

Analysis of Magnetic Communications for Use on Rotorcraft

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Abstract

Physical channel characteristics of magnetic data communications systems offer key advantages in eavesdropping and jamming prevention. When considering the non-propagating magnetic field, signal strength reduces at a rate of 60 dB per decade of distance traveled from the source as opposed to the 20 dB per decade distance found with propagating Electro-Magnetic waves. This paper intends to quantitatively analyze the feasibility of jamming or eavesdropping upon a rotorcraft-borne magnetic communications system. Results for an envisioned magnetic communications system are provided in terms of far-field (propagating) and purely magnetic (near-field) field components both of which include analysis from the jamming and eavesdropping perspective.

Introduction

TRADITIONAL propagating radio frequency (RF) communications channels are easily eavesdropped upon by remote parties. When high security is desired, strong encryption of these signals is one technique that is used to prevent decoding of sensitive data by unwanted parties. Although encrypted data may be unintelligible by a remote eavesdropper, they will *know that something is there*. This still gives the possibility for triangulation or range-finding of an electro-magnetic (EM) source. In addition, land based eavesdropping equipment using highly directional antennas, can both listen and potentially jam rotorcraft communications (Figure 1).

The concept of magnetic communications implies that only the near-field and non-propagating magnetic component be used for transmission of information. Since magnetic fields decay at a rate of 60 dB per decade of distance, it thus becomes more difficult to build a suitable eavesdropping receiver. Range of a magnetic communications system is ultimately limited to the presence of deep space noise. Typically, a loop of wire much smaller than a wavelength is sufficient to produce a magnetic field. These electrically small loops, or in some cases dielectric discs, produce a relatively strong magnetic field near the antenna and a corresponding weak propagating EM field. There is a low probability that these weaker propagating EM fields can be eavesdropped upon, as is discussed later in this report.

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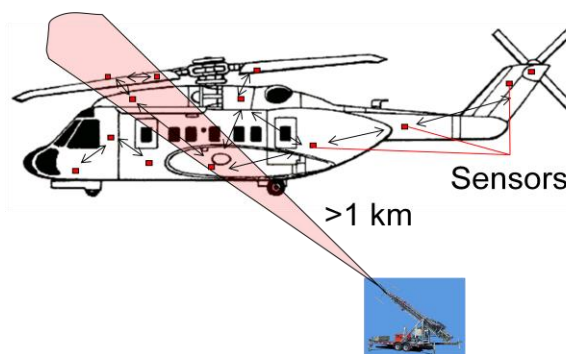


Figure 1 Example jamming/eavesdropping scenario showing ground based high gain directed antenna.

Fundamental limits

Limits on Antenna Gain

When considering the ability of an adversary to eavesdrop on the magnetic communications system from afar, it's important to analyze exactly what kind of signal levels would be available at the eavesdropping location. One approach to determine these levels uses the fundamental limits on antenna gain which are well known in the literature [1, 2]. These fundamental limits dictate the maximum theoretical gain an antenna may have when given the volume occupied by that antenna and the frequency of operation. For the purposes of our application, the antennas on the helicopter will be limited in the amount of volume they can practically occupy. The eavesdropper will be considered to have unlimited volume, within reason.

Once the maximum theoretical gain of an antenna pair is known, a path loss equation can be used to determine the

received power in both the near-field and far-field regions. An analytical description of the near and far field regions is shown in Figure 2. The distance to a region is a function of the wavelength (λ) and diameter (D) of a sphere which encompasses the radiating element.

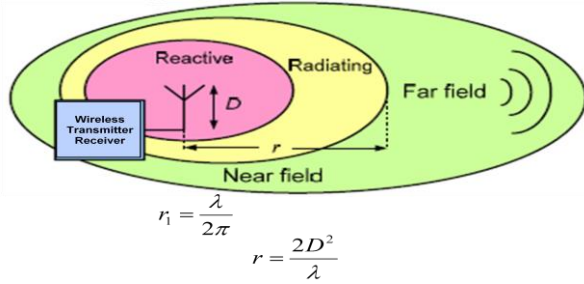


Figure 2 Near, Radiating and Far Field zones with respect to a wireless transmitter.

It must also be considered that in the near field, certain antenna designs are better at creating electric fields (dipole) while other designs are better at creating magnetic fields (wire loop). For this reason, two scenarios are considered, one where the Tx and Rx antennas are like (i.e. electric and electric) and one where they are unlike (i.e. electric and magnetic). It's important to remember that these two cases need only be considered in the near field region.

Table 1 illustrates scenarios where the distance between, and size of the antennas varies. The parameter **a1** in Table 1 is limited by the expected maximum size an antenna can occupy on the helicopter. As will be shown later, **a1** is also limited by the relationship **ka** << **1** which ensures the antenna element remains sufficiently small to ensure minimal far-field radiation.

Considering the values **a1** and **a2** in Table 1, the theoretical maximum gains can be calculated as shown in Figure 3. It can be seen in Figure 3, that the maximum gain for an antenna with dimensions on the order of 3 mm is -80

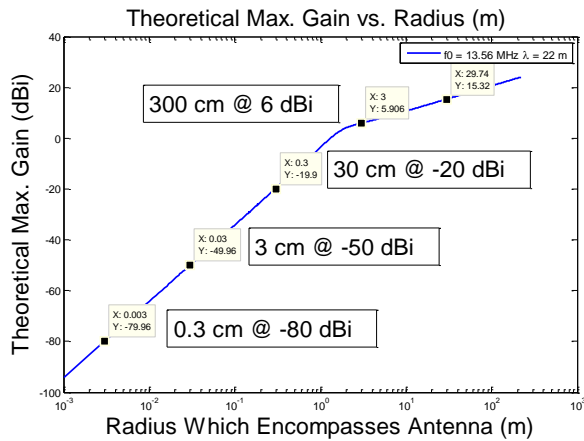


Figure 3 Theoretical maximum gain in dBi for various radii of spheres which completely encompass the antenna element. In this case the frequency of operation, 13.56 MHz has a wavelength of 22 meters.

dBi at 13.56 MHz. As a comparison, most antenna designers will aim for a gain on the order of 0 dBi or greater. Similarly an antenna with dimensions on the order of 3 cm has a gain of -50 dBi. This gain value is the gain provided by the antenna for propagating waves, so in this case, the antennas would be a poor choice for long range communications. The size of antenna used on the helicopter is likely to be on the order 3 mm in size. This is because the intended sensor application requires small package sizes to support proper integration into the helicopter structure, reduce weight and minimize impact on aerodynamic efficiency. However, when considering the remote eavesdropper, there is potentially unlimited space in which to construct a receiving antenna. Considering an antenna with dimensions in the range of 300 cm to 3 m, the

TABLE I
EAVESDROPPING SCENARIOS @ 13.56 MHz

Scenario	a1 (cm) (dBi)	a2 (cm) (dBi)	Ptx (dBm)
1	0.3 (-80)	3 (-50)	30
2	3 (-50)	3 (-50)	30
3	30 (-20)	30 (-20)	30
4	0.3 (-80)	300 (5.9)	30

a1 = Radius which surrounds heli. Antenna
a2 = Radius which surrounds eavesdropper Antenna
f0 = Frequency of operation
Ptx = Transmission Power of heli. Antenna
d = Distance between helicopter and eavesdropper
dBi = Theoretical maximum isotropic gain

theoretical maximum gains are 6 and 15 dBi respectively.

Using the maximum theoretical gains of Figure 3, the received signal strength can be determined for the scenarios of Table 1. Figure 4 shows the results for Scenario 1 and

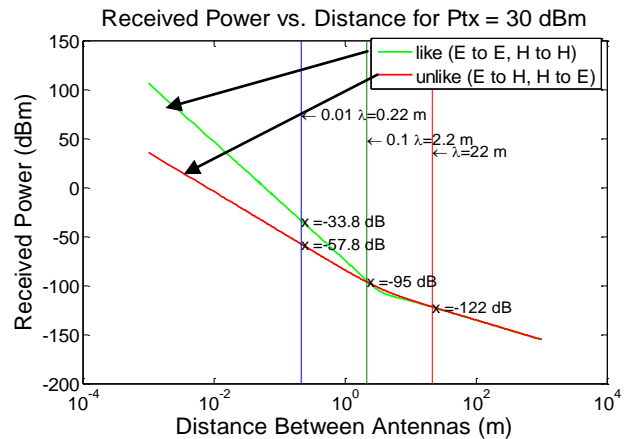


Figure 4 Received Power vs. Distance for the antennas in scenario 1 of Table 1.

that the received signal strength at 1 meter is -73 dBm which is a realistically detectable signal. Similarly at 2.2 meters (near-field/far-field boundary) the received signal strength is -95 dBm. Beyond 2.2 meters the far-field region begins and the signal strength decays at a slow rate such that at 100 meters the received strength is -135 dBm and at

TABLE II

RECEIVED SIGNAL @ 13.56 MHz $\lambda = 22m$

Scenario	Prx (dBm) @ 1 m	Prx (dBm) @ 10 m	Prx (dBm) @ 100 m	Prx (dBm) @ 500 m	Prx (dBm) @ 1 km
1	-73.6 -83.8	-116	-135	-149	-155
2	-43.6 -53.8	-85.6	-105	-119	-125
3	-16.5 -6.28	-25.0	-44.9	-58.9	-64.9
4	-17.8 -28.0	-51.0	-79.2	-93.2	-99.2

Values in bold italics are for like Tx and Rx antennas, all others are for unlike Tx and Rx antennas.

500 meters -149 dBm.

Table II summarizes the results for the other scenarios listed in Table I. Scenario 4 of Table II shows that it is still feasible to detect signals from a helicopter borne antenna as small as 3 mm in radius when 30 dBm of input power is used at 13.56 MHz. Noting that the Rx antenna for all scenario's in Table II is 3 meters in radius, it is still a feasible size for a ground based eavesdropper. The received signal of -99.2 dBm for scenario 4 is well within the reach of an inexpensive modern radio receiver. When researching the claims of recent near-field communications technologies such as those from FreeLinc[®], it is clear that there is still some level of far field radiation. FreeLinc[®] claims that the far field radiation of their modules is up to 60 dB less than a comparable RF system. When addressing the concern of eavesdropping they recommend intentionally adding an artificial noise floor to mask or destroy the far-fields. From a jamming perspective, FreeLinc[®] recommends a shield be used around their modules to shield them from any incoming far-field radiation.

The results of Table II support the need for these additional measures where the absolute best jamming and eavesdropping resistance is required.

Another typical frequency of operation for near-field communications devices is around 125 kHz. Table III gives the received signal strength for a 125 kHz system. In this case the wavelength is 2.4 km meaning the loops are physically very small in comparison with the wavelength. Keeping in mind that both Table II (13.56 MHz) and Table III (125 kHz) are using identical loop sizes, it is clear that operating at 125 kHz has the added benefit of further reducing far-field radiation levels for distances of 10 m or

greater. It must also be pointed out that for a distance of 1 m; there is little difference in received signal strengths when comparing the 13.56 MHz system with the 125 kHz system for **like** antennas. When **unlike** antennas are considered, the 125 kHz system has the advantage of further field strength reductions meaning an eavesdropper or attacker listening with a high gain antenna would have harder time hearing the 125 kHz signal as opposed to the 13.56 MHz signal assuming identically sized antennas at both frequencies.

TABLE III

RECEIVED SIGNAL @ 125 kHz $\lambda = 2380m$

Scenario	Prx (dBm) @ 1 m	Prx (dBm) @ 10 m	Prx (dBm) @ 100 m	Prx (dBm) @ 500 m	Prx (dBm) @ 1 km
1	-73.3 -125	-133 -165	-194 -205	-232	-237
2	-43.3 -94.9	-103 -135	-164 -175	-202	-207
3	-16.7 -34.9	-43.3 -74.9	-104 -115	-138 -142	-146
4	-13.3 -64.9	-73.3 -105	-134 -145	-168 -172	-176

Values in bold italics are for like Tx and Rx antennas, all others are for unlike Tx and Rx antennas.

Radiation Resistance and Gain

To support the findings of the previous sections, it is also useful to determine values of radiation resistance for antennas occupying a given volume. This will provide a gauge by which these antennas can be compared to mainstream antennas which have appreciable radiation resistances (>1 Ohm). The classical definition for antenna gain is given by:

$$G = \frac{R_{rad}}{R_{rad} + R_0} \frac{P_d}{P_{avg}} \quad (1)$$

Where G is the resultant antenna gain, R_{rad} is the radiation resistance, R_0 is the loss resistance, P_d is the power density and P_{avg} is the average power density at a distance. Assuming that the loss resistance, R_0 is very small ($\ll 1$) we can look at the variance of R_{rad} vs. operation frequency for a fixed size antenna. For an electrically small dipole (electric) antenna the radiation resistance is approximated by:

$$R_{rad(Dipole)} = 790 * \left(\frac{l_{th}}{\lambda} \right)^2 \Omega \quad (2)$$

Where l_{th} is the length of one antenna element. Similarly for a magnetic loop the radiation resistance is given by:

[®] FreeLinc is a registered trademark of Radeum, Inc., DBA Freelinc

$$R_{rad(Loop)} = 31200 * \left(\frac{(Na)^2}{\lambda^4} \right) \Omega \quad (3)$$

Where N is the number of loop turns, and a is the loop radius. Examining equations 2 and 3 we can see that in an electric dipole, the radiation resistance increases with the length squared whereas in a magnetic loop the radiation resistance increases with either number of turns (N) or area squared. Notably the magnetic loop radiation resistance decreases with the wavelength to the power of 4. Table IV gives the theoretical maximum radiation resistances for magnetic loops and electric dipoles for two different frequencies and four different radii.

The squared and fourth power dependence on area for the electric and magnetic elements is clear in Table IV. The theoretical maximum gain achievable for a given pair or antennas has already been shown in Table II. What Table IV provides is a direct gauge to determine just how difficult it is to achieve a certain radiation resistance. Considering that a normal antenna design might focus on maximizing radiation resistance to a value greater than 10 Ohms; the values in Table IV show that it would be very difficult to achieve a radiation resistance greater than 1 Ohm at 125 kHz. When considering the 13.56 MHz radiation resistances however, it is more feasible to create a loop or dipole antenna with excellent radiation resistance as the loops or dipole elements approach a wavelength in size. Even for the smallest radius (0.3cm), loops or dipoles at 13.56 MHz show some radiation resistance and will give rise to propagating waves. This reinforces the results of Tables II and III where it was shown it's not impossible to eavesdrop on the magnetic communications signal given the right combination of Tx power and loop size. Specifically, referring to Eq. 1, there may be sufficient gain for a modern receiver to detect a signal.

TABLE IV
THEORETICAL MAXIMUM RADIATION RESISTANCE FOR:
MAGNETIC LOOP (N=1)
(ELECTRIC DIPOLE)

Frequency	a=0.3cm	a=3cm	a=30cm	a=300cm
125kHz	7.7E-19 (1.3E-9)	7.7E-15 (1.3E-7)	7.7E-11 (1.3E-5)	7.7E-7 (1.3E-3)
13.56MHz	1.1E-10 (1.5E-5)	1.1E-6 (1.5E-3)	1.1E-2 (1.5E-1)	110 (15)

Bidirectional Communications Link and Prototype

The previous sections have outlined the advantages of using the magnetic portion of the EM field as an effective communications medium with the added advantages of (a) reliable and robust communications in the presence of jamming signals and (b) security from eavesdropping receivers. The next step is to outfit the physical layer of communications with three or four layers from a notional

open systems interconnection (OSI) model and demonstrate the benefits of jamming resistance and security from eavesdroppers. The two lowest layers are now discussed beginning with the physical (PHY) layer and following up with the medium access control (MAC) layer.

PHY: Initial applications of using magnetic communications such as passive keyless entry (PKE) have used pulse position modulation (PPM) to communicate marks and spaces traditionally used in binary communications. This method is more than adequate for the low data rates required of PKE systems in which a remote terminal (key) is bound to a specific fixed terminal (automobile). In addition to the low data rates, data bandwidth is limited, restricting the overall functionality of a sensor type of network that may be required for a helicopter. Thus our prototype was developed to use Gaussian minimum shift keying (GMSK) modulation for the physical layer. A block diagram for transceiver is shown in Figure 5.

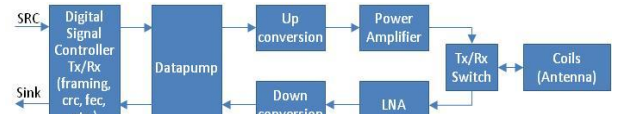


Figure 5: PHY transceiver block diagram

MAC: The MAC layer was implemented in software using time-division-multiple-access (TDMA) with a provision for up to thirty two transceivers in which one transceiver was configured as the master time keeper that transmitted a sync pulse at the start of each frame. In addition to keeping the implementation simple, the TDMA architecture makes more efficient use of the available data bandwidth as long preambles are not required for purposes such as clock recovery and synchronization. The TDMA frame is as outlined in Figure 6.



Figure 6: TDMA MAC Frame

This full duplex communications scheme was implemented using commercial-off-the-shelf (COTS) components. The first iteration achieved channel data throughputs of 4 kbps and the second iteration achieved an over ten-fold increase to approximately 45 kbps. The design capacity of the network is 250 kbps. Bit-error-ratio (BER) measurements using nominal telecommunications polynomials (PRBS¹⁵) were better than 10⁻⁸ over a range of 2 meters using a carrier frequency of 13.56 MHz. These values were measured using a 1st discrete component prototype shown in Figure 6. Once the 1st prototype was developed, a more refined and compact prototype was implemented on a single layer PCB as shown in Figure 7.

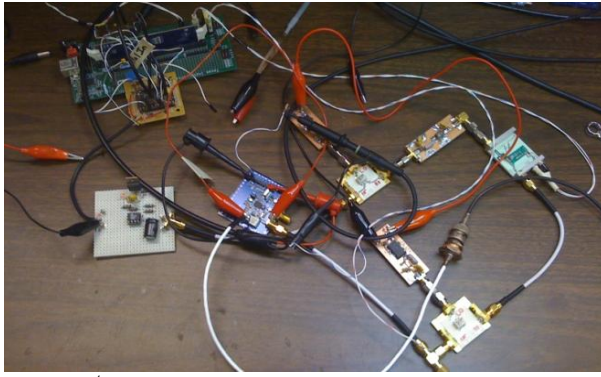


Figure 6 1st discrete component Magnetic communications transceiver prototype

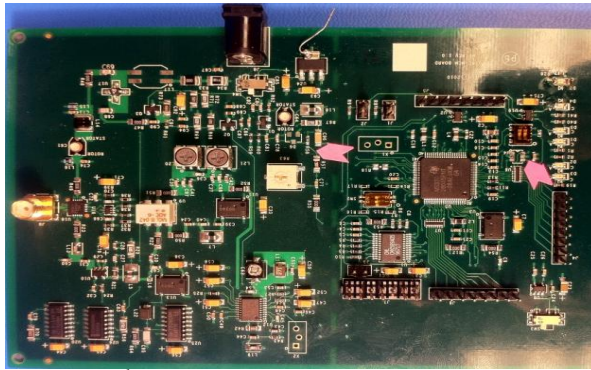


Figure 7 2nd Magnetic communications transceiver prototype on single layer PCB

Conclusion

This work has shown that through careful selection of frequency, transmit power and magnetic coil size, transmissions between points on rotorcraft can be significantly secured from remote eavesdropping and jamming. Use of an LF magnetic communications system with range < 2 meters was shown to be practical using off-the-shelf components and power levels available to small sensors.

Acknowledgements

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