Transmit Arrays and Circuitry

Gregor Adriany
gregor@cmrr.umn.edu
University of Minnesota, Center for Magnetic Resonance Research
2021 6th Street SE, Minneapolis, MN 55455, USA

Target Audience: Engineers and Scientists interested in research at higher magnetic fields (3T and above)

Objectives: Understand how Transmit Arrays address key RF coil related issues such as B_1^+ field in-homogeneities, that arise at ultra high fields due to the increased operating frequency (UHF) and resulting shortened RF wavelength.

Background: Transmit arrays can help mitigate [1-4] a number of challenging issues that come up at higher magnetic fields and the concomitant higher operating frequencies. The two most noticeable difficulties encountered are increased B_1^+ field in-homogeneities and SAR related challenges associated with the overall increase in RF power demands and E-field heterogeneity.

For body dimensions at 3T and head dimensions at 7T and above the RF wavelength in dielectric tissue is comparable or smaller than the dimensions of the human anatomy. This in turn leads to RF phase related traveling time differences, prominent wave behavior and the potential for a significant difference between transmit B_1^+ and receive B_1^- fields [5-10]. It is possible to correct some of the resulting B_1 field in-homogeneities within traditional multi-mode resonant volume transmit coils through individual amplitude and phase control of quadrature feed points [5], coil design modifications[11], as well as individual resonance element adjustments [12, 13]. However even better control of these effects can only be achieved with more degrees of freedom provided by, for example, dedicated transmit array systems that are capable of supporting a higher number of independent channels for RF transmission and that allow for “RF shimming” [14-24]. Ideally transmit arrays can provide for B1 transmit field homogeneity, transmit efficiency and SAR minimization the equivalent of what receive arrays achieve for optimal SNR and parallel imaging performance. Particularly since transmit arrays support parallel excitation pulses across multiple coil elements, as first proposed by Katscher [25] and Zhu [26].The related rapidly emerging parallel transmission methods significantly improve RF excitation homogeneity and they can achieve high spatial selectivity and pulse acceleration by taking full advantage of the ability to influence B_1^+ fields through temporally and spatially varying RF excitation pulses [21, 27-37].

Achieving consistent and safe performance with such complex systems requires stable, well characterized and calibrated transmit array channels as well as good electromagnetic decoupling and/or a clear understanding of the interaction between the individual transmit elements. Various coil decoupling methodologies have been proposed [38-43] and have shown to yield excellent transmit array element separation. Recently decoupling methodology has been extended to include a number of promising directions incorporating novel RF amplifier designs and more sophisticated RF front-end designs. Some of these concepts hold promise to reduce

RF amplifier related costs and eventually allow for a higher number of transmit channels [18, 44-48]. Similar to static magnetic field shimming (B_0), RF transmit field (B_1^+) shimming methods using transmit arrays for subject specific and region of interests (ROI) shimming have been introduced [49-54]. Optimum utilization of transmit array coils, also requires overcoming challenges for rapid B_1 mapping, B_1 optimization and various RF safety related implications [55, 56]. Here promising methodology has been described [31, 54, 56-59] indicating that such challenges can be addressed.

The most important component of a transmit array system is the RF coil and the related tune and decoupling circuitry. For transmit array RF coil designs, multichannel combination of standard RF coil circuitry elements such as various shapes of loop coils [14, 22, 60-64] or transmission lines[20, 23, 65-72] are typically used. Like TEM volume coils [73], transmission stripline arrays utilize the fact that at very high frequencies, radiation losses and coil coupling are elegantly addressed by circuit designs that incorporate a ground plane or RF shield into the resonance structure as an integral part of the circuitry [65, 66, 68, 74-77]. Furthermore, the broadband decoupling characteristic of transmission line elements [40, 65] due to the RF shield in close proximity reduce the difficulties of decoupling nearest neighbor elements. However, this potentially limits RF penetration and coupling to the sample. Similarly ultra high field loop coil arrays can be built with an RF ground plane in close proximity to improve reliability and limit interaction with the overall MR bore environment [60, 61, 64, 78, 79]. For coils in close proximity to the sample it has been shown that it is possible to built loop arrays without an RF ground plane [22, 62, 63]. For loop type structures it is also possible to achieve the desired individual RF feed points and decoupled resonant elements by following the “degenerated” birdcage circuitry design principles [80]. To improve longitudinal coverage and overall RF efficiency coils can be arranged in rows along the z-direction - this was initially proposed by Mao[52] and first demonstrated for stripline arrays by Adriany [69] and later confirmed for loop arrays by Gilbert Avdievich and Shajan [81-83]. Raaijmakers et al. [84] successfully extended the basic building blocks of loops and transmission lines towards radiative antenna elements and introduced dipole antennas for human torso applications. Raaijmakers also pointed out the importance of the complex poynting vector as an evaluation measure for effective RF energy flux. It was indeed demonstrated that efficient spin excitation and RF signal penetration with dipole antennas for sites located one or more wavelength deep could be achieved. More recently a number of researchers simulated and built modified dipole geometries; for example, Winter et al. described a bow tie antenna electric dipole array [85]. It has indeed been shown that both loops and dipole antennas have more favorable pointing vectors towards the center of the sample compared to striplines; which have significant energy flux in the longitudinal ‘transmission’ direction. Since antennas in various designs and configurations are extensively described in the literature they are an exciting addition to nearfield coil resonant circuitry and hold great promise for ultra high field/frequency MR. It appears that dipoles in combinations with loops and/or stripline elements indeed hold great promise to emulate the ideal current patterns[86] and thus have the potential to yield optimal transmit efficiency and minimal SAR.

The question of the benefits or drawbacks of a higher number of channels is currently under investigation. Simulation results by Mao [52],Wu [32] and Lattanzi [87] indicate general benefits for a higher number of channels in terms of the ability to influence field homogeneity, transmit efficiency and SAR. The extension in longitudinal coverage also immediately requires a higher number of transmit channels beyond the typically available eight channels of commercially available standard parallel transmit systems. One way to nominally increase the number of independent RF transmit coil elements is the utilization of mode based excitation patterns generated by a Butler matrix [88-90], however Butler matrices offer significantly less control.

There is some hope that arrays combined with lower cost “on coil” or “near coil” RF amplifiers are promising building blocks for more cost-efficient transmit arrays with higher number of channels [91].

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