Antenna-Pattern Measurement Using Spectrum Analyzer for Systems with Frequency Translation

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Abstract

Pattern measurements using a network analyzer are typically based on measuring the transmission coefficient, $S_{21}$. When the transmitting and receiving frequencies are different, it is not possible to directly measure the antenna pattern using a network analyzer. In this paper, an antenna-pattern measurement system using a spectrum analyzer, designed to measure the radiation pattern of an antenna with a microwave sampling beamformer (MSBF) structure, is presented. A synthesized oscillator was used as the transmitter in the measurement setup. The instruments were controlled through GPIB by a program specifically designed for the system. High-quality pattern measurements were obtained for several antenna types. The measurement results were verified using HFSS simulations.

Keywords: Anechoic chambers (electromagnetic); antenna measurements; antenna radiation patterns; spectrum analyzer; beam steering; frequency conversion; microwave sampling beamformer

1. Introduction

Vector network analyzers (VNA) have become standard tools in indoor antenna-pattern measurement systems. Antenna-pattern measurement using a vector network analyzer is based on measuring the transmission coefficient ($S_{21}$) at a given frequency. The modern vector network analyzers are convenient for antenna-pattern measurements in terms of frequency control and stability, spectral purity, and dynamic range requirements \cite{1}. However, when the transmitting and receiving frequencies are different, it is not possible to directly measure the antenna pattern using a vector network analyzer. State-of-the-art vector network analyzers allow $S$-parameter measurements when there is a frequency mixing in the receiver. For this type of measurement, a complicated and tedious calibration procedure, which usually requires an extra calibration.
kit, is necessary. Furthermore, the accuracy of the measurement is rather intolerant to the imperfections in the calibration process.

In this paper, a simple and efficient antenna-pattern measurement system using a spectrum analyzer is presented. The setup was originally developed to measure the radiation pattern of a microwave sampling beamformer (MSBF) [2, 3], but has been used for measurement of other antenna types. In an MSBF structure, antenna-element signals are switched using fast switches that are driven by pulses with controlled pulse widths and time delays. By adjusting the time delay and pulse width, the phase shift and the attenuation are controlled. In the MSBF structure, the frequency of the received signal is initially the same as the transmitting frequency, but it is shifted to a different frequency after switching [2]. The beamformer output frequency is therefore different from the transmitting frequency. The measurement setup is based on using a synthesized oscillator (SO) as the transmitter, and a spectrum analyzer (SA) as the receiver. The antenna under test (AUT) is connected to the spectrum analyzer and the pattern is measured in the receiving mode.

There are other antenna examples for which the transmitter and receiver frequencies are different. Local beamforming [4] is one example, in which the phase shifters are located in the local oscillators and the mixer output signals experience the phase shift. Another example is hybrid analog-digital beamforming [5]. In this case, the frequency of the beamformer's output is different from the transmitting frequency due to the application of the beamforming weights in the analog intermediate-frequency (IF) domain. A similar situation arises in active antennas [6], particularly the frequency-conversion type. In such applications, active elements, such as mixers, are integrated with the antennas. The output frequency of the integrated structure is thus usually different than the RF frequency.

There are several instances where spectrum-analyzer measurements are advantageous. For example, an advantage is the flexibility in choosing the type of RF source that can be used. This is specifically apparent in pattern measurements for mobile terminals. When using a vector network analyzer, an RF feed cable must be used to connect the mobile terminal to the vector network analyzer. The effect of cable radiation on the measured pattern was studied in [7]. It was shown that the disruption caused by the feed cable was avoided when a spectrum analyzer was used as the receiving instrument. A pattern-measurement setup with a spectrum analyzer allows for the study of the spatial response of the possible harmonics in the receiver or transmitter. In receiving subsystems, high dynamic range and sensitivity are important requirements, and noise reduction is necessary for most antenna measurements. In a spectrum analyzer, noise reduction can be accomplished by reducing the resolution bandwidth. The effect of noise on the displayed signal can also be reduced by using the video filter. Video filtering performs an averaging over the received signal, thereby reducing the rapid variations caused by noise. This function is useful for measuring a low-level signal close to the noise level. However, a limitation of pattern measurement with a spectrum analyzer is that only signal amplitude is measured. Therefore, when pattern phase is desired, it cannot be used.

The work in this paper is organized as follows. The specifications of the instruments used in the setup and the controller software are described in Section 2. The MSBF is briefly described, and various pattern measurements are presented in Section 3. The measured patterns are verified by comparison with the simulation results.

2. Measurement Setup

2.1 Hardware Block Diagram

The pattern measurements were carried out in a rectangular anechoic chamber that measured 4 m in length, 3 m in width, and 2 m in height, as shown in Figure 1. The setup used an HP8672A synthesized oscillator that operated over 2 GHz to 18 GHz as the transmitter source. A double-ridged EMCO 3118 waveguide horn antenna that operated from 1 GHz to 18 GHz was used as the source antenna. The output of the AUT was connected to the HP8569B spectrum analyzer, which had a frequency range of 10 MHz to 22 GHz. The antenna positioner was controlled by an ARA HD201E antenna-positioner controller. The spectrum analyzer, synthesized oscillator, and the ARA HD201E azimuth rotator were interfaced through a GPIB card to a PC, as shown in Figure 2. The controller software was developed in LabVIEW for automated pattern measurements. In order to reduce the cable losses, the synthesized oscillator and the spectrum analyzer were placed inside the chamber.
3. MSBF Structure

3.1 Fundamentals

In pattern measurements, it is essential to reduce the noise effects in the receiving instrument. The HP8569B spectrum analyzer can be reduced in three different ways: averaging, reducing the frequency resolution, and reducing the video filter bandwidth. Since averaging slows down the measurement speed, in this measurement setup, frequency resolution and video filter control were used for noise reduction. Since the noise in the spectrum analyzer has a wide bandwidth, the total noise power that passes through can be controlled by adjusting the width of the resolution bandwidth filters. Video filtering was used for smoothing the rapid fluctuations caused by the noise. This was accomplished by reducing the cutoff frequency of the video filter below the bandwidth of the resolution bandwidth filter. In this case, the rapid fluctuations of the signal envelope were filtered out by the video filter. This resulted in smoothing the signal on the display.

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Figure 3. The front panel of the LabVIEW control program.

Figure 7a. The measured power in dBm as a function of frequency and angle, for a frequency resolution of 2 MHz.

Figure 7b. The measured power in dBm as a function of frequency and angle, for a frequency resolution of 30 kHz.
\[ t_{sl} = \frac{\omega_f - \tau_f}{2\pi}. \]  

(1b)

In Equation (1a), \( \tau_f \) is adjusted in the range \([0,0.5]\) for full-range amplitude control and with a fixed \( \tau_f \), and \( t_{sl} \) is adjusted in the range \([0,1]\) for full-range phase-shift control using Equation (1b). In Figure 5, in each antenna element a phase switch with a 180° phase shifter is used instead of a simple switch. If a simple switch is used, the received power is wasted during the OFF state of the switch. In other words, through using this switch the transmission coefficient of the switch changes from 0 to -1, which is equivalent to a 6 dB power increase at the output of the switch [2]. In addition, through using this switch, the antenna and combiner ports are always matched. Moreover, using this switch attenuates or totally removes some undesired spectral replicas.

In Figure 6b, the measured and HFSS-simulated radiation patterns for a scan angle of \( \theta_s = 20^\circ \).

In Figure 6c, the measured and HFSS-simulated radiation patterns for a scan angle of \( \theta_s = -10^\circ \).

In Figure 6d, the measured and HFSS-simulated radiation patterns for a scan angle of \( \theta_s = 35^\circ \).

### 3.2 Prototype Description

The four-element inset-feed microstrip-patch antenna array presented in [2] was measured using the pattern-measurement setup. Rogers RO-4350B substrate with \( h = 20 \text{ mils} \), \( \varepsilon_r = 3.66 \), and \( \tan \delta = 0.0031 \), was used for the antenna and microwave circuitry. A return loss of around 14 dB with a 10 dB bandwidth of 50 MHz was measured for the antenna array. The antenna array signals were combined using a corporate feed, which was composed of three two-way Wilkinson combiners. The Wilkinson combiners were designed for \( f_c - f_s \), which was equal to 5.7935 GHz with \( f_s = 6.49 \text{ MHz} \). For each two-way Wilkinson combiner, a return loss of 16 dB, an isolation of 18 dB, and an insertion loss of 3.1 dB were measured. After each antenna ele-
ment, a phase switch was implemented that had an insertion loss of around 1.2 dB and a return loss of better than 15 dB over a bandwidth of 400 MHz.

The control hardware had four branches that generated four signals to control the switches. Each branch had a pulse-width control block, a time-delay block, and a PIN driver IC. In order to have all branches synchronized, the same oscillator drove all four branches. In each branch, the pulse width was controlled, and then the time delay. The outputs of the time-delay ICs were fed to the PIN-diode drivers to provide the high currents required during the ON-OFF transition of the PIN diodes. For each pulse-width control block, a 12-bit programmable pulse generator with a pulse-width step of 0.25 ns was used. The pulse width was adjusted using 12-bit binary inputs, which could also be controlled directly using a processor. For the time-delay generator, an eight-bit programmable delay line was used, where the time delay varied in 1 ns steps. The high time-delay and pulse-width resolutions made it possible to achieve high-resolution phase shift and attenuation in the MSBF structure.

3.3 Measurement Results

In this part, the measurement setup was used to verify the beam-steering capability of the MSBF structure. The synthesized oscillator and the center frequency of the spectrum analyzer were adjusted to 5.8 GHz. The switching frequency of the control circuit was chosen to be 6.49 MHz. Figures 6a-6d shows the steered uniform normalized patterns measured when the control-pulse time delays and pulse widths were adjusted for scanning at $\theta_e = 0^\circ$, 20°, -10°, and 35° with respect to the broadside of the array, respectively. In each case, the pattern obtained using HFSS simulation is also shown for comparison. In the HFSS simulations, only the antenna array with proper excitations was simulated, and the MSBF structure was not included in the simulations. It was observed that the pattern was scanned to the corresponding angles in all cases. In addition, the measurements agreed well with the HFSS simulation results. The received power pattern for a four-element inset-feed microstrip-patch antenna array as a function of scan angle and frequency is shown in Figure 7. The radiation pattern of the array was measured over a wide frequency range. Three different harmonic frequencies were observed. It was noted that the scan angles were different at each frequency. Based on the theory of the MSBF structure and the prototype, the three replicas occurred at $f_c - f_s = 5793.51$ MHz, $f_c = 5.8$ GHz, and $f_c + f_s = 5806.49$ MHz. In Figure 7a, the corresponding maximum power angles with respect to broadside should have occurred at -35°, 0°, and 55°, respectively. In Figure 7b, they should have occurred at 50°, 0°, and -40°, respectively. In order to demonstrate the effect of resolution bandwidth, different measurements were performed using different resolutions. The frequency resolution was adjusted to 2 MHz in Figure 7a, and to 30 kHz in Figure 7b. It was observed that the noise level decreased as the frequency resolution decreased. The video-filter frequency was the same for the two cases. It was noted that video filtering did not affect the average noise level on the display. It was used for smoothing the rapid noise fluctuations to measure low-level signals that were close to the noise level. On the other hand, the noise floor and sensitivity could be improved by using a smaller frequency resolution.

4. Conclusion

A simple and efficient antenna-pattern measurement system was designed to measure the radiation pattern of a microwave sampling beamformer (MSBF) structure. When the transmitting and receiving frequencies are different, it is not possible to directly measure the antenna pattern using a network analyzer. In the measurement setup, we used a synthesized oscillator as the transmitter. The antenna under test was connected to the spectrum analyzer, and the pattern was measured in the receiving mode. A program was developed in LabVIEW for controlling the instruments and monitoring the measurements in real time. Illustrative examples were presented to demonstrate the accuracy of the measurement setup.

5. References

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