Comparisons of RF Signal Tuning and Matching Networks

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Target audience
RF engineers and MR scientists with a basic knowledge of MR hardware circuits and systems.

Purpose
An RF coil is a basic part of hardware in magnetic resonance (MR) imaging and spectroscopy. An RF coil must be tuned at the Larmor frequency and matched to 50 ohm to achieve maximum performance when an RF coil excites protons and receives nuclear magnetic resonance (NMR) signals.[1] There are three basic tuning/matching circuit topologies (L-, Pi-, and T-network) in RF designs, but most RF coils in MR applications employ a L-network with a capacitor-capacitor circuit because it has a simple structure and is easy to manipulate.[2] The use of an inductor is not preferred because it may cause problems: RF radiation, signal loss causing decreased B1 field, and, most of all, difficulty in building a variable component. In an L-network, the series variable matching capacitor must pass all RF power for the coil through it, which can result in high temperature, current and/or voltage. The stress on this component can be a limiting factor in advanced circuit design, such as actively controlled capacitor.[3] Therefore, a different tuning and matching method must be developed for next-generation RF coil design. This study proposes a new Pi-network and shows comparisons of impacts of three aforementioned networks on MR images. The results will guide the reader to the proper tuning and matching network selection for a given RF coil application.

Methods
The Pi-network described here is composed of three capacitors. For the series capacitor, a fixed value capacitor is used for durability and simplicity. Two variable capacitors are in parallel for adjusting resonant frequency and input impedance of the coil. Three RF signal tuning and matching networks have been built with a same TEM resonating element (a 12 cm x 1.9 cm strip on a epsilon = 2.2 substrate) as shown in the first row of Table 1 and evaluated with the performances of single-channel RF coils. The second row shows conceptual tuning and matching steps starting with the terminating capacitor (a), the effect on the Smith Chart of the microstrip line of a TEM resonator (b), the matching/tuning network (c-e), and ending with the 50 ohm input coaxial cable in the center of the Smith Chart. Although the L-network has a clear ability for adjusting the real and imaginary part of the input impedance of RF coils, the Pi- and T-networks with three components have the advantage of more flexibility than two-component L-network and provide enough variety to fit most loading situations. After loading with a phantom, proper capacitances were chosen to create a well resonating circuit at 297.2 MHz for 7T on the test bench. The efficiency of tuning and matching networks was verified by comparing the intensity of B1+ fields.

Results
Workable capacitor values and acceptable microstrip length for 7T are shown in the third row in Table 1. In an L-network, low capacitance produces high impedance resulting in high insertion loss and local E-field. A T-network can extend the length of a microstrip line for long field of view imaging because C_{ST2} (C on the Smith chart diagram) compensates the extended length. The forth row in Table 1 presents MR images with a cylindrical phantom with the respective tuning and matching circuit topologies. The Pi-network with all three capacitors creates higher B1 field than others because the low impedance of a series capacitor (C_{SPi}) which has a simple (not variable) structure reducing the loss of RF signal. The MR images confirm that the Pi-network reduces losses compared to the L-network, which has a spatially large, lower-Q, variable capacitor in series with the input power. This circuit topology is compatible with adding additional complex circuits to the network. In addition, the Pi-network can minimize common mode current through its symmetric structure; therefore, the Pi-network does not need a cable trap.

Conclusion
The results of this study show that the Pi-network with three capacitors creates the highest B1 field and a more balanced circuit that does not need a cable trap. The most important thing is that a spatially large variable capacitor with a complex structure causing high loss is not required on the main RF signal line. Thus, this technique makes it possible to build additional circuits (e.g., electrically adjusted capacitor array, power monitor, or electrical decoupling) inside a tuning and matching network by only adjusting shunt capacitors.

Acknowledge
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References
[1] Sung-Min Sohn., et al., 22th ISMRM. p.318, 2014 [2] D. M. Pozar. Microwave Engineering. Wiley, 2012 [3] The RF capacitor handbook. American technical ceramics. 1994

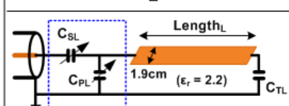
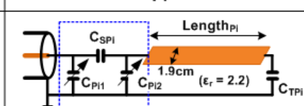
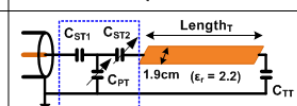
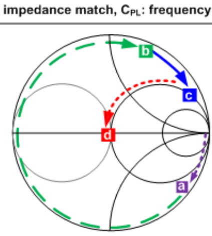
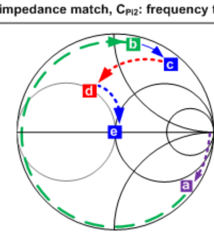
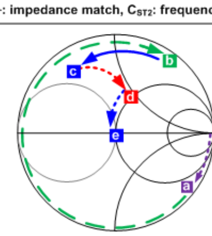
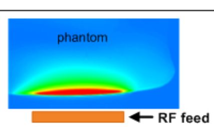
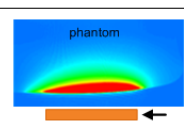
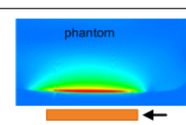
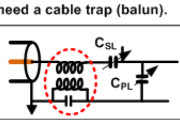
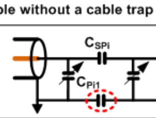
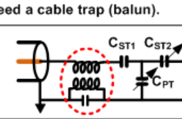
		L	Pi	T
1	Topology (variable, and fixed capacitor)	 C_{SL}: impedance match, C_{PL}: frequency tune	 C_{Pi1}: impedance match, C_{Pi2}: frequency tune	 C_{PT}: impedance match, C_{ST2}: frequency tune
2	Conceptual tuning and matching steps (on the Smith chart)	 a C_{TL}, b $Length_T$, c C_{PL}, d C_{SL}	 a C_{TPi}, b $Length_{Pi}$, c C_{Pi2}, d C_{SPi}, e C_{Pi1}	 a C_{TT}, b $Length_T$, c C_{ST2}, d C_{PT}, e C_{ST1}
3	Proper capacitance and conductor length range for 7T	C_{SL}: 1-5 pF, C_{PL}: 1-20 pF, C_{TL}: 2-6 pF 14 cm < $Length_L$ < 18 cm @ C_{TL} = 3 pF 12 cm < $Length_L$ < 16 cm @ C_{TL} = 5 pF	C_{SPi}: 5-30 pF, C_{Pi1} & C_{Pi2} 1-20 pF, C_{TPi}: 2-6 pF 13 cm < $Length_{Pi}$ < 21 cm @ C_{TPi} = 3 pF 11 cm < $Length_{Pi}$ < 19 cm @ C_{TPi} = 5 pF	C_{ST1}: 10-20 pF, C_{ST2} & C_{PT}: 1-20 pF, C_{TT}: 2-6 pF 16 cm < $Length_T$ < 26 cm @ C_{TT} = 3 pF 13 cm < $Length_T$ < 23 cm @ C_{TT} = 5 pF
4	MR images (low flip angle) with single element at 7T	 phantom, RF feed	 phantom	 phantom
5	Impact of common-mode current	Unbalanced: need a cable trap (balun).	Semi-balanced: acceptable without a cable trap (balun)	Unbalanced: need a cable trap (balun).
6	True-balanced structure			

Table 1. Comparisons of RF signal tuning and matching methods and MR images: L, Pi and T network.