 802.11b

Juan Wei [a], Zhengguang Liu [b], Zhi Chai [b], Jing Yuan [a], Jianyu Lian [c], Gary X. Shen [a,*]

[a] *Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam, Hong Kong*
[b] *School of Automation and Electrical Engineering, Tianjin University, Tianjin, China*
[c] *XinAoMDT Technology Co., LTD. Langfang Economic & Technical Development Zone, Hebei Province, China*

Received 1 December 2006; revised 13 February 2007
Available online 12 March 2007

Abstract

In this paper, a digital wireless transmission system based on 802.11b standard for magnetic resonance imaging (MRI) application is designed and built for the first time to eliminate the interference aroused by coil array cables. The analysis shows that the wireless receiver has a very high sensitivity to detect MRI signals. The modulation technique of differential quadrature phase shift keyed (DQPSK) can be applied to MRI data transmission with rate of 2 Mbps and bandwidth of 2 MHz. The bench test verifies that this wireless link has a dynamic range over 86 dB supporting up to 3T MRI system data transmission. The 2D spin echo imaging of phantom is performed and the SNR of the image obtained by the wireless transmission can be comparable with that got by the coaxial cables.

Keywords: Magnetic resonance imaging (MRI); Digital wireless transmission; Coil array; IEEE 802.11

1. Introduction

It is advantageous in magnetic resonance imaging (MRI) systems to employ multiple local or surface coils, which can be optimized for large volume samples without significantly sacrificing signal-to-noise ratio (SNR) [1]. Each coil arrangement is connected to the reception circuit via a coaxial cable. The cable and the required connectors, however, represent a limitation on the ease of operation, especially as the number of coil elements increase due to the requirement of MR parallel imaging [2]. Also because of the proximity of coaxial cables of the multiple receive coils with respect to one another, disturbing effects, ghosting and other SNR related problems are liable to occur [3,4].

Wireless transmission should be a good choice to replace cable connections of the coil arrays to minimize their cross talks. In recent years, several proposals of using wireless transmission for MRI have been reported [5,6]. Amplitude modulation (AM) and single sideband (SSB) analog wireless techniques have been used to design transponders for RF coils [7]. Compared to this analog transmission technique, digital transmission has better noise immunity, more stability and flexibility, and is code error free.

A simple schematic figure of the MRI transceiver is shown in Fig. 1. A transmitter excites the object with RF pulse sequence, and a receiver processes the RF signal induced by the precessing net magnetization from the object. Two different designs of wireless transmission for MRI signals are shown in Fig. 2. The analog transmission as in Fig. 2a is realized if a wireless transceiver is added between 1-1″ in Fig. 1 or between 2-2″, a digital transmission as in Fig. 2b is implemented.

In this work, a digital wireless transmission system for MRI signals has been built. This system is based on wireless local area networks (WLAN) 802.11b standard [8], which reaches the speed of 11 Mbps in 2.4 GHz band.

---

[*] Corresponding author. Fax: +852 2559 8738.
E-mail address: gxshen@eee.hku.hk (G.X. Shen).

1090-7807/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.jmr.2007.03.003

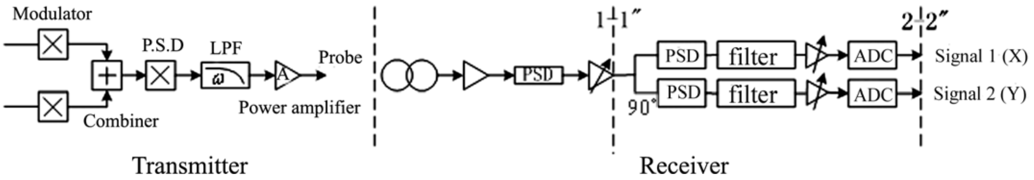

Fig. 1. Schematic figure of MRI transceiver circuit.

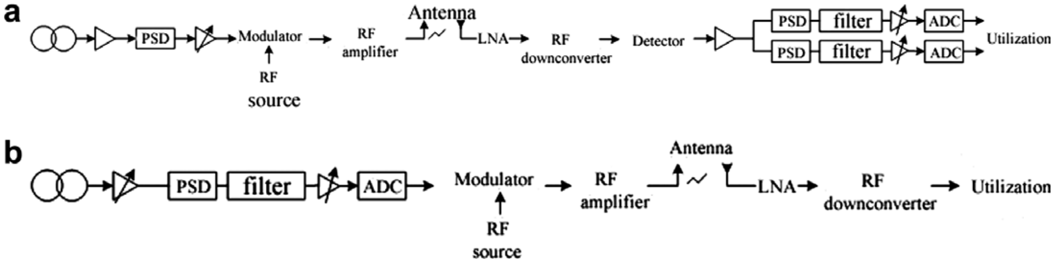

Fig. 2. Schematic figure of wireless transmission for MRI signals. (a) Analog method. (b) Digital method.

2. Methods

2.1. System overview

The system schematic of digital wireless transmission in this work is shown in Fig. 3. The digital signal processor (DSP) controls the down converting reference signal which is generated by using the technique of direct digital synthesizer (DDS), accepts the data from the analog to digital converter (ADC) and sends the processed data to wireless transceiver by Ethernet Port which is integrated on board with DSP. All these processing circuits and wireless transmitter can be integrated with the receive coil in the future work. The data accepted by the wireless receiver are sent to the PC to be imaged.

Our wireless transmission link is based on 802.11b standard. There are 14 standard channels defined for 802.11b from 2.4000 to 2.487 GHz. All channels are evenly spaced at 5 MHz intervals and each channel occupies the bandwidth of 22 MHz. However, only three channels like 1, 6, and 11 can be assigned to an 802.11 network simultaneously without frequency overlap. If one channel transmits one coil element signal, there are only three coil array signals can be wirelessly transmitted. In order to transmit much more MRI signals simultaneously, the method of frequency division multiplexing (FDM) is applied here, which makes it possible for each transmission channel defined by 802.11b to carry multi-channel MR signals modulated at different frequencies.

The MRI signal can be treated as a resonant frequency modulated RF signal with a typical bandwidth of dozens of kHz on both sides. In the pre-processing circuit, the multiplier mixes original MRI signal with synchronous reference signal generated by programmable DDS device, which is controlled by DSP. After the mixed signal is sent to the filter and the up converting part is removed, the MR signal frequency of each channel is down converted to different lower frequencies, such as 200, 400 kHz, etc. respectively. Each of these down converted signals occupies the bandwidth of less than 200 kHz. Then these FDM signals are combined together and sent to the post-processing unit to be digitized and ready to be transmitted wirelessly.

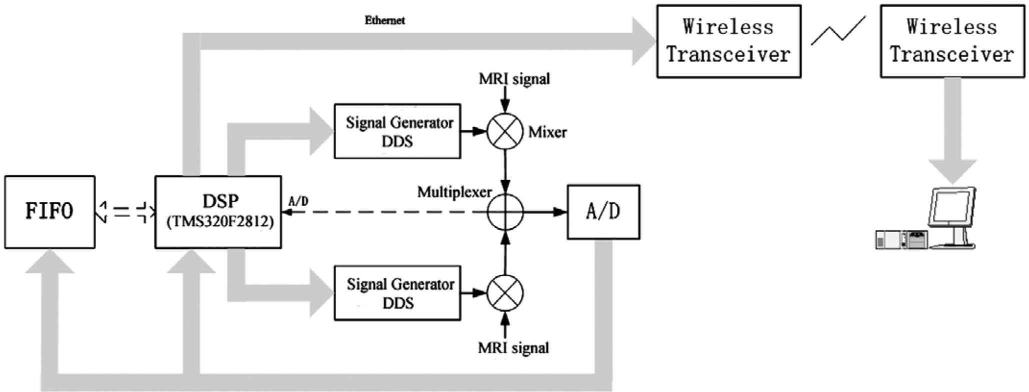

Fig. 3. Schematic figure of digital wireless transmission system based on 802.11b.

In our system, a wireless embedded device WiPort™ (Lantronix, Irvine CA, USA) is used as the wireless transceiver, which is a complete network-enabling solution based on the IEEE 802.11b wireless standard. This Wiport module can function independently of PC and is connected to the signal processing circuit by an Ethernet interface.

2.2. Wireless link budget

Assume an MRI image pixel size is 128 × 128, and each pixel contains 4 bytes (Siemens Trio 3T) to describe the image depth with gray scale. For such an image, it contains 1M bits (real and imaginary part together). If we assume one image per second normally (for typical ultra high-speed imaging echo-planar imaging (EPI) [9], the rate is 10–18 images/s), then the transmission data rate is 1 Mbps. So in this work, a wireless digital link capable of at least 1 Mbps throughput at about 30-m indoors (MRI accommodation) is desired. However, in order to accommodate framing, overhead, and checksum for the wireless link, the higher data rate more than 1 Mbps may be necessary. Typically, throughput is about 70–75% of peak data rate. Thus, the required data rate for the wireless link is roughly 1.4 Mbps. Differential quadrature phase shift keyed (DQPSK) modulation technique is used here to transmit data up to 2 Mbps (R for rate) and its null-to-null bandwidth is 2 MHz (B for bandwidth). In communication, the bit error rate (BER) should be required below 10^{-9} for good connections [10,13]. Here, BER is also required below 10^{-9} for MRI applications for conservative calculation. To achieve such a BER, the required energy per bit relative to the noise power (E_b/N_0) is 13 dB, which is independent of the system data rate and can be directly found in the figure of probability of bit error for common modulation methods [10]. Then the required SNR can be determined as follows:

$$\begin{aligned}\mathrm{SNR} &= (E_b/N_0) * (R/B) = 19.95 * (2\ \mathrm{Mbps}/2\ \mathrm{MHz}) \\ &= 13\ \mathrm{dB}\end{aligned} \tag{1}$$

where E_b is energy required per bit of information, N_0 is thermal noise in 1 Hz of bandwidth, R is system data rate and B is system bandwidth.

The noise level at room temperature within the bandwidth of 2 MHz is:

$$\begin{aligned}\mathrm{Noise} &= kTB \\ &= 1.38 \times 10^{-23}\ \mathrm{J/K} \times 290\ \mathrm{K} \times 2{,}000{,}000\ \mathrm{s}^{-1} \\ &= 8 \times 10^{-12}\ \mathrm{mW} = -111\ \mathrm{dBm}\end{aligned} \tag{2}$$

Assume the receiver has a noise figure of 6 dB, and the receiver noise floor N is,

$$N = -111\ \mathrm{dBm} + 6\ \mathrm{dB} = -105\ \mathrm{dBm} \tag{3}$$

So the sensitivity S is:

$$S = N + \mathrm{SNR} = -105\ \mathrm{dBm} + 13\ \mathrm{dB} = -92\ \mathrm{dBm} \tag{4}$$

The free space path (PL) loss at 30 m for indoor propagation is 80 dB [10], and the fade margin (FM) is conservatively assumed as 30 dB for reliability, so the transmit power is estimated as:

$$\begin{aligned}P &= N + \mathrm{SNR} + \mathrm{PL} + \mathrm{FM} \\ &= -105\ \mathrm{dBm} + 13\ \mathrm{dB} + 80\ \mathrm{dB} + 30\ \mathrm{dB} = 18\ \mathrm{dBm}\end{aligned} \tag{5}$$

The technical specifications of the wireless module (WiPort™) chosen in this work are all within the range of this link budget.

3. Results

The performances of the pre-processing circuit were evaluated by a bench test with HP 8595E spectrum analyzer and HP 8647A signal generator. In the measurement, the internal receiver bandwidth of the spectrum analyzer was set as 10 KHz and within this bandwidth, the noise floor was detected about −76 dBm. The power of input signals was varied from −76 to −1 dBm and their frequencies were adjusted within 10 MHz around the synchronous reference frequency set by DDS device.

The linearity and the frequency response of the MRI signal pre-processing circuit are respectively shown in Figs. 4–6. In Fig. 4, the output power increases with the input monotonously from −76 dBm. The power gain is 10 dB. As the input power is over −6 dBm, the power gain compresses. The 1 dB compression point is −4 dBm. For the noise floor of the spectrum analyzer within the bandwidth of 10 KHz is −76 dBm, then within the bandwidth of 1 Hz, the noise floor ($\mathrm{NF}_{1\ \mathrm{Hz}}$) is −116 dBm. So the rough calculation of the dynamic range is 112 dB. However, in fact, if we consider the range over which a receiver does not compress an input signal and no spurious signal is above the receiver's noise floor, the "spurious-free dynamic range" is

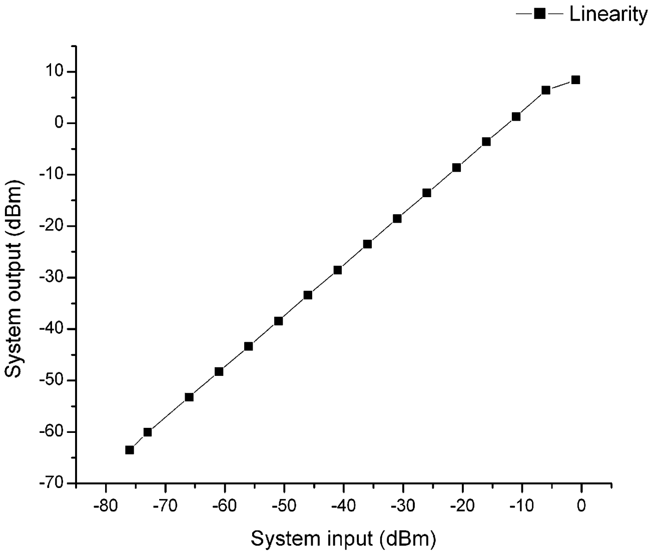

Fig. 4. The linearity of the FDM pre-processing circuit.

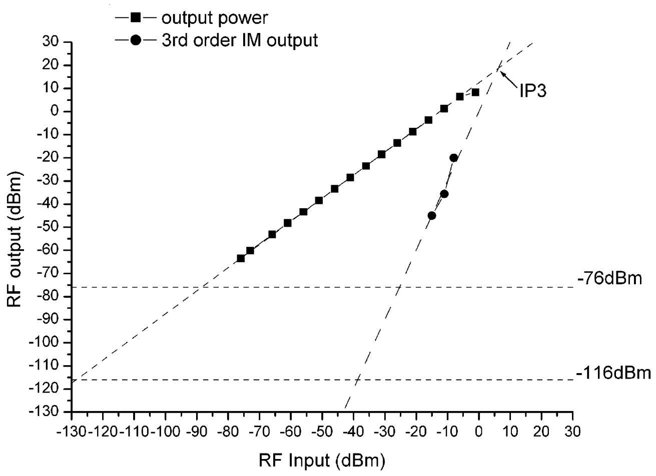

Fig. 5. Illustration of pre-processing circuit output characteristic showing third order intercept point referred to input.

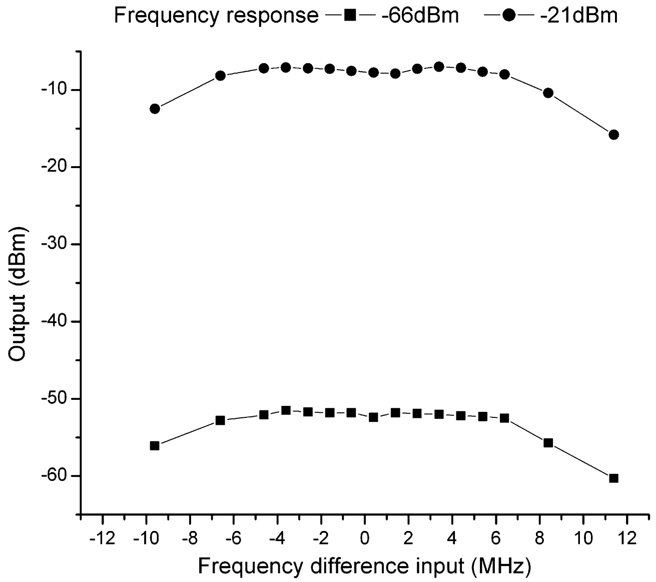

Fig. 6. Frequency response of FDM pre-processing circuit with the input power at −21 dBm and −66 dBm.

the best operating region. In the measurement of this dynamic range, two signal generators were used to supply two equal-amplitude RF sine wave signals with a small gap of frequency, like 12.4 and 12.6 MHz. Then the two-third order IM terms occurs at 12.2 and 12.8 MHz. For these two interferences are so near to the fundamental RF signal that it is difficult to get rid of them through a filter. Therefore, these IM terms must be minimized below the noise floor to avoid distortion. The magnitude of the fundamental output and third order inter-modulation (IM) output are plotted in Fig. 5. If the curves of the fundamental and the third order IM terms within their linear regions, the input power at which these two curves intersect is called the third order intercept point (IP3). For most of practical links, both the fundamental and the third order IM curves have been in the compression region at IP3, so IP3 is just an ideal parameter for measure of link dynamic range. According to [11], the spurious-free dynamic range (SFDR) is:

$$\begin{aligned} \mathrm{SFDR} &= \tfrac{2}{3}(\mathrm{IP3} - \mathrm{NF}_{1\ \mathrm{Hz}}) = \tfrac{2}{3}[18.8 - (-116)] \\ &= 89.9\ \mathrm{dB} \end{aligned} \tag{6}$$

Still, the dynamic range of the pre-processing circuit can satisfy the requirement of 86 dB dynamic range in power at 3T [12].

For digital communication, the dynamic range of the receiver is affected by A/D conversion. Under most conditions, the dynamic range of MRI signal is about 72–96 dB and a 12–16 bit ADC is sufficient. In this study, a 16 bit ADC is chosen to guarantee a wider dynamic range.

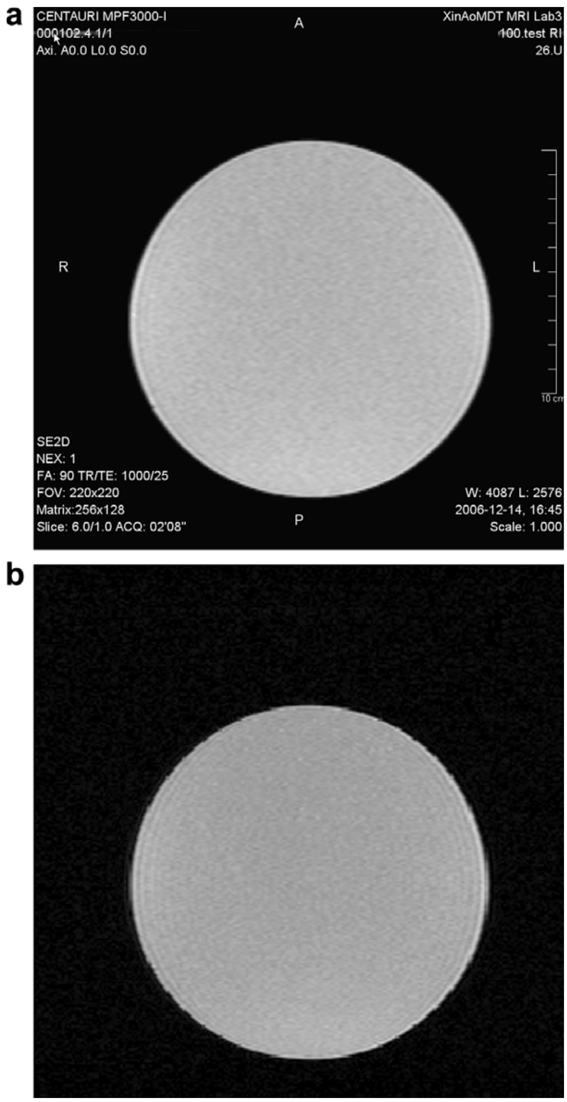

Fig. 7. The phantom images obtained by (a) 0.35T XinAo MRI system (b) wireless transmission system.

It is found in Fig. 6 that the frequency responses are flat within the bandwidth of 8 MHz around the center frequency set by the DDS at the input power of −21 dBm and −66 dBm respectively. Because each of the down converted signals occupies the bandwidth of less than 200 kHz, then an 8 MHz bandwidth can transfer at least 30 channels of MR signals modulated at different frequencies. Consequently, three wireless transmission channels based on 802.11b can carry about 90 channels of MR array signals [13].

The 2D spin echo images of phantom obtained by the traditional coaxial cable and wireless link are shown in Fig. 7. In this MRI experiment, a commercial receive-only head RF coil was used to detect the signals. The input of the pre-processing circuit was connected to the output of the preamplifier attached to the coil. MRI system synchronization clock was used to synchronize our wireless transmission system and control digital sampling.

Fig. 7a is got directly from XinaoMDT 0.3T MRI system (Langfang, China). Fig. 7b is constructed with the raw data obtained by our wireless transmission system. In these two figures, the noise region is selected as four separate square parts of the whole background in the images. The signal region is selected as 80% of the circular region covering the phantom. The SNR of the phantom image obtained by XinAoMDT 0.3T system (SNR = 73.2) is a little higher than that obtained by our wireless transmission system (SNR = 61.7). This means our transmission system adds few noises in the transmission, but the SNR performances are comparable for two methods.

4. Discussion and conclusion

In this work, only the MRI signal transmission is implemented wirelessly for simplicity and feasibility. In fact, there are still some short cables existing for connecting the receive coil, pre-processing circuit and post-processing circuit. In the future work, the multiplexer and digital processing circuit could be integrated with the receive coil, so there will be no cables for MRI signals transmission. In this work, the power is supplied directly from the DC source with cables and the synchronization signals for wireless transmission and digitization are obtained from the XinaoMDT MRI system. In later work, the battery or some circuit supplying the power from the transmission power and the transmitter for wireless synchronization clock signal will be designed and built to realize the truly and completely wireless transmission system.

The DQPSK modulation method can support normal MRI data transmission with rate of 2 Mbps and bandwidth of 2 MHz. However, this modulation method must be changed if fast imaging sequences are used. For example, in the EPI imaging, if still assume an MRI image pixel size is 128 × 128, and each pixel contains 4 bytes to describe the image depth with gray scale, then in one second, there would be 10–18M bits to be transmitted. Also considering about accommodate framing, overhead, and checksum, the final required data rate should be 14–25 Mbps. Then the standard of IEEE 802.11a which specifies the use of OFDM modulation and supports data rates up to 54 Mbps can be used. Also for parallel imaging, with the number of array channels increasing even to 96, capacity of the standards based on 802.11 even with the application of FDM can not satisfactorily transmit these large quantities of data simultaneously. While more advanced modulation techniques applied in wireless communication such as code division multiplexer (CDM), etc. nowadays can be used to transmit these large number channels of signals, but much more complexities would be added into the circuit design.

In summary, a digital wireless transmission link based on 802.11b for MRI application has been designed and implemented, which eliminates cables for array coils and minimizes the interference between channels. The link budget has shown that the sensitivity of the wireless receiver is high enough to detect the weak MRI signals and the DQPSK modulation method can support normal MRI data transmission with rate of 2 Mbps and bandwidth of 2 MHz. The bench test has verified that the pre-processing circuit has a dynamic range over 86 dB, wide enough for 3T or lower field strength MRI systems. The SNR of phantom image obtained by the wireless transmission can be comparable with that got by the coaxial cables. The signal processing circuit will be integrated with the receive coil and the whole system will be improved in the future for multi-channel imaging.

Acknowledgment

This project is supported by RGC Earmarked Research Grant 7045/01E, 7170/03E and 7168/04E.

References

[1] P.B. Roemer, W.A. Edelstein, C.E. Hayes, S.P. Souza, O.M. Mueller, The NMR phased array, Magn. Reson. Med. 16 (1990) 192–225.

[2] P. Pruessmann, M. Weiger, M.B. Scheidegger, P. Boesiger, SENSE: sensitivity encoding for fast MRI, Magn. Reson. Med. 42 (1999) 952–962.

[3] J. Gosbee, J. DeRosier, MR Hazard summary. Available online: http://www.patientsafety.gov/alerts/MRI.doc (2001, Aug.)

[4] The Intranet architecture: MRI safety in US Food and Drug Administration. Available online: http://www.fda.gov/cdrh/safety/mrisafety.html.

[5] Murakami et al., Nuclear magnetic resonance inspection apparatus and its method, US Patent 5 384 536, Jan. 24, 1995.

[6] Boskamp, Wireless RF module for an MR imaging system, US Patent Application Publication 2003/020619 A1, Nov. 6, 2003.

[7] G. Scott, K. Yu, Wireless transponders for RF Coils: Systems Issues, presented at the 13th Proc. Int. Soc. Magn. Reson. Med. Annu. Meeting, US, 2005, p. 330.

[8] R. Olexa, Implementing 802.11, 802.16, and 802.20 Wireless networks—Planning Troubleshooting and Operations, Newnes, Oxford, UK, 2005.

[9] P. Mansfield, Multi-planar image formation using NMR spin echoes, J. Phys. C: Solid State Phys. 10 (1977) L55–L58.

[10] A. Bensky, Short-range Wireless Communication—Fundamentals of RF System Design and Application, Newnes, Oxford, UK, 2004.

[11] Robert C. Dixon, Radio Receiver Design, Marcel Dekker Inc., 1998.

[12] J. Yuan, P. Qu, J. Wei, G.X. Shen, Noise figure and dynamic range optimization in optical links for MRI applications, presented at 14th Proc. Int. Soc. Magn. Reson. Med. Annu. Meeting, US, 2006, p. 2031.

[13] G.C. Wiggins, A. Potthast, C. Triantafyllou, F. Lin, T. Benner, C.J. Wiggins, L. Wald, A 96-channel MRI system with 23- and 90-channel phased array head coils at 1.5 Tesla, presented at 13th Proc. Int. Soc. Magn. Reson. Med. Annu. Meeting, US, 2005, p. 671.