Time-Modulated Beamforming in Antenna Arrays with Multiple Sub-Branch RF Switches

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***Abstract*—This paper presents a time-modulated beamforming technique in antenna array with multiple sub-branch RF switches. The proposed technique exhibits the attractive capability in the suppression of the unwanted harmonic components in RF channels before power delivered to antenna arrays. Moreover, without using digital phase shifters and digital attenuators, the first positive harmonic component is utilized to realize scanning beams with low sidelobe levels (SLL). A 16-element isotropic linear array is utilized for numerical analysis. The scanning beam with less than -20.0 dB sideband levels (SBL) is achieved with uniform excitations, while it exhibits -30.0 dB SLL and less than -25.0 dB SBL with the Dolph Chebyshev distribution.**

Keywords—beamforming network, time-modulated antenna array, RF switch

I. Introduction

Digital phase shifters and digital power attenuators are widely used in conventional beamforming networks. However, these digital components exhibit "stair-step" approximations to continuously variable phase shifting and tapered power weighting, which leads to quantization errors such as raised sidelobes and main beam pointing errors [1], [2]. Theoretically, these quantization errors could be minimized to a sufficiently low level with larger numbers of digital bits. However, the cost of the digital phase shifters with more than 6 bits is quite high, and prohibits the applications in large phased arrays. On the other hand, the time-modulated antenna arrays (TMAAs), also known as the four-dimensional (4-D) antenna arrays have attracted a great interest in field of antenna array over the past decades [3]-[5]. In TMAA, a high-speed radio frequency (RF) switch periodically modulate each antenna element with a particular time sequence. One of the most significant features of TMAAs is the sideband radiation, and in most cases the sideband radiation needs to be suppressed with algorithms, which sacrifices the design freedom of the time modulation sequences [6].

In this paper, a time-modulated beamforming technique in antenna array with multiple sub-branch RF switches is investigated. This technique exhibits the capability in the suppression of the unwanted harmonic components in RF channels before power delivered to antenna arrays. Moreover, without using digital phase shifters and digital attenuators, the first positive harmonic component is utilized to realize scanning beams with low sidelobe levels (SLL). This paper could be viewed as an extension study of [7], and we find that scanning beams with satisfied sideband levels (SBL) and SLL are obtained without using optimization algorithms if a relatively complicated RF switch is adopted as the amplitude-phase control module.

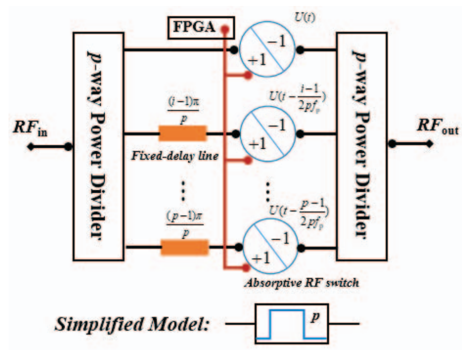

Fig. 1. Amplitude-phase control module with multiple sub-branch RF switches.

II. Multiple Sub-Branch RF Switch

Fig. 1 shows the configuration of the amplitude-phase control module with multiple sub-branch RF switches. It consists of p sub-branches. An absorptive RF switch that provides three statuses of +1, -1, and 0 is inserted in each sub-branch, whose operating statuses are controlled by a field programmable gate array (FPGA). As it can be seen, two p-way power dividers exist in the input and output ports of the module. The fixed delay lines in each sub-branch is utilized for suppressing the unwanted harmonic signals. In theory, the three statuses of the RF switch can be mathematically described as

$$U(t)=\begin{cases}-1 & , \quad status \quad 1\\ 1 & , \quad status \quad 2\\ 0 & , \quad status \quad 3\end{cases} \tag{1}$$

$$U(t)=U(t+qT_{\mathrm{p}}),q\in\mathbb{Z} \tag{2}$$

where T_{p} is the time modulation period for $U(t)$, which implies that the time modulation frequency $f_{\mathrm{p}}=1/T_{\mathrm{p}}$.

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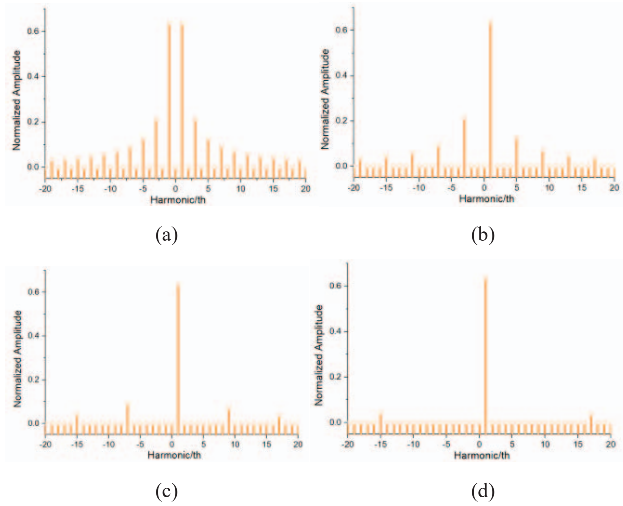


Fig. 2. The output amplitude spectrum for different values of p. (a) $p = 1$; (b) $p = 2$; (c) $p = 4$; (d) $p = 8$.

Due to the periodical status switching, $U(t)$ could be decomposed into Fourier series,

$$U(t) = \sum_{h=-\infty}^{+\infty} u_h e^{j2\pi h f_p t} \tag{3}$$

Specifically, the Fourier coefficient u_h at the hth harmonic could be calculated by,

$$u_h = \frac{1}{T_p} \int_0^{T_p} U(t) e^{-j2\pi h f_p t} \mathrm{d}t \tag{4}$$

According to (1), we define the switch-on time and duration time of the *status* 2 as t_s and τ_s, respectively. We also define the +1[st] harmonic as the desired harmonic signal, while other harmonics are the unwanted harmonic signals. Therefore, for a given amplitude attenuation α and phase shift β, the corresponding time modulation sequence could be determined from,

$$\tau_s = \frac{\arcsin(\alpha)}{\pi f_p} \tag{5}$$

$$t_s = -\frac{\beta}{2\pi f_p} - \frac{\tau_s}{2} \tag{6}$$

Fig. 2 shows the output amplitude spectrums of the proposed amplitude-phase control module when the number of the branch is 1, 2, 4, and 8, respectively. We assume that the duration time of *status* 1 and *status* 2 is the same $0.5T_p$, and the insertion losses of the p-way power dividers, the RF switches are not taken into account. As it can be seen, all the signals on the carried frequency ($h = 0$) and the even harmonic signal have not been transmitted. For $p = 1$, all the odd harmonic signals are transmitted. For $p = 2$, the suppressed odd harmonic signals are: -1st, +3rd, -5th, +7th, ⋯. Therefore, the image frequency components are suppressed. For $p = 4$, the suppressed odd harmonic signals are: -1st, ±3rd, ±5th, +7th,⋯.For $p = 8$, the suppressed odd harmonic signals are: -1st, ±3rd, ±5th, ±7th, ±9th, ±11th, ±13th, +15th,⋯. With larger p, more unwanted harmonic signals will be suppressed, but it is a trade-off design among the performance requirement for RF switches, unwanted harmonic suppressions and the implementation complexity.

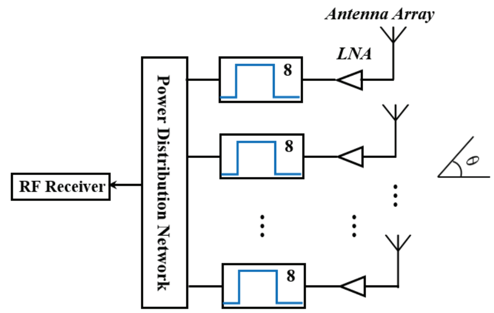


Fig. 3. Time-modulated beamforming network in receiving antenna arrays.

III. Time-Modulated Beamforming Network

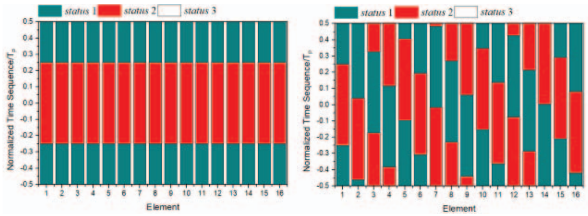
Under the assumption of $p = 8$, the time-modulated beamforming network is investigated for a receiving antenna array, as shown in Fig. 3. The 8-sub-branch RF switch is connected to each antenna element. Compared with the conventional beamforming networks, the digital phase shifters and digital power attenuators are eliminated, and replaced with the RF switches. Therefore, our proposed time-modulated beamforming network is supposed to realize real-time, precise and continuous beam scanning with low SLL and low SBL.

For convenience purpose, the ideal 16-element isotropic antenna array with an inter-element space of $\lambda_0/2$ is considered as the receiving antenna array. The mutual coupling and edge effects are not considered. Unlike the excitations in conventional TMAAs that should be optimized by optimization algorithms, in the following discussions, the numerical results with equivalent both uniform and -30.0 dB Dolph Chebyshev excitations will be given.

It is worth mention that the following results are obtained only when ideal RF switches are utilized. Therefore, ideal amplitude and phase unbalance are considered. However, in practical applications, it is impossible to build such RF channels without amplitude and phase unbalance. The more sub-branch means more complicated circuit topology as well as more uncontrollable amplitude and phase unbalance.

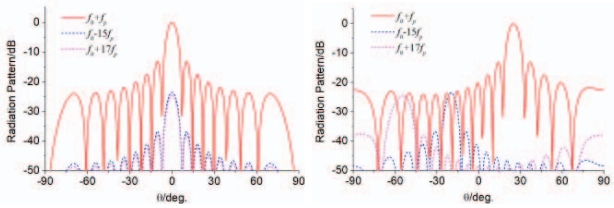
A. *Uniform Equivalent Excitation*

The uniform excitations in antenna array is considered in this subsection. According to (5) and (6), the time modulation sequence could be obtained, then pre-programmed in FPGA. As an example, the time modulation sequences for the broadside and 25°-scanning beams are calculated. Figs. 4(a) and (b) show the time modulation sequences for the broadside and 25°-scanning, respectively. The functionality of excitation tapering is not utilized for uniform excitations. Therefore, the *status* 3 of the RF switch is not included in the time modulation sequences. Figs. 5(a) and (b) shows the corresponding radiation



(a) (b)

Fig. 4. Time modulation sequences of uniform equivalent excitations for different scan angles. (a) broadside; (b) $\theta = 25°$.



(a) (b)

Fig. 5. Radiation patterns of uniform equivalent excitations with different time modulation sequences. (a) broadside; (b) $\theta = 25°$.

patterns under the time modulation sequences in Figs. 4(a) and (b). Due to the 8-sub-branch RF switch, most of the unwanted harmonics have been suppressed in RF channels. The operating frequency of the desired radiation pattern is f_0+f_p, while the two unwanted harmonic radiations with largest power at the frequencies of f_c-15f_p, and f_c+17f_p. As it can be seen, without using the optimization algorithms, a less than -20.0 dB SBL is realized.

B. -30.0 dB Dolph Chebyshev Equivalent Excitation

In this subsection, the widely used Dolph Chebyshev excitations for realizing low SLL patterns are calculated for beamforming. Under the assumption of $\lambda_0/2$ inter-element spacing, Fig. 6 shows the normalized tapered amplitudes of each element for -30.0 dB SLL. As an example, Figs. 7(a) and (b) show the time modulation sequences for 12.5°- and 40°-scanning, respectively. Figs. 8(a) and (b) show the resulting radiation patterns for 12.5°- and 40°- scanning with the calculated time modulation sequences. Similar to the analysis of uniform excitations, the operating frequency of the desired radiation pattern is f_0+f_p, while the two unwanted harmonic radiations with largest power at the frequencies of f_c-15f_p, and f_c+17f_p. The SBLs are less than -25.0 dB without optimizing the time modulation sequences.

IV. Conclusion

In this paper, the multiple sub-branch RF switches have been investigated, analyzed, and then utilized for time-modulated beamforming. The proposed technique has demonstrated its attractive capability in the suppression of the unwanted harmonic components in RF channels. Without using digital phase shifters and digital attenuators, the first positive harmonic component is utilized to realize scanning beams with low sidelobe levels (SLL). Moreover, the quantization errors due to discrete phase and amplitude variations have been eliminated. Numerical results show less than -20.0 dB SBL with uniform equivalent excitations, and less than -25.0 dB SBL with -30.0 dB SLL Dolph Chebyshev equivalent excitations.

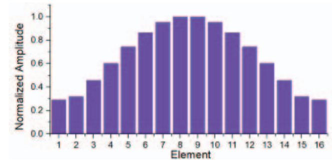
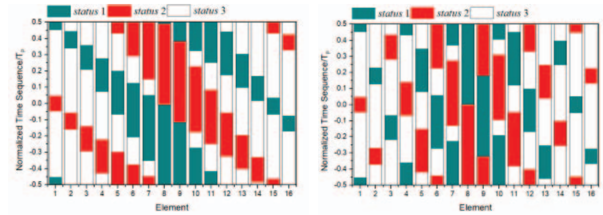
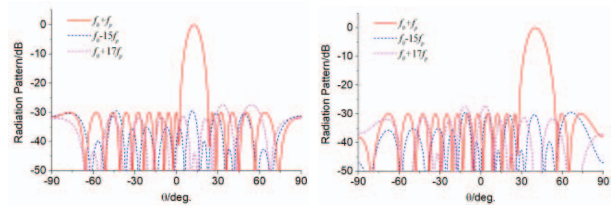


Fig. 6. Dolph Chebyshev excitations for -30.0 dB SLL patterns.



(a) (b)

Fig. 7. Time modulation sequences of -30.0 dB SLL Dolph Chebyshev equivalent excitations for different scan angles. (a) $\theta = 12.5°$; (b) $\theta = 40°$.



(a) (b)

Fig. 8. Radiation patterns of -30.0 dB SLL Dolph Chebyshev equivalent excitations with different time modulation sequences. (a) $\theta = 12.5°$; (b) $\theta = 40°$.

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