Spectrum Attributes of Frequency-Steerable Phased Array Antennas

***Abstract*—When considering phased array radar systems it is important to consider the possible differences in the spectral content of radar emissions when comparing boresight to off-boresight. This detail is important as it can accentuate potential electromagnetic interference (EMI) effects between radar and other devices competing for space in a crowded spectrum. In order to analyze the potential impact of off-boresight radar emissions to other electronic devices, a MATLAB and electromagnetic model of a simple eight element slotted waveguide linear array operating at 3.5 GHz was simulated with an element spacing of a half-wavelength. The model was stimulated utilizing continuous wave (CW), pulsed amplitude, and linear Frequency Modulated Continuous-Wave (FMCW) waveforms. The spectral content of these emissions in the far-field was assessed at a variety of angles with respect to boresight. It was concluded that the eletromagnetic emissions power may be under measured if out of band emissions of a waveguide slot array are measured only at boresight resulting in compliance testing issues. This could result in interference to other electronic devices being underestimated.**

I. Introduction

Phased array radars have been in use for many years, used largely in long distance air search by the military and civilian air traffic controllers. Recently, with the influx of wireless systems available worldwide, such as WiMAX, there has been competition between radar and wireless transceivers in the band from 2.0-4.0 GHz (S band). With the World Radio Conference 2012 approaching [1], discussion among nations has intensified as to what degree the RSEC's and ITU's spectral emission masks for radars in S band require steeper role offs beyond the allowable 40 dB bandwidth. When considering phased array radar systems, it is important to determine the differences in the spectral content of radar emissions when comparing boresight to off-boresight. For example, when dealing with potential electromagnetic interference (EMI) between a radar on a ship and a WiMAX base station on shore.

The National Telecommunications and Information Administration (NTIA) has studied the problem and showed significant differences between estimated out of band emission levels based on boresighted measurements and direct measurements [2]. This study however only examined boresight versus off-boresight emission levels for Continuous Wave (CW) waveforms and did not consider other commonly used waveforms. Chan et al. examined frequency steerable, arrays such as waveguide slot arrays, combined with linear Frequency Modulated Continuous Wave (FMCW) waveforms, but considered only the performance aspects and did not examine out of band emissions [3]. What is needed is an assessment of the impact of frequency steerable arrays on the spectrum of commonly used radar waveforms and the implications of these off-boresight emissions have on EMI of other devices.

The rest of this paper is divided into five sections. Section II introduces the concept of the array spectrum. Section III presents the simulation setup used to evaluate the boresight and off-borsight emissions of a phased array radar system. Section IV provides the results of this simulation. Section V discusses these results in detail. Section VI provides some conclusions about the simulated phased array radar off-boresight emissions.

II. Array Spectrum

Antennas and antenna arrays can have an effect on the spectrum of the signal that they are transmitting. Figure 1 demonstrates this concept. Consider a waveguide slot array that is aimed along boresight at its design frequency, f_c. As the operating frequency moves to some other frequency, for example f_0, the beam is steered off-boresight. Now consider a broadband signal that has a flat spectrum stretching from f_c to f_0. A receiving station at boresight will see a spectrum that rolls off from f_c to f_0. That roll-off will be a function of the width of the beam and the squint angle at f_c. This resulting array spectrum could be thought of as the projection of the array pattern onto a frequency axis similar to the discussion in [3]. To obtain the spectrum of any arbitrary waveform, the waveform spectrum is simply multiplied by the array spectrum.

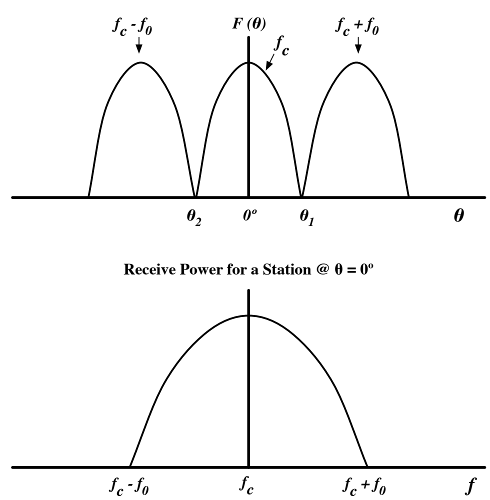


Fig. 1: Array spectrum illustration

III. Simulation

A transmitter connected to an eight element slotted waveguide linear array operating at 3.5 GHz was simulated using the phased array toolbox in MATLAB. Using the symmetry of the problem, nineteen receivers were set up in a 180° arc as shown in Figure 2. The radar signals evaluated with this model were CW, pulsed, and linear FMCW. The slotted array was a scaled version of the array in an NTIA report that discusses phased array antenna pattern variations with frequency [2].

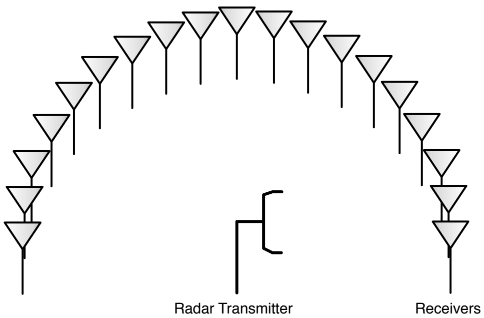


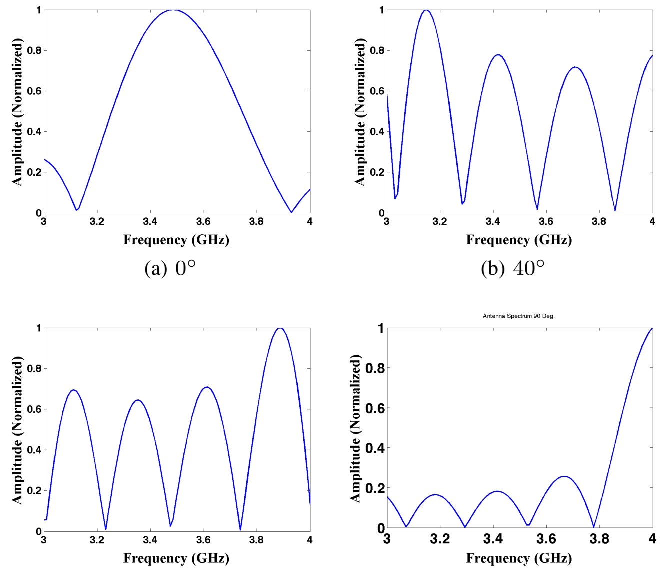
Fig. 2: Phased array antenna simulation setup: one transmitter surrounded by nineteen receivers

The phased array toolbox is a time-domain simulations tool that models radar parameters including the transmit power, receive power, antenna pattern and the target model. It simulates a system assuming a fixed frequency response and as a result it cannot directly model a frequency steerable phased array. To overcome this limitation the array spectrum was first constructed by examining the Power Spectral Density (PSD) of a CW waveform at each receiver for several individual frequencies. A CW signal was transmitted at the first frequency and the corresponding receive power was recorded at each receiver. Then the frequency count was incremented and the procedure repeated until the required bandwidth was covered.

To model the frequency steering properties of a slotted waveguide a steering vector was created and used to weight the array elements. At each frequency the waveguide propagation constant, β, was calculated and used to determine the phase progression between slots. The phase progression was then used as the weights of the steering vector.

An array spectrum, as introduced in Section II, was created from received power measurement at 100 frequencies from 3–4 GHz. The array spectrum was then compiled by cutting the data so that the received power could be viewed as a function of frequency at each receiver. The spectrum was then normalized to obtain a maximum value of one. The resulting array spectrum is a normalized function of frequency, θ, and ϕ as shown in Figure 3.

MATLAB's phased array toolbox works strictly in the time domain and cannot handle a radiation pattern that is a function of frequency. In other words, it cannot directly simulate a linear FM waveform with the waveguide slot array. The "array spectrum" concept was created to address this problem. We multiply this array spectrum by our waveform spectrum to obtain the resulting spectrum of the transmitted waveform.



(a) 0° (b) 40° (c) 60° (d) 90°

Fig. 3: Examples of array spectrums at different angles

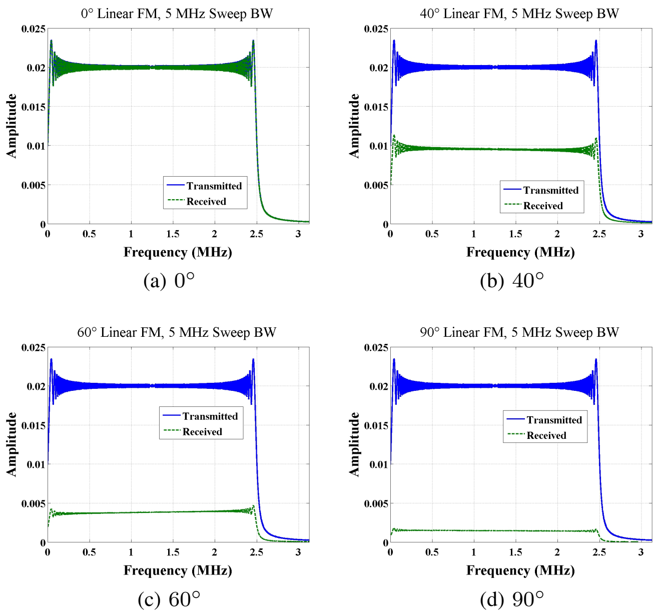
IV. Results

An FMCW waveform with its flat spectral shape serves as an ideal waveform for evaluating the potential spectral distortion induced by a frequency steering array. Two characteristic FMCW waveforms were created, FMCW waveform 1 has a swept bandwidth of 5 MHz while FMCW waveform 2 has a swept bandwidth of 40 MHz. The one sided baseband spectrum for FMCW waveform 1 at several angles can be seen in Figure 4. The solid blue line denotes the waveform spectrum at the transmitter, while the dashed green line denotes the received waveform spectrum. Similarly, the baseband spectrum from FMCW waveform 2 can be seen in Figure 5.

In addition to the FMCW waveforms two pulsed waveforms were simulated. While the sinc shaped nature of the pulsed waveforms spectrum makes the definition of bandwidth one of nuance, the pulse widths were selected to give the two waveforms similar bandwidths to the previously described FMCW waveforms. The baseband spectrum of pulsed waveform 1 can be seen in Figure 6. A pulse width of 0.1 μs gives pulsed waveform 1 a bandwidth similar to FMCW waveform 1 and Figures 5 and 6 are plotted on the same frequency scale. Pulsed wavefrom 2 has a 5 μs pulse width giving it the narrowest bandwidth. The baseband spectrum is plotted in Figure 7.

V. Discussion

An understanding of the effect of the array spectrum upon any generic radar waveform starts by examining Figure 3 in detail. The radar system examined in this paper is operating at 3.5 GHz and it is insightful to note the trend of the array spectrum around this frequency. A receiver on boresight, Figure 3a, sees a slow, symmetric roll-off of the distorted radar waveform. This is markedly different than the distorted



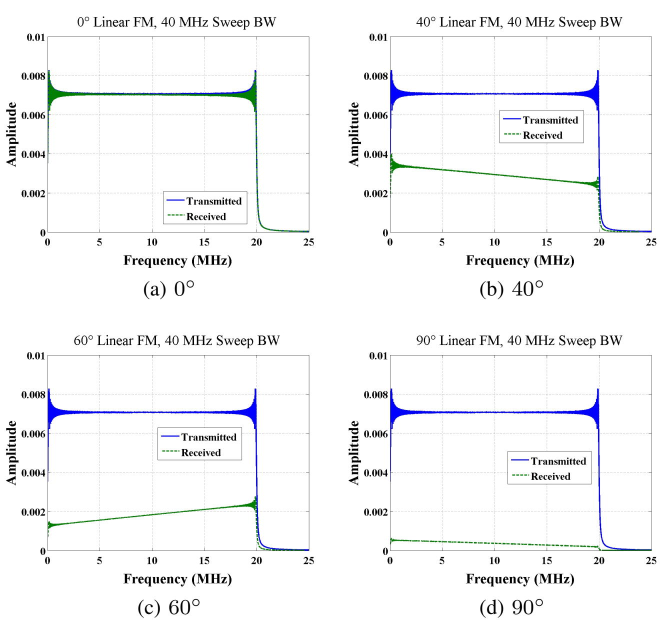
(a) 0°

(b) 40°

(c) 60°

(d) 90°

Fig. 4: FMCW waveform 1 spectrum at several angles with a 5 MHz sweep bandwidth. The blue solid and the green dashed lines represent the transmitted and received signals, respectively.



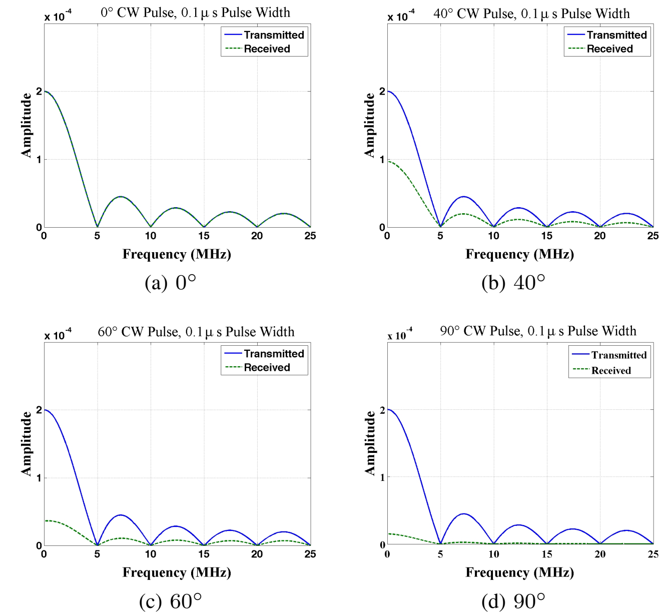
(a) 0°

(b) 40°

(c) 60°

(d) 90°

Fig. 5: FMCW waveform 2 spectrum at several angles with a 40 MHz sweep bandwidth. The blue solid and the green dashed lines represent the transmitted and received signals, respectively.



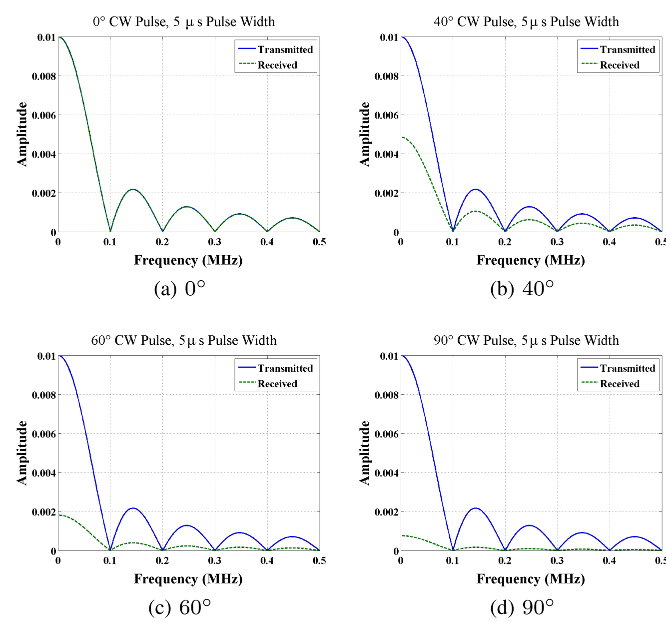
(a) 0°

(b) 40°

(c) 60°

(d) 90°

Fig. 6: Pulsed waveform 1 spectrum at several angles with a 0.1 μs pulse width. The blue solid and the green dashed lines represent the transmitted and received signals, respectively.



(a) 0°

(b) 40°

(c) 60°

(d) 90°

Fig. 7: Pulsed waveform 2 spectrum at several angles with a 5 μs pulse width. The blue solid and the green dashed lines represent the transmitted and received signals, respectively.

waveforms at 40° and 60°, Figures 3b and 3c. At these locations the array spectrum has a sharp negative and positive slope respectively. Finally, at 90° Figure 3d reveals that the array spectrum is both sloped and also significantly repressed. From this it follows that a unique distortion is imparted onto the waveform for each receiver.

By examining Figure 4 one can directly assess the impact of the array spectrum on an FMCW waveform. Figure 4a shows little to no distortion at the boresight receiver. This corresponds well with the previous observation that the array spectrum is at a maximum and symmetrically rolling off. With the array spectrum changing slowly over the 5 MHz bandwidth little distortion is expected at boresight. Figure 4b reveals the received waveform has a suppressed spectrum with a small negative slope. This negative slope was noted earlier in the array spectrum, and at this bandwidth is not pronounced. A similar spectrum is seen in Figure 4c but with a slightly positive slope. Finally 4d shows a significantly suppressed waveform spectrum. While the distortions in the received waveform spectrum is not particularly pronounced for this waveform, a 5 MHz sweep bandwidth is a relatively narrow band waveform.

The bandwidth of FMCW waveform 2 is four times that of waveform 1 making the impact of the array spectrum much more pronounced. Some roll-off of the received waveform spectrum is even evident at the boar-sighted receiver, Figure 5a. The roll-off in the spectrum at 40° and 60° is approaching 3 dB, as seen in Figures 5b and 5c respectively. The distortion is now prominent enough to affect system performance as well as deviate from expected off-boresight emission levels.

Similar trends can be seen in the received pulsed waveform spectrums. The sinc like shape of these waveform spectrums makes the trends less obvious, but an astute observer will note that the same trends pointed out for the FMCW waveforms are present in Figure 6. Pulse waveform 2 has a much narrower bandwidth than the previously discussed waveforms, and a close examination of Figure 7 reveals that the array spectrum is changing too slowly for any significant distortion to occur.

Distorted off-boresight emissions could have an impact on EMI to other devices that is unanticipated based on standard compliance testing [4]–[8]. If only boresight emissions of phased array radar systems are considered the severity of possible interference could be underestimated and could result in unintended consequences.

VI. Conclusion

An influx of wireless systems worldwide has lead to an increasingly crowded spectrum. It is important to fully understand radar emissions to reduce potential EMI to other devices in this increasingly crowded spectrum. The spectral content in both boresight and off-boresight emissions of a phased array radar system needs to be considered to completely address these EMI issues. A MATLAB model using the phased array toolbox of an eight-element slotted waveguide array operating at 3.5 GHz with half-wavelength spacing was simulated. This model was stimulated using several waveforms, such as CW, linear FMCW, and pulsed waveforms. Nineteen receivers were placed in a 180° arc to examine the boresight and off-boresight emissions. It was found that the off-boresight received waveform spectrums show significant deviations from boresight spectrums. This deviation is related to the waveform bandwidth and the squint angle deviation versus frequency rate of the array. These deviations are principally in wide bandwidth FM signals, though they can be present in pulsed waveforms as well.

Future work will verify these results with physical measurements. In addition, conclusions will be drawn with respect to the severity of possible interference to other electronic devices and to what extent the change in spectral content of the emissions affects this degradation.

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