A Mechanically-Based Antenna (AMEBA) Enabling Communication in RF-Denied Environments

Jarred Glickstein[1] and Soumyajit Mandal[2]

[1]Department of Electrical Engineering and Computer Science, Case Western Reserve University

[2]Department of Electrical & Computer Engineering, University of Florida

Abstract

Wireless communications between the earth's surface and underground or deep-water facilities is limited by the strong attenuation of electromagnetic (EM) waves within conductive media such as earth or seawater. These environments are therefore considered RF-denied. Extremely low frequency (ELF) transmitters would enable long distance communication through conductive media, however at these frequencies electrical antennas require large facilities and high power consumption. We have developed an ultra-miniaturized and highly power-efficient ELF transmitter using a mechanically-rotated magnetic dipole instead of an electrical antenna. Our radically different approach has a broad range of application including communication from the Earth's surface to submarines and in emergency search-and-rescue missions.

The ELF Channel

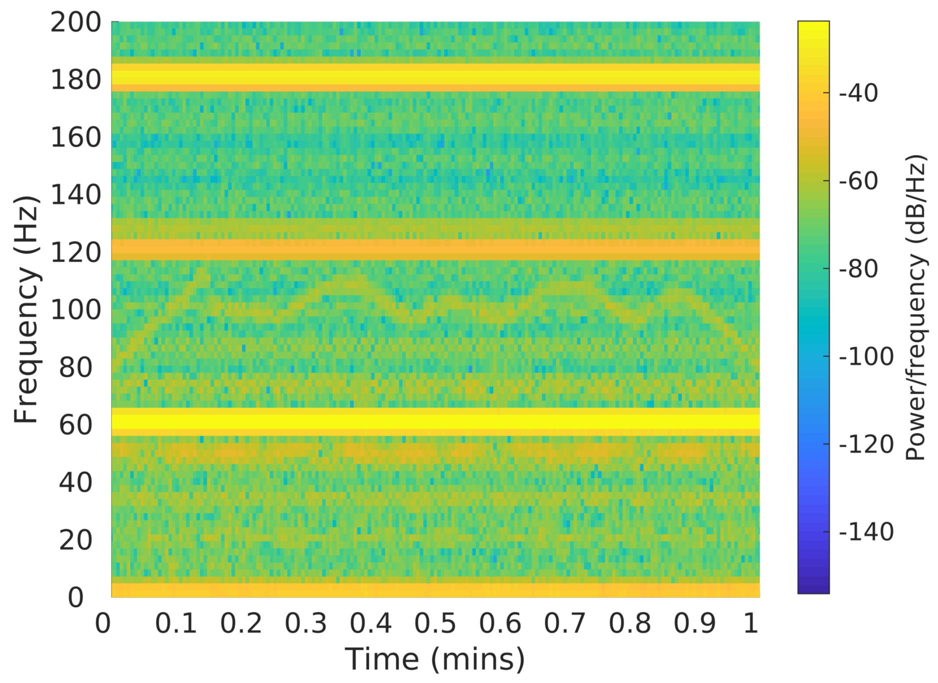

Figure 1: Spectrogram showing part of the ELF channel with data transmission and nearby interference.

The ELF channel is characterized by a variety of interference sources; one of particular concern is mains hum (from power lines) and its higher harmonics. The first iteration transmitter operates at a nominal frequency of 100 Hz with a bandwidth of 96-116 Hz. A spectrogram of data transmission in this channel along with nearby interference is shown in Figure 1. Active Twin-T notch filters are used to remove this interference and a low noise preamplifier (SR560, noise floor 4 $nV/\sqrt{Hz}$) amplifies the signal. A lock-in amplifier (SR860) is used to demodulate to baseband.

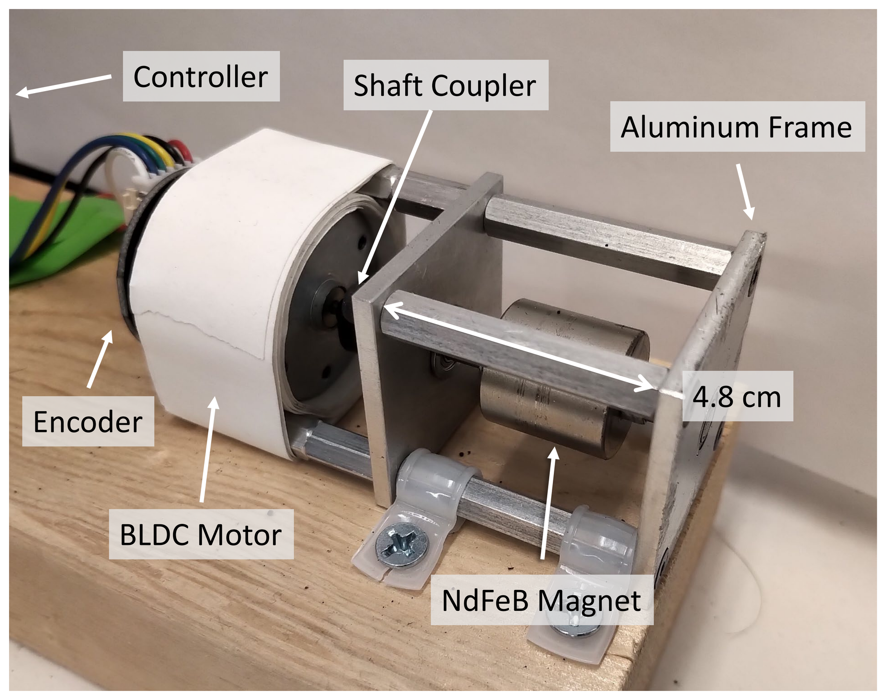

Figure 2: A labeled photo of the prototype mechanical transmitter. Controller electronics are not shown.

Realized Transmitter

An electro-mechanical transmitter designed to operate at 100 Hz was realized using a small brushless DC (BLDC) motor which drives a grade N42 neodymium alloy (NdFeB) magnet. The transmitter assembly is shown in Fig. 2. The mechanical transmitter has inertia, which requires acceleration $\alpha(t)$ and modulation torque τ_{mod} remain finite. To satisfy these constraints we developed a continuous phase modulation (CPM) scheme with no discontinuities in $\varphi(t)$ or its derivative $d\varphi(t)/dt = \omega(t)$. We call this scheme M-ary CP-FSK, with a waveform defined as

$$s(t) = A_c \cos\left(\omega_0 t + 2\pi\Delta f \times (n * h)(t)\right),$$

where $h(t)$ is the impulse response of a low-pass filter (LPF) and $n(t) \equiv \int_0^t m(t_1)dt_1$ is the filtered version of the transmitted symbols $m(t)$. This integral ensures that $\varphi(t)$ remains continuous (as required for a CPM waveform), as does its derivative.

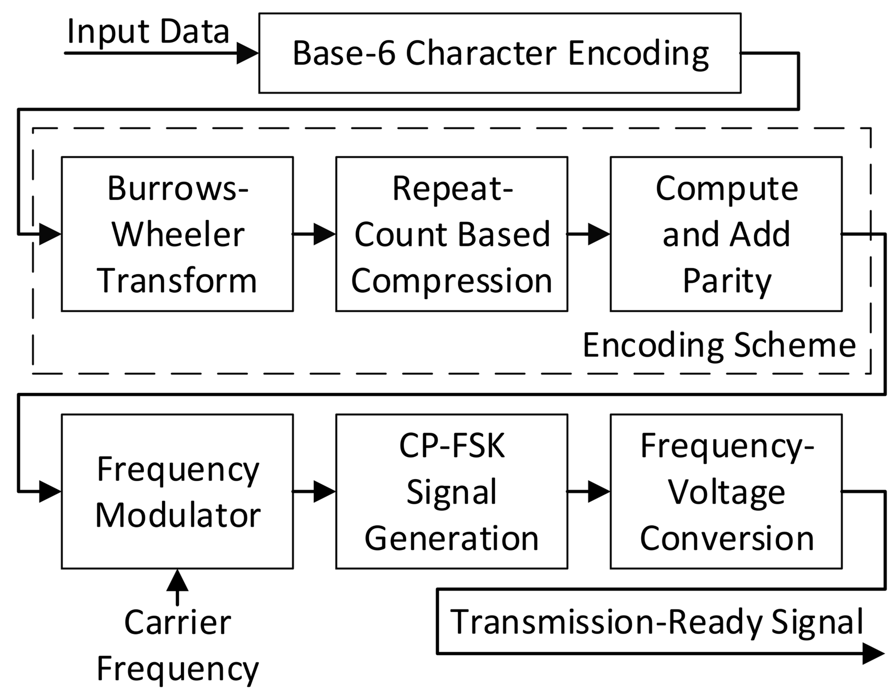

Figure 3: Data encoding scheme for the transmitter, including compression and error checking capabilities.

Experiment Performance

Increasing the number of symbols M increases the required rms motor acceleration σ_α (and therefore power) to transmit a symbol, and also increases the number of bits per symbol. This trade-off suggests an optimum value of M that minimizes the power required to transmit a fixed-length message. The value of σ_α in terms of the bit rate R_B is modeled as

$$\sigma_\alpha = \frac{\pi R_B^2 \sigma_D}{(\log_2(M))^2}.$$

The optimum value using this model is $M = 7$. Using 7-ary CP-FSK, each symbol is encoded as two base-6 bits. The 7th level is used for compression and error checking controls. The encoding scheme is outlined in Figure 3.

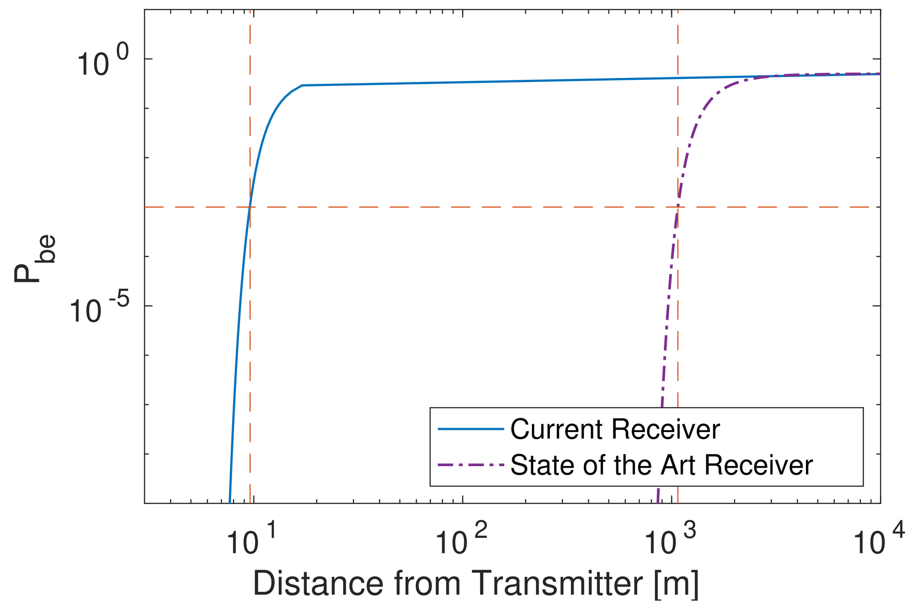

Figure 4: Projected BER performance using the current B-field sensor and the much larger AWESOME receiver [2]. The horizontal line denotes $P_{be} = 10^{-3}$.

Applications

We have explored applications in communication through conductive media - examples include bidirectional communication with submarines and in caves for search and rescue missiosn. Our transmitter has applications in other areas as well, which include:

1. Study of the ionosphere
2. Field propagation through soil
3. Unregulated communication channels

These applications are enabled by the unique properties of the ELF band, which include:

1. Low skin depth in conductive media
2. Not regulated by the FCC below 9 kHz
3. ELF waves natrually occur between the Earth's surface and the ionosphere

Results and Conclusion

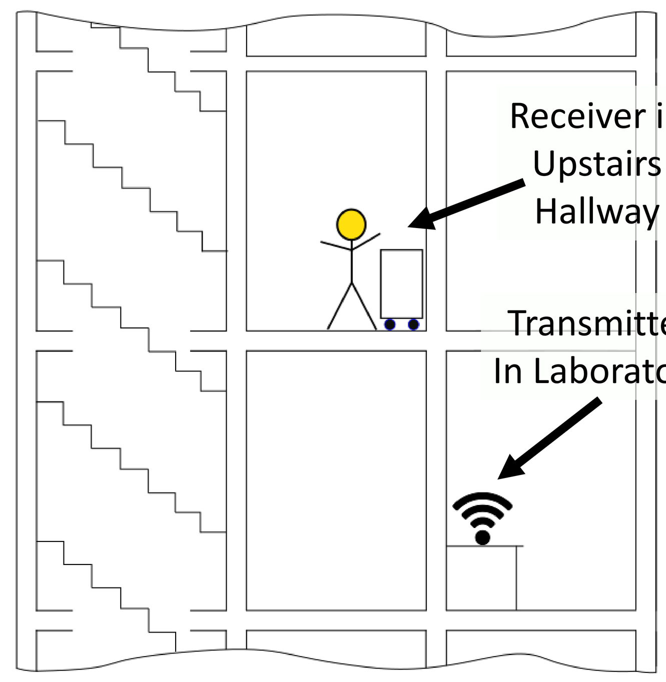

Figure 5: Position of transmitter and receiver for non-line-of-sight (NLOS) communication experiments.

The transmitter can successfully transmit data through solid walls to a distance 4.67 m away. The experimental setup for the version 1 prototype is shown in Figure 5.

	Version 1	Version 2
Carrier Frequency	100 Hz	500 Hz
Effective Transmit Distance	4.67 m	1 km
Dimensions (HxWxD) [in]	1.5x1.5x3.25	2x2.25x8
Magnet Volume	1.2 in^2	82 in^2

Table 1: Comparison of version 1 and 2 transmitters.

The next iteration of design will use a larger magnet and a state of the art receive antenna [2]. With these improvements the effective transmit distance is expected to be beyond 1 km. The carrier frequency will be increased to reduce powerline noise.

Contact Information

Jarred Glickstein, Ph.D. Candidate.
EECS Department,
Case Western Reserve University.
<jarred@case.edu>

Further Reading

[1] J. Glickstein, J. Lang, S. Choi, et al. Power-efficient ELF Wireless Communications using Electro-Mechanical Transmitters. *IEEE Access*, 8, 2019.

[2] M. Cohen, U. Inan, and E. Paschal. Sensitive Broadband ELF/VLF Radio Reception With the AWESOME Instrument. *IEEE Transactions on Geoscience and Remote Sensing*, 48, 2010.

[3] L. Couch. Digital and Analog Communication Systems, 4th ed. Macmillan Publishing Company, 1993. b