Spatial-Spectral Coexistence: Dual Approach to Search Radar Transmission Synthesis Using a Spatial Mask

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Abstract— **The crowded wireless spectrum environment is prompting consideration of novel sharing techniques. In search radars, wide beamwidth is desired from the phased array transmitter to allow target presence in any direction to be accurately detected. Furthermore, the radial distance to the target can be most precisely detected when a wide-bandwidth waveform is used. In the case of spectral coexistence, however, multiple wireless devices may surround the search radar at nearby operating frequencies. We demonstrate the concept of providing a spatial mask for the azimuth transmission beam pattern, derived from the positions and sensitivities of nearby wireless receivers, to maximize the array transmission beamwidth while ensuring coexistence with the wireless receivers. Rather than enforce the coexistence constraints on the bandwidth of the waveform through a spectral mask, this paper demonstrates a dual, alternative option of masking the array transmission pattern. This approach will be useful in allowing next-generation radar coexistence with wireless communications, as well as utilizing the directional capabilities of fifth-generation (5G) wireless systems to provide an additional degree of freedom in ensuring coexistence.**

Index Terms— **Cognitive radar, interference suppression, phased arrays, radio spectrum management.**

I. Introduction

As radar bands continue to be re-allocated for sharing with wireless communications, as in the case of the 3.45 to 3.65 GHz band, new approaches for radar transmission are required to ensure accurate, high-resolution radar detection while coexisting with other wireless devices. In the fifth-generation (5G) radio spectrum management structure, spectrum is expected to be allocated in real-time for the microwave and millimeter wave bands [1]. While coexistence has often been considered in terms of the spectral dimension, the spatial direction of transmission provides an additional degree of freedom to achieve spectral coexistence. As new technologies shift to operating in fifth-generation (5G) wireless systems that utilize more directional transmission patterns with multi-element phased array antennas, coexistence between radar and communications platforms becomes a more substantial challenge to overcome. In this 5G environment, many communications receivers operating at different frequencies could be present within a radar's transmission path. The necessity for real-time optimization in both the spatial and spectral domain has become significantly more important as a result. To complement real-time spectrum allocations, antenna transmission beampatterns may also be optimized in real-time to mitigate interference [2, 3, 4]. The spatial and spectral domains should therefore be used as the degrees of freedom to solve the coexistence problem for both radar and communications.

Range radar applications typically require wide-bandwidth waveforms to provide proper range resolution, allowing differentiation between targets that are closely spaced apart radially. If a highly directional antenna pattern is transmitted with this type of waveform, any communications receiver within the radar's path will suffer from an enormous amount of interference. Our previous work considers the construction of a spatial-spectral mask and a mapping of this mask to fewer dimensions to either a spectral mask or a spatial mask [5]. It was demonstrated that a projection to the spectral mask of a wide-bandwidth radar waveform can allow wide bandwidth transmission while maintaining coexistence with spatially co-located communications receivers in the radar's transmission path. In this case, a fixed antenna transmission pattern was assumed, and the radar spectrum was optimized to provide the highest allowable transmission bandwidth in dBm/Hz.

In the present work, we utilize transmission direction as an additional degree of freedom in the optimization of the transmission. The dual approach to constraining with a spectral mask in the spatial domain (a "spatial mask") is considered. Using a fixed radar spectrum, the phased array antenna transmission pattern can be optimized for a desired transmission pattern while maintaining coexistence with co-located communications receivers of known position, operating frequency, and sensitivity. Search radars, which typically operate with wide beamwidth transmission patterns, can benefit particularly as a result of this concept. The objective of this type of radar is to scan a full 360-degree space and keep a target in its transmission path long enough for accurate detection [6]. Using the dual approach to the spectral mask and projecting the radar's transmission pattern to a spatial mask provides a suitable application to search radars.

II. Spatial Mask Formulation

In our previous work [5] a basis for a free space spatial-spectral constraint map was constructed to determine the maximum allowable transmission power density for a radar in each spatial direction ϕ and at each frequency f in a

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simulated wireless environment with many communications receivers. This spatial-spectral constraint map assumes information about the environment such as allowable interference power densities of the communications devices in the environment as well as their operating frequencies. This ultimately results in an allowable spatial-spectral transmit power density $P_t(f,\phi)$ in dBm/(Hz x degree) for a radar that is governed by the equation

$$P_t(f,\phi) = \min_{0\leq R\leq\infty}\left[P_r(f,R,\phi)\frac{(4\pi R)^2}{2\pi G_r\lambda^2}\right], \tag{1}$$

where $P_r(f,R,\phi)$ described the interference spatial-spectral power density for each communications device at a given frequency f, at a given radial distance R from the radar, and at a given bearing ϕ relative to the radar. The allowable spatial-spectral power density in (1) can then be mapped to a spatial constraint map in which the normalized transmission waveform spectrum $|X(f)|$was predetermined and fixed. The known signal spectrum is applied as a weight on the constraint map in (1). This ultimately resulted in the spatial constraint map defined by

$$Q_t(\phi) = \int_{f_1}^{f_2}\min_{f_1\leq f\leq f_2}\left[P_t(f,\phi)\frac{1}{|X(f)|}\right]df, \tag{2}$$

where $Q_t(\phi)$ describes the allowable transmission spatial power density in dBm/degree and the signal bandwidth is described by $f_1 \leq f \leq f_2$. The spatial constraint map in (2), however, should be translated from a spatial transmission power density quantity to a spatial transmission gain quantity to synthesize a transmission beampattern. This can be accomplished by multiplying (2) by 2π and dividing by the transmitted power P_t. This cancels the dBm/degree units defined in (2) and results in a transmission gain spatial mask defined by

$$M_t(\phi) = Q_t(\phi)\frac{2\pi}{P_t} \tag{3}$$

where P_t is the transmitted power. The translated spatial mask $M_t(\phi)$ is unitless and utilizes the transmit power P_t in dBm instead of the transmit power density $P_t(f,\phi)$ which was a quantity defined in dBm/(Hz x degrees). The transmission phased array antenna pattern $G_t(\phi)$ is then confined by the spatial mask in (3).

III. Experimental Setup and Results

A. Simulation Environment

Fig. 1 shows the same constructed spatial transmission scenario used in our previous paper [5], which considers a single search radar located at the origin and 1000 nearby communications receiver devices operating between 3.5 and 3.6 GHz (indicated by red circles).

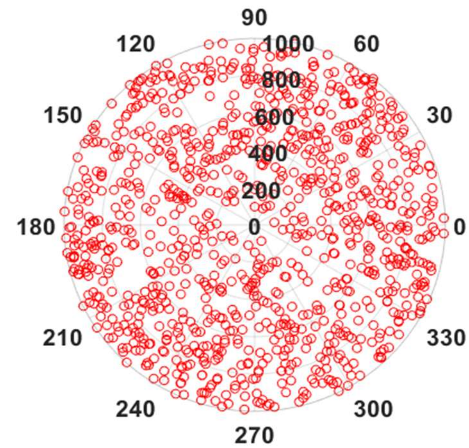

Fig. 1. Spatial transmission scenario for regulation with 1000 receiver devices (distance in meters, angular azimuth dimension in degrees). The radar is located at the origin, and each red circle describes the location of a communication receiver operating between 3.5 and 3.6 GHz.

For this scenario, knowledge of the receiver locations, frequencies, antenna gains, and maximum tolerable received interference spatial power densities are assumed. The radar uses 20 MHz of bandwidth within the 3.5 to 3.6 GHz range. The radar additionally has a maximum transmission spatial power density of 60 dBm/degree that is enforced in (2) and is translated to an antenna gain restriction in (3).

B. Fixed Range Radar Waveform

A fixed range radar waveform is assumed to be transmitted by the search radar. For this waveform, no spectral mask restrictions are imposed to synthesize a waveform with the maximum transmission bandwidth possible. Figs. 2 shows the spectrum of the fixed range radar waveform.

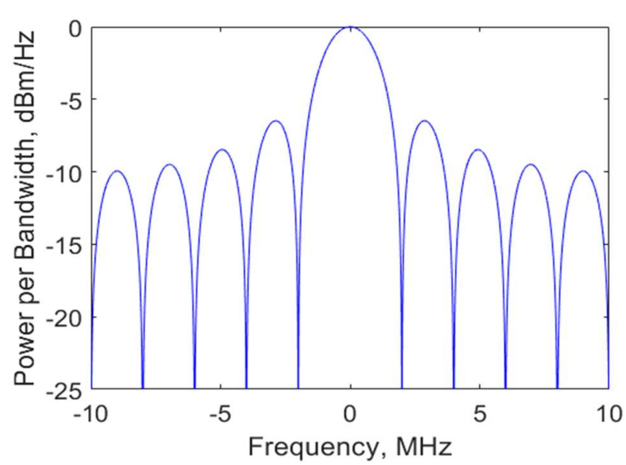

Fig. 2. Range radar waveform with fixed normalized signal spectrum $|X(f)|$

As the radar waveform operates over 20 MHz within a 100 MHz band, the unrestricted high bandwidth waveform provides appropriate range resolution according to

$$\Delta R = \frac{c}{2B} = \frac{3 \times 10^8}{2(20 \times 10^6)} = 7.5 \text{ m}, \qquad (4)$$

which allows the radar to distinguish between two targets that are located 7.5m apart radially from the radar. Fig. 3 shows the resulting range ambiguity function of the fixed transmit range radar waveform that is shown in Fig. 2. A range radar minimization template is used to synthesize the radar's ambiguity function. The range ambiguity function is constructed to closely match the minimization template defined in Fig. 3 (left). As a result of fixing an unrestricted transmit range radar waveform, its ambiguity function in Fig. 3 (right) closely matches the minimization template for a range radar.

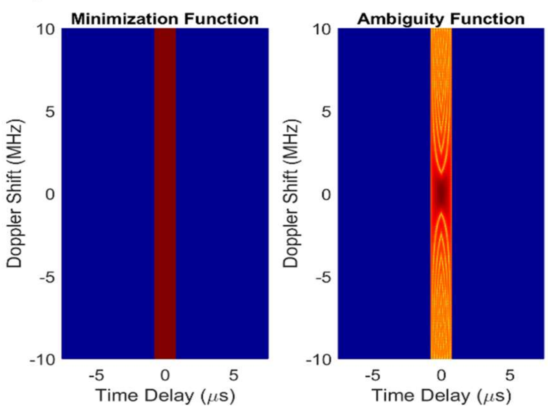

Fig. 3. Resulting range ambiguity function of fixed range radar waveform

C. Spatial Mask Generation

To justify transmitting an unrestricted range radar waveform with significant bandwidth, the radar's antenna pattern can be adjusted using a spatial mask to mitigate any potential inference to the communications devices in the environment. For this scenario, (2) is used to map the spatial-spectral constraint map in (1) into a spatial constraint map through the fixed radar waveform. This is ultimately translated into a spatial constraint map suitable for an antenna transmission pattern by (3). In the directions that no constraint exists by (3), the maximum transmission pattern is allowed. Ideally, this would produce an antenna pattern with the widest possible beamwidth to scan as much of the space as possible where these directional constraints do not exist. Each communications device in this scenario is assumed to have a 5° beamwidth in which interference can be received. The resulting notched spatial mask is shown in Fig. 4.

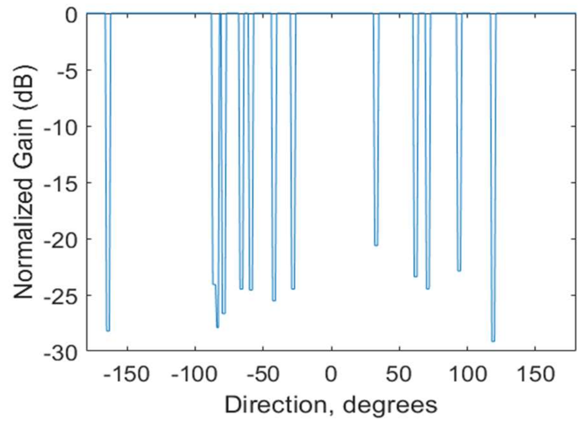

Fig. 4. Generated spatial mask dictating radar transmission antenna beampattern spatial requirement

D. Radar Beam Pattern Synthesis

An azimuth dimensional phased-array transmission pattern can be synthesized to adhere to the azimuth spatial constraints dictated by the spatial mask in Fig. 4. As shown in Fig. 4, the radar's antenna pattern may transmit freely over certain areas in the space. The most unrestricted transmission pattern comes from steering the beampattern to the middle of an unrestricted area so that there is no interference with other co-located communications devices. Some techniques for synthesizing antenna patterns exist in the literature [7, 8, 9, 10], however, in this work, the lobes of the beampattern are simply adjusted to fall below the spatial mask at the directions in which the spatial constraint was violated. Directivity can also be maintained and as a result, the lobes are increased and decreased in magnitude to adjust the ratio of the maximum power over the average power accordingly.

A 16-element antenna array was selected to conform to the spatial mask from Fig. 4. This two-dimensional azimuth pattern reduced its transmissions in the directions where constraints exists. The beampattern was steered to the first unrestricted area. A result of this projection onto the spatial mask is shown in Fig. 5.

The main lobe of the 16-element phased array was first steered to -125°, which is the center of the first unrestricted area according to the spatial mask. The magnitudes of the sidelobes that violated the mask were decreased to be within compliance. The magnitudes of some of the other lobes located in smaller unrestricted areas were then increased to maintain the directivity of the array. Assuming the fixed-bandwidth radar waveform, a proper range resolution for any potential targets located in this unrestricted space would be realized. Another unrestricted area can be found at the 0° direction. The main lobe of a 16-element array search radar can still fit within the constraints of the spectral mask. When the radar scans the space, its main lobe can be placed freely with a high-bandwidth radar waveform in this direction, as shown in Fig. 6. The sidelobes are once again adjusted according to the requirements discussed to conserve the array directivity.

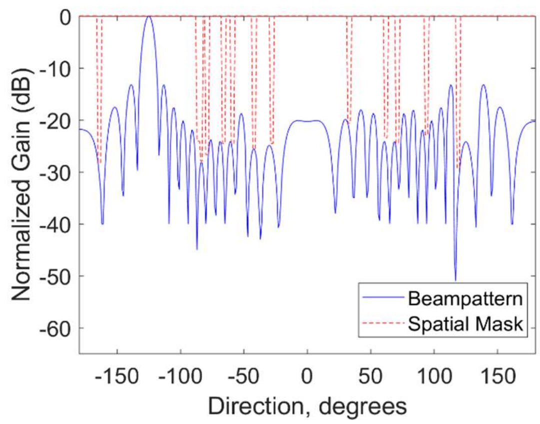

Fig. 5. Spatial mask (red dashed lines) and synthesized beampattern (blue solid lines) for a 16-element phased array steered to a spatially unconstrained area of -125°

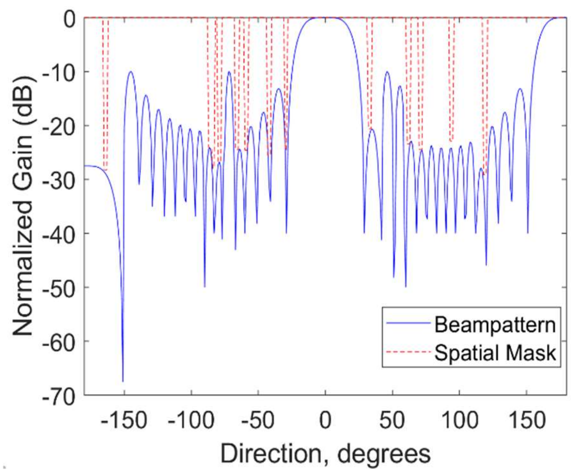

Fig. 6. Spatial mask (red dashed lines) and synthesized beampattern (blue solid lines) for a 16-element phased array steered to a spatially unconstrained area of 0°

These results show that a 16-element antenna transmission pattern can adhere to the spatial mask constraints well for various directions in the 360° scan space. A variation of multi-element transmission patterns could be used to adhere to these constraints as well, so the selection of the number of elements to use in this case depends on the requirement of how well the radar transmission beampattern should adhere to these spatial restrictions. If more elements are used, the beampattern can certainly more easily adhere to some of the more restrictive spatial constraints, but will be limited on the beamwidth that can be achieved.

E. Cooperative Spectral Mask

A search radar is expected to scan a large volume of space continuously and if these spatial restrictions as well as the high bandwidth transmit radar waveform remain fixed, there will be some directions in the space in which the radar will be unable to detect targets. In the event the search radar attempts to scan in a spatially restricted direction, the magnitude of the beampattern could be too low to illuminate any targets and keep these targets in the radar's transmission path as a result. For this reason, the spectral mask can be once again utilized to mitigate this concern. Since spatial constraints can now be defined by the spatial mask, the spectral mask can be utilized in conjunction with the spatial mask to mitigate interference in these directions, which would allow the main lobe of the antenna pattern to transmit freely where spatial restrictions would otherwise limit this possibility. This allows a fixed antenna beampattern to transmit in these directions, and in this case, the radar waveform would be optimized to mitigate interference and transmit with the widest bandwidth possible to still maintain acceptable range resolution performance.

With the knowledge of spatial restrictions on the antenna transmission pattern that results from the formulation of the spatial mask, the spectral mask can now operate cooperatively with the spatial mask. When the radar attempts to scan the space in a spatially more restrictive direction according to the spatial mask from Fig. 4, the radar can switch to using the spectral mask to restrict its operational bandwidth to mitigate interference to co-located communications receivers. As was shown in [5], the spectral mask is formed by

$$S_t(f) = \int_0^{2\pi} \min_{0 \le \phi \le 2\pi} \left[P_t(f,\phi) \frac{1}{G_t(\phi)} \right] d\phi \qquad (5)$$

where $G_t(\phi)$ is the steerable transmission antenna pattern that previously adjusted to fit the spatial mask as shown in Fig. 5 and Fig. 6. When the radar switches to a region in the spatial mask that is restricted spatially, $G_t(\phi)$ now becomes fixed to transmit freely at this direction where a strong spatial constraint exists, and the spectral mask is now used to limit the radar's operational bandwidth to mitigate spectral interference instead. Fig. 7 shows a fixed antenna transmission sent to a spatially constrained direction. Fig. 8 and Fig. 9 show the resulting spectrally confined radar waveform and its ambiguity function. As can be seen in the spectral plot of Fig. 8 (in comparison with the Fig. 2 unconstrained waveform spectrum), the bandwidth is decreased, but this allows the radar to scan in the -60° direction. As such, the spatial constraint can be relaxed if the spectral constraint is made more restricted. As Fig. 9 shows, the ambiguity function fit of the resultant waveform to the range-radar template is less desirable than the Fig. 3 ambiguity function from the wider-bandwidth waveform.

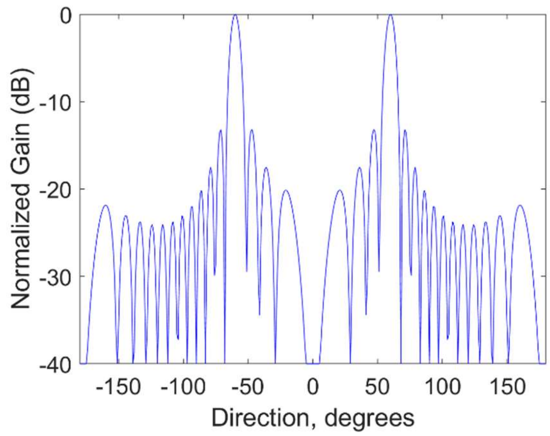

Fig. 7. Fixed 16-element phased array steered to a defined spatially constrained direction of -60°

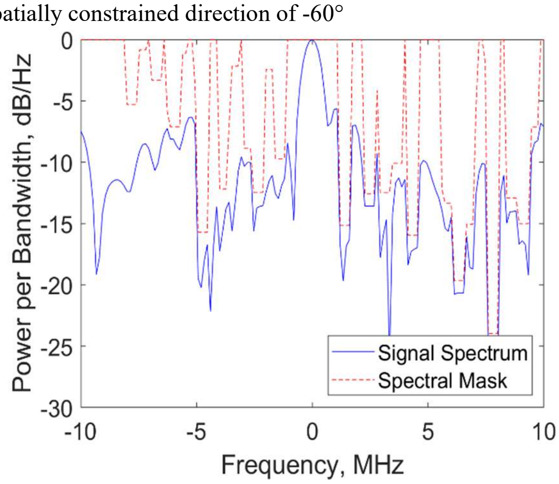

Fig. 8. Spectral mask (red dashed lines) and resulting optimized waveform (blue solid lines) centered at 3.52 GHz for a fixed phased array beampattern sent to the spatially constrained direction of -60°

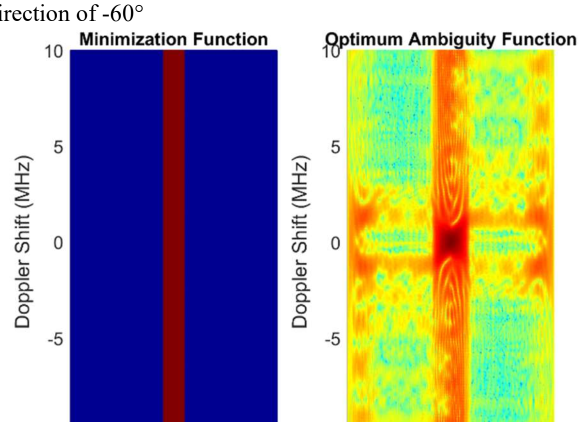

Fig. 9. Ambiguity function minimization template (left) and resultant ambiguity function (right) for the optimized waveform centered at 3.52 GHz for a fixed phased array beampattern sent to the spatially constrained direction of -60°

While the bandwidth of the range radar waveform needed to be restricted as a result of allowing the antenna pattern to transmit freely at a spatially constrained point to avoid spectral interference to the co-located communications receivers, this occurs far less often when a spatial mask is formulated for the antenna transmission pattern. The radar waveform's bandwidth needs only to be restricted in the worst-case scenario when a significant spatial constraint exists. This results in a sacrifice of proper range resolution performance far less frequently than when using only the spectral mask to ensure coexistence.

IV. Conclusions

The implementation of a spatial gain quantity constraint map, a "spatial mask", that is projected from a spatial-spectral transmission constraint map has been demonstrated in simulations using a high bandwidth fixed range radar waveform. This allows for a search radar to synthesize its azimuth antenna transmission pattern to scan in directions where no spatial constraints exist. Additionally, where spatial constraints exist on the antenna pattern, the spectral mask can once again be utilized to allow the search radar to continue scanning in the congested direction while reconfiguring the radar waveform bandwidth to mitigate interference to communications receivers. This work demonstrates the dual approach to using a spectral mask by using a spatial mask for wireless coexistence resource management and provides the additional degree of freedom necessary for search radar coexistence applications.

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