AGILE JAMMING WITH A SWARM OF DRONES

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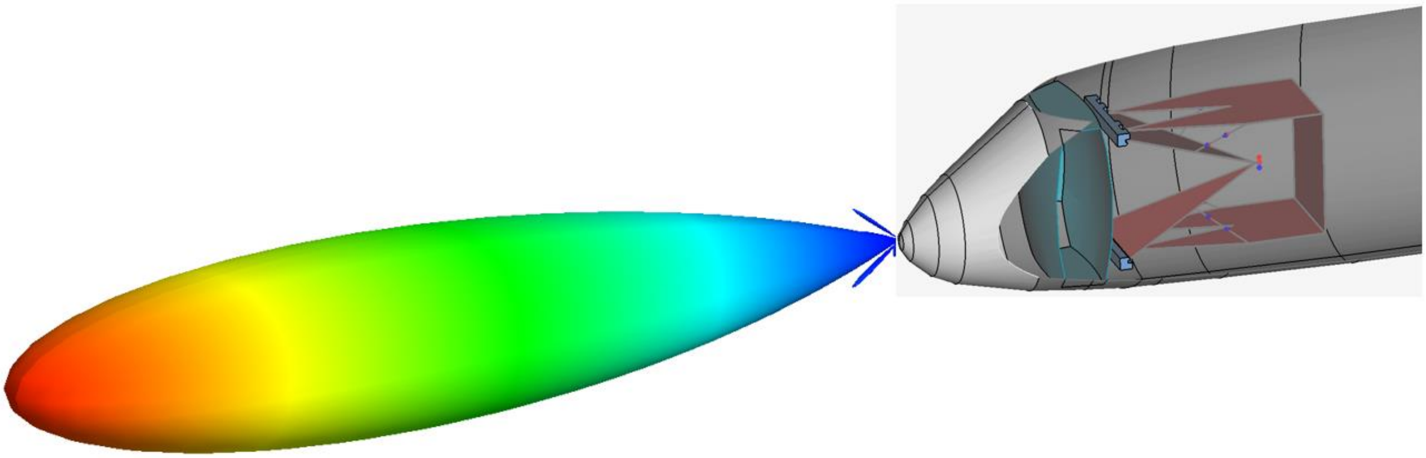

Figure 1 – Ultra-wideband antenna in a drone

Introduction

Studies regarding the projection of force on a modern battlefield almost always involve joint operations in which wireless communication between all assets is a key aspect. For beyond-line-of-sight communication, satellites play an important role, while for reasons of resilience and redundancy and low latency, multi-hop ground-based systems are needed as well. Concerning the assets involved, unmanned aerial vehicles ("drones") are rapidly growing in importance. Especially the concept of swarms of collaborating drones is attractive: they can overwhelm an adversary, while the loss of a fraction of the drones does not necessarily prevent the swarm from carrying out its mission.

In this white paper, the feasibility of effective and agile jamming by a swarm of drones is quantified by means of simulations. This involves ultra-broadband compact antenna design to have a jammer that can operate on any frequency, and the effectiveness of *collaborating* drones to jam a hostile communication system from a distance.

A future white paper will deal with beyond line-of-sight communication by means of terrestrial repeaters as well as satellites, for redundancy, to call in the swarm when it's needed on the battlefield.

Challenges

In the scenario of interest, hostile army units occupy a large area of land. Those units are spread out, and handle communication between them via high-speed point-to-point data links over distances up to 40 km. The goal of a forward friendly unit is to call in a swarm of drones that are on standby at a safe distance, beyond line-of-sight. The drones are to fly in, and collaboratively jam one or more such data links. Challenges are to decide how many drones are needed per hostile link, and to communicate initially beyond line-of-sight. The first challenge is addressed in this white paper while the second, using repeaters as well as satellites, is the topic of future work.

Problem Description and Approach

The capability of a medium-sized drone to jam a hostile radar system or communication link will be investigated based on a realistic example. After obtaining insight into the jamming scenarios, we will describe the design of an ultra-wideband antenna, to be carried on the drone, that can be used at any frequency (Figure 1). In some instances, one drone will not be enough to jam a communication link effectively, but that objective can be achieved with a swarm of collaborating drones. Throughout, the Altair Feko tool suite [1] is used extensively for antenna design, as well as for radar and radio coverage over terrain.

Jamming Power Needed

Jamming effectiveness has been investigated with WRAP (https://altair.com/wrap-applications), which is part of the Feko suite [1], for two cases. Those are a radar station and a point-to-point communication link.

Case 1: Jamming of a radar station

Consider a radar station that operates at 9.9 GHz with an effective isotropic radiated power of 79 dBW, which is the combination of a transmit power of 10 kW and an antenna gain of 39 dBi. The jammer in this example transmits 100 W with an antenna gain of 24 dBi; this jammer could be carried on one drone. The jammer is at a distance of 60 km from the radar, well outside its detection range. Figure 2 shows the impact of the jammer on the radar's ability to detect targets at 300 m altitude. The colors represent the target radar cross section (RCS) in m^2 that can be detected. In the red area, a modest drone can be detected. When the jammer is off, the radar detects targets with RCS of 1 m^2 up to a distance of 24.5 km. When the jammer is ON, this distance has fallen in all directions, never exceeding 16 km. In the direction of the jammer, the distance has fallen to 1 km, meaning that the radar is practically blind in that direction.

Further analysis shows that even a jammer that is 40 dB weaker than this one can be effective: it reduces the detection distance in the direction of the (weak) jammer from 24.5 km (jammer OFF) to 6 km (jammer ON). For later comparison: the strong-jammer's power flux density at the radar station is -63 dBW/m^2; the weak jammer's power flux density at the radar station is -103 dBW/m^2.

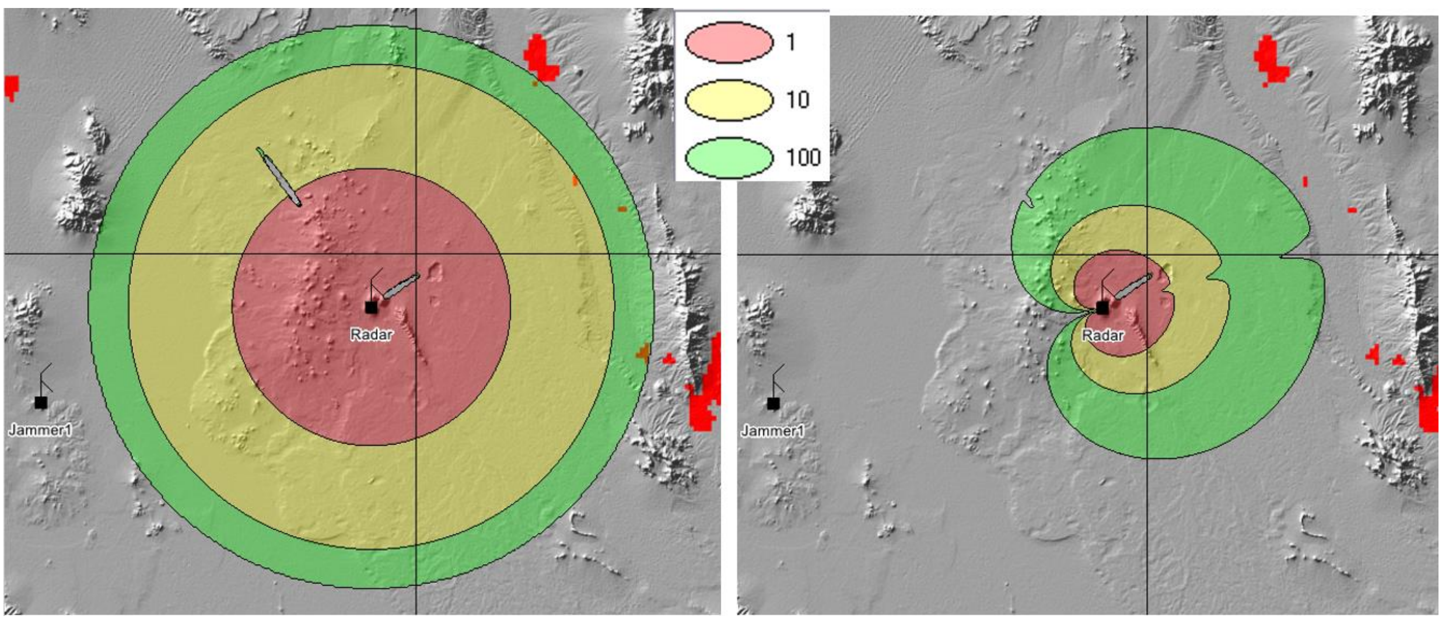

Figure 2 – Ability of the radar to detect targets with a certain radar cross section at 300 m altitude. Left: jammer OFF; right: jammer ON.

The analysis was performed with an empirical propagation model, ITU-R P.2001 [2], which takes the topography of the terrain into account in a deterministic way. The small gaps in radar coverage are due to the effects of hills.

Case 2: Jamming of a point to point communication link

Consider a high-speed point-to-point communication link between two army units, 40 km apart. The antennas used for this link are 1.2-meter dish antennas on 15-meter masts (Fig. 3). The system operates at 2.2 GHz.

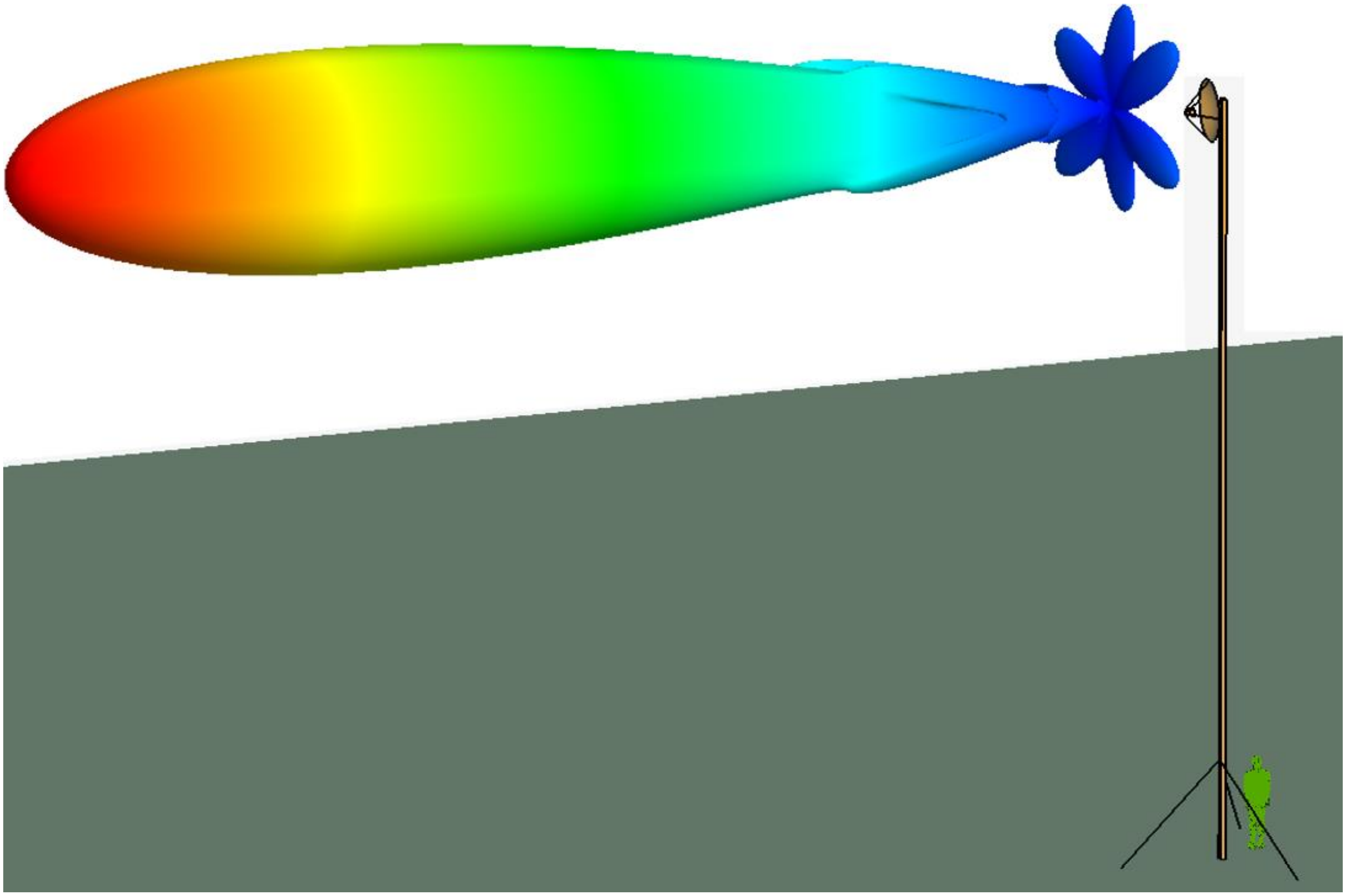

Figure 3 – Communication system with antenna pattern at 2.2 GHz (dB scale)

The transmit power is 1 W, which is enough to communicate without making the probabilities of detection or interception higher than necessary. One may assume that the area between the units is well defended against intruders, so jamming has to be done from a distance. An analysis in WRAP, using Feko results for the precise antenna patterns including side lobes (Figure 3) reveals that, to be most effective, the jammer beam should be on the line from transmitter to receiver. In our example, assuming the area between transmitter and receiver is well-defended, we have placed the jammer on a drone at a distance of 20 km *behind* the transmitter. Figure 4 shows the simulation results with the jammer OFF and the jammer ON. The colors correspond to signal-to-noise-and-interference ratio (SNIR) in dB. For high-speed communication, a SNIR of 22 dB is required. This corresponds to the green color in the plots. For communication at lower data rates, a SNIR of 8 dB (color yellow) is needed. WinProp (https://help.altair.com/winprop/index.htm), which is part of the Feko suite, has detailed wireless standards that show how the achievable data rate depends on the SNIR [3]. For completeness, a SNIR of 1 dB has also been plotted, but then communication is practically impossible. Clearly, in this scenario in which the jammer is 20 km behind the transmitter in the main beam of the receiver, it can easily make communication completely impossible.

The propagation analysis has been performed in WRAP with the Longley-Rice model in area mode [2]. This takes the topography into account in a *statistical* way. The Longley-Rice model was chosen because, when troops are on the move, it is advantageous to have a simulation result that does not depend on the precise topography of one specific location.

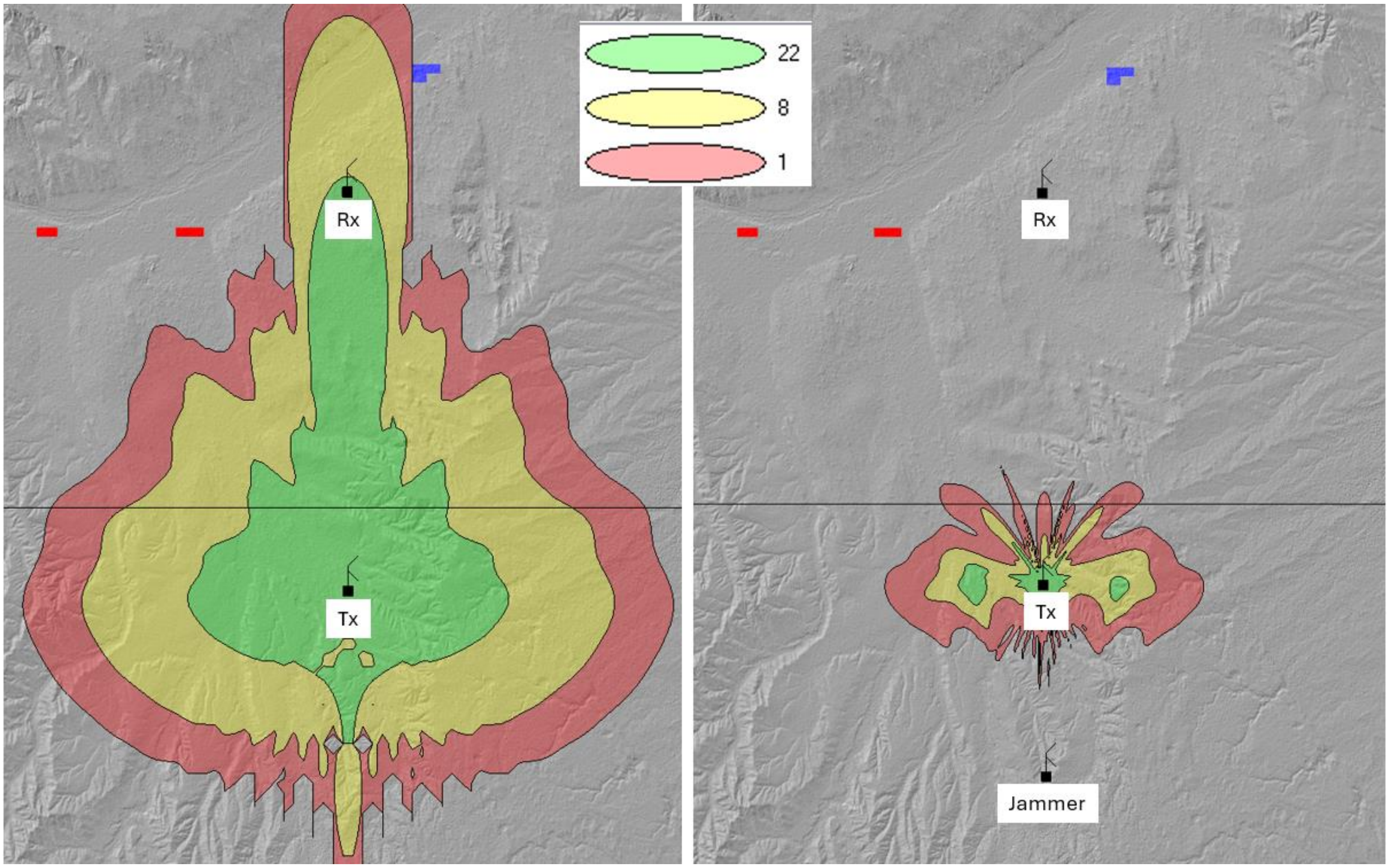

Figure 4 – Ability of the point-to-point link to operate with certain SNIR. Left: jammer OFF; right: jammer ON.

The jammer's power flux density at the receiver is -78 dB/m^2. This makes communication impossible. Further investigation shows that a power flux density of -106.5 dBW/m^2 is already enough to make communication impossible (SNIR 0 dB at the receiver) when the distance between the army units if 40 km.

However, this is only enough if several conditions are satisfied:

- the jammer beam points along the transmitter-receiver axis,
- the communication operator does not increase the transmit power to counter the jamming,
- the distance between the army units is not much less than 40km,
- the communication system does not employ frequency hopping.

We should assume that, to counter the jamming signal, the communication operator will immediately increase the transmitted signal power and will employ frequency hopping. To jam the increased transmit power, the jammer may have to be at least 10 dB stronger. If frequency hopping is used, the jammer may have to increase its power by a further 20 dB or more to be effective, because, not knowing the frequency sequence and timing, the jammer has to spread its power over the entire frequency range used by the frequency-hopping system. To be effective against the system under all these circumstances, we may need 40 dB more than the aforementioned minimum of -106.5 dBW/m^2. Hence, we want to achieve a jamming power flux density at the receiver of -66.5 dBW/m^2. For this, one drone is not enough, because one drone only achieves -78 dB/m^2 at the receiver in this example. Multiple drones in the swarm will need to cooperate.

We see that jamming the communication system is more challenging than jamming the radar system. Part of the reason is that a radar signal has to travel a two-way path, to the target and back, so it suffers attenuation both ways. A communication signal and a jamming signal only travel one way. Against both systems, we have seen that one drone can do the job, but against the radar even a very weak jammer can be effective, while against the communication system, depending on their countermeasures, one drone will quickly not be enough.

In the next section, we will present specifics of the antenna that is used for the jamming operations. After that, we will investigate how a swarm of drones can be effective against the communication system in spite of countermeasures.

Ultra-Wideband Antenna

Using Feko, a compact ultra-wideband antenna has been designed. The aperture width and height are 24 cm and 30 cm, respectively. The lens adds a few centimeters to these. The total length of the device including the lens is 66 cm. The antenna, with its directivity pattern at 2.2 GHz as an example, is shown in Figure 5.

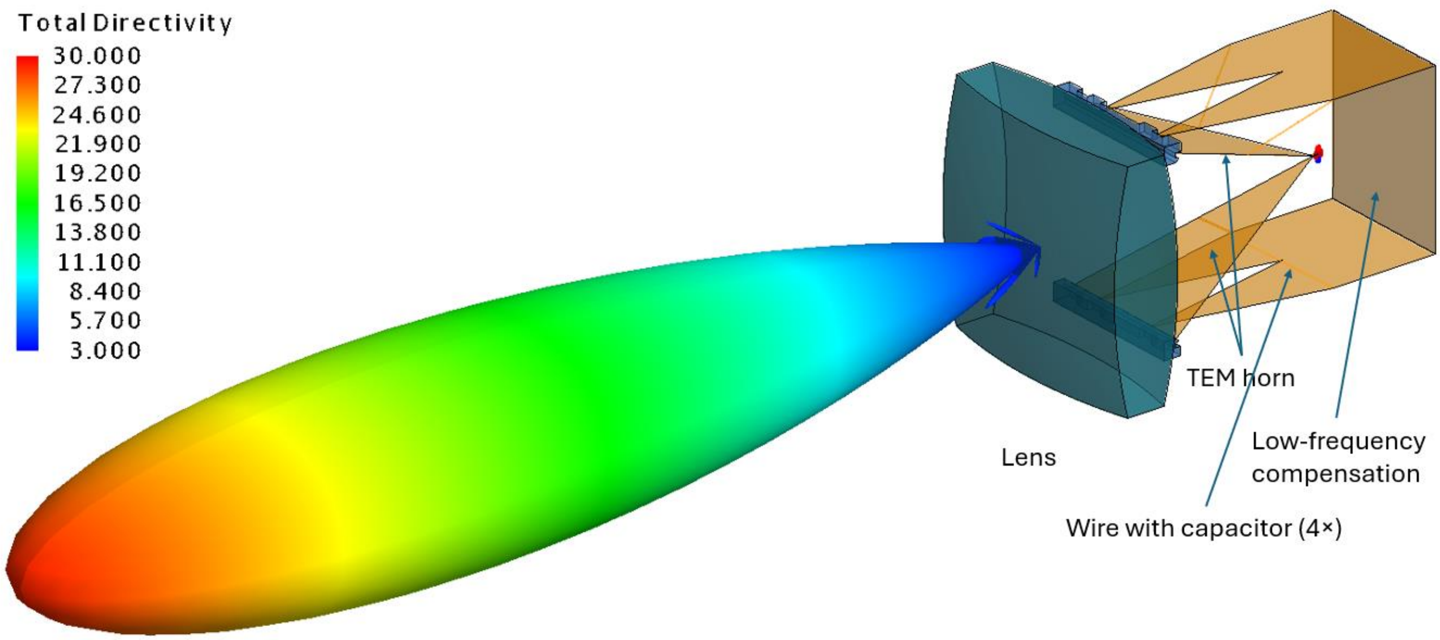

Figure 5 – Ultra-wideband antenna with antenna pattern at 2.2 GHz (linear scale)

The antenna's return loss is below -10 dB from DC to 100 MHz and from 1.14 GHz upward (Fig. 6). Even between these two frequencies, the return loss is acceptable. The highest return loss occurs when the horn length is a quarter of a wavelength. Such an ultra-wideband antenna has several benefits. It can be used to communicate or to listen on any frequency, as well as to jam almost any system, from VHF/UHF to the highest radar frequencies. Furthermore, it can be used to produce powerful ultra-short pulses at high repetition rate to cause hostile systems to malfunction. The antenna can be carried by a medium-sized drone, preferably in the nose, but mounting on the exterior of the drone could also be possible. For smaller drones, this design can be scaled down, at the price of a shift in its frequency characteristics.

The antenna's forward directivity exceeds 2.6 dBi at all frequencies, including the lowest, where it is 5 dBi thanks to the low-frequency compensation (Fig. 7). This means that at all frequencies, including the lowest, radiated power is directed forward. To be fair, since the antenna contains resistors and has a (modest) return loss, the forward *realized* gain, which takes these losses into account, is significantly smaller than the directivity at low frequencies.

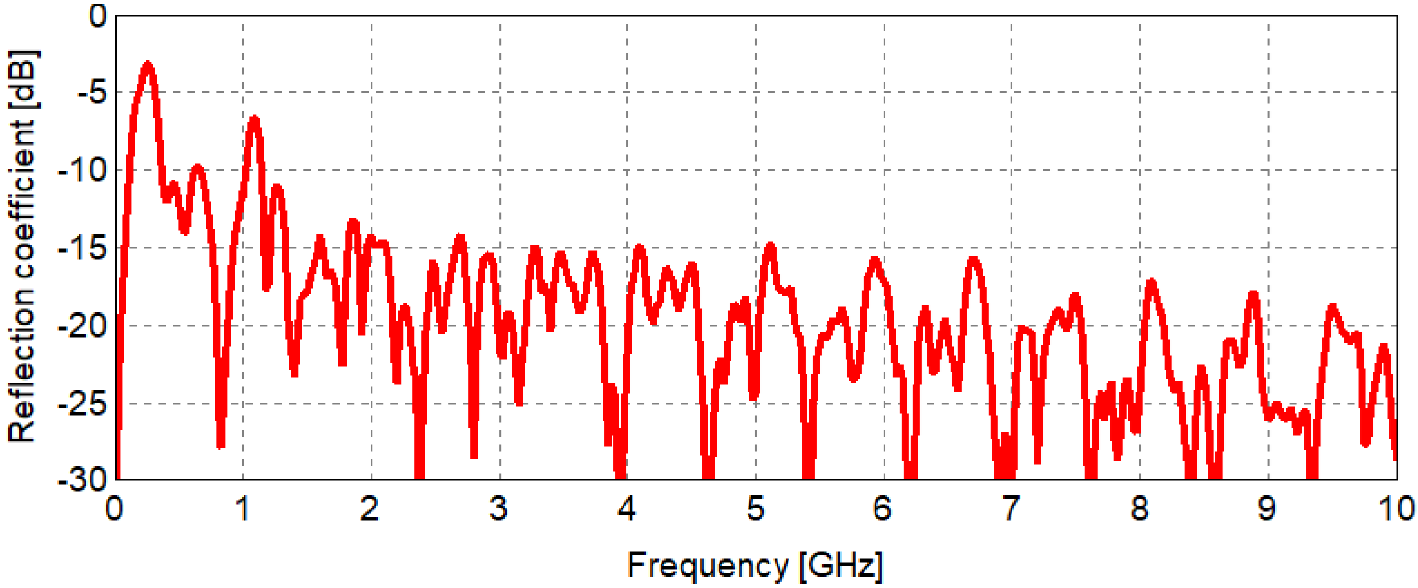

Figure 6 – Ultra-wideband antenna reflection coefficient S_{11}

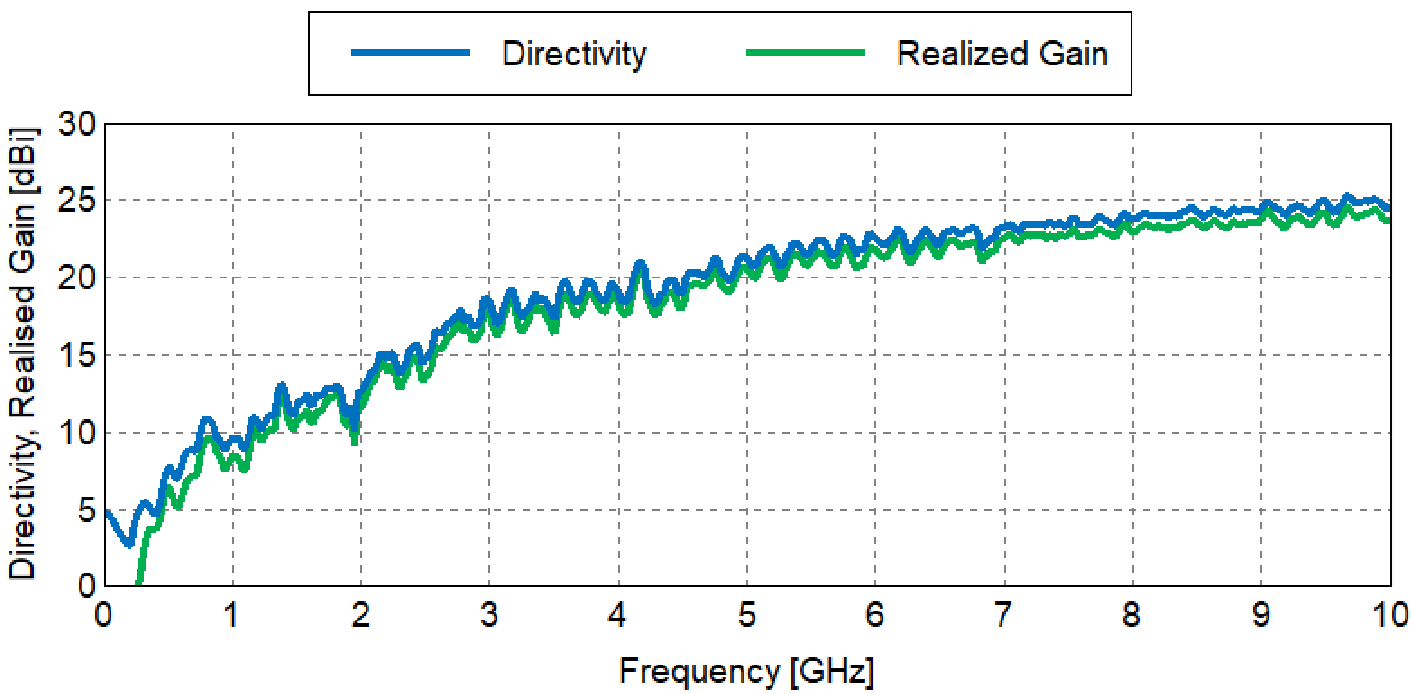

Figure 7 – Ultra-wideband antenna directivity and realized gain

Several techniques have been employed for the design of the antenna to achieve this performance. The basic concept is a TEM horn; this is a horn without side walls so it doesn't have a cut-off frequency. A low-frequency compensation has been added to the horn to prevent a large return loss at low frequencies and to maintain a significant forward directivity at low frequencies [4]. An analysis of the antenna's characteristic modes [5] inspired an improvement at intermediate frequencies. This improvement was realized with wires and capacitors to eliminate a particular unwanted mode by providing a short circuit for that mode at a certain frequency without affecting a wanted mode too much. A modest amount of absorbing material at the horn's edges avoids unwanted far-field effects (a hint of beam splitting) at high frequencies caused by certain hot spots in the local currents. Finally, the lens improves the directivity at high frequencies.

Swarm Operating as One Jammer

We have seen that, to jam the communication link, the jamming power at the receiver has to be -66.5 dBW/m^2. The goal is to achieve this from a safe distance of 20 km behind the hostile transmitter, i.e., 60 km from the receiver. We assume that each drone can direct its beam accurately enough to illuminate the target with practically its peak directivity. This is easy to achieve since the beam of a single antenna is not very narrow.

We will present different cases. In all cases, the swarm consists of 50 drones with an average spacing between them of 17.3 m (10 m in X, Y and Z directions). This is more than 100 wavelengths at 2.2 GHz, so in terms of antenna arrays, the drones form a sparse array. The drones fly high enough to ensure their beams are not attenuated by propagation over terrain.

In the ideal case, the drones, which know each other's relative positions accurately, harmonize the phases of their jamming signals to achieve maximum constructive power at the target. In a variation on the ideal case, there is a random inaccuracy between -45º and +45º in the relative phase of each signal. In both these cases, the drones fly in a known formation that is not a regular grid to reduce wasting power by forming grating lobes. This is important, because the drones are forming a sparse phased array antenna with the spacing between the antennas much larger than half a wavelength. If they were to fly in a regular grid, many powerful grating lobes in useless directions would be formed. In the third case, all drones direct their beams to the target but do not coordinate their phases. The power would still be directed at the target, but the benefit of constructive interference at the target would be lost. Figure 8 shows the results.

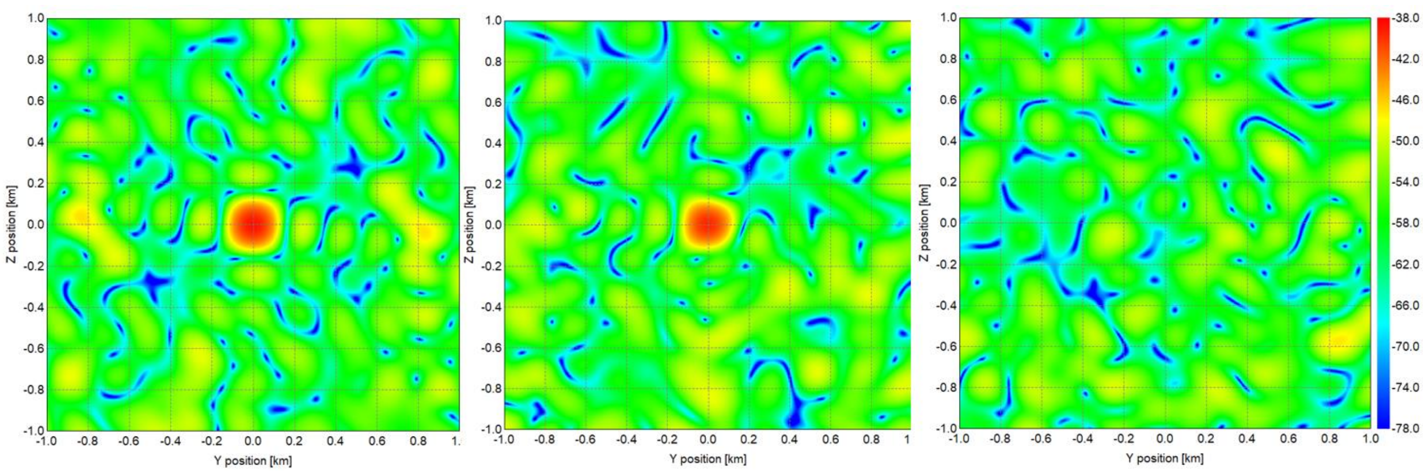

Figure 8 – Power flux density [dBW/m^2] at and around the target produced by a drone swarm
Left: perfect phase coordination. Center: phase inaccuracy between ±45º. Right: random phases

In the ideal case (Figure 8, left) the power flux density at the target is -38.7 dBW/m^2. This is well above the requirement of -66.5 dBW/m^2. The high-power focus has a diameter of 200 m, so accurate aim should not be a problem. Furthermore, even outside the focus, the power is strong enough over an area of multiple km^2.

Of course, in practice there will be inaccuracies in the phase coordination. The center plot in Figure 8 shows the result for the situation where the phases are between -45º and +45º off their ideal value. Remarkably, the power in the focus is only 1 dB less than in the ideal case. The reason is that the radiated field from every drone still makes a *constructive* contribution.

The right-hand plot in Figure 8 shows the power level that is achieved when phase coordination is not possible. Fifty drones still produce significant power in the volume where their beams overlap, with an irregular distribution of local maxima and minima. The goal of -66.5 dBW/m^2 is mostly achieved. During flight, there may be instances where the jamming power at the target briefly falls below the goal, but most of the time the drone swarm makes communication among hostile forces impossible, even if they employ frequency hopping and increase their transmit power.

Conclusion

The Feko tool suite, which includes WinProp and WRAP software, was used to analyze jamming effectiveness in radar and communication applications. To achieve realistic results, an ultra-broadband jamming antenna was designed in Feko and used in subsequent simulations. Radio-frequency propagation simulations were performed with methods that take the terrain topography into account, either in a statistical way for troops on the move or in a deterministic way for fixed assets. For the effectiveness of jamming against communication systems, wireless standards in the Feko tool suite were consulted.

We have demonstrated that one drone will always be enough to jam a radar system, but may struggle to jam a communication link. A swarm of drones, however, can be effective against a communication link, even if the link employs frequency hopping.

References

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