Low Cost Microwave Imaging System Using Eight Element Switched Antenna Array

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Abstract—**A low-cost microwave medical imaging system, which uses software defined radio (SDR) technology, is presented. SDR technology has long been used to quickly develop and prototype new communication system applications. Due to its generic nature, it has the potential to be mass-produced lowering the cost. Here, we re-purpose SDR technology to perform near-field biomedical radar with the use of a switching networking and an array of antennas. To verify its operation, two different antenna arrays using the frequency range from 1-4 GHz are used. The results show that using low-cost technology it is possible to successfully image a bio-mimicking phantom.**

Keywords— software defined radio; microwave imaging; antenna array.

I. INTRODUCTION

Microwave imaging has the potential to be complimentary diagnosis tools for many abnormalities in the human body. It has the potential to have a low-cost, be portable and has a non-ionizing radiation [1]. The enabling factor of microwave frequencies is the significant dielectric contrast between healthy and unhealthy tissues such as tumors, bleeds and clots in the human body [2, 3]. On the other hand, significant challenges exist due to the limited penetration of microwave frequencies into the human body and the complex propagation/scattering scenarios [4].

Traditionally, prototypes of microwave imaging systems have used off-the-shelf measurement systems such as vector network analyzers and channel sounders. These systems are able to provide extremely accurate results over a high frequency range with a high degree of dynamic range. This means that excellent data is made available which can allow measurement of weak targets hidden in strong clutter. Unfortunately, these systems are also quite costly and often not portable.

On the other hand, low-cost systems that have more limited performance also exist. One such technology is software defined radio (SDR). Originally these devices were only used to develop and prototype communication systems, however the performance specifications has evolved over time, and now they are able to provide a wide frequency tuning band and have ever-increasing instantaneous bandwidth. Due to being multi-purpose they have much lower cost than off-the-shelf measurement systems, although at the same time they are not particularly designed for this purpose either.

In past work, the authors have demonstrated how SDR technology can be extended to provide the capability to be used as part of a microwave medical imaging system [5, 6]. This is done by developing a suitable calibration procedure which allowed the tunable bandwidth to be used in the system.

This paper shows how the measurement time can be reduced from tens of minutes to just over one minute by using an antenna array and microwave switching system. Together with this system, the software system is updated to include a full cable and antenna calibration system. The measurement is performed using a mono-static radar based approach, and collects data similar to a series of reflection coefficients (using a VNA based analogy).

II. SYSTEM DESCRIPTION

The major part of the low-cost microwave medical imaging system is the SDR board. This device has an instantaneous bandwidth (BW), which refers to the real-time maximum bandwidth that can be transmitted and received at one time and a tuning BW, which refers to the range of carrier frequencies that the instantaneous BW can be modulated onto. The instantaneous BW is proportional to the sampling rate that the SDR system runs at, and is typically much smaller than the tunable BW by up to 100 to 1000 times. For near-field radar for applications such as microwave medical imaging, the required BW is at least 0.5 GHz, and with larger BW higher resolutions can be obtained. This means that the tunable BW must be used. To effectively use this, a combination of hardware and software needs to be used. They are described below.

A. Hardware Subsystem

The hardware subsystem decides on a number of factors such as the dynamic range, the sensitivity and the speed of operation. The dynamic range of the system refers to the difference between the strongest and weakest signal that can be measured by the system. This is a function of the resolution of the analog-to-digital converter (ADC) at the receiver, as well as the sensitivity of the system at different frequencies. With ideal mixing and amplification, an ADC with 12-bits of resolution can provide up to 72 dB of dynamic range.

To provide uniform illumination at each frequency, the gain at the transmitter needs to be adjusted for each frequency. As RF devices typically have decreasing performance at higher frequencies, an external amplifier can be used to allow a higher overall transmitter power to be transmitted over the entire frequency band of the system (1-4 GHz). It should be noted that the low frequencies do not require external amplification. Therefore to ensure a flat signal spectrum over the wide band, the internal amplifier can be used at a lower setting for the lower frequencies to compensate for this.

At the receiver some frequencies may also be affected by the non-ideal transmission of signals inside the board. This results in unequal performance over different frequencies at the receiver. Applying varying amounts of gain at the receiver does not solve the problem, as at the receiver the system would be amplifying both the signal and noise. Due to this reason, it needs to be accepted that the dynamic range at higher frequencies may be lower in the tunable BW.

To convert an SDR that is a communication-oriented device with a single transmitter and receiver to one that can measure a body under test, a directional element is required. This needs to separate the transmitted signal from the received signal. In previous work [6], an RF circulator was used. It should be noted that circulators typically have only up to one octave of bandwidth, meaning that only 1-2 GHz of BW would be available. In the new system, a directional coupler is used.

A directional coupler allows the measurement of the reflected signal from the body under test. If the phase information is required, a reference phase signal can also be measured. Directivity of the directional element has a direct effect on the effective dynamic range of the system; therefore components with excellent performance are recommended. Here, we use a directional element with at least 25 dB of directivity.

To measure the body under test, instead of a single antenna and a rotating platform, an array of eight antennas is used. To connect this to the system, a switching network formed using two SPDT and two SP4T switches is used. The schematic of this system is shown in Fig 1.

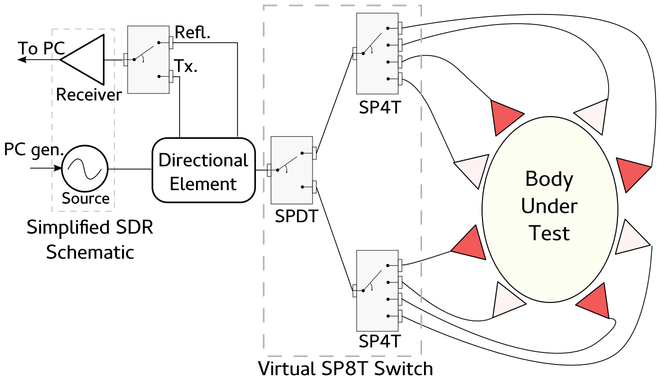

Fig. 1 Schematic of the proposed 8 port measurement system.

One of the SPDT switches is used to measure a reference or calibration measurement, whereas the other three switches are used to form a virtual SP8T switch, which connects the measurement system to eight antennas. To ensure good performance of the system overall, the measurement of an open, short and matched load is performed at each of the antenna locations. The calibration for that port of the device is applied to any antenna measurement made on that port.

The antenna array is a uniform array of antennas equally spaced around the body under test. Each antenna, which is a tapered slot in this case, has a 10 dB BW from 1-4 GHz.

B. *Software Subsystem*

The software-based system controls both the SDR as well as the switching and measurement procedure. The SDR functions are controlled via GNUradio [7] and are similar as previous systems, in that a single frequency at a carrier is measured in both the calibration/reference and measurement state. The reference needs to be measured each time the carrier frequency is changed. When the signal is switched to different antennas but kept at the same frequency, the single calibration can be used for all of the measurements.

The process of measurement is described graphically in Fig. 2.

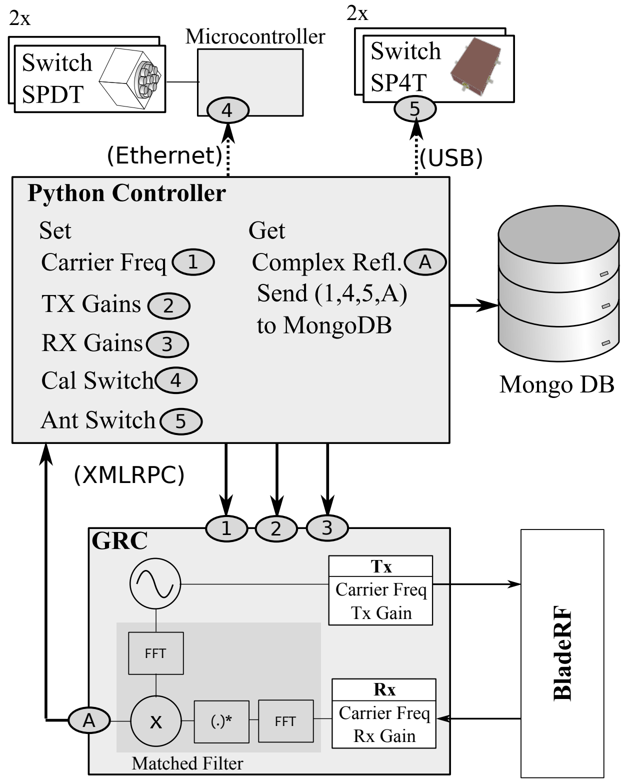

Fig. 2 Measurement process of SDR system.

The python controller for each frequency in the sweep range, configures the SDR to transmit and receive at that frequency, and helps carefully selecting the gains. For each frequency, the calibration or reference needs to be measured, followed by the eight measurements, which is for each of the antennas surrounding the body under test.

III. RESULTS

To demonstrate the capabilities of this system, a simple phantom is used as a body under test. The reflection coefficient at each of the eight antennas is measured for each frequency between 0.3 and 3.8 GHz, with a spacing of 10 MHz. This is a total of 351 frequency points. As mentioned previously, each antenna measurement is calibrated using the previously stored calibration for that measurement point.

This data is then transformed to time domain and converted to an image using the delay-and-sum method [8, 9]. Due to the limited number of antennas, the image has more clutter than normally; however the target is clearly defined (shown with a white border).

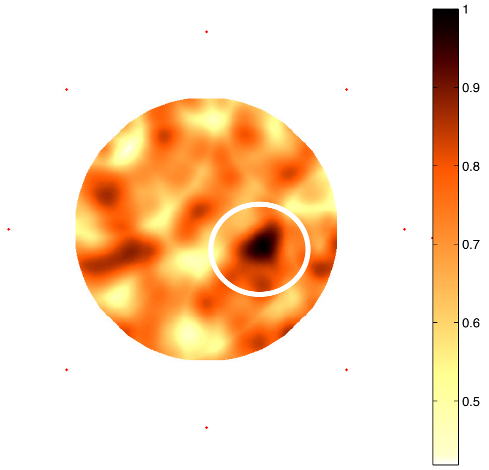

Fig. 3 Image produced using SDR measurement system with 8-port switch.

As one of the main benefits of the new system is the measurement speed and the lack of moving parts, the measurement type is compared between this system and the previous one [6]. It should be noted that the moving parts system only scan 1 GHz of spectrum, whereas the new system captures 3 GHz of spectrum. Although three times more measurements are being taken, the measurement time of the new system is only several minutes, and is over 6 times faster than the previous one.

TABLE I. MEASUREMENT TIME

Measurement Type	***Movement***	***Switched***
One location (including move, switch)	6 min	1 min
Complete Body Under Test	45 min	6 min

IV. CONCLUSIONS

This paper presents a low-cost microwave measurement system based on software-defined radar for medical applications. By using a switching system, the system has no moving parts, and is able measure almost six times faster than a previous mechanically moved system. To assist with the use of multiple antennas, the calibrations for each antenna are stored and used to calibrate measurements from each antenna. A verification of the system is performed by measuring a body under test in the form of a bio-mimicking phantom. The image shows that abnormalities in this medium are easily detected by this system.

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