Adaptive Beamforming using Scattering from a Drone Swarm

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***Abstract*—There may be situations where a direct line of sight between a transmitter and a receiver is blocked. In such a situation it may be possible to transmit a signal upward from a transmitter to a swarm of drones, each of which carries a scattering object. By positioning each drone properly, the scattered signal from the drones can add coherently in a given direction, forming a beam in that direction. The altitude of each drone is used as a degree of freedom in order to change the phase of the signal scattered by the drone. For a given set of horizontal drone positions, the drone altitudes can be determined to produce a main beam in a given direction. The drone positions can also be optimized to focus a beam in a given direction while producing pattern nulls in other prescribed directions with very small sidelobes.**

***Index Terms*—Drones, arrays, beamforming, scattering.**

I. Introduction

Sometimes communications between a transmitter and a receiver are blocked, so that there is no direct line of sight between the transmitter and the receiver. For example, in search and rescue it is desired to transmit from mobile first responders to a base station that is some distance away. The first responders may be located in a forest or in a valley or in some other environment where direct communications are blocked. Inserting a relay between the mobile transmitter and the base station(s) could restore communications. Using a swarm of drones is one option for accomplishing this [1].

In the concept proposed here, a swarm of N drones is used to fly at a certain altitude above the transmitter (e.g., a transmitter on the ground that is used by the first responders). Using the transmitter on the ground as the origin of the reference frame, the nth drone is at location (x_n, y_n, z_n), and the center of the drone swarm is denoted as (x_s, y_s, z_s), with z_s thus denoting the altitude of the swarm center (with the definition of the center being somewhat arbitrary).

Each drone carries a scattering object, such as a vertical resonant half-wavelength long wire. By positioning the drones appropriately, the scattered signals from each drone can be made to add coherently in a given azimuth direction along the horizon, to beam a maximum signal to a base station at some distance away. The concept is illustrated in Fig. 1. The relaying can be passive, where each drone carries a simple passive scatterer as described, or it can be active, where each drone also has an amplifier on board to amplify the signal that is received and scattered. In this case each drone would be equipped with a sensor, amplifier, and antenna. The electronics remain simple because the phase shifting of the signals from each drone is still performed by adjusting the drone locations. Therefore, the drones do not need phase-shifting circuitry. Each drone is simply a repeater that amplifies the received signal coming from the transmitter on the ground below in the same fashion. The amplifier scheme could be used for those scenarios where further range is needed than could be obtained with purely passive scatterers.

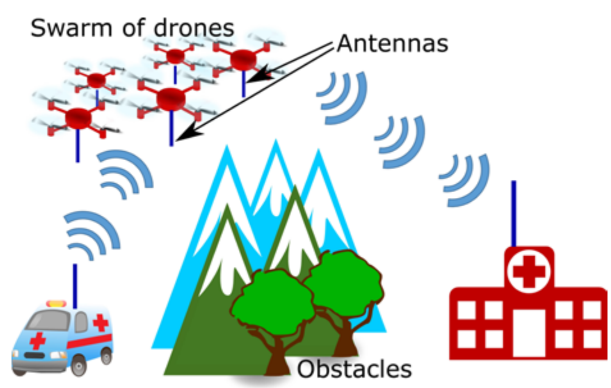

Fig. 1. An illustration of using a swarm of drones to relay a signal from an obstructed transmitter location to a base station by coherently scattering the signal from each drone. Each drone carries a scattering object, acting as an antenna.

II. Analysis

A. Radiation Pattern of Drone Swarm

Assume that we have N drones, each carrying a vertical wire scatterer hanging below the drone. (The length of the wire should ideally be one-half of a wavelength at the operating frequency f to get the maximum scattering, but the most important thing here is that we assume that the scatterer is the same for each drone.) The observer (receiver) is located on or above (at some arbitrary but fixed height h) the surface of the earth at (x, y, h) in the far field, making an angle ϕ in the horizontal plane with respect to the defined x axis, where

$$\tan\phi = \frac{y}{x}. \quad (1)$$

If we assume that the swarm is far enough away from the transmitter that each drone sees the same incident plane wave, and if we ignore mutual coupling between the scatterers, then the dipole moment of scatterer n is given by (for some constant A_0)

$$A_n = A_0 \frac{1}{R_s} e^{-jk_0 r_n}, \quad (2)$$

where

$$r_n = \sqrt{x_n^2 + y_n^2 + z_n^2}. \quad (3)$$

(The time convention of $\exp(j\omega t)$ is assumed and suppressed.) Here R_s is the distance from the transmitter to the center of the swarm. The constant A_0 accounts for the power radiated by the transmitter and the polarization of the transmitter, as well as the length of the wire scatterers. (It is assumed that the transmitter sees each scatterer as being at approximately the same angle θ). The far field radiated in the horizontal plane by scatterer n is then given by [2]

$$E_{\theta n} = \left(\frac{-j\omega\mu_0}{4\pi}\right)\frac{1}{R_r} e^{-jk_0 R_r} A_n \, e^{jk_0 x_n \cos\phi} e^{jk_0 y_n \sin\phi}, \quad (4)$$

where R_r is the horizontal distance from the transmitter to the receiver along the surface of the earth. The total field radiated horizontally by the swarm is then

$$E_{\theta} = \left(\frac{-j\omega\mu_0}{4\pi}\right)\frac{1}{R_r} e^{-jk_0 R_r} \sum_{n=1}^{N} A_n \, e^{jk_0 x_n \cos\phi} e^{jk_0 y_n \sin\phi}, \quad (5)$$

so that

$$E_{\theta} = A_0 \left(\frac{-j\omega\mu_0}{4\pi}\right) e^{-jk_0 R_r} \frac{1}{R_s}\frac{1}{R_r} \sum_{n=1}^{N} e^{-jk_0 r_n} e^{jk_0 x_n \cos\phi} e^{jk_0 y_n \sin\phi}. \quad (6)$$

The magnitude of the normalized far-field pattern (ignoring all constants) is then [3]

$$F(\phi) = \left| \sum_{n=1}^{N} e^{-jk_0 r_n} e^{jk_0 x_n \cos\phi} e^{jk_0 y_n \sin\phi} \right|. \quad (7)$$

To be slightly more explicit,

$$F(\phi) = \left| \sum_{n=1}^{N} e^{-jk_0 \sqrt{x_n^2 + y_n^2 + z_n^2}} e^{jk_0 x_n \cos\phi} e^{jk_0 y_n \sin\phi} \right|. \quad (8)$$

If we assume that the drone swarm is in the far field of the transmitter on the ground, then we can approximate this as

$$F(\phi) \approx \left| \sum_{n=1}^{N} e^{j\phi_n} e^{jk_0 x_n' \cos\phi} e^{jk_0 y_n' \sin\phi} \right|, \quad (9)$$

where

$$\phi_n = -k_0 x_n' \sin\theta_s \cos\phi_s - k_0 y_n' \sin\theta_s \sin\phi_s - k_0 z_n' \cos\theta_s \quad (10)$$

is the phase of the radiating current on scatterer n accounting for the x, y, z coordinates of the nth drone, and the primed (local) coordinates denote positions relative to the center of the drone swarm. The center of the drone swarm is denoted as (r_s, θ_s, ϕ_s) in spherical coordinates, measured from the origin (the transmitter). In going from the unprimed (global) to the primed (local) coordinate system, a common phase term has been ignored, since such a term does not affect the magnitude of the total scattered field. In order for the scattered signal from each drone to add in phase at the receiver, we enforce a beam focusing condition, discussed next.

B. Beam Focusing Condition

The above analysis has not placed any particular constraints on the positions of the drones. However, for beamforming purposes we wish to focus the radiation from the drone swarm in a particular azimuth direction $\phi = \phi_0$ (towards the receiver). To do this, we require that the scattered signal from all N drones adds coherently in the direction ϕ_0. From Eq. (9), this leads to the beam focusing condition

$$\phi_n = -k_0 x_n' \cos\phi_0 - k_0 y_n' \sin\phi_0 - 2\pi k_n, \quad (11)$$

where k_n is an integer. Using Eq. (10), this yields

$$z_n' = \sec\theta_s \left(-x_n'\alpha_s - y_n'\beta_s + x_n' \cos\phi_0 + y_n' \sin\phi_0 + k_n\lambda_0\right), \quad (12)$$

where

$$\alpha_s = \sin\theta_s \cos\phi_s, \; \beta_s = \sin\theta_s \sin\phi_s. \quad (13)$$

Equation (12) is the basic equation for determining what the relative altitudes of each drone should be (relative to the center of the drone swarm) so that the scattered signal from each drone adds up in phase in the direction of the receiver, at $\phi = \phi_0$. For any given geometrical arrangement of the N drones in the horizontal plane, i.e., specifying the local drone positions, Eq. (12) determines what the drone altitudes should be to get the beam focusing in the direction $\phi = \phi_0$. Note that the height of the receiver h is not important, since the receiver is assumed to be in the far field of the drone swarm horizontally.

Equation (9) gives the 2-D far-field pattern in the horizontal plane as a function of the azimuth angle ϕ. However, it may also be desirable to examine the full 3-D pattern in all directions as well, including off the horizontal plane. The magnitude of the normalized 3-D pattern is

$$F(\theta,\phi)=\left|\sum_{n=1}^{N}E(\theta)e^{-jk_0r_n}e^{jk_0x_n\sin\theta\cos\phi}e^{jk_0y_n\sin\theta\sin\phi}e^{jk_0z_n\cos\theta}\right|, \tag{14}$$

where $E(\theta)$ is the elevation element pattern of the scatterers. If the scatterers are simple vertical resonant half-wavelength wires, the elevation element pattern is given by

$$E(\theta)=\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}. \tag{15}$$

If each drone carries a sensor, amplifier, and phase shifter, then each drone can radiate from an arbitrary antenna instead of relying on natural scattering from an object such as a vertical wire. In this case one possibility is to suspend a vertically-oriented linear array of vertically-polarized elements below each drone. This can be used to focus the element pattern more tightly towards the horizon (the horizontal plane $\theta = \pi/2$).

The beam focusing condition (12) allows for an arbitrary positioning of the drones within the swarm in the horizontal direction. Reasonable horizontal configurations could include cross or polygon shapes, with a geometric spacing kept small enough to avoid grating lobes in the pattern.

C. Optimization of Drone Positions

If we allow the horizontal positions of the drones to be degrees of freedom, then we can perform optimizations on the horizontal positions of the drones to achieve other beamforming attributes. One example would be to optimize the horizontal drone positions to produce a null in the pattern at some direction $\phi = \phi_{\text{null}}$, and to lower the sidelobe level of the pattern. Such an optimization routine can be designed to minimize the cost functional

$$c(x,y)=\lambda_1 F(x,y,\phi_{\text{null}})+\lambda_2 \max_{\phi} F_s(x,y,\phi) \tag{16}$$

where λ_1 and λ_2 are positive parameters, and F is the same function as in (9), but this time taken also as a function of the horizontal position of the drones $\underline{x} = (x_1, x_2, \ldots x_N)$ and $\underline{y} = (y_1, y_2, \ldots y_N)$, and F_s is a restriction of F to ϕ angles outside of some interval containing ϕ_0. The first term ensures a minimal radiation at ϕ_{null} while the second term minimizes the side lobe level by forcing the magnitude of the far-field pattern to be minimal outside a neighborhood of the main beam direction at ϕ_0.

III. RESULTS

We first assume a swam with $N = 5$ drones, scattering a transmitted signal at 300 MHz. The center of the drone swam was chosen to be located at an altitude of 100 meters above the transmitter on the earth, and down range by 25 meters from the transmitter in the easterly direction (corresponding to the positive x direction). The positions of the drones are chosen to be located horizontally 0.25 meters apart from each other, flying in the formation of a cross, with one drone at the center of the cross and each of the other four drones located 0.25 meters away from the center drone, to the east, west, north, and south of the center drone. Figure 2 presents the results for this case.

Figure 2a shows the far-field scattered pattern of the drone swarm in the horizontal plane that was achieved by varying the altitudes of the drones in order to achieve beam focusing according to Eq. (12). To demonstrate how the beam can be changed by a simply reconfiguration of the drone swarm, the drone altitudes were first optimized to focus the beam at $\phi = 45^{\circ}$, and then the drone altitudes were changed to focus the beam at $\phi = 270^{\circ}$.

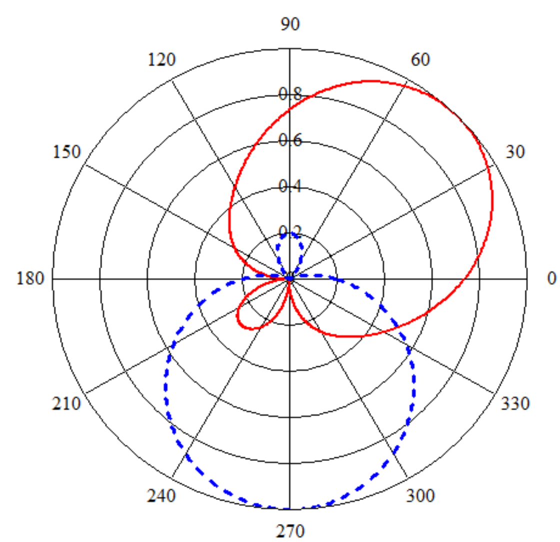

Figure 2a. Normalized far-field pattern from a swarm of five drones flying in a cross-shaped formation at an altitude of 100 meters. To demonstrate reconfigurability, the drone altitudes have been chosen to first create a beam at $\phi = 45^{\circ}$ (red solid curve) and then at 270° (blue dashed curve).

Figure 2a demonstrates that a simple reconfiguration of the drone swarm (changing the drone altitudes) can easily re-direct the beam to any desired direction.

Figure 2b shows the 3-D locations of the drones within the swarm when the beam is focused to 45°, and Fig. 4c shows the locations when the beam is focused to 270°.

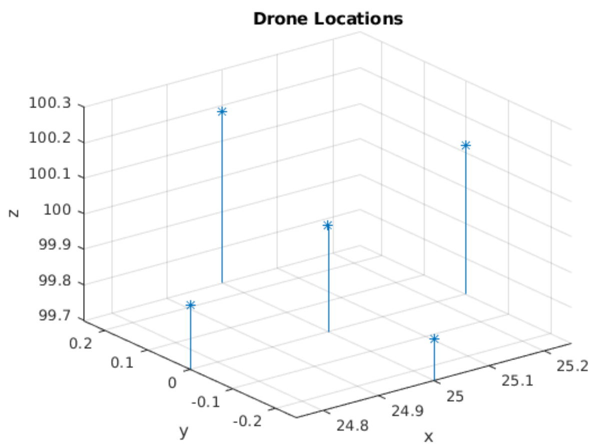

Figure 2b. A 3-D view of the optimized drone locations that were used to produce the far-field scattered pattern shown in Fig. 2 when the beam is focused to 45°. The center of the drone swarm is located at (25, 0, 100) meters. All coordinates are in meters.

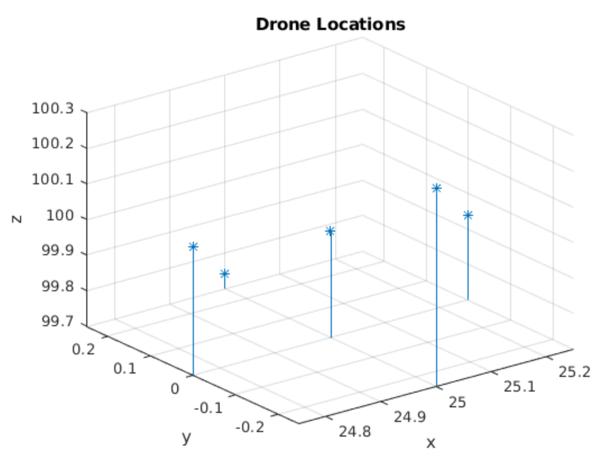

Figure 2c. A 3-D view of the optimized drone locations that were used to produce the far-field scattered pattern shown in Fig. 2 when the beam is focused to 270°. The center of the drone swarm is located at (25, 0, 100) meters. All coordinates are in meters.

In both cases the (x,y) positions of the drones are the same, located in a cross layout with a spacing of 0.25 meters between the elements, as mentioned previously. The vertical positions are very different in the two cases, and are determined by Eq. (12). For a main beam pointing at 45°, the (x, y, z) locations for drones (1, 2, 3, 4, 5) are

$$\begin{aligned} x &= \big(25.000,\ 25.000,\ 25.000,\ 24.750,\ 25.250\big) \\ y &= \big(0,\ 0.250,\ -0.250,\ 0,\ 0\big) \\ z &= \big(100.000,\ 100.182,\ 99.818,\ 99.880,\ 100.120\big). \end{aligned}$$

For a main beam pointing at 270°, the (x, y, z) locations for drones (1, 2, 3, 4, 5) are

$$\begin{aligned} x &= \big(25.000,\ 25.000,\ 25.000,\ 24.750,\ 25.250\big) \\ y &= \big(0,\ 0.250,\ -0.250,\ 0,\ 0\big) \\ z &= \big(100.000,\ 99.742,\ 100.258,\ 100.062,\ 99.938\big). \end{aligned}$$

Figure 3 shows results for a case where there are $N = 9$ drones. Again, the frequency is 300 MHz and the center of the drone swarm was chosen to be at an altitude of 100 meters and down range from the transmitter by a horizontal distance of 25 meters in the x direction. The beam focusing condition (12) is still used to focus the main beam at $\phi = 45°$. However, in this case the (x,y) positions of the drones are not specified ahead of time, but have been optimized to produce a null in the pattern at $\phi = 315°$ and also to minimize the sidelobe level in the pattern. The optimization parameters used in (16) are λ_1=1.9 and $\lambda_2 = 2.8$.

Figure 3a shows the far-field scattered pattern in the horizontal plane.

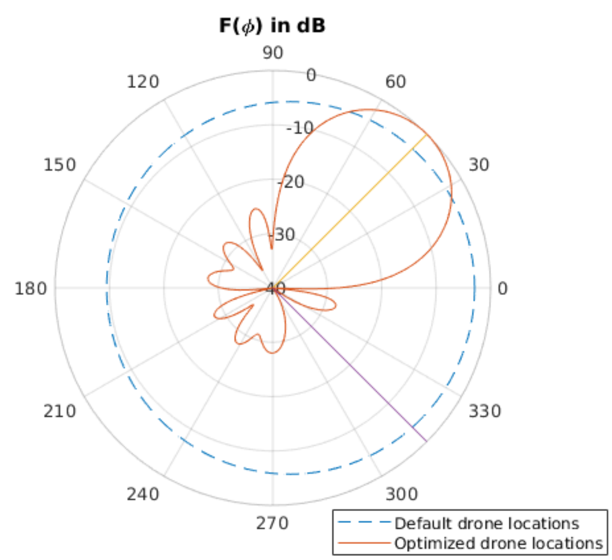

Figure 3a. Normalized far-field patterns from a swarm of nine drones flying at an altitude of 100 meters. The drone positions have been optimized to produce a null at 315° while producing a main beam at 45° and maintaining a low sidelobe level. Also shown is the pattern from the initial (default) drone positions.

The pattern of an initial "default" configuration (where the drones are arranged on a circle in the (x,y plane) is shown along with the pattern of the optimized configuration. As can been seen, the optimization was quite successful at producing a deep null at $\phi = 315^{o}$ as well as maintaining a sidelobe level of less than -25 dB relative to the beam peak.

Figure 3b shows a top view of the drone locations that produced these patterns, while Fig. 3c shows a 3-D view of the drone locations.

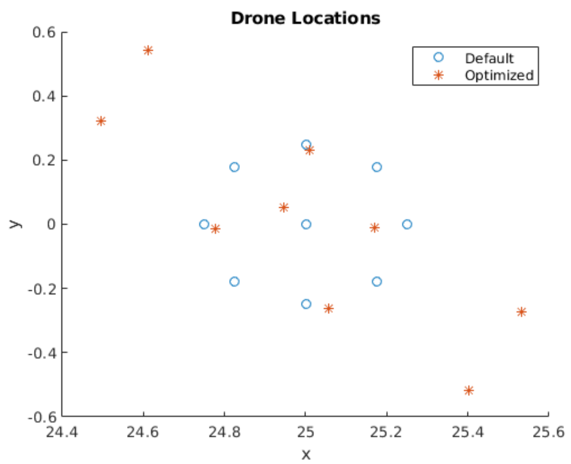

Figure 3b. Horizontal (x,y) positions of the nine drones that were used to produce the far-field scattered patterns shown in Fig. 3a. The optimized positions are shown along with the initial (default) positions. All coordinates are in meters.

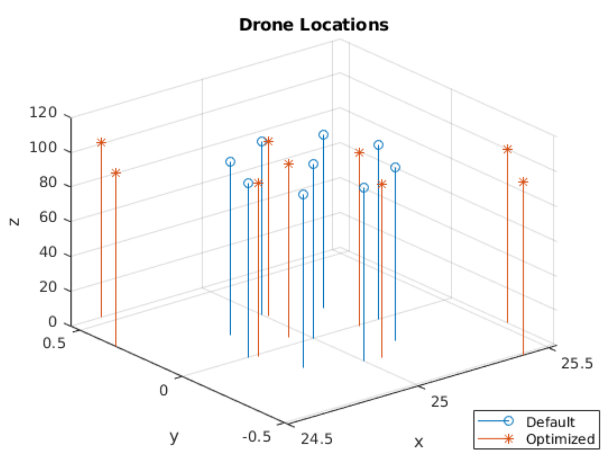

Figure 3c. A 3-D view of the drone locations that were used to produce the far-field scattered patterns shown in Fig. 3a. The optimized positions are shown along with the initial (default) positions. All coordinates are in meters.

IV. CONCLUSION

A simple method for beamforming from a swarm of drones was proposed. In this method a ground-based transmitter radiates upward to illuminate a swarm of drones. Each drone carries a scattering object, such as a vertical resonant half-wavelength wire. Each scattering object acts as an antenna and radiates a signal. By varying the altitude of the drones, the phase of the scattered field from each drone scatterer can be adjusted, to enable pattern shaping from the swarm of drones that then acts as a radiating array.

A beam focusing condition was derived that determines the altitude of each drone in order for the swarm to coherently radiate a main beam in a specified azimuth direction in the horizontal plane, once the horizontal (x,y) coordinates of the drones are specified. In this scheme the horizontal positions of the drones are arbitrary, though the drones should not be positioned too far apart in order to avoid grating lobes. Results have shown that a main beam is created at the azimuth angle specified, demonstrating the effectiveness of the method.

As an extension of the method, the (x,y) positions of the drones can be used as degrees of freedom and optimized in order to produce a pattern with a null in a specified direction and a low sidelobe level. An optimization scheme for accomplishing this was proposed. Results show that the optimization procedure is an effective way to produce a main beam in one direction and a null in another direction, while maintaining a low sidelobe level in the scattered pattern.

Other optimizations schemes are also possible in order to achieve for different pattern effects, and this will be explored in the future.

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