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# Functional Microwave Imagining System based on Cognitive Scanning for Brain Activities Monitoring: A Feasibility Study

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*Abstract*—**In cognitive systems we need to make a supplementary link between architecture and supporting algorithms to exchange information and manage the extracted data. This paper presents a new concept of cognitive scanning using hybrid MIMO-phased array radar (HMPAR) for functional near-field imaging of brain activity in the framework of algorithm/architecture co-design. In the proposed paradigm, the communication challenges of cognitive scanning are concurrently searching, detecting and tracking the activated brain regions. The proposed system model is a HMPAR approach including MIMO array for target detection and MIMO-phased sub-array for tracking the detected targets in the allocated subarrays. In the current paper, we assess the feasibility of using a waveform and pattern (beam-forming and beam-steering) diversities for developing the proposed framework. In order to improve the resolution, contrast and accuracy of a characteristics target inside a biological phantom, some initial methods are employed for 1D time domain reflectometry and 2D visualization. Simulated results show that the proposed framework could be feasible for functional microwave imaging application.**

***Index Terms***— **Algorithm/Architecture Co-Design, Hybrid MIMO-Phased Array Radar (HMPAR), Cognitive Scanning, Functional Microwave Imaging System (FMIS), Waveform Diversity, Near-Field Phased Array.**

## I. INTRODUCTION

In 2010, the overall European share of the cost incurred due to brain disorders was estimated at €798 billion including direct health care cost, direct nonmedical cost, and indirect costs [1]. Current diagnostic techniques for brain imaging include x-rays, computed tomography (CT), ultrasound (US), and magnetic resonance imaging (MRI). Conventional X-rays and CT scanners emit ionizing radiation, and exposure to them should therefore be minimized [2-4]. Ultrasound requires direct skin contact, and is suited only for short term monitoring. Due to their mechanical complexity and size, magnetic resonance imaging is not practical for long term continuous monitoring. In addition, metallic objects are prohibited, thereby excluding patients with a surgical prosthesis or pace maker [5]. Although medical technology is progressing fast and researchers continue their efforts on finding new methods to study the brain activities, the need for a non-invasive, low-cost and portable system for neuro imaging is as present as ever before. Among neuro imaging techniques, functional magnetic resonance imaging (fMRI) is currently the most widely used as it can provide excellent detailed anatomical and physiological information related to pathologies such as brain tumors, Alzheimer’s disease, and epilepsy. However, todays’ fMRI scanners are excessively large and expensive, while suffering from the associated problem of ionization of the irradiated cells.

Array based microwave imaging system has great potential to provide the means of noncontact long-term continuous monitoring of cancerous tissues, brain stroke tomography, and even functional brain imaging not possible using other existing techniques [6-7]. The underlying hypothesis of microwave based functional brain imaging is that, if we can detect local changes in blood volume inside the brain precisely enough, we can infer which parts of the brain are active when performing various tasks such as moving various muscles, making decisions, experiencing emotions and others. According to the author’s knowledge, there has been only one reported feasibility study partially related to the proposed concept, and that has been focused on a single transceiver and based on their results detection of physiological activities are not yet possible at the predicted levels of attenuation [8]. In a general sense, multistatic-radar-based imaging approaches use arrays of transmitter and receiver antennas to obtain the backscattered signals [9]. Furthermore, tomography approaches require a large number of antennas for gathering sufficient backscattered field, needed to solve the inverse scattering problem. For each transmitting antenna a number of receiving antennas, located at different locations measure the field [10]. A large acquisition time is the major disadvantage associated with these types of system and several signal-image processing methods are proposed to estimate medium properties [11]. In the case of brain activities monitoring a novel ultra-fast super-resolution technique is required to overcome these bottlenecks.

In this paper, we present a novel functional microwave-imaging paradigm based on cognitive scanning approach for concurrently searching, detecting and tracking of brain activities as a multiple moving targets scenario under test. The envisioned cognitive scanning based on HPMAR framework has the waveform diversity capability in the MIMO framework to improve the resolution, contrast, and accuracy of target localizing for 1D time domain reflected signal and reconfigurable antenna array flexibility to determine sub-phased-array transmitter antennas to 2D imaging results. In order to show the feasibility study of the proposed framework we put together some of the high-resolution techniques, based on the methods that we published from 2014 in this area [12-14]. The time domain reflectometry (TDR) analysis is proposed to study of the waveform diversity effects on range resolution improvement. Also for realizing space scanning using confocal focusing algorithm, two receiver's subarrays configurations including rectangular and round structures are used. This 2D visualization proves that it possible to make a trade of between resolution and contrast improvement. Simulated results show that the proposed framework could be a good candidate for functional microwave imaging application.

## II. ALGORITHM/ARCHTECTURE CO-DESIGN PRESPECTIVE OF FUNCTIONAL MICROWAVE IMAGING

The envisioned algorithm/architecture co-design for the proposed functional microwave imaging system is shown in Figure 1. As shown in Figure 1, unlike conventional multi-static microwave imaging systems that have data and control flows processes, in the proposed cognitive scanning a supplementary information fusion process is needed. In the point of information fiusion and knowledge extraction view, existing methodologies and tools of cognitive descision making related to modern imaging systems pose as serious bottlenecks in the overall product development cycle. By relying on cognitive scanning techniques and the proposed reconfigurable structures, it aims at developing an innovative desiccation making scheme suitable to functional microwave imaging system [15].

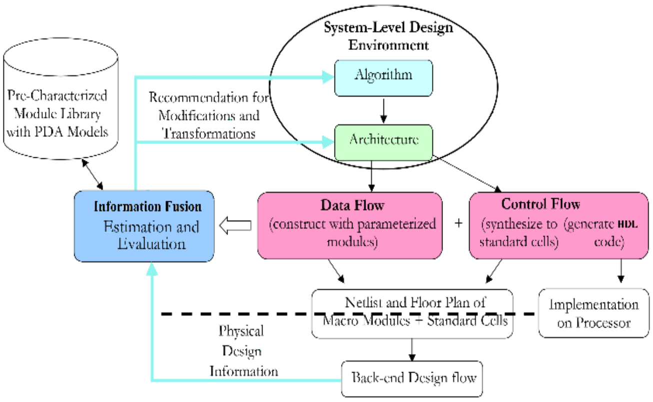
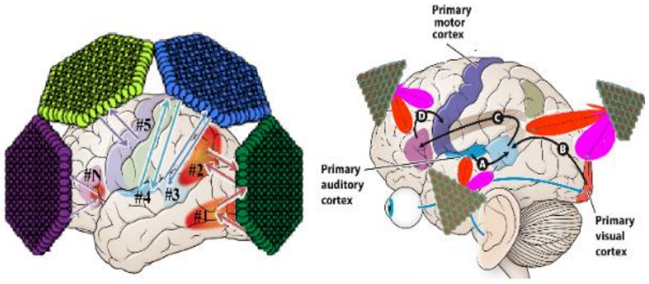


Figure 1. The proposed algorithm/architecture co-design based on knowledge extraction and information fusion for functional microwave imaging system.

Figure 2 shows a functional neuro-imaging example of the brain during language activation that can be consider as multiple moving target scenario [16]. In addition, spanned-beams and steered-beam of the partitioned sub-arrays based on cognitive HMPAR are shown Figure 2. The proposed concurrently searching, detecting and tracking using HMPAR includes two cognitive operations, one is the sub-array partitioning based on using orthogonal signals in MIMO framework, and another is the phased array radar that each element transmits a scaled version of a single waveform.



(a) (b)

Figure 2. Example of the concurrently searching, detecting and tracking of activated regions of brain during language activation (a) MIMO structure of the meta-array to detect activated regions as a multi targets scenario, and (b) Phased array structures to track activated region’s variations by creating several sub-arrays.

The scheme of the envisioned cognitive partitioning of sub-arrays in the proposed HMPAR framework is shown in Figure 3. In software section, cognitive algorithm will support waveform and pattern diversities, which will be controlled by switching matrix in the architecture section. The proposed cognitive scanning program prepares code division in order to provide a set of smart pulse shaping scheme and array configuration based on self-organizational techniques. In other words, anatomical information that can be obtained from the radar based imaging system includes the depth, orientation, size and shape of tissue materials. In addition, in order to enhance the generated images in terms of resolution and contrast, the designed array configuration must be change based on anatomical and physiological information that have been extracted in each iteration of the cognitive program.

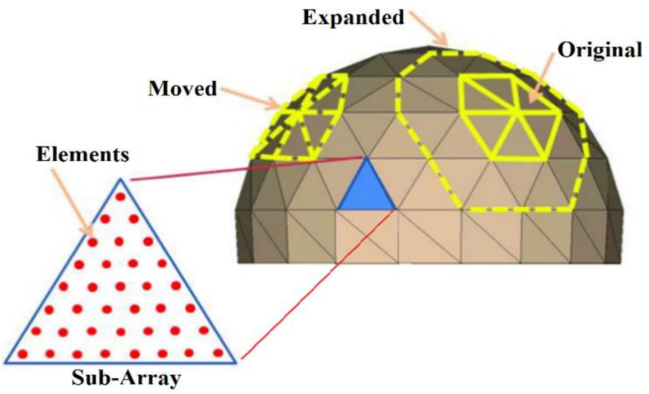


Figure 3. Scheme of the envisioned cognitive partitioning of sub-arrays in the proposed HMPAR framework.

The focus of this study is on realization of the hardware requirements for the proposed framework. In this point of view, Figure 4 shows the required hardware reconfigurable structures of antenna array and waveform-diversity techniques that enable super resolution, high precisions and contrast capabilities for anatomical and physiological feature extractions of the brain. Regarding to waveform diversity view, rise time, settling time and pulse aberrations of the stimulus signal can significantly affect system's resolution of impulse radars [17]. Moreover, a novel beam-steering subsystem providing true time-delay capability can be developed based on switched antenna array configuration in order to reduce mutual coupling between antenna elements and increasing reflections from the region of interest [18].

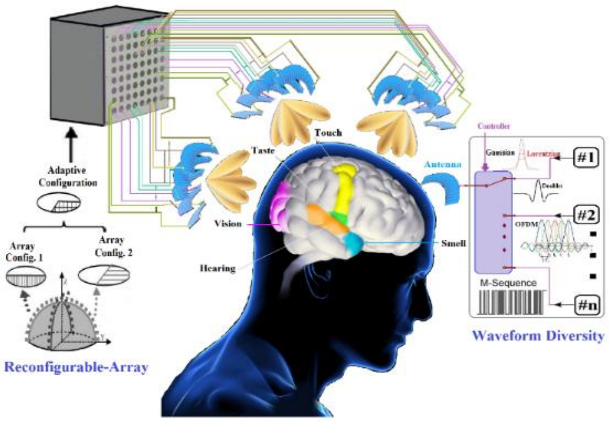
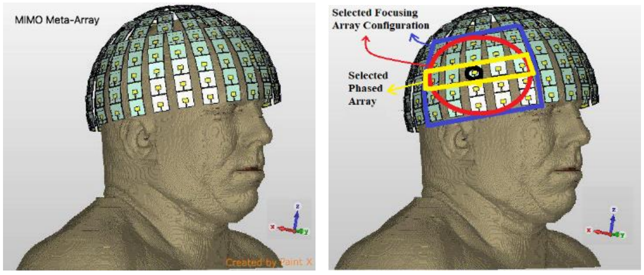


Figure 4. The proposed super resolution techniques for anatomical and physiological feature extracting from the brain activities, (a) Pattern diversity based on reconfigurable antenna array structure, and (b) waveform-diversity based on arbitrary waveform generator.

## III. RESULTS AND DISCUSSIONS

In this section some time-space scanning techniques are employed to improve the resolution, contrast and accuracy of target characteristics for 1D time domain reflectometry and 2D visualization results. In brain surface scanning, we proposed two antenna array structures to create 2D imaging results. From these results, we found that using round antenna array can get a relative higher contrast and using rectangular antenna array can get a relative higher resolution. In brain depth scanning, we explore the advantages of generating a novel stimulus, similar to the traditional signal but instead of a Gaussian like impulse, a modified signal using new shapes will be employed. The advantage conferred by “high resolution” is that decreased rise time is available and by “high precision” is that more energy is available at higher frequencies than with conventional impulse TDR, subsequently a relatively higher bandwidth and higher accuracy in identifying the reflected voltage is achieved [12].

Figure 5 illustrates the proposed conformal antenna array configuration around full head voxel model in the CST medium for functional microwave imaging system [19]. Figure 5 shows generating MIMO meta-array based on adaptive waveform diversity and phased sub-array to beam steering and focusing beamforming algorithms capable of gathering high-resolution and high-precision backscattered signals from the moving targets. As shown in Figure 5 (b) for phased array we selected 5 antennas in the center row of the selected subarray also for beamforming in focusing algorithm two rectangular and round antenna array configuration have been selected. In this study in order to simplicity in simulation we have used a configuration of a hemispherical biological tissue phantom model (radius: 10 cm) with a spherical target (radius: 1 cm) in the canter of the medium [14].



(a) (b)

Figure 5. (a) Meta-array of the MIMO array for signalling strategies, amd (b) Sub-array selection for beemsteering and beamforming (balck: refrence transmitter in focusing algorithm, red: round array configuration, blue: rectangular array configuration and yellow: phased array configuration).

### A. *Waveform Diversity Approches for Range Resolution Improvment*

One of the challenging problems in imaging radar is range resolution improvement. Rise time, settling time and pulse aberrations of the stimulus signal can also significantly affect the system's range resolution [13]. Typically, if an imaging radar system has insufficient range resolution, small or closely-spaced targets may be smoothed together into a single aberration in the waveform. In order to demonstrate waveform diversity effects on reflected signals, first we present novel time domain pulse shaping approaches for high-resolution and high-precision techniques. In order to focus on time domain sampling we present here one dimensional time domain reflectometry (TDR) results simulated in ADS [20]. Here we present three basic peaks such as Gaussian, Lorentzian and Voigt. General formulas of Gaussian and Lorentzian pulses are shown in equations (1) and (2), in which $\sigma$ and $\gamma$ are time constants.

$$G(t,\sigma)=e^{-\left(\frac{t-t_0}{\sigma}\right)^2} \tag{1}$$

$$L(t,\gamma)=\frac{\gamma}{\pi\left(t^2+\gamma^2\right)} \tag{2}$$

The Voigt function is made by convolving Gaussian and Lorentzian functions with equal widths [13]. The Voigt pulse is generated using the following formula:

$$V(t,\sigma,\gamma)=\int_{-\infty}^{\infty} G(t',\sigma).L(t-t',\gamma)dt' \tag{3}$$

Therefore for the Voigt pulse the function is as following:

$$V(\gamma,\sigma)=\frac{1}{\sqrt{4\pi\sigma}}\int_{-\infty}^{\infty}\frac{e^{-(\gamma-t)^2/(4\sigma)}}{1+t^2}dt \tag{4}$$

A comparison of this peak with Gaussian and Lorentzian peaks is given in the Figure 6. All three of these functions have equal widths of 100 psec.

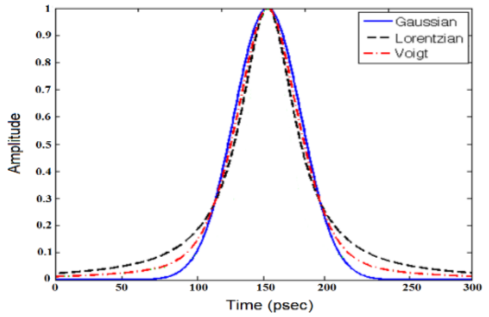


Figure 6. Graph of the Gaussian, Lorentzian and Voigt (their convolution) functions.

For comparison, the reflected waveforms comparison for simulated results by ADS, ideal pulse (a rectangular pulse with 10 psec pulse-width), Gaussian, Lorentzian and Voigt pulses for the mentioned biological tissue phantom with a target is shown in Figure 7. The simulated results showed smooth reflection for the Lorentzian pulse results. Smooth TDR can be advantageous when the user is looking for precision in spatial localization [12]. Otherwise, the reflection for the Gaussian pulse has a sharper edges that leads to higher accuracy of the target's location. Therefore, the TDR results in modified case follow the reference target more closely than does the ordinary TDR results as shown in Figure 7. In addition, it is clearly seen from Figure 7 that TDR results with the proposed Voigt signal has very good localization resolution and smooth TDR for precision [12]. It was found out that by using the modified excitation Voigt signal generated by convolving Gaussian and Lorentzian both the location resolution and the reflected voltage value can be precisely and simultaneously achieved.

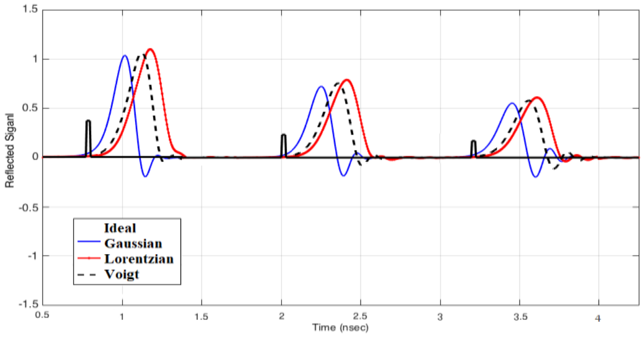
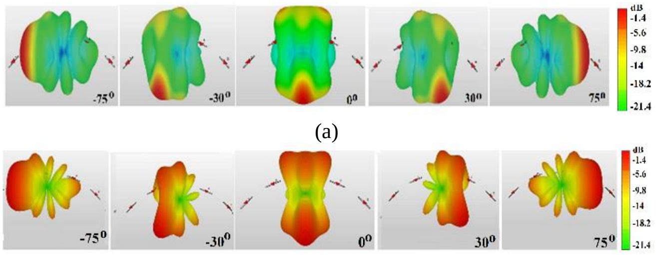


Figure 7. The reflected waveforms comparison for simulated results by ADS, idael pulse, Gaussian, Lorentzian and Voigt pulses for the biological tissue phantom with a target.

### *B. Near-Filed Beamforming Approaches for Cross-Resolution Improvment*

In order to illustrate effects of using reconfigurable array structure in cross resolution, we investigated a phased array configuration in the selected subarray and two antenna arrays configurations to collect backscatter signals as shown in Fig. 5. Figure 8 shows beam-steering situations of the selected phased array for both far-field and near-filed radiation patterns. In order to analyses the near-field performance of the antenna, finite-difference time-domain (FDTD) method based electromagnetic simulator, CST Microwave Studio is utilized. Several time-domain near-field probes are placed at 20 mm distance from the antenna surface with 20° angular difference around the antenna. As shown in Figure 8 the selected phased array has the beam steering ability to span all of the degrees. The phase difference in far-filed and near filed are $\Delta\emptyset = \pi/6$ and $5\pi/6$ respectively [21].

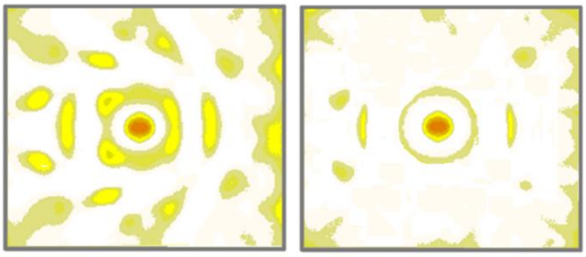


(a)

(b)

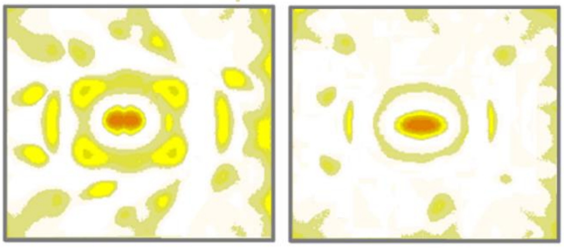
Figure 8. Beam-steering situations of the selected phased array, (a) Far-field radiation patterns, (b) Near-field radiation pattern.

In addition to illustrate the focusing method performance, a biological tissue phantom with a tumour was simulated and the 2D imaging results using CST software and confocal beamforming are presented and discussed [9]. Only one transmitter was applied in the system to transmit detecting signal and 16 receivers were applied to receive backscatter signals. As shown in Figure 5 (b) reflection signals are received by an antenna array in two different configurations: round and rectangular array. The reconstructed images with spherical tumour located inside the biological tissue phantom are shown in Figures 9 and 10. It can be found that in both pictures, target appears very clearly; which indicates that the proposed microwave imaging really has high contrast. It is also easy to find contrast of target and biological tissue in Figure 9 (b) is higher than that in Figure 9 (a). Therefore, as far as the contrast is concerned, focusing algorithm with round antenna array is prior to with rectangular antenna array [14]. However, this cannot be followed that round antenna array is better than rectangular antenna array. The reason is detailed in the Figure 10. Another criterion used to judge an imaging system is resolution. Figure 10 (a) shows when the image of two targets of equal strength at the same azimuth and elevation angles, and the distance between them is 20 mm. Rectangular imaging system cannot distinguish the two targets in this separation distance. This means that rectangular antenna may can get a higher resolution than round antenna array when using the same image reconstruction algorithms. The reason is: resolution is higher when the synthetic aperture is larger [13]. Simulation results shown in Figures 9 and 10 demonstrate that both antenna array configurations can catch the target in biological tissue successfully. Only the contrast and resolution are different.



(a) (b)

Figure 9. Imaging result achieved by (a) the rectangular antenna array, and (b) the round antenna array.



(a) (b)

Figure 10. Imaging result for two targets with 1 cm horizental distance between them achieved by (a) the rectangular antenna array, and (b) the round antenna array.

## IV. CONCLUSION

The main objective of the proposed feasibility study is making possible realization of a functional microwave near-filed imaging using the hybrid MIMO-phased array radar. To demonstrate this point, a new algorithm/architecture co-design based on cognitive programing has been presented and discussed. The advantage of this hybrid approach is that the cognitive scanning capability can be realized in iterative scenario of reconfigurable structure. In addition, we have shown some aspects of HMPAR capabilities to increase the spatial resolution of backscattered signals and reconstructed images. In order to validate the usefulness of the proposed framework, novel hybrid time-space scanning techniques is presented to improve the resolution, contrast and accuracy of reflected signals from nominal biological tissue with a static target. we improved range resolution by waveform diversity and spatial resolution by creating configurability in focusing algorithm. From the imaging results, we found that each configuration has its merit: Using round antenna array can get a relative higher contrast and using rectangular antenna array can get a relative higher resolution. Simulated results show that functional microwave imaging is a promising technique for developing a portable and low-cost functional neuroimaging device with high spatial and temporal resolution.

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