Published in final edited form as:

Magn Reson Med. 2019 March ; 81(3): 2176–2183. doi:10.1002/mrm.27513.

Integrated Radio-Frequency/Wireless Coil Design for Simultaneous MR Image Acquisition and Wireless Communication

Dean Darnell¹, Jonathan Cuthbertson^{1,2}, Fraser Robb³, Allen W. Song^{1,2}, and Trong-Kha Truong^{*,1,2}

¹Brain Imaging and Analysis Center, Duke University, Durham, NC, USA

²Medical Physics Graduate Program, Duke University, Durham, NC, USA

³GE Healthcare, Inc, Aurora, OH, USA

Abstract

Purpose—An innovative radio-frequency (RF) coil design that allows RF currents both at the Larmor frequency and in a wireless communication band to flow on the same coil is proposed to enable simultaneous MRI signal reception and wireless data transfer, thereby minimizing the number of wired connections in the scanner without requiring any modifications or additional hardware within the scanner bore.

Methods—As a first application, the proposed integrated RF/wireless coil design was further combined with an integrated RF/shim coil design to perform not only MR image acquisition and wireless data transfer, but also localized B_0 shimming with a single coil. Proof-of-concept phantom experiments were conducted with such a coil to demonstrate its ability to simultaneously perform these three functions, while maintaining the RF performance, wireless data integrity, and B_0 shimming performance.

Results—Performing wirelessly controlled shimming of localized B_0 inhomogeneities with the coil substantially reduced the B_0 root-mean-square error ($> 70\%$) and geometric distortions in echo-planar images without degrading the image quality, signal-to-noise ratio ($< 1.7\%$), or wireless data throughput (maximum variance = 0.04 Mbps) of the coil.

Conclusion—The RF/wireless coil design can provide a solution for wireless data transfer that can be easily integrated into existing MRI scanners for a variety of applications.

Keywords

RF coil; Wireless; WiFi; iPRES; B_0 shimming

*Correspondence to: Trong-Kha Truong, Ph.D., Brain Imaging and Analysis Center, 40 Duke Medicine Circle, Room 414, Durham, NC 27710, USA. Phone: (919) 684-1216. trongkha.truong@duke.edu.

Introduction

In MRI, data transfer between (a) the scanner subsystems, such as the radio-frequency (RF) coil arrays, shim coils, and peripheral systems, and (b) the console or auxiliary computers outside the scanner room is ubiquitous in its day-to-day operation (Fig. 1a). The RF coil arrays in modern MRI scanners have an increasingly large number of coil elements (e.g., for parallel imaging (1)), which requires a complex network of RF traps, baluns, and coaxial connections to the scanner. Similarly, the shim coils (e.g., spherical harmonic shim coils, multi-coil shim coil arrays (2), integrated RF/shim coil arrays (3, 4, 5)) require multiple direct current (DC) connections to the scanner. Additionally, peripheral systems also require connections to transfer data from/to the scanner room, for example, to: correct for subject motion using cameras (6, 7), perform physiological monitoring using sensors (e.g., heartbeat and breathing), perform field monitoring using NMR probes (8), and present stimuli to, or record responses from, subjects during functional MRI. Currently, all of these data are typically transferred through a large network of wired connections to the scanner that require careful cable routing and RF filtering to maintain the data integrity and MR image quality, thereby increasing the cost and maintenance of the system (9).

To reduce the number of wired connections and connectors, other groups have proposed additional antenna systems to wirelessly transfer data between the RF coil array and the scanner (9, 10). However, these prototype solutions require dipole antennas (9), “sniffer” coils (10), and supporting subsystems (e.g., fiber optic cables, splitters, etc.) to be added both to the RF coil array and within the scanner bore to enable the wireless data transfer, which adds complexity and cost to the RF system.

To address these limitations, we propose an innovative RF coil design that can perform wireless data transfer with the existing coil elements of an RF coil array. As such, this design enables simultaneous MRI signal reception/excitation for imaging and wireless data transfer between the RF coil array in the scanner and computers outside the scanner room (Fig. 1b). Since the integrated RF/wireless coil design requires no scanner modifications or additional antenna systems within the scanner bore, it provides a cost-effective, low-maintenance, easy-to-implement solution for wireless data transfer. In this work, proof-of-concept phantom experiments were performed to demonstrate the advantages of the proposed design.

Theory

The integrated RF/wireless coil design allows RF currents at the Larmor frequency, I_{Larmor} , (e.g., 127.7 MHz for a 3T scanner) and within a wireless communication band, I_{wireless} , (e.g., 2.4 GHz for the IEEE 802.11 standard) to flow simultaneously on the same coil element for MRI signal reception/excitation and wireless data transfer, respectively, while maintaining the coil signal-to-noise ratio (SNR). To this end, two custom high-impedance bandstop filters are inserted at the phase planes between the coil element and each of the corresponding transmission lines (Fig. 2c) to provide RF-isolation between the MRI preamplifier and the wireless module. Specifically, a bandstop filter is inserted between the coil element and the MRI preamplifier transmission line (Fig. 2c, red filter) to prevent losses incurred as a result of termination of I_{wireless} into a resistive load. Likewise, a second

bandstop filter is inserted between the coil element and the wireless module transmission line (Fig. 2c, orange filter) to prevent SNR loss as a result of termination of I_{Larmor} into the resistive load of the module. In addition to the bandstop filters, inductors, L , which present a high impedance at the Larmor frequency and a low impedance at the wireless frequencies, are added to the coil element to maintain the resonant frequency and to provide the correct electrical length for resonance in the wireless band.

The RF/wireless coil design can further be adapted to perform, for example, wirelessly controlled localized B_0 shimming. Figure 2b shows a standard integrated parallel reception, excitation, and shimming (iPRES) coil element (3, 4, 11) on which both an RF current at the Larmor frequency and a DC current can flow to perform simultaneous MRI signal reception/excitation and localized B_0 shimming, respectively. In this design, the inductors, L , allow a DC current to bypass the capacitors and flow on the perimeter of the coil element, while the inductors, L_{choke} , maintain the SNR by preventing termination of the RF currents into the DC power supply. The RF/wireless and iPRES coil designs can be combined to create a wireless iPRES (iPRES-W) coil design that can perform simultaneous MRI signal reception/excitation, wireless data transfer, and localized B_0 shimming with a single coil element (Fig. 2d). The inductors, L , previously added to enable wireless data transfer (Fig. 2c) also allow a DC current to flow on the coil element for B_0 shimming without affecting either the RF performance or the wireless data throughput. In this coil design, the DC current is supplied from the wireless module's programmable general purpose input/outputs (GPIOs) rather than from an external DC power supply. As in the original iPRES coil design, the inductors, L_{choke} , maintain the coil SNR and the wireless radiated power by preventing termination of the RF currents, I_{Larmor} and I_{wireless} , into the load presented by the GPIOs.

Methods

The integrated RF/wireless coil design can in principle be used to wirelessly transfer various types of data, including MRI data and other types of data (e.g., physiological monitoring, camera, NMR probes). In this work and as a first application, we used it to perform wireless localized B_0 shimming, while the MRI signal was still transferred from the coil to the scanner through a conventional wired connection. Three experiments were conducted to evaluate the RF/wireless coil design's 1) impact on the SNR, 2) localized B_0 shimming performance, and 3) MR image quality and wireless data integrity during simultaneous scanning and wireless data transmission. These performance metrics were evaluated by acquiring data sets with a single 5×7 cm coil in four configurations: conventional RF coil (baseline) (Fig. 2a); iPRES coil (Fig. 2b); RF/wireless coil (Fig. 2c); and iPRES-W coil (Fig. 2d). The coil's impedance (Z), return loss (S_{11}), isolation (S_{21}), and quality factor were monitored on a vector network analyzer (VNA) (ZNB4, Rhode & Schwarz, Munich, Germany) during each configuration modification to prevent SNR mismatch loss and to monitor the isolation between the preamplifier and the wireless module. The results of the first experiment were presented in (12).

Coil Implementation

The coil was implemented on a 32-channel head coil array enclosure (Fig. 2e). The remaining 31 RF coil traces were not used (open circuit). First, the coil was modified from the baseline configuration into the iPRES configuration by adding the aforementioned inductors, $L = 800$ nH and $L_{\text{choke}} = 800$ nH, to allow a DC current to flow for localized B_0 shimming (Fig. 2b). Each of these inductors provided a minimum isolation of -25 dB and a maximum DC resistance of 0.02Ω . The DC current used for B_0 shimming was provided by an external 32-channel modular DC power supply (W-IE-NE-R, Plein & Baus Corp., Springfield, OH) for this coil configuration.

Next, the DC power supply connections were removed and the coil was modified into the RF/wireless configuration by adding: a 2.4 GHz 802.11b/g WiFi module (Adafruit, New York, NY; $25 \times 38 \times 5$ mm); a new WiFi 50Ω transmission line to connect it to the coil; and a bandstop filter ($S_{21}^{2.4 \text{ GHz}} \sim -0.6$ dB, $Z^{127.7 \text{ MHz}} > 100 \Omega$) to prevent SNR loss. A second band filter ($S_{21}^{127.7 \text{ GHz}} \sim -0.2$ dB, $Z^{2.4 \text{ GHz}} > 100 \Omega$) was added between the MRI 50Ω transmission line and the coil to isolate the WiFi module from losses incurred to the preamplifier and to maintain the radiated power at 2.4 GHz. In addition to these coil modifications, a 2.4 GHz/5 GHz WiFi access point (AP, Apple Airport Extreme, Apple Inc., Cupertino, CA) was positioned inside the scanner room on the wall to enable wireless data to be transmitted between the RF/wireless coil and a peripheral computer in the console room. The access point and the computer were connected by a local area network cable.

Finally, the RF/wireless coil was modified into the iPRES-W configuration by connecting the coil to the WiFi module GPIOs to supply the DC current for B_0 shimming. As in the iPRES configuration, additional inductors, $L_{\text{choke}}^{127.7 \text{ MHz}} = 800$ nH and $L_{\text{choke}}^{2.4 \text{ GHz}} = 18$ nH, were added in series between the coil and the GPIOs to isolate both the preamplifier and the WiFi module from losses incurred to the GPIOs.

SNR Measurements

In this experiment, SNR maps of a uniform spherical water phantom were acquired with the coil in each of the four configurations to demonstrate that the coil modifications performed to enable wireless data transfer and localized B_0 shimming did not degrade the SNR. The SNR maps were acquired on a 3T MR750 scanner (GE Healthcare, Milwaukee, WI) by using a gradient-echo pulse sequence (repetition time (TR) = 500 ms, echo time (TE) = 1.5 ms, voxel size = $4 \times 4 \times 4$ mm) and were calculated by dividing the signal intensity of each pixel by the standard deviation of the noise in a background region outside the phantom.

B_0 Shimming Experiment

To show the utility of the RF/wireless coil design in an application, the iPRES-W coil was used to wirelessly control the DC current needed to shim B_0 inhomogeneities in a phantom. The WiFi module had four GPIOs, each of which could provide a specific DC current. Any of these four DC currents could be combined to generate the total DC current (up to 360 mA) used for B_0 shimming. The appropriate combination of GPIO currents was activated by

sending a set of telnet commands from the computer in the control room to the WiFi module via the iPRES-W coil.

First, a calibration was performed to determine the magnetic field pattern generated by the iPRES-W coil. Specifically, a B_0 map was acquired with the DC current from all four GPIOs (360 mA) applied to the coil. A baseline B_0 map was also acquired with no DC current and was subtracted from this B_0 map. The resulting B_0 map was then normalized by 360 mA to yield a basis B_0 map representing the magnetic field per unit current generated by the coil.

Next, B_0 inhomogeneities were introduced into the uniform phantom by applying a DC current, $I_{\text{pert}} = 300$ mA, from an external power supply to an RF-isolated perturbation loop placed between the phantom and the iPRES-W coil. The optimal DC current for shimming, I_{optimal} , was determined by minimizing the root-mean-square error (RMSE) between a B_0 map acquired with the perturbation on and the basis B_0 map weighted by the DC current. The combination of DC currents from the GPIOs that provided the closest current to I_{optimal} was selected to shim the B_0 inhomogeneities. In this case, the DC current, $I_{\text{shim}} = 360$ mA, from all four GPIOs was applied to the iPRES-W coil. B_0 maps and echo-planar images (EPI) were acquired under five conditions:

1. No DC current was applied to the perturbation loop or the iPRES-W coil (baseline).
2. I_{pert} was applied to the perturbation loop, but no DC current was applied to the iPRES-W coil.
3. I_{shim} was applied to the iPRES-W coil, but no DC current was applied to the perturbation loop.
4. Both I_{pert} and I_{shim} were applied to the perturbation loop and the iPRES-W coil, respectively.
5. Same as 4., but while performing wireless data transfer at a data rate of ~5 Megabits per second (Mbps) between the iPRES-W coil and the computer in the console room.

The B_0 maps were acquired by using a gradient-echo pulse sequence ($TR = 500$ ms, $TE = 1.5$ ms, ..., 11.2 ms, voxel size = $4 \times 4 \times 4$ mm). The EPI images were acquired by using a single-shot spin-echo EPI (SE-EPI) pulse sequence ($TR = 2$ s, $TE = 30$ ms, voxel size = $2 \times 2 \times 4$ mm).

Wireless Communication Experiment

In this experiment, wireless data was transmitted at three different data rates between the iPRES-W coil and the AP while scanning with three different pulse sequences to evaluate the impact that (a) the wireless data transmission at each data rate had on the image quality and (b) each pulse sequence had on the wireless data integrity. Specifically, a transmission control protocol/internet protocol (TCP/IP) WiFi 802.11g data stream was transmitted between the coil and the AP at 3.7, 9.7, and 15.7 Mbps while acquiring: gradient-echo (GRE) images ($TR = 500$ ms, $TE = 1.5$ ms, voxel size = $4 \times 4 \times 4$ mm, 5 slices); single-shot gradient-echo EPI (GRE-EPI) images ($TR = 2$ s, $TE = 30$ ms, voxel size = $4 \times 4 \times 4$ mm, 5

slices, 20 repetitions) as typically used in functional MRI; and diffusion-weighted single-shot SE-EPI images (TR = 4.4 s, TE = 80 ms, voxel size = $2 \times 2 \times 4$ mm, 5 slices, b-value = 800 s/mm², 6 diffusion-weighting directions) as typically used in diffusion tensor imaging. The TCP/IP data streams were generated on the computer in the console room and wirelessly sent to the iPRES-W coil via the AP at the specified data rate. A third-party network protocol analyzer program (www.wireshark.org) was used to monitor the wireless TCP/IP data throughput between the AP and the iPRES-W coil.

First, images of the phantom were acquired and SNR maps were calculated for each combination of pulse sequence and data rate to show that the wireless data transfer did not impact the image quality. The SNR maps were calculated as described above and the SNR was averaged over all slices, repetitions, and/or diffusion-weighting directions for each of the pulse sequences. At the same time, wireless TCP/IP data throughput was measured with the Wireshark program over the duration of each pulse sequence to demonstrate that imaging did not affect the wireless data integrity. Additionally, two baseline conditions were also included in which (a) images were acquired without wireless data transfer and (b) wireless data throughput was measured without imaging. The experimental setup used for this experiment was the same as that used for the B_0 shimming experiment.

Results

SNR Measurements

The SNR maps were virtually identical with the coil in the: baseline configuration (Fig. 3a); iPRES configuration (Fig. 3b); RF/wireless configuration (Fig. 3c); and iPRES-W configuration (Fig. 3d). The corresponding SNR averaged over the whole phantom was 86.6, 86.5, 86.7, and 85.9, respectively. The change in the average SNR between the baseline configuration and the iPRES, RF/wireless, and iPRES-W configurations was only 0.30%, 0.17%, and 1.0% respectively.

B_0 Shimming Experiment

The DC current, I_{pert} , applied to the perturbation loop introduced B_0 inhomogeneities into the uniform phantom (Fig. 4b) that produced significant geometric distortions in the EPI image (Fig. 4g). Performing wirelessly controlled B_0 shimming with the iPRES-W coil drastically reduced these B_0 inhomogeneities (Fig. 4d) and geometric distortions (Fig. 4i). The B_0 RMSE in the phantom was reduced by 72.5% from 44.4 Hz to 12.2 Hz. Further, transmitting wireless data while shimming did not degrade either the B_0 shimming performance (Fig. 4e) or the EPI image quality (Fig. 4j).

Wireless Communication Experiment

The images and SNR maps acquired with the GRE (Fig. 5a,b), GRE-EPI (Fig. 5c,d), and SE-EPI (Fig. 5e,f) pulse sequences were not impacted by the wireless data transmission between the iPRES-W coil and the AP at any data rate. The largest change in the average SNR for the GRE, GRE-EPI, and SE-EPI pulse sequences at any data rate (0, 3.7, 9.7, 15.7 Mbps) was only 0.87%, 0.05%, and 1.6%, respectively (Table 1).

Likewise, the average wireless data throughputs between the iPRES-W coil and the AP were not affected by any pulse sequence. The largest change in the average wireless data throughput for the 3.7, 9.7, and 15.7 Mbps data rates and for any pulse sequence (no scan, GRE, GRE-EPI, and SE-EPI) was only 0.27%, 0.76%, and 1.1%, respectively (Table 2). The largest percentage of the number of data packets lost relative to the number of data packets sent between the coil and the AP, or packet error rate (PER), for any wireless data throughput measurement was only 0.03%. Additionally, the standard deviations of the wireless data throughput were small for each of the pulse sequences, which ensured a reliable wireless data connection between the iPRES-W coil and the AP.

Discussion and Conclusions

In this work, we proposed an innovative RF/wireless coil design that can simultaneously perform MR image acquisition, wireless data transfer, and localized B_0 shimming with a single coil. The experiments showed that: the coil modifications to enable wireless data transfer and shimming did not affect the SNR; the coil in the iPRES-W configuration could perform wireless B_0 shimming and data transfer; the image quality was not affected by wireless data transfer; and the wireless data integrity was not affected by imaging. These results also show that the RF/wireless coil design can perform wireless data transfer with an RF coil without requiring any additional antenna systems or modifications within the scanner bore.

In our proof-of-concept B_0 shimming experiment, we only used a single iPRES-W coil that had a limited DC current resolution and range to achieve an effective B_0 shimming in vivo. However, the digital output voltage of each GPIO can be modulated and amplified to provide an output voltage, and thus DC current, with a higher resolution and range, which would only require a single GPIO per coil element. Additionally, a single iPRES-W coil element can be used to wirelessly control the DC shim currents for an entire iPRES coil array. For example, a 4-channel coil array can be made of three iPRES coil elements and one iPRES-W coil element, the latter of which is used to wirelessly control the DC shim currents of all four coil elements (13).

As a first application, we used the RF/wireless coil design to perform wireless localized B_0 shimming. However, this coil design can also potentially be used to wirelessly transfer MRI data or other types of data (e.g., physiological monitoring, camera, NMR probes). With the data rate of 15.7 Mbps used in our preliminary RF/wireless coil implementation, typical anatomical ($1 \times 1 \times 1$ mm, ~120 MB), functional MRI ($4 \times 4 \times 4$ mm, 5-minute run, ~175 MB), and diffusion tensor imaging ($2 \times 2 \times 2$ mm, 15 diffusion-weighting directions, ~150 MB) data sets acquired in the whole brain with parallel imaging and with an 8-channel coil array could in principle be wirelessly transmitted in about 60 s, 90 s, and 75 s, respectively. For applications with larger data sets, new electronics would be required to increase the data throughput.

In conclusion, the proposed RF/wireless coil design can provide a low-cost solution for wireless data transfer that requires no modifications or additional antenna systems within the scanner bore, and thus can be easily integrated into current MRI scanners. As such, this

design can be readily used for a variety of applications, such as wireless localized B_0 shimming to improve image quality, in both a research and clinical environment.

Acknowledgments

This work was in part supported by grants R21 EB018951, R24 MH106048, R21 EB024121, R01 NS 075017, and S10 OD 021480 from the National Institutes of Health and grants from GE Healthcare and the Duke-Coulter Translational Partnership. We thank Yixin Ma, Julia Bresticker, and Sebastian Luce for their technical assistance.

References

1. Keil B, Wald LL. Massively parallel MRI detector arrays. *J Magn Reson* 2013;29:75–89.
2. Juchem C, Nixon TW, McIntyre S, Boer VO, Rothman DL, de Graaf RA. Dynamic multi-coil shimming of the human brain at 7T. *J Magn Reson* 2011;212:280–288. [PubMed: 21824794]
3. Truong TK, Darnell D, Song AW. Integrated RF/shim coil array for parallel reception and localized B_0 shimming in the human brain. *NeuroImage* 2014;103:235–240. [PubMed: 25270602]
4. Darnell D, Truong TK, Song AW. Integrated parallel reception, excitation, and shimming (iPRES) with multiple shim loops per RF coil element for improved B_0 shimming. *Magn Reson Med* 2017;77(5):2077–2086. [PubMed: 27174387]
5. Stockmann J, Witzel TP, Keil B, Polimeni JR, Mareyam A, LaPierre C, Setsompop K, Wald LL. A 32-channel combined RF and B_0 shim array for 3T brain imaging. *Magn Reson Med* 2016;75(1):441–451. [PubMed: 25689977]
6. Maclaren J, Herbst M, Speck O, Zaitsev M. Prospective motion correction in brain imaging: a review. *Magn Reson Med* 2013;69:621–36. [PubMed: 22570274]
7. Zaitsev M, Dold C, Sakas G, Hennig J, Speck O. Magnetic resonance imaging of freely moving objects: prospective real-time motion correction using an external optical motion tracking system. *Neuroimage* 2006;31:1038–50. [PubMed: 16600642]
8. Barmet C, DeZanche N, Pruessmann K. Spatiotemporal magnetic field monitoring for MR. *Magn Reson Med* 2008;60:187–97. [PubMed: 18581361]
9. Aggarwal K, Joshi K, Rajavi Y, Taghivand M, Pauly J, Poon A, Scott G. A millimeter-wave digital link for wireless MRI. *IEEE Trans Med Imaging* 2017;36:574–83. [PubMed: 27810803]
10. Bulumulla SB, Fiveland E, Park KJ, Foo TK, H CJ. Inductively coupled wireless RF coil arrays. *Magn Reson Imaging* 2015;33:351–57. [PubMed: 25523607]
11. Hui H, Song AW, Truong TK. Integrated parallel reception, excitation, and shimming (iPRES). *Magn Reson Med* 2013;70:241–247. [PubMed: 23629974]
12. Darnell D, Cuthbertson J, Ma Y, Luce S, Song AW, Truong TK. Wifi-enabled RF coil for simultaneous MR image acquisition and wireless communication. *Proc ISMRM* 2017; 25:4430.
13. Cuthbertson J, Darnell D, Bresticker J, Stormont R, Robb F, Song AW, Truong TK. The iPRES-W AIR coil: A flexible RF coil for simultaneous MR image acquisition, wireless communication, and localized B_0 shimming. *Proc ISMRM* 2018;26:16.

Figure 1:

The wired connections within a traditional MRI scanner (a) can be removed by transmitting MRI data (red line), shim control data (blue line), and peripheral systems data (magenta lines) wirelessly with an RF/wireless coil (orange) (b).

Figure 2:

A standard RF coil (a) was modified to further enable localized B_0 shimming(b), wireless data transfer (c), or both (d, e) by allowing an RF current at the Larmor frequency (red) for MR imaging, an RF current in a wireless communication band (orange) for wireless data transfer, and/or a DC current (blue) for shimming to flow on the coil. In this work, the MRI signal was transferred from the coil to the scanner through a conventional wired connection.

Figure 3: SNR maps of the coil (red line) in the: (a) RF coil, (b) iPRES coil, (c) RF/wireless coil, and (d) iPRES-W coil configurations, showing that the SNR was not affected by the modifications made to enable B_0 shimming or wireless data transfer.

Figure. 4:

Localized B_0 inhomogeneities were introduced into a uniform phantom (b) with an RF-isolated perturbation loop (magenta line), resulting in severe geometric distortions in the corresponding EPI image (g). The iPRES-W coil (red line) was able to generate a magnetic field for shimming (c) that substantially reduced the B_0 inhomogeneities by more than 70% and the geometric distortions in the EPI images, without (d,i) and with (e,j) simultaneous wireless data transfer.

Figure. 5:

The images and SNR maps of the phantom acquired with the GRE (a,b), GRE-EPI (c,d), and SE-EPI (e,f) pulse sequences showed no degradation in either image quality or SNR during wireless data transfer between the iPRES-W coil and the AP at the 3.7, 9.7, and 15.7 Mbps data rates.

Table 1:

Average SNR for each pulse sequence and data rate.

	0 Mbps	3.7 Mbps	9.7 Mbps	15.7 Mbps
GRE	96.3	95.7	95.9	95.5
GRE-EPI	164.8	164.8	164.8	164.8
SE-EPI	87.1	86.0	87.4	87.4

Table 2:

Wireless data throughput (average $\pm$ standard deviation) for each pulse sequence and data rate.

	3.7 Mbps	9.7 Mbps	15.7 Mbps
No Scan	3.73 $\pm$ 0.02	9.73 $\pm$ 0.02	15.65 $\pm$ 0.15
GRE	3.72 $\pm$ 0.02	9.73 $\pm$ 0.03	15.76 $\pm$ 0.14
GRE-EPI	3.73 $\pm$ 0.02	9.69 $\pm$ 0.11	15.83 $\pm$ 0.16
SE-EPI	3.73 $\pm$ 0.02	9.76 $\pm$ 0.05	15.77 $\pm$ 0.21