An Investigation of RF Frontend Scalability

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Introduction: Phased array[1] is an effective RF frontend scheme due to its support for tailoring spatial sensitivity and optimizing multi-port signal combination. The scheme is the foundation for numerous MR coils, including an arsenal of dedicated workhorse receive coils each optimized for a certain body region, parallel MRI acceleration, and nucleus or Larmor frequency. To improve scan workflow a significant recent development strives to consolidate a clinical scanner's suite of phased array coils with a multi-element coil ensemble that encloses a subject in a fixed fashion but allows application-dependent multi-port signal selection/combination (through hardware/reconstruction).

The ultimate task of creating a "one-structure-fits-all" coil that can replace various dedicated coils with comparable or better performance is very challenging. Against the backdrop of lowering parts cost and increasing channel count, it appears meaningful to explore the perspective of optimizing RF frontend *scalability*, the ability for a same RF coil structure to adapt to most imaging tasks by leveraging flexible and advantageous signal combination afforded by a large number of channels. We present below a theoretical analysis as well as example full-wave EM simulation results.

Theory: A common approach to assessing an RF coil in terms of transmit, receive, SAR and body noise is through mapping $B1^+$ and $B1^-$ fields and quantifying loss (power and noise). These quantities are determined by the radio-frequency **B** and **E** fields that the coil induces in the body[2,3] and the body conductivity. Calculations of these quantities from **B**, **E**, and conductivity are widely employed in single- and multi-port coil design work. The point is that the **B** and **E** fields in the body determine body's influences on and contributions to signal, noise and power. In a given coil-subject configuration these define the coil's *inherent performance*. While degradations from the inherent performance happen down the stream due to losses in the coil, coil-system interface and system electronics, assessing and managing such degradation is not in the scope of the present investigation.

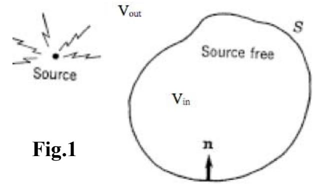
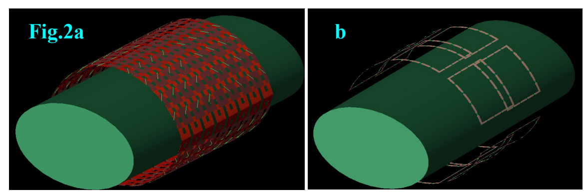


Fig.1

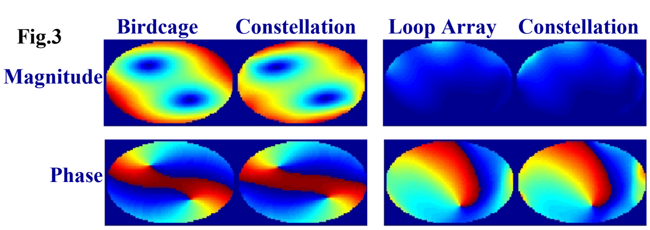
To analyze a coil structure and the **B** and **E** fields in the body, the *field equivalence principles* of electrodynamics[4] offer important insights. Consider any hypothetical enclosing surface *S* (see Fig.1) that defines an inside region V_{in} containing the body and an outside region V_{out} containing radiating sources (RF coils). Love's equivalence theorem states that the EM field within the entire V_{in} produced by the given sources in V_{out} is the same as that produced by a system of virtual sources on the surface *S*. Furthermore, if the field produced by the original sources is **E**, **H**, then the virtual sources on *S* consist of a current sheet of density $\mathbf{n} \times \mathbf{H} + \mathbf{E} \times \mathbf{n}$, where the normal **n** points from V_{out} into V_{in}. This statement's assertion on *completeness* has implications for MR – an enclosing surface capable of accommodating diverse surface current distributions can possibly replace *any* external MR coils, and further, act as a coil creating EM fields that delivers ultimate performance[5]. The transmit and receive channels have the role of being the driver for surface current distributions (the receive case is understood with the principle of reciprocity[2,3]), and a large channel count tends to facilitate the creation or control of desired distributions. In other words, as far as EM fields and inherent performance are concerned, the combination of a single surface structure and a surface current driving mechanism, in theory, can do what existing MR coils can, and more. This is an intriguing aspect underpinning the scalability perspective.

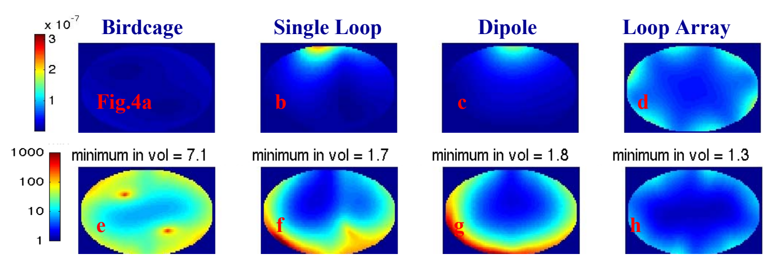


Method and Results: Full-wave EM simulations were performed at 3T frequency with xFDTD (Remcom, State College, PA) to investigate scalability. Approximation of a continuous surface structure with controllable RF current distribution was done using a constellation coil[6] that accommodates various RF current grid patterns at 128MHz. The structure encloses the mid section of a uniform 36cm x 22cm x 70cm elliptical phantom (σ=0.6SI/m and ε_r=80) in a two-piece clamshell form, spanning 60cm and 38cm in horizontal and longitudinal directions respectively (Fig.2a). Each piece is consisted of two sets of evenly populated hollow patches (4.2cm x 3.8cm) sandwiching a 0.79mm-thick substrate (ε_r=10.2). The patches, each capacitively coupled to its four immediate neighbors on the other side of the substrate, form a grid structure accommodating RF current distribution on a 3D surface substantially enclosing the phantom. Sinusoidal currents were injected (128MHz, 50Ω source impedance) into 128 regularly distributed ports, with individually set magnitudes and phases (port coefficients), to drive the creation/control of the RF current distribution on the grid. 128 pairs of **B** and **E** fields resulting from individually driving the 128 ports with unit-magnitude 128MHz current were calculated. Because of linearity the actual **B** and **E** fields resulting from an arbitrary set of port coefficients will be the coefficient-weighted sum of the 128 **B** and **E** fields respectively.

A first study tested the coil's ability emulating various MR coils that included a quadrature-drive birdcage coil (∅=61cm, L=45cm), a 10cmx10cm loop coil above the phantom, a 20cm-long adapted $\lambda/2$ dipole antenna above the phantom, and a torso array composed of 12 loop elements driven under an arbitrary set of port coefficients (Fig.2b). In each emulation case, volume profiles of both the **B** and **E** fields were simultaneously targeted, and the set of port coefficients applied to the constellation coil's 128 ports were determined by least squares fitting. Fig.3 shows comparisons of $B1^-$ components at a center trans-axial slice location. Comparisons at other locations, of E fields, and with loop and dipole coils also show good agreement between profiles created by a target coil and by the emulating constellation coil, despite the fact that the capacity of surface current distribution is confined by the limited coverage/continuity of the surface and the finite number of ports.

A further study compared relative SNR of all five coils. In the constellation, the loop array, and the 2-port birdcage cases, optimal voxel-by-voxel combination of multi-port signals was applied[1] (where $B1^-$'s were derived from **B**'s and noise covariance matrices were calculated using σ and **E**'s). For the four conventional coils Fig.4 shows, for the center trans-axial slice location, their SNR maps (a-d) and the ratio of constellation coil SNR to their SNR (e-h). The improvement in SNR with the constellation coil was found to be at least 30% in the torso volume.





Discussions: In this study the task of developing a "one-structure-fits-all" coil is investigated from the perspective of scalability. The theoretical and simulation analysis indicate that a structure that best accommodates various current distributions on an enclosing surface may enable not only emulations of but higher performance than existing externally applied coils, and further, for approaching ultimate versatility and performance. Prior studies suggested that phased array has the potential to support scalability to the point where dense small loops start to suffer from coil noise dominance or fabrication difficulty. Constellation coil offers alternative structures that are potentially more scalable. An experimental investigation is on-going comparing the scalability of phased array and constellation structures. For the latter there are indications that the classic recipe for interfacing a phased array with parallel receive chains may not be applicable. Low input impedance pre-amp decoupling for example tends to substantially impede the flow of RF current at the port locations, working against the principle of having structural continuity for RF current. In addition to interface electronics, designing a constellation structure to work with 32 or less channels is also important given the typical configurations of existing scanners.

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